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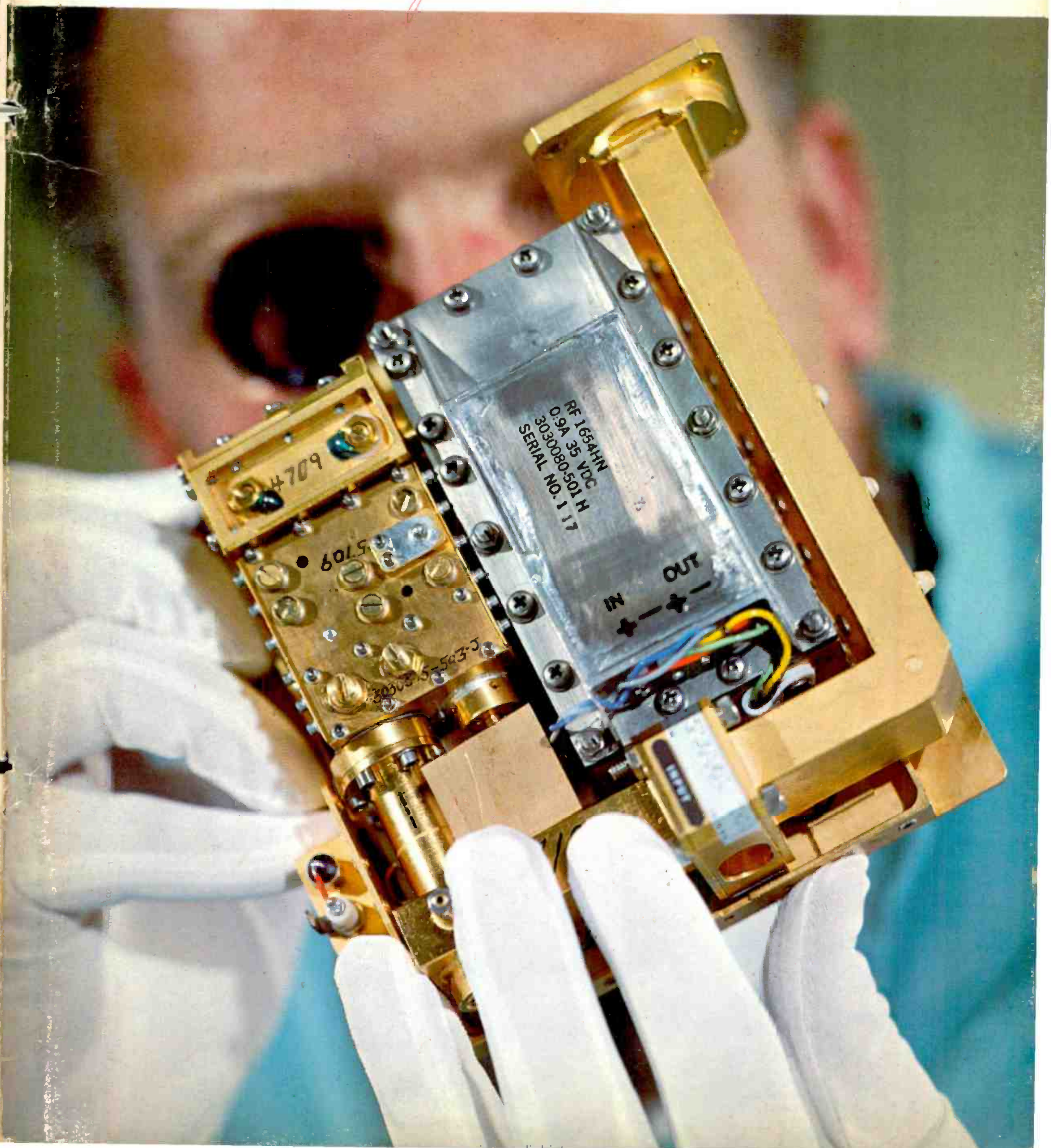
See Pg 91



Microwave devices and special electronic components

Two of RCA's activities in Electronic Components are featured in this issue of the *RCA Engineer:* the Microwave Devices Operations Department (MDOD) and Special Electronic Components (SEC).

As industrial time goes, the art and science of making and using microwave devices is quite young. And yet these devices too have been caught up in the incredibly swift and ever-increasing pace at which all technology is advancing. It is hard to believe that from the first ten-pound magnetron until today's postage-stamp-sized microwave integrated circuit only about 30 years have passed.

To stay in the running, therefore, requires creative but practical engineering—engineering that produces sophisticated devices that not only perform the functions needed but that can be manufactured efficiently and sold at a profit. The Microwave Devices Operations Department has reached its present well-entrenched position in the microwave market by using this kind of engineering—as the papers in this issue of the *RCA Engineer* show.

Right now microwave devices are used mostly in existing government electronics systems, both military and aerospace. We are supplying devices for many of these systems and for other commercial systems as well.

MDOD's future rests on a well-thought-out plan. The plan, which is well balanced, calls for supplying hardware to the military as long as it is needed, but it also includes doing the groundwork needed to expand in the commercial market when military demands fall off. For example, pencil-tube subsystems for aircraft collision avoidance systems; cost-reduced medium-power traveling-wave tubes for communication systems; in solid states, the transferred electron oscillator to replace the klystron in local oscillators.

The two groups in Special Electronic Components—Thermoelectric Products and Superconductive Products—are developing exotic technologies. Thermoelectric generators convert heat into electric current. Superconductive Niobium-Tin conductors are used for making the windings of very high field, cryogenically-operated magnets. RCA has demonstrated and is now supplying excellent products in both of these fields. We await an increasing demand for them.

One of the most exciting developments in the microwave solid-state area is our ever-increasing work with MIC's—microwave integrated circuits. In contrast to our old way of doing things—starting with the customer's need, to idea, to block diagram, to schematic, to wiring diagram, and to production drawing—we have a new approach. The customer's need goes through computer-aided design to feasible configuration and expected performance, into the Solid-State Technology Center, and out as a subsystem ready for test and evaluation. The Center, just completed in Harrison's Building 55, is an extremely important link in the chain that produces MIC's: from Microwave Applied Research at the Laboratories, to Product Design, the Technology Center, and Manufacturing in Harrison.

It is this forward-pressing work that enables RCA to demonstrate the technical leadership that keeps it in the forefront of today's swift-moving advance in technology. Thus MDOD-SEC helps RCA to do its share in filling the country's needs in war and peace, maintains itself as a healthy part of the Corporation, and contributes substantially to the art and science of electronics.

C. H. Lane
Division Vice President and
General Manager
Industrial Tube Division
Electronic Components

Our Cover

Jim Napoleon, electrical project engineer, in Microwave Devices Operations Department (MDOD) clean room in Harrison, N.J., examines gold-plated solid-state velocity sensor oscillator modulator, one of two MDOD-designed units in the landing radar of Apollo's Lunar Module. The sensor, essentially a speedometer, tells rate of descent to moon's surface; the other unit in the radar is an altimeter. Other MDOD solid-state subsystems in the LM rendezvous radar and Command Module transponder are used together to help LM rendezvous with moon-orbiting CM for return trip to earth. Photo credit: John Semonish, Electronic Components, Somerville, N.J.

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RCA Engineer

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RCA Engineer articles are indexed annually in the April-May Issue and in the "Index to RCA Technical Papers."

• To disseminate to RCA engineers technical information of professional value • To publish in an appropriate manner important technical developments at RCA, and the role of the engineer • To serve as a medium of interchange of technical information between various groups at RCA • To create a community of engineering interest within the company by stressing the interrelated nature of all technical contributions • To help publicize engineering achievements in a manner that will promote the interests and reputation of RCA in the engineering field • To provide a convenient means by which the RCA engineer may review his professional work before associates and engineering management • To announce outstanding and unusual achievements of RCA engineers in a manner most likely to enhance their prestige and professional status.

Contents

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dilemma... devices or systems?

Several significant changes in the microwave field confronted the editors "head-on" this issue—these changes, occuring in a brief 10-year span, concern not only the quality and effectiveness of microwave equipment but the nature and extent of the engineering behind the equipment.

Years ago, transmitters, microwave devices, electron tubes, or transistors, though related, were fairly well defined . . . and the distinction between the roles of the system designer and the device designer were likewise clearly defined. Today, the "devices" perform a new and more comprehensive set of microwave functions—while the systems are becoming still more complex and more versatile.

One outstanding result of such change is the gradual disappearance of a well-defined interface between the system designer and the device designer. This "fuzzy" interface gave the editors no little difficulty in planning the present issue (devoted to Microwave devices) and the subsequent issue (devoted to Microwave systems). Originally planned as just one issue on microwave devices, the response to a call for papers brought forth articles with both system emphasis and device emphasis. The large number of papers and their varying contents seemed sufficient to justify two issues. An arbitrary split between devices and systems seemed natural enough at the time, but now that we have the "devices" issue "on the press" and the "systems" issue in preparation, we are still not convinced that we have all the devices papers in this issue with the systems papers in the next.

Our dilemma indicates a trend toward a higher degree of system involvement on the part of device manufacturers, and this trend is not limited to the microwave field. For example, the advent of integrated circuitry coupled with computer-aided design and computer techniques has defined new roles for device, circuit, and systems engineers throughout the electronics industry. (See the article by H. Kihn, "The Impact of Integrated Circuits on Engineering," Vol. 13, No. 3, Oct/Nov. 1967, *RCA Engineer).*

This idea was expressed another way by Dr. George H. Brown in the June/July 1967 issue (Vol. 14, No. 1) of the *RCA Engineer* when he described the present unification as "a pulling together of the separate disciplines, devices, systems, and applications which make up the science and practice of electronics."

The authors in the present issue give eloquent testimony that they recognize the close tie between devices and systems—a "reformation" currently revolutionizing the microwave industry. Each microwave device paper demonstrates an acute awareness of the total system environment surrounding the device. The bulk of the papers were contributed by authors from the Microwave Device Operations Department and Special Electronic Components of Electronic Components.

This close relationship between devices and systems is further emphasized by the papers from the RCA Laboratories, the Defense Communications Systems Division, the Advanced Technology Laboratories, and the Missile and Surface Radar Division.

Special thanks go to Herb Wolkstein, Manager of TWT Product Design and Editorial Representative for the Industrial Tube Division at Harrison, N.J., whose careful planning and initiative helped produce an issue that documents RCA's lead position in the rapidly changing microwave field.

Future Issues

The next issue of the *RCA Engineer* features Microwave Systems. Some of the tcpics to be discussed are:

Microwave phased-array systems

Frequency-division multiplex equipment

Phased-array radars

Velocity extractor for missile radar

Millimeter wave applications

Integrated electronics for microwave systems

Mobile radio systems

Microwave phase shifters

Modern optics

Discussion of the following themes are planned for future issues:

Interdisciplinary aspects of modern engineering

Lasers

RCA engineering on the West Coast

Linear integrated circuits

Consumer electronics

Computerized educational systems

Computers: the next generation

Mechanical engineering

Legal restraints on the exportation of technical data—an update

R. J. Modersbach

An authoritative article on the subject of legal restraints on the exportation of technical data, by C. E. Yates, appeared in the RCA Engineer in 1964[1], and a short note appeared later in the year[2] outlining several modifications to the restrictions that had occurred since publication of the original article. Since that time, other modifications to the various export regulations have been made, illustrating the fluid nature of these most complex regulations. The purpose of this note is to briefly describe the current regulations controlling exportation of technical data, and to remind the engineer of their importance and broad nature.

THE TWO SETS OF LAWS AND REGULATIONS most pertinent to the exportation of technical data are the *Mutual Security Act of 1954* with its Regulations, pertaining to the so-called *Munitions List*, and the *Export Control Act of 1949* with its accompanying *Regulations*. The Department of State administers the relevant portions of the Mutual Security Act, while the Office of Export Control, Department of Commerce, is responsible for the Export Control Act. The underlying Congressional objectives in enacting these laws are to protect the domestic economy, to further US foreign policy, and to provide vigilance over exports relating to the national security. Beyond the scope of this note are the requirements relative to classified technical data, special clearances required by government contract, exportation of commodities, and restrictions imposed by the *Patent Act of 1953*.

Technical data

The definitions given *technical data* are sufficiently broad to permit the observation that most technical papers written by engineers will comprise technical data as will, in many instances, the subject matter of oral discussions involving technical matters. Likewise, the definitions given to "exportation" are equally broad. They include:

Mailing or shipping technical data to a destination outside the United States;

Carrying technical data by hand outside the United States;

Disclosing technical data through foreign visits by American personnel (such as, for example, through foreign visits by RCA employees to visit their foreign counterparts or to participate in conferences or symposia); or

Disclosing technical information to foreign nationals in the United States (such as, for example, employees of RCA's foreign subsidiaries and RCA technical aid licensees, exchange visitors, plant visitors, attendees at conferences or symposia, and others who are in the United States temporarily on some other basis)

The release of technical data to foreign licensees under RCA technical assistance agreements is administered by International Licensing. Should questions arise concerning written, oral or visual communications with licensees, such questions should be routed through International Licensing or the Law Department.

Prior publication exception

If the material *is* technical data and *is* intended for possible export, the cardinal question arises: "*Can* it be exported?" Among the many exceptions presently contained in the two sets of Regulations is one important exception which is contained in each and which permits the exportation of technical data to any country without restriction. This exception relates to unclassified data available in published form. Such data can be exported when one or more of the following criteria are met:

1) Sold at newsstands and bookstores;

2) Available by subscription or purchase without restrictions to any person or available without cost to any person;

3) Freely available at public libraries;

4) Data released orally or visually at open conferences, lectures, trade shows or other media open to the public; or

5) Granted 2nd class mailing privileges by the U.S. Government (applies to Munitions List items only).

This exception, which is appropriately termed the "prior publication" exception, represents a liberalization of the State Department Regulations since the appearance of Mr. Yates' articles in 1964.[1,2] At that time, data could not be released to Communist-controlled countries, whether or not previously published, unless a validated export license was secured.

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Princeton, New Jersey
received the AB from the University of Missouri in 1958 and the LLB from the University of Missouri School of Law in 1963. He practiced with the Law Firm of Shughart, Thomson and Kilroy in Kansas City, Missouri from 1963 to 1965, when he joined the RCA Law Department in Harrison, New Jersey. Since February 1968, he has been counsel for Astro-Electronics Division, Graphic Systems Division and the Laboratories. He is a member of the Missouri and American Bar Associations.

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Purely scientific information

Another important modification was recently made to the Regulations of the Office of Export Control. Effective January 17, 1969, the three general licenses for export of technical data (GTDP, GTDS and GTDU) were abolished and replaced by two general licenses—GTDA and GTDR. The effect of general license GTDA is to permit, without restriction, the export of technical data which is exempted by virtue of its prior publication or which is purely scientific in nature, viz., information not directly related to design, production or utilization in industrial processes. General license GTDR, on the other hand, permits only certain restricted exportation under an exceptionally complex regulatory scheme. Without coverage under one of these two general licenses, technical data controlled by the Office of Export Control can be exported only after a validated license from that office has been secured.

Conclusion

The above description of the export restrictions on technical data is admittedly general and limited in scope. Its purpose is threefold:

1) To update an important subject which Mr. Yates previously treated in great detail;

2) To make the engineer aware of the existence of the myriad and complex obligations and requirements which are imposed; and, consequently,

3) To alert all employees who may be involved in the exportation of technical data that proper guidance and approval from the Law Department should be secured prior to such exportation.

In many cases, these will be accomplished as a matter of routine by operation of applicable major operating unit and divisional policies and procedures relating to technical reports, presentations, etc. Under these procedures, the Technical Paper Administrator (TPA) is the focal point in initiating and securing required approvals.

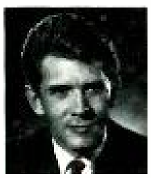
References

1. Yates, C. E., "Legal Restraints on the Exportation of Technical Data," RCA ENGINEER, February-March, 1964, Vol. 9, No. 5, p. 2.
2. Yates, C. E., "New Information on Legal Restraints on the Exportation of Technical Data," RCA ENGINEER, June-July, 1964, Vol. 10, No. 1, p. 78.

Recent technical books by RCA authors

Presented here are brief descriptions of technical books which have recently been authored by RCA scientists and engineers, or to which they have made major contributions. Readers interested in any of these texts should contact their RCA Technical Library or their usual book supplier. For previous reviews of other books by RCA authors, see the August-September 1967 and August-September 1968 issues of the RCA ENGINEER. RCA authors who have recently published books and who were not cited in these listings should contact the editors, Bldg. 2-8, Camden, Ext. PC-4018.

The Ionosphere and its Interaction with Satellites

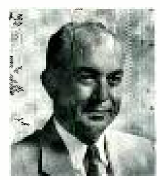


M. A. Kasha
Research Laboratories
Montreal

It is useful to consider this book as composed of two parts, the first consisting of a simplified description of the ionosphere, not so much as a physical entity but rather as an environment in which some system is required to operate. An important component of this part of the book is the series of graphs showing the variation with altitude (out to 100,000 km) of not only the basic parameters of the ionosphere, but also the derived functions. A chapter giving an elementary introduction to the subject of the transmission of waves through the ionospheric medium can be classed with this description of the environment. The rest of the book is devoted to a discussion of the various forms of interaction that are possible between the ionospheric medium and an artificial satellite. This takes into account such problems as the surface potential of the satellite, the existence of sheaths and wakes about such a body, specific problems associated with the passage of a satellite through the earth's magnetic field, and the behavior of antennas in the anisotropic ionospheric medium. *(Gordon and Breach, Science Publishers, Inc., N.Y., June, 1969)*

MICHAEL KASHA graduated in 1957 from London University with a BSc in Honours Physics. After a short time as Lecturer in Mathematics and Physics at the Harrow Polytechnic, he joined the United Kingdom Energy Authority at Harwell, to work in the Controlled Thermonuclear Reactions Division. There he was engaged on plasma physics studies, which work was continued, in 1961, at the Culham Laboratory of the UKAEA, where he worked on Tarantula, an experiment using a 100 kV, 100 kilojoule machine. Mr. Kasha joined the Research Laboratories of RCA Limited in 1964, at which time was engaged on studies of satellite interactions with the ionosphere, using simulation techniques in the Laboratory. He has since continued in the field of satellite technology and space science, with reference to various satellite systems, especially the ISIS series of satellites. He is an Associate of the Institute of Physics (UK) and a Member of the American Geophysical Union.

An Introduction to the Luminescence of Solids



Humbolt W. Leverenz
Laboratories
Princeton, N.J.

Observations regarding luminescent materials are hundreds of years old. However, an understanding of the process of luminescence (as contrasted to the emission of light due to temperature) has been reached only within the last 30 years. The present volume is particularly important in gathering, integrating and evaluating these data, offering a consistent system of terminology, notations, and definitions. Not simply an encyclopaedia of phosphors, it is an easily followed introduction to the area in terms of preparations, compositions, structures, and physical characteristics. Although this book is intended for science graduates and nonspecialists in luminescence, it will be useful as a text in training future specialists and in aiding scientists who wish to use phosphors for detecting radiation. *(This Dover edition, first published in 1968, is an unabridged and corrected republication of the work first published in 1950 by John Wiley & Sons, Inc.; price $4.50).*

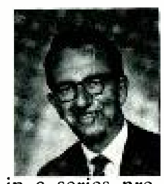
HUMBOLDT W. LEVERENZ graduated from Stanford University in 1930 with the BA. He studied Physics and Chemistry as an exchange fellow of the Institute of International Education at the University of Muenster, Westphalia, Germany, from 1930 to 1931. He joined the Electronic Research Group at RCA in Camden, N.J. as a chemicophysicist in 1931. In 1938, he transferred to RCA in Harrison, N.J., and in 1942 to RCA Laboratories at Princeton, N.J., where he has been in charge of research on electronically active solid materials. In 1954 he was named Director, Physical and Chemical Research Laboratory. In 1961 he was appointed Associate Director of RCA Laboratories, a post he held for five years, when he became a Staff Vice President in 1966. Mr. Leverenz is a Fellow of the American Physical Society, the Optical Society of America, the IEEE, the American Association for the Advancement of Science, and the American Chemical Society. He is a member of the Swiss Physical Society, Sigma Xi, and Phi Lambda Upsilon. He has been issued 67 patents for his inventions, and has written many technical and educational articles.

Optical Properties and Band Structure of Semiconductors

David L. Greenaway | Gunther Harbeke
RCA Laboratories, Zurich, Switzerland
(photographs and biographies of the authors were not available for this issue).

An introduction, from the experimental viewpoint, to the study of the deep-lying energy-band structure of semiconductors from investigations of their optical properties. For the sake of completeness, there is some discussion of the theoretical concepts behind the experimental work, e.g. theory of interband transitions, group theoretical considerations, and classification of electronic states. Potential readership extends over solid state physics and electronics, materials science and theoretical physics. *International Series of Monographs in the Science of the Solid State—Volume 1. (Published by Pergamon Press, Ltd., Elmsford, N.Y., 1968; price $9.00).*

Planning for Effective Utilization of Technology in Education



Dr. W. R. Bush
(contributor)
Instructional Systems
Palo Alto, California

This volume is the sixth in a series prepared and edited by Edgar L. Morphet and David L. Jesser who are directors of "Designing Education for the Future: an Eight-State Project" which is funded by ESEA, Title V. Dr. Bush contributed a chapter entitled, "Systems Analysis: A Method for Logical Decision-Making" *(Bradford Printing, Denver, Colorado, 1968: price $2.00).*

W. R. BUSH, Manager of Educational Research and Planning for the Instructional Systems Division, received the AB and MA from Brown University and the PhD from the University of Rochester in 1954. On the faculty at the University of Rochester, he taught graduate and undergraduate courses in Physiology and Psychology, and directed a research program in Aerial Reconnaissance for the Air Force. Dr. Bush joined RCA in 1956 and has held a series of positions in Defense Electronic Products from that date until 1967. In January, 1967, Dr. Bush joined RCA Instructional Systems where he has been responsible for studies involving the use of data processing systems in instruction and school administration, for developing functional specifications for instructional systems products which incorporate the requirements and needs of the education community, and for the preparation and implementation of study and research contracts.

Forward Edge in American Education, Book I: The New System

Dr. W. R. Bush (contributor)
(photograph and biography are given above)

This volume represents a series of papers discussing education and the applications of technology and has largely been supported by the Office of Education. Dr. Bush contributed a chapter entitled, "Applications of Systems Management" *(National Center for Educational Innovation, Tempe, Arizona).*

Microwave operations—an introduction

W. G. Hartzell

SPECIAL ELECTRONICS COMPONENTS AND THE MICROWAVE DEVICES OPERATIONS DEPARTMENT were born into RCA Electronic Components with a rich heritage of materials and processing technology. This technology has been vital to our growth and technical success. Only with this foundation—which also developed such revolutionary components as the camera tube and the color picture tube—could we have come as far as we have, and have so many promising prospects for future achievement.

In our fast-moving era, however, we cannot rely on what we already know. We must continue to innovate, using both our existing technologies and new ones synergistically, to produce new components and to attain higher standards of component performance. I see this as the mission of the Microwave Devices Operations Department and Special Electronic Components and I have attempted to provide that type of direction. The articles in this issue illustrate quite well this approach to the development of components.

Microwave components, for example, have always required the intimate coupling of the active component with the passive circuit. Only when this coupling was achieved in such devices as the klystron and magnetron, and later in the traveling-wave tube, could the microwave age begin. So the older technologies of the vacuum tube were blended with the newer microwave circuit technologies to create new devices and higher standards of component performance.

This necessary blending of the two technologies, however, brought on additional technical challenges. Primarily, it did away with our ability to design broadbased components, the plug-ins, so to speak. Each component had to be designed with the ultimate user in mind, because there is no such thing as an all-purpose circuit. And, lo, we were now required to be in the circuit business.

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This need for making specific devices for specific customers brought us closer to system problems and put us squarely in the middle of strange new interfaces. Our next step was to become more expert in the technologies of system packaging, power supplies, and modulators. We also had to become more sophisticated in the environmental and space sciences. In some cases, we solved technical and financial problems by supplying integral power supplies and control circuits directly with the component.

In the non-technical aspects of the business, there have had to be parallel adjustments and accommodations. The salesman no longer has his catalog and his warehouse stock list. His catalog is the past accomplishments of our business and his stock is the technology and fast response of our operations personnel. He describes our technological capabilities to the customer, and once again we adjust and innovate to satisfy new needs.

In many respects, our relationship with the customer has changed to one of junior partner rather than vendor. This new relationship compels us to run a customer's development program at his pace, but not necessarily at our optimum pace.

Just as our operations have successfully blended the two technologies—that of the older vacuum tube and that of the new microwave tubes—we are now offering industry and the government new, useful, economically produced components that are the result of the newer technologies of the microwave solid-state art, thermoelectricity, and superconductivity. This process of technological change is the great vitality of the components business. This change must begin here and continue here if the electronic industry is to achieve its full potential.

I am proud of the accomplishments of our engineers told in the following articles and hope this introduction will add to your perspective and understanding as you read on.

William G. Hartzell, Mgr.
Microwave Devices Operations Department
Industrial Tube Division
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Harrison, N.J.
received the MSEE from Lehigh University and the BS in Physics from Franklin and Marshall College. From the time he joined RCA in 1950, he has had a number of varied assignments. As an engineer in the Industrial Tube Products Division in Lancaster, Pa., he worked on the design and development of test equipment. As a manager in the same division in Marion, Ind., he was responsible for establishing a reliability engineering group and reliability and control procedures. Back again in Lancaster, he became an administrator in the Power Tube Product Planning group. His next assignment was as administrator of Market Planning for the Microwave Tube Operations Department in Harrison, N.J. He then moved up to the post of Manager of Product Operations of the Department. In this capacity, he directed a staff engaged in planning and exercising production controls and in the manufacture of RCA pencil tubes, magnetrons, traveling-wave tubes, and solid-state microwave devices. Mr. Hartzell was recently appointed Manager of the Microwave Devices Operations Department. Some of the products designed and manufactured by the Department were and are used in such equipment as weather radar, ground microwave relay equipment, satellite transmitters (the Relay satellite), airborne electronic countermeasures equipment, and the voice transmitters of the Project Mercury astronauts. Other products are used in missiles and electronic countermeasures systems, and still others are being prepared for use in the coming Apollo moon project.

A review of microwave devices and their applications

F. E. Gehrke

This paper provides a survey of the microwave field in historical form. Starting first with the gridded tubes of the World War II era through magnetrons, TWT's, and amplitrons to some of the recent (and future) developments in solid-state microwave devices. This treatment serves well as an introduction to many of the microwave papers in this issue.

THE TREND OF FREQUENCY SPECTRUM UTILIZATION has been progressing upward in an exponential manner over the past 50 years. Microwaves first experienced widespread use in 1940 through the use of radar and the development of the magnetron. Initially associated with the military needs of World War II, microwave systems have today become a necessary medium for commercial and industrial applications, as well as military uses in communications, surveillance, guidance, navigation, telemetry, and a host of others.

Table I lists major active microwave devices. Tubes predominated as sources of microwave energy at all power levels and frequencies until about 1960. During this time, practically all microwave systems were used by the military. The rapid technological advances in transistors and other solid-state devices, primarily varactors and tunnel diodes, opened the microwave spectrum to these devices and thus set the stage for the surge in microwave system developments, both commercial as well as military, which is under way today.

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Table II lists the major military applications of microwaves, which span the many types of radars and ECM systems at frequencies covering L-band (1000 to 2000 MHz) to X-band (8000 to 12,000 MHz), as well as a variety of IFF and communications systems.

Table III shows the applications of microwaves in a rapidly growing commercial/industrial market. Major nonmilitary uses of microwaves include avionics systems such as weather-avoidance radar, air-traffic-control transponders and interrogators, and the soon-to-be-operational collision-avoidance systems for all commercial and general aviation carriers. Non-avionic commercial applications of microwaves for food processing and controlled heating for a variety of industrial processes will lead to an industrial revolution in microwaves expected during the next decade.

Gridded tubes

In the decade beginning with World War II, vacuum tubes of many shapes appeared on the electronic scene; each

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received the BSEE from the University of Wisconsin in 1944 and the MSEE from the Brooklyn Polytechnic Institute in 1946. He joined the RCA Microwave Devices Operations Department in 1962 as Manager, Market Planning. He is responsible for market planning for pencil tubes, magnetrons, traveling-wave tubes, and solid-state microwave devices. Prior to joining RCA, Mr. Gehrke was employed at Sylvania from 1944 to 1961 as an Engineer and Engineering Leader on the design and development of fuze tubes and subminiature tubes; as Section Head of a manufacturing group producing subminiature tubes, microwave planar tubes, and reflex klystrons; as Plant Manager for magnetrons, planar, and TR tubes; and as Division Marketing Manager for Microwave tubes. While employed at Sylvania, Mr. Gehrke received six patents on his work. Mr. Gehrke is a senior member of the IEEE.

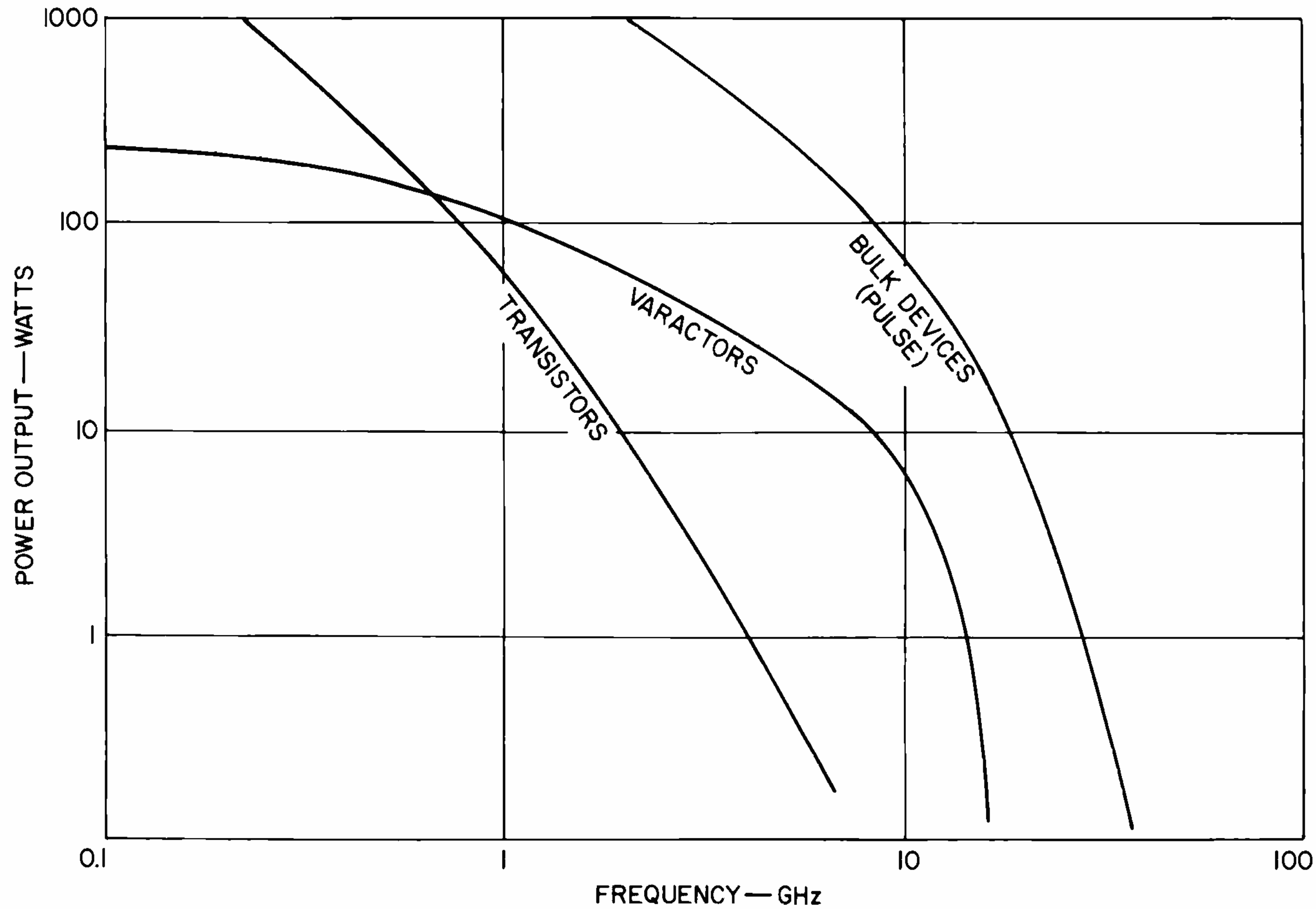

Fig. 1—State of the art in bulk devices compared with varactors and transistors.

Table I—Types of microwave devices.

Tubes
Gridded tubes
Magnetrons
Klystrons
Traveling-wave tubes
Backward-wave oscillators
Carcinotrons
Amplitrons
Crossed-field amplifiers
Solid-State Devices
Transistors
Tunnel diodes
Varactors (frequency multiplier—paramp)
Gunn devices (TEO's)
Avalanche (IMPATT) diodes
Step-recovery diodes
Hot carrier diodes (Schottky barrier)
PIN diodes

shape was intended to improve tube performance or integration into the microwave system. Early techniques for adapting tubes to microwave systems involved the transition from the standard octal-socketed tube to double-ended tubes and then to tubes in which the internal elements were brought out in a most direct manner to sleeves and cylinders in order to enchance high-frequency performance by reducing electron transit time, internal inductance, and capacitance. The acorn, lighthouse, and pencil tubes, in all of which RCA played a leading part, are examples of this evolution of the gridded microwave tube.

The RCA pencil tube, developed at Harrison and first appearing in 1949, is typical of triodes used at low power levels from UHF through C-band. Applications for these tubes included the ARC-34 Airborne Radio Communications equipment operating in the 225-to-400-MHz frequency range and the AMT-4 radiosonde weather telemetry transmitter used in the 1660-to-1700-MHz range.

Magnetrons and klystrons

While these developments were taking place with gridded tubes, other avenues were also being followed. The need to generate and amplify microwaves to higher frequencies at higher power brought on to the scene in rapid sequence magnetrons and klystrons. These tube designs carried the work going on with gridded tubes one step further: the tuned circuit into which they operated was made an integral part of the tube structure. They departed from gridded tubes in a most important aspect: instead of transit time being a limitation upon upper frequency and power of operation, transit time was used to advantage by devising structures for increasing the interaction time for the tuned circuit to act with the stream of electrons.

The magnetron, basically a single-frequency free-running oscillator, has high pulsed-power capability at high efficiencies and is still the lowest-cost (dollars per kilowatt) transmitter tube in the microwave field. These devices can be mechanically tuned over a 10% to 15% bandwidth.

The high-power form of the klystron is used mostly as an amplifier to high power levels, pulsed or cw, where absolute control over frequency or phase is retained by lower-level stages. Efficiencies are good, but not as high as those of the magnetron; frequency and power-handling capabilities are about the same. The klystron, however, can be electronically tuned over approximately a 20% bandwidth.

The reflex klystron is a specialized version of the klystron which operates only as an oscillator. It is highly frequency stable and is capable of being designed to operate at a very high microwave frequency. It can also be electronically tuned, but only over a relatively restricted range (5%).

Table II—Military microwave systems.

Radar
Fire control
Search
Early warning
Acquisition
Guidance
Terrain avoidance (altimeters)
Mortar and personnel locating
Beacons
ECM (electronic countermeasures)
Evasive
Jamming
Deceiving
Decoy
ECCM
IFF (Identification—friend or foe)
Interrogators (airborne, ground, shipboard)
Transponders (airborne—hand carried)
Surveillance receivers
Altimeters
Data Link and Telemetry
Rocketsondes—Radiosondes
Communications
Satellite
Radio relay
Troposcatter

Table III—Commercial Industrial microwave systems.

Radio relay
Television
Phone
Teletype
Radar
Weather avoidance
Traffic control
Surveillance (airport)
Intrusion alarms
Radiosondes—Rocketsondes
Telemetry
Transponders—interrogators
Distance measuring equipment
Altimeters
Collision-avoidance systems
Test equipment
Communication satellites
Accelerators (particle)
Industrial heating
Food processing
Material processing
Home kitchen appliances
Cooking
Fast thawing

TWT's and backward-wave oscillators

The traveling-wave-tube amplifier and its close relative, the backward-wave oscillator, were the next devices on the scene to turn the previous limitations of transit time to greatest advantage. The helix-type interaction circuit used in most low-power-level TWT's, being non-resonant, is limited in instantaneous frequency coverage only by the ability of the designer to devise input and output coupling circuits of sufficient band pass. Practical limitations allow an octave, although TWT's with two and even three-octave bandwidths have been built. Gain also is high, and is limited only by the ability of the designer to suppress coupling of energy from the output back to the input. Most TWT's are designed for 30 to 40 dB of gain; 50 to 60 dB can be obtained over a more restricted bandwidth.

The backward-wave oscillator is basically a TWT in which coupling from the output is allowed to re-enter the output. Although it is not as frequency stable as the reflex klystron, its advantage is its ability to rapidly sweep electronically an octave range of microwave spectrum.

Carcinotron and amplitron

The carcinotron and amplitron are basically special variations of the magnetron. The carcinotron is an electronically tunable high-power oscillator. Tuning speed is limited, and bandwidths are about 15%.

The amplitron can best be compared to a locked oscillator in which output varies with the amplitude of the injection frequency. Phase variations are not followed, however, and therefore the output is not a faithful replica of the input. Gain is about 15 dB; power levels are measured in kilowatts and bandwidths are 10% to 15%.

Solid-state devices

The development of high-frequency transistors, particularly the interdigitated and overlay types, in the early 1960's made solid-state microwave devices a reality. While they were initially employed in low-frequency (below 1000 MHz) low-level cw applications, these devices competed very effectively with small gridded tubes in applications where size, warmup, power-supply simplicity, and long life were important system considerations. Although they did not outperform vacuum tubes in efficiency, cost, and environmental capability, solid-state devices nevertheless began to carve their unique niche in microwave systems.

Varactors and tunnel diodes

Close on the heels of UHF and microwave transistor development came technological advances in varactors and tunnel diodes. Varactors with extremely high cutoff frequencies allowed the design of transistor and varactor frequency multipliers to achieve microwave power not yet attainable through the use of transistors alone. Transistor-oscillator multipliers (TOM's) are now being used as sources of microwave power at frequencies between 2000 and 16,000 MHz for local oscillators and low-level cw transmitters (phased array, portable radars and homing devices, beacons, intrusion alarms, and rocketsondes) where they compete with triodes and reflex klystrons. Continued rapid developments in transistors and varactors are advancing power capabilities of these devices at any particular frequency at about 3 dB per year.

Tunnel-diode amplifiers find extensive use as low-noise, broadband amplifiers in many radars and radio-relay links. Their small size and relatively simple circuitry make them a very attractive substitute for the more expensive and complicated parametric amplifiers and traveling-wave tubes for microwave receivers in which their restricted dynamic range can be tolerated.

Bulk-effect and avalanche devices

Newest solid-state stars in the microwave firmament are the bulk and avalanche devices such as Gunn-effect and avalanche (IMPATT) oscillators. These devices promise to revolutionize the microwave industry because they not only represent the simplest, most economical method of obtaining microwave energy but also hold promise for achieving truly monolithic microwave integrated circuits of extreme miniaturization and reliability. Current state-of-the-art bulk devices and a comparison of transistor and varactor capability are shown in Fig. 1.

Hot-carrier diodes

Hot-carrier (Schottky barrier) diodes are a recent development in low-noise devices which are finding increased usage in low-noise mixer applications. These diodes are replacing tunnel-diode amplifiers and parametric amplifiers in many microwave systems because of their low cost, simplicity, and reliability. The current state-of-the-art in hot-carrier diodes is 5.5 to 6.0 dB noise figure in S-band.

PIN diodes

PIN (p-intrinsic-n) diodes are used in fractional-microsecond switching in phased arrays for antenna switching attenuation and limiting applications. Such devices are superior to conventional switching devices; a typical PIN diode switch possesses 80-dB isolation between ports and 2-dB insertion loss and 15-nanosecond switching time.

Organizing effectively to resolve system/subsystem interfaces

W. E. Breen | H. K. Jenny

Increasing system complexity and progress in circuit integration technology are pushing the interface between the system and component designer deeper and deeper into the system. This evolution requires increased cooperative efforts between system and component designer, as illustrated by very dynamic interface movement. This trend, as shown in this paper, is not limited to young and new technologies, but is equally applicable to mature product lines when sufficient initiative is shown to remain competitive.

TODAY'S AFFLUENT SOCIETY is supporting the continued rapid expansion of technology in its quest for higher and higher living standards. The equipment designer of yesterday who surrounded himself with a host of component catalogs from which he chose the most suitable, standard, off-the-shelf building blocks has given way to the highly specialized systems researcher and developer thinking in terms of black boxes or functions which comprise his vast and sophisticated systems. He is no longer able to involve himself in all the details down to the individual component level, but seeks "functions" or black boxes capable of fulfilling specific and usually rather complex tasks.

The component designer, on the other hand, is now deeply involved in utilizing a new complex technology in combining many individual components into "integrated circuits", such as those shown in Fig. 1, which are capable of performing complex functions. Thus, the task of both system and component designers has become more complex.

Microwaves—integrated circuits through necessity

The microwave tube engineer has been involved in "integrated circuits" for the past twenty-five years. Microwaves, covering very high frequencies where circuit dimensions become comparable to wavelengths, were confronted by the problem of parasitic elements in their early childhood. Because it was not practical to decrease the size of the elements utilized, the only solution to this problem was to combine the tube elements proper with the key circuit elements. The now well-known microwave tubes such as magnetrons, klystrons, wave tubes, and other special devices were all functional oscillators or amplifiers containing tube and circuit in one indivisible envelope. They greatly facilitated the task of the equipment designer; on the other hand, because of the limitations of the built-in circuits, they were highly limited in their usefulness. For example (although at lower frequency) a tube could be used as an oscillator for any application in the range from audio to high frequencies; yet many magnetron types were needed to cover a range of several octaves in the microwave band.

Microwave tube engineers were thus among the pioneers of the "function" or "integrated-circuit" concept. The wide gamut of work ranging from materials technology through process development to circuit design and systems understanding has been a highly motivating force attracting top scientific and engineering talent and providing a most challenging field of endeavor in the microwave area.

The following examples illustrate how several microwave operations are serving the systems designers by supplying them with applicable subsystems.

Microwave solid-state devices are new and young, pushing the state of the art and very much in flux. In this operation, the creative applied research and development engineer plays the leading role. The moderately mature *traveling-wave-tube* product line requires the incorporation of new characteristics to fulfill very specific system performance needs which put the product design engineer into focus. The mature *pencil-tube* line covering coaxial microwave triodes matches available experience and customer needs and thus puts the customer service engineer into a key role.

Microwave subsystems—general requirements

The change of product from a standard component to a subsystem means that the interface between system and component designer has moved deeper into the system by a substantial amount. Fig. 2 shows, as an illustrative example, the evolution of a radar system.

The interface is not a well-established, fixed boundary, but a rather dynamic one which must be defined in every application and has a tendency to move as the system develops and new problems appear.

The task of adequately describing the interface is now one of the major and most important tasks of the component designer and a major contributor to the success of the program. Accuracy in describing the desired function, determined by an understanding of the system and its operation, has more bearing on cost and time required to develop a usable product than technical difficulties.

A close relationship between system and component designer characterized by good communications, respect, and trust represents the real key to successful performance.

A most important factor in the successful interplay is the realization that the interface represents a dynamic boundary which may move rather substantially during the development phases. The interface change may result from improvements in system concept or design, elimination of unexpected problems, or new requirements, or it may be caused by a change required by the subsystems designer to improve performance, reduce cost, increase reliability, etc. Only excellent communication between system and subsystem designer allows satisfactory control over the interface. Interface changes are often dictated by the necessary compromise

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between required performance and available time and funds.

Microwave solid-state subsystems

The microwave solid-state art is still very young and is moving rapidly forward. A typical characteristic of this stage of evolution is that of the systems designer visualizing all of the advantages of performance published from laboratory data suddenly being available as a mature, proven product. The result is very often disillusionment and sometimes even the resubstitution of a tube for a solid-state device.

In this environment, the role of the mature component manager and engineer is the key to the successful development of the useful function or subsystem (rather than standard component) which allows the system engineer to evolve not only a newer, but a better operating system. A rather well-operating method allowing successful introduction of very new and advanced subsystems has been developed, as shown in Fig. 3, and can be described as follows. The component manufacturer has three activities working as a unit:

1) Microwave Applied Research (MAR), a function staffed with creative and highly motivated scientists backed with the necessary facilities and supportive staff. Very specific areas are vigorously pursued and the state of art is constantly being advanced.[1]
2) Microwave solid-state device or subsystems product development, a function staffed with product-oriented engineers (motivated to develop economic, reliable, systems-oriented products) and strongly supported by customer-oriented applications engineers.
3) Manufacturing, a function capable of producing complex subsystems economically upholding pertinent component and quality control.

The first technical contact between the customer designing a new system and the Microwave Applied Research (MAR) member usually keys the major decision. Having understood the customer's requirements, MAR will, based on the advanced efforts going on in its laboratories, recommend a specific approach to fulfill these needs. If the customer is reasonably convinced that this high-quality technical center is available and capable of helping him, an approach will evolve in an atmosphere of mutual respect and trust which will yield the most desirable interface. A program is then developed leading from conception of the function, through breadboard and prototype to final design and production phases.

Example No. 1—weather radar

New subsystems keep weather radar equipment in leading competitive role. The creative cooperative working relationship between systems and component (subsystems) organization is illustrated by the example of the RCA weather radar systems (starting with the AVQ-10 and evolving into the new AVQ-30).

When these systems were first developed, about 15 years ago, the component manufacturer developed a long-life magnetron substantially better (by more than an order of magnitude) than any product available at that date to give the system one of its distinctive advantageous characteristics.

After a few years of successful life, a tunnel-diode amplifier, which could be

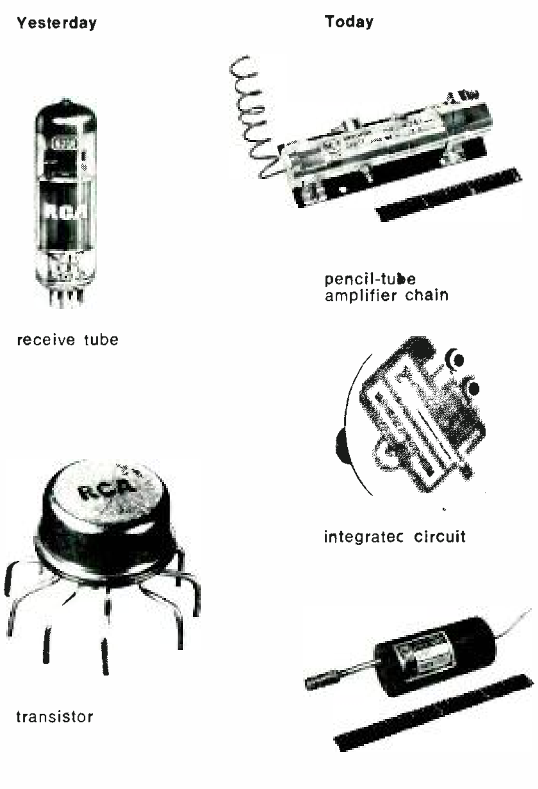

Fig. 1—Comparison of products supplied by the component manufacturer yesterday and today.

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received the MSEE from the Swiss Federal Institute of Technology in 1943. He was then associated with the Institute as assistant professor, where for a period of two years he did research work on klystrons and reduction of their noise figure. Mr. Jenny joined RCA in 1946 and was given the responsibility for the development of CW magnetrons and frequency-modulating schemes for magnetron oscillators. In 1950, he was promoted to engineering manager which he held until 1965. In this responsibility he covers the development of magnetrons, traveling-wave tubes, backward-wave tubes, penc l tubes, special microwave tubes, tunnel oscillators, amplifiers and downcoverters, transistor oscillators and amplifiers, varactor multipliers and tuners, and laser modulators and detectors. In this present position, Mr. Jenny is responsible for applied research, advanced development, product engineering, and manufacturing of microwave solid-state components, devices, and subsystems. These products cover microwave solid-state power sources and amplifiers including transistor oscillators and amplifiers, varactor multipliers, Gunn oscillators, tunnel-diode amplifiers, ferrite components, microwave integrated circuits, and subsystems comprised of many components. Mr. Jenny holds a dozen patents in the fields of magnetrons, cavity tuning and modulation, crossed-field amplification, and radar systems. He has publications in many areas pertaining to microwave devices. He is a Fellow of the IEEE.

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Pencil-Tube Components and Subsystems
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joined RCA in Harrison, N.J. in 1942 from a financial management position with the Commonwealth of Pennsylvania. From 1942 through 1953, he assisted in the planning and implementation of the Lancaster facility, specializing in managerial positions in the Power Tube Department. In 1954, he was selected for a managerial position responsible for new product planning and manufacturing of color picture tubes. In 1957, he accepted a managerial position in the Microwave Devices Department and was subsequently responsible for the planning and implementation of a traveling-wave-tube manufacturing facility. In 1961, he was assigned the complete management responsibility for the planning, engineering, and manufacturing of pencil-tube components and subsystems product line.

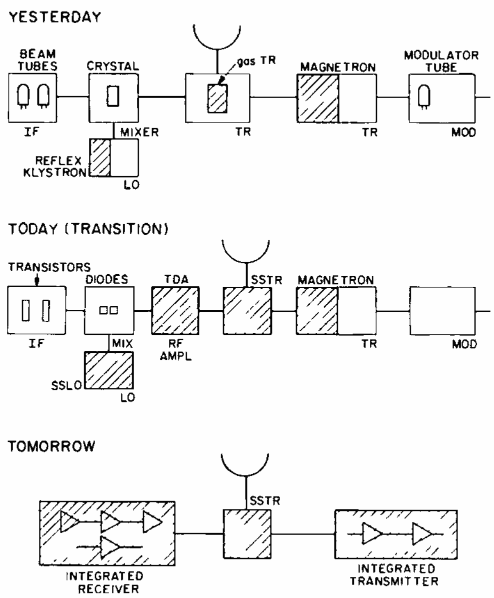


Fig. 2—Evolution of a radar system.

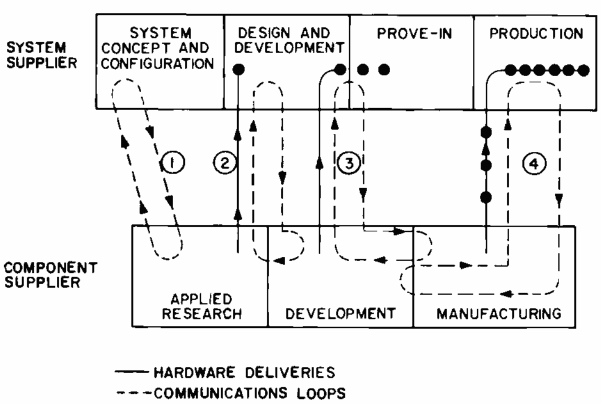


Fig. 3—Interplay between system and component supplier: 1) systems concept and early design; 2) development of subsystems prototype; 3) development of final subsystem; 4) production of final subsystem.

retrofitted into the equipment, was supplied to increase the system value through enhanced sensitivity and range. Lately, the system has been thoroughly modernized and a new subsystem, a high-power solid-state switch, has been added to eliminate the use of a gas TR (one of the major remaining causes of failure) and to increase substantially the system life and reliability. Replacement of the local oscillator with a TEO (transferred-electron oscillator) subsystem is planned. These new subsystems are shown in Fig. 4. Modern integrated system modules for the receiver function are presently evolving in the subsystems designers' minds as continuing contributions to keep RCA weather radar systems number one in the business and further extend their usage and life.

Example No. 2—component supplier provides complex function

Subsystems of higher complexity can be illustrated by the solid-state power sources used in the LM (lunar excursion module) and in a missile system[2]. In the case of the LM power sources, four slightly different subsystems represent the nucleus of the radars that are used as altimeters, velocity sensors, rendezvous functions, and transponders. The missile local oscillator is an electronically tunable subsystem capable of full specified performance over a most adverse environment. In these applications, the systems designers were faced with extremely demanding performance requirements and most rigid environmental and reliability needs. These goals could best be met by breaking the system down into manageable, self-contained functions which could be adequately specified and evaluated.

In the case of the LM power sources, four slightly different subsystems that represent the nucleus of radars are used as altimeter, velocity sensor, rendezvous function, and transponder. The missile local oscillator is an electronically tunable subsystem capable of full specified performance over a most adverse environment.

During the early development of these subsystems, the function requirements increased rather substantially from those foreseen at the outset of the programs. The interface negotiation between system and subsystem functions was quite dynamic and extended over most of the development period.[3] Fig. 5 shows these subsystems.

Pencil-tube subsystems

The pencil-tube product line is technically highly developed and vaunts a mature and long-established lineage of coaxial microwave triodes. With a solid engineering foundation, featuring economy and reliability, the pursuit of subsystems development was able to follow the shortest course to meeting the system designer's needs. A useful product was achieved with a minimum of original design and experiment.

Success was primarily attained through a complete shakedown of the existing organizational structure, which centered around the manufacturing activity, to one which established the customer-service engineer in the role of program manager, as shown in Fig. 6. The key concept was the placement of the customer in the primary decision responsibility and the pencil-tube operation in the reactive role.

In his move to the forefront, the customer-service engineer assumes as his fundamental responsibility that of determining the customer's needs. From this base, he proceeds to defining the technical objectives of the program:

- Accurately estimating the magnitude of the interface problem;
- Establishing the interface responsibility between system and subsystem manufacturer and keeping liaison between these organizations;
- Developing product specifications and evaluating the performance against the program objective;
- Providing mutual technical assistance and assuring continued compatibility with the systems dynamic needs and problems; and
- Documenting the test and performance criteria and establishing the quality-control system required to insure unremitting performance.

The design engineer makes no unilateral attempts to enter new product areas, but instead finds his primary assignments to be reactions to the customer-service engineer. Highly creative pioneer effort becomes secondary to rapid, economical development of useful prototypes. His success is measured by the number of starts required to demonstrate a product that can be moved into an early fabrication cycle without having to be phased through a special model shop or lab. Throughout this process, the customer-service engineer remains the responsible coordinator between the customer and engineering.

Upon achievement of the desired performance, the design engineer completes the product documentation and turns the project over to the production engineer. The production engineer, in addition to his normal control of current volume product, has production development responsibilities for all new and/or modified products. He reacts rapidly to implement the necessary methods, facilities, and personnel skills to supply either pilot or production quantities. All his activity requires evaluation and approval from the customer-service engineer.

The manufacturing group finds its initial task easier because it has furnished the early support to the design engineer. The team effort of the production engineer assisting the design engineer and the use of the resources of the manufacturing group in place of the lab facilities allows expeditious and economical transfer of responsibility. The customer-service engineer still controls the project by monitoring the technical competence of manufacturing.

Example—pencil-tube transponder subsystem

The Pencil Tube Operation had vast experience in the manufacture of cw cavity oscillators for the well-known "weathersonde" and from this base had developed an excellent pulsed ceramic oscillator capable of a high rate of modulation and narrow pulse operation.[4] A project involving this product with a customer's needs showed the advisability of moving the interface deeper into the system.

During the early stages of the system development, serious problems arose as a result of antenna output loading, and the frequency stability and pulse shape of the oscillator were adversely affected. A study of the problem by the subsystem design engineer resulted in the development of a buffer amplifier between the oscillator and the antenna. Output loading was eliminated, power output was markedly increased, and improved pulse and frequency stability resolved the initial problem.

At this time, unanticipated changes were made in the system requirements, but the close relationship and mutual assistance atmosphere that existed with the customer led to the rapid introduction of temperature-compensation materials into the oscillator. In addition, a DC choke was phased into the amplifier cathode circuit to provide improved centering of the risetime. The interface had moved even deeper into the system.

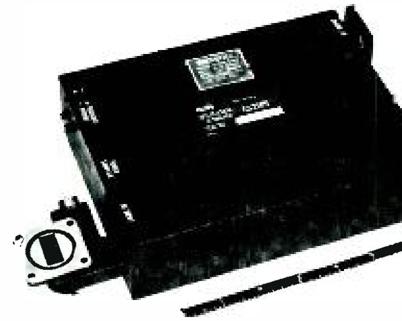
A serious mating problem between the oscillator-amplifier chain and the modulator arose, and again the subsystem designer was able to evaluate the situation rapidly. The study revealed that a redesign of the modulator was a more economic solution than a redesign of the chain. This redesign was accomplished by the subsystem designer and transferred to the customer, who built the new modulator. The integration problem was solved.

Already work is well along by the subsystem designer to develop an integral modulator built into the existing oscillator without a major form-factor change. The interface continues to move deeper into the system as new needs or complexities arise. The systems designer has been served. A photograph of the present transponder package is shown in Fig. 7.

Traveling-wave tube subsystems

Traveling-wave tubes, in age and maturity, lie somewhere between solid-

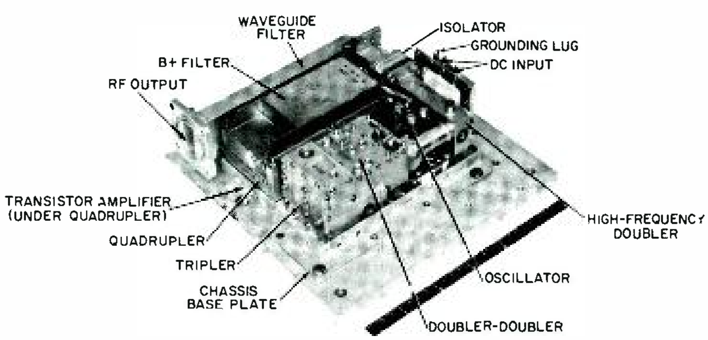
4a



4b

4c

Fig. 4—Weather radar microwave subsystems: a) low-noise RF amplifier; b) high-power solid-state transmit-receive switch; c) local oscillator.



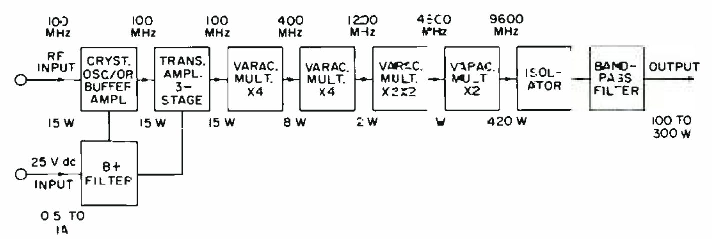
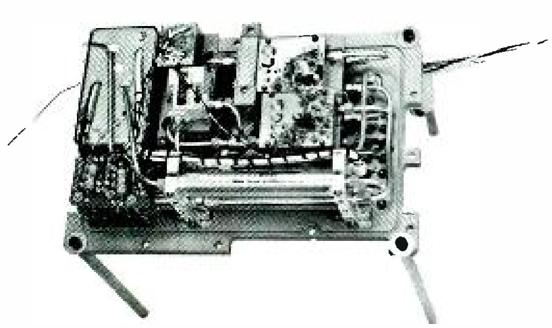


Fig. 5a—Microwave power source for the lunar module; photo and block diagram.



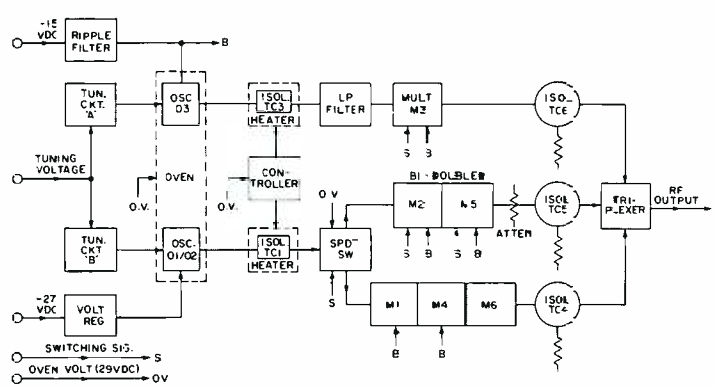


Fig. 5b—Electronically tunable missile local oscillator; photo and block diagram.

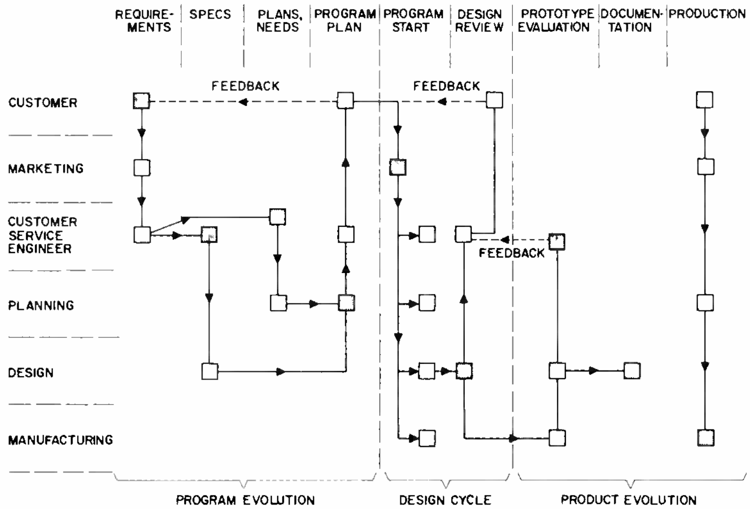


Fig. 6—Pencil-tube supplier-customer interaction.

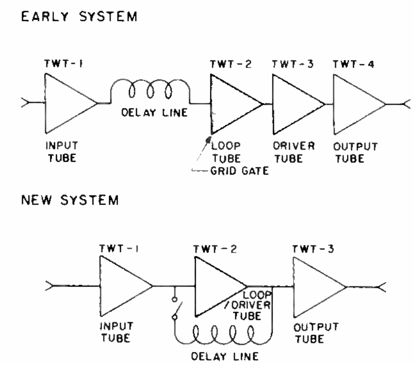


Fig. 9—Traveling-wave-tube ECM system evolution.

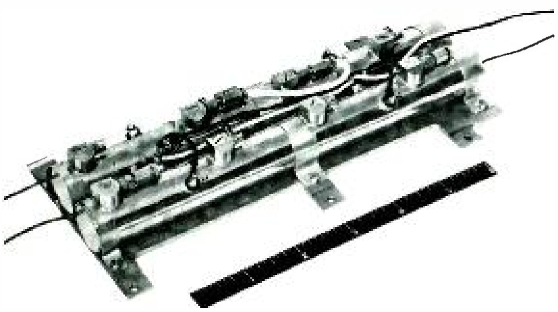


Fig. 7—Transponder package including pencil tubes and cavities.

a)

b)

c)

d)

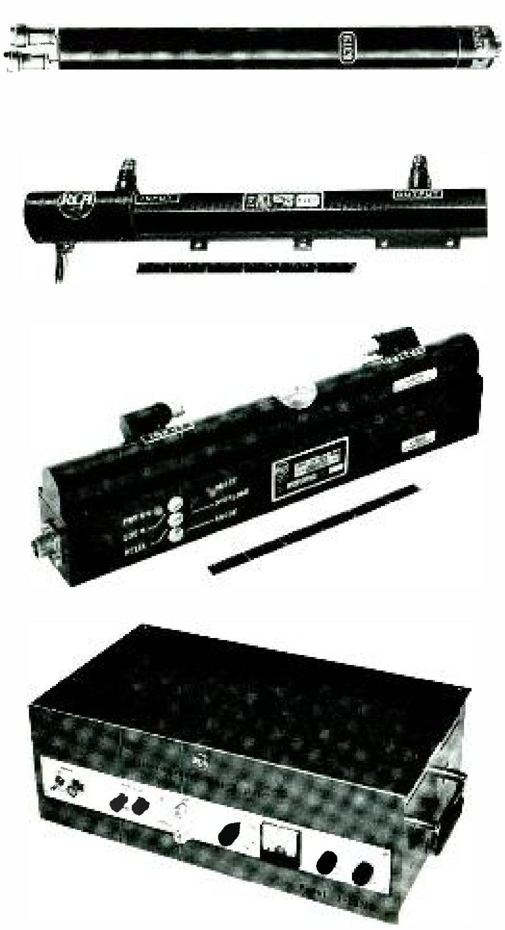


Fig. 8—Traveling-wave-tube subsystem evolution: a) TWT without focusing structure; b) TWT with focusing structure; c) TWT with power supply; d) TWT amplifier subsystem.

state and pencil devices. Some of the applications, especially those concerned with commercial communications systems, are quite mature and handled much like pencil devices.

However, in the many military applications of traveling-wave tubes, innovation is still a key requirement and the interface between subsystem and system is quite complex. Systems requirements necessitate very close control of all operating parameters over extremely wide frequency ranges, and very often the only practical solution allowing reasonable manufacture is to combine a member of critical components interacting with the traveling-wave tube itself into a subsystem. In such cases, the design engineer who is intimately familiar with the balance of parameters versus characteristics plays the key role in determining the configuration of the subsystem and defining the interface and specifications.

For example, in a commercial communications system, the components manufacturer may supply a traveling-wave-tube envelope containing gun, helical RF structure, and collector (bottle), while the subsystem used for an ECM application may include bottle, coupling structures, beam-focusing structure, limiters and filters, and voltage regulators, as shown in Fig. 8. In this latter application, the component manufacturer has relieved the systems designer from the almost impossible task of adjusting a great many variables to achieve satisfactory performance at the cost of many test hours and also selection of matching components.

The intimate understanding of the systems requirements by the component designer often yields the beneficial result of simplifying the system, as shown by the example of an electronic countermeasures system utilizing a memory loop.[5] As shown in Fig. 9, the performance previously obtained from two traveling-wave tubes (a driver and a loop tube) were combined into a single tube with resulting gains in cost, space, weight, and power requirements. The composite tube must now meet much more complex requirements: minimum gain and overdrive, interface for input and output tube, gain contour to complement delay-line loss, memory storage capacity, and operation at increased power level.

Thus, the component manufacturer has greatly eased the system designer's task of mating, optimizing, and balancing many parameters to obtain adequate systems performance. These procedures are now carried out during the subsystem fabrication cycle, where a higher degree of parameter control is possible. Again, the interface has moved deeper into the system and more value has been added to the component designer's functional product.

References

1. Sterzer, F., "The Microwave Applied Research Laboratory", *this issue*.
2. Vaccaro, F., Napoleon, J., "Microwave Solid-State Subsystems Engineering", *this issue*.
3. Lorentzen, R. R., Askew, R., Presser, A., "Microwave Solid-State Transmitters for Rockets and Projectiles", *this issue*.
4. Rose, E., Johnk, O., "New Pencil Tube and Cavities for Air Traffic Control", *this issue*.
5. Wolkstein, H., Puri, M., Freeling, M., "The Role of Traveling-Wave Tubes in ECM Systems", *this issue*.

The microwave applied research laboratory

Dr. F. Sterzer

This paper describes the Microwave Applied Research Laboratory which supports the various Product Design groups of Electronic Components with applied research work on hybrid integrated microwave circuits, microwave subsystems, avalanche and transferred-electron power sources, ferrite devices, gas lasers, and electro-optic products.

Fig. 1—Members of the Microwave Applied Research Laboratory. Not present when the photograph was taken were A. Brum, A. Ehrlich, Dr. A. Gobat, W. Klatskin, D. E. Nelson, J. P. Paczkowski, and Dr. J. F. Reynolds. C. Harper is on the RCA Laboratories marketing staff and does R & D marketing for MAR. Reading from left to right are: first row: C. Harper, H. J. Kuno, K. Pinkerton, M. Markulec, B. Perlman, V. Lawson, S. Legates, J. O'Brien, A. Rosen, A. San Paolo, and J. Bienek; second row: B. Berson, F. Sterzer, R. Steinhoff, M. Schindler, and V. Mankovich; third row: E. McDermott, T. Walsh, R. Paglione, L. Zappulla, W. Levin, H. Johnson, A. Presser, W. Solomon, E. Mykietyn, L. Guarino, and D. Blattner; fourth row: L. Mackey, L. Carr, J. Collard, S. Y. Narayan, E. Belohoubek, R. Kipp, W. Siekanowicz, D. Stevenson, L. Semenistow, R. Marx, and C. Sun. Dr. Walsh is now Manager, Microwave Solid State Technology Center in Harrison. W. Solomon has left RCA.

Dr. Fred Sterzer, Manager
Advanced Technology Laboratory
Electronic Components
David Sarnoff Research Center
Princeton, N.J.
received the BS in physics from the College of the City of New York in 1951, and the MS and PhD from New York University in 1952 and 1955, respectively. From 1952 to 1953 he was employed by the Allied Control Corporation, New York. During 1953 and 1954 he was an instructor in physics at the Newark College of Engineering, Newark, New Jersey, and a research assistant at the New York University. Dr. Sterzer joined RCA in 1954. He is now Manager of the Advanced Research Laboratory in Princeton and the Technical Programs Laboratory in Somerville. His work has been in the field of microwave spectroscopy, microwave tubes, light modulators and demodulators, microwave solid-state devices including parametric amplifiers, harmonic generators, tunnel diode amplifiers and frequency converters, microwave computing circuits, and bulk effect devices. Dr. Sterzer is author of over 50 technical papers. He is a fellow of the IEEE and a member of Phi Beta Kappa Sigma Xi, and the American Physical Society. He holds 19 patents in the microwave field.

The origins of the Microwave Applied Research (MAR) Laboratory date back to the years immediately following World War II, when an Advanced Development group was formed in the Microwave Department of the Tube Division in Lancaster. In 1950 the Microwave Department moved from Lancaster to Harrison, and the Advanced Development group moved with it. The group remained in Harrison until December 1956, when it moved to its present location in Building 3 in Princeton to become the first Applied Research Laboratory at the David Sarnoff Research Center. At the time of the move to Princeton the laboratory consisted of a manager, six members of the technical staff, and three technicians, and occupied 1500 square feet of floor space. During the past twelve years, the size of the laboratory has more than quadrupled; today it consists of a director, three group leaders, fifteen members of the technical staff, three research associates, three technical staff associates, fifteen technicians, and two secretaries (see Fig. 1), and occupies over 6600 square feet of floor space. In May of 1969, MAR was administratively separated from the Microwave Department and combined with the Technical Programs Laboratory. The head of the combined laboratory reports to E. O. Johnson, Manager Engineering, EC Technical Programs.

The pleasant research atmosphere prevailing at the David Sarnoff Research

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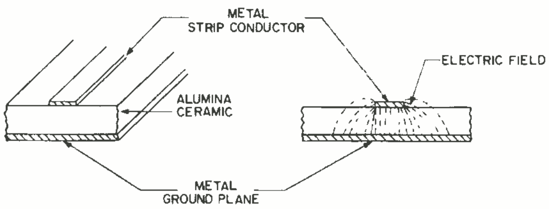


Fig. 2—Section of a microstrip transmission line. In a typical transmission line, the thickness of the ceramic is in the range of 0.02 to 0.05 inch.

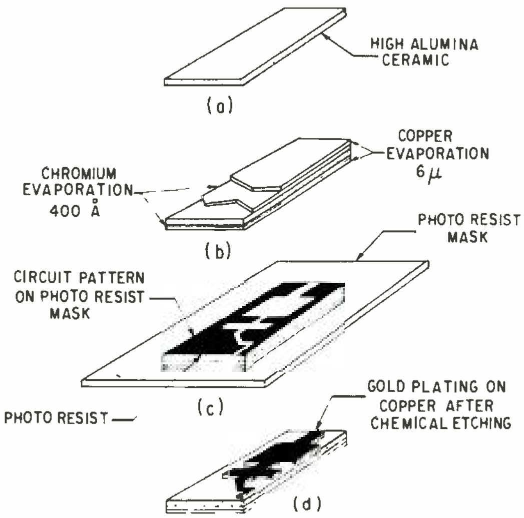


Fig. 3—Sequence of steps involved in making microstrip circuits; note that every step in the fabrication process lends itself to batch processing.

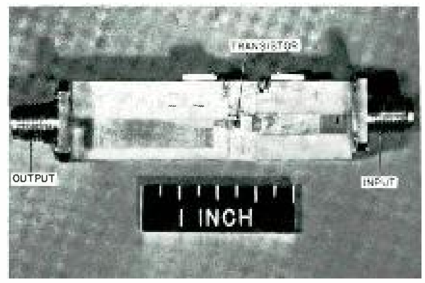


Fig. 4a—L-band transistor amplifier P_{in}=1 watt; P_{out}=7 watts; center frequency=1450-MHz; bandwidth=10%; efficiency=55% (courtesy Dr. D. Stevenson).

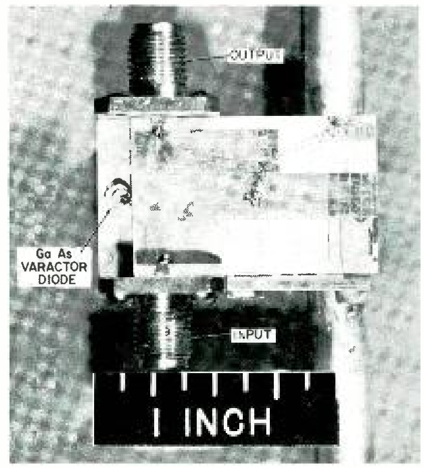


Fig. 4b—Single-ended L- to S-band varactor doubler: center input frequency=1.6 GHz; bandwidth=10%; P_{in}=10 watts; efficiency=53% (courtesy A. Rosen).

Fig. 4e—Packaged version of oscillator shown in Fig. 4d (courtesy A. Presser).

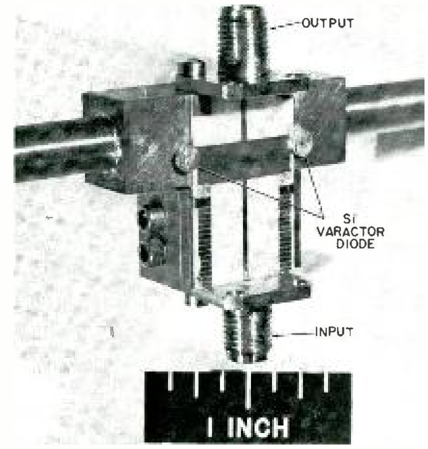


Fig. 4c—Balanced L- to C-band quadrupler: input frequency=1.9 GHz; P_{in}=8.4 watts; efficiency=30% (courtesy Dr. W. W. Siekanowicz).

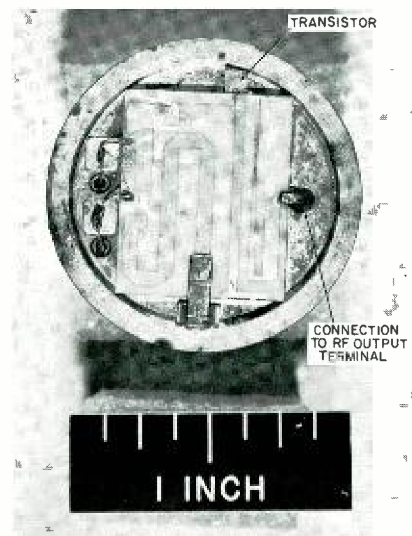


Fig. 4d—Mechanically tunable L-band transistor oscillator: frequency range 1660-1700 MHz; P_{out}=150 mW (courtesy A. Presser).

Fig. 4—Photographs of several hybrid integrated microwave circuits that were developed in Dr. E. F. Belohoubek's group. All data given are for continuous operation of the circuits.

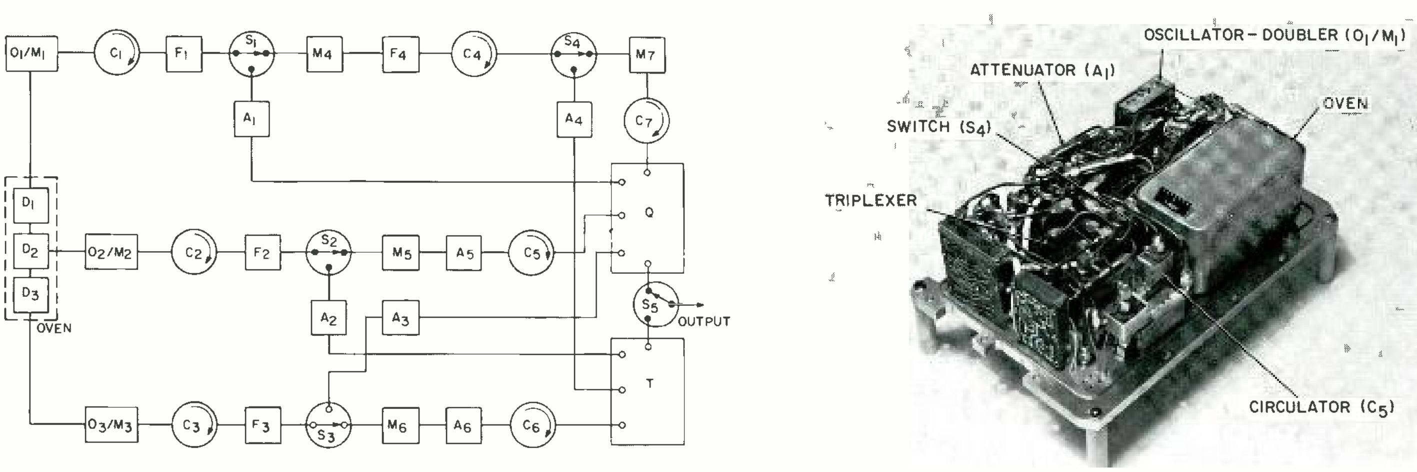
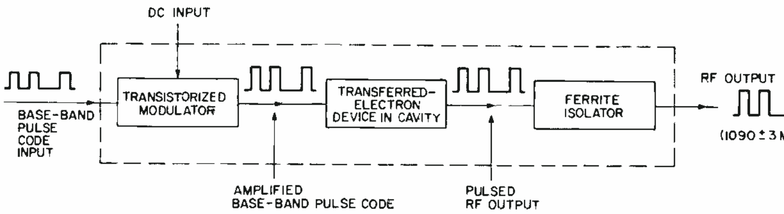
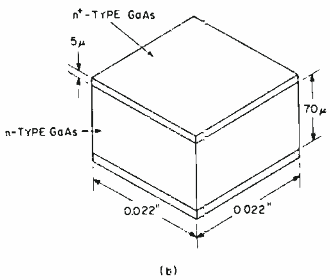
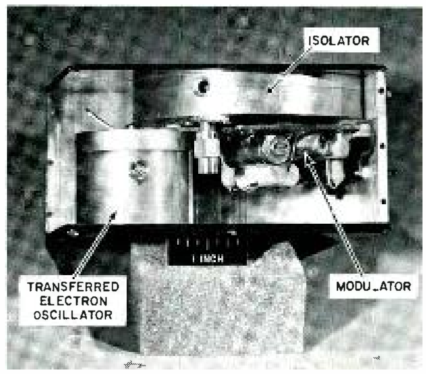


Fig. 5—Wideband, voltage-tuned, transistor-driven harmonic-generator power source. (Courtesy D. E. Nelson and R. Steinhoff). Left is a block diagram of wideband power source [A=attenuator, C=circulator, D=linearity control circuits, F=bandpass filter, M=varactor doubler, Q=quadruplexer, S=single pole double throw switch, T=triplexer.] The transistor oscillators are electronically tuned by means of varactor diodes, and frequency versus voltage characteristics of the oscillators are linearized by means of linearity control circuits. The output of the oscillators is channeled into the various frequency multipliers to achieve multiple-octave frequency coverage at the output. On the right is a photograph of wideband the power source.







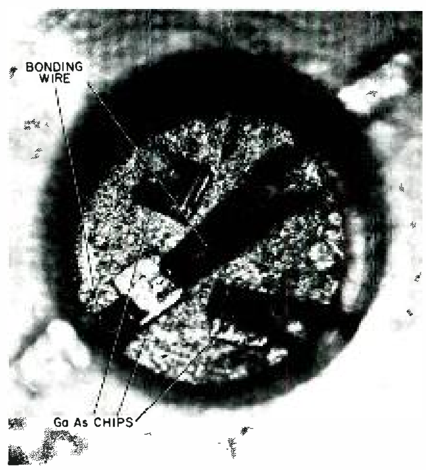
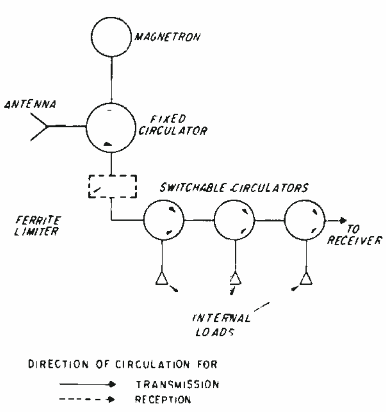


Fig. 6—This figure shows some of the details of a particular transferred-electron oscillator program in B. E. Berson's group. The goal of this program, which is sponsored by the U.S. Air Force, is to develop a transmitter module for an airborne 1-kW L-band IFF transponder. Top is a block diagram of a transmitter module; upper left is a sketch of a *GaAs* chip used in the oscillator. A chip with the dimensions shown can generate as much as 115 watts of pulse power at 1090 MHz with an efficiency of over 30%. The epitaxial wafers used in fabricating the chips for this program are grown by Dr. R. Enstrom of the RCA Laboratories. Directly to the left is a photograph of GaAs chips mounted in an RCA V5000 metal-ceramic package. The cross-sectional dimensions of the GaAs chips are 0.020" × 0.020". Directly above is a photograph of an intermediate model of the transmitter module (courtesy B. E. Berson and Dr. J. F. Reynolds).



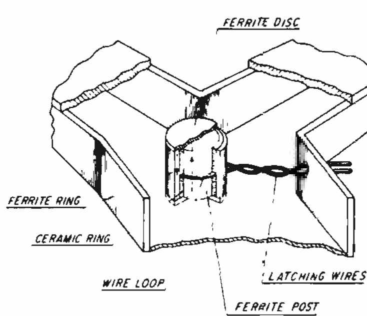


Fig. 7—This figure shows how the transmit-receive functions in the RCA AVQ-30 weather radars are accomplished by means of ferrite devices. The ferrite limiter is a passive device having a small-signal insertion loss of 0.1 dB, and a high-level (100 kW) insertion loss of 13 dB. The switchable circulators (see right) use a magnetically closed ferrite assembly that can be switched between opposite directions of magnetization (and therefore between opposite directions of circulation) by passing current pulses of the appropriate polarity through the latching wires. The insertion loss of each circulator is of the order of 0.1 dB and the isolation in excess of 30 dB. (courtesy D. J. Blattner, Dr. W. W. Siekanowicz and Dr. T. E. Walsh).

Center has greatly helped MAR to assemble a staff of competent professional people not only from the United States but also from many parts of the world. The staff presently includes engineers and scientists from Austria, Belgium, India, Israel, Japan, Switzerland, United Kingdom, and Taiwan. About 80% of the professional staff are electrical engineers; the rest are physicists or physical chemists. More than half hold PhD degrees. The presentation and publication of papers is strongly encouraged, and there is rarely a conference concerned with microwave devices that does not include at least one paper from a MAR author.

Most of the work at MAR is directed toward military or civilian-government end uses, and more than 85% of the laboratory budget is usually derived from government R & D contracts. These contracts enable MAR to vigorously participate in the shaping of the future directions of government support in the microwave and electro-optics areas, and therefore also in the shaping of the whole future of microwave and electro-optic technology. The "seed" money that is needed to attract government R & D support is supplied by the Microwave and Power Tube Operations, and by applied research programs sponsored by the RCA Laboratories.

Examples of current programs at MAR

During all the years of MAR's existence, its primary responsibility has never changed: to provide new and useful products to various Product Design groups of Electronic Components. Ideas for new products are generally generated within MAR itself or at one of the Research Laboratories in Princeton, particularly the Microwave Research Laboratory headed by Dr. L. S. Nergaard. More than 75% of the current effort on new products at MAR is concerned with solid-state microwave amplifiers and generators using transistors, varactors, transferred-electron devices, and avalanche diodes. The remainder of the effort is devoted to subsystems, ferrite devices, delay tubes, gas lasers, and infrared modulators and detectors. The division of effort among the three groups that make up the laboratory is shown in Table I. Microwave products generally move from MAR to the Microwave Solid-State

Erwin Belohoubek	*Bertrand Berson*	*Jacques Collard*
Microwave hybrid integrated circuits (transistor amplifiers and oscillators, varactor multipliers)	Avalanche amplifiers and oscillators	Ferrite devices (circulators, limiters, and switches)
Delay tubes	Transferred-electron amplifiers and oscillators	Gas lasers
Subsystems	Monolithic microwave integrated circuits	Infrared modulators and detectors
		Parametric amplifiers and varactor diodes
		GaAs epitaxy

Table I—This table shows the group leaders and the areas of interest of the three groups that make up the Microwave Applied Research Laboratory.

Operation in Harrison headed by H. K. Jenny, and electro-optic products to the Power Tube Operations Department in Lancaster headed by M. B. Shrader.

Integrated microwave circuits

Many of the solid-state power sources now being developed at MAR are being built in hybrid integrated form. The passive components of the power sources, i.e., transmission lines, filters, cavities, and the like, are formed in metal-ceramic microstrip, as shown in Fig. 2. The active semiconductor chips are usually mounted in special miniaturized packages specifically designed for microstrip or, in some cases, are mounted directly on the microstrip circuits. There are several important advantages to hybrid integration:

1) Hybrid integrated microwave circuits are compact. The reduction in size as compared to similar circuits in waveguide or coaxial construction can be orders of magnitude. This feature is of particular importance in airborne or "manpack" applications.
2) Microstrip circuits can be batch-fabricated by use of photolithic techniques, as illustrated in Fig. 3. Circuits made in this manner are extremely uniform, and when they are produced in large quantities, the cost per circuit promises to be very low.
3) Hybrid integrated circuits can be readily ruggedized. For example, Dr. E. F. Belohoubek and A. Presser of MAR have developed L-band integrated telemetry transmitters that can withstand 50,000 g's of shock.

Dr. Belohoubek's group has complete facilities for making hybrid integrated circuits, and is a leader in the industry in high-power microwave integrated circuits. Examples of some of the integrated transistor and varactor circuits built in these facilities are shown in Fig. 4: Circuits (a) and (b) are designed for an airborne ECM application, circuit (c) for an airborne phased-array transmitter, and the circuit of (d) and (e) for a balloon-born telemetry transmitter of weather information.

Subsystems

In some cases, complete subsystems are built around components developed in the laboratory. An example of such a subsystem using discrete-component voltage-tuned transistor oscillator and varactor multipliers is shown in Fig. 5. This subsystem, which was built by D. E. Nelson and R. Steinhoff, is a power source that can be electronically tuned over several octaves in the microwave range. A narrow-band version of this source is now in production in Harrison.

Epitaxial GaAs power sources

Although transistors and transistor-driven harmonic-generator chains are still used in the majority of solid-state microwave power sources being developed at MAR, an increasing amount of effort in the power-generation area is being channeled toward the "second generation" of microwave power-generating devices, i.e., avalanche and transferred-electron devices. Both of these new types of devices can produce much higher power outputs than transistors; for example, with transferred-electron oscillators several kilowatts of pulsed microwave power have already been obtained. Furthermore, it ought to be possible to produce both avalanche and transferred-electron oscillators at a significantly lower cost than high-power microwave transistors. The fabrication of high-power microwave transistors involves a long series of high-precision masking and diffusion operations. By contrast, many types of transferred-electron devices consist merely of a slab of mechanically or chemically formed high-purity GaAs with two ohmic contacts. At the present time, B. E. Berson's group is developing transferred-electron oscillators for operation at L-, S-, C-, X-, and Ku-band frequencies, avalanche oscillators for L- and X-band frequencies, and avalanche and transferred-electron amplifiers for X-band frequencies. MAR has complete facilities for growing epitaxial GaAs wafers and for processing these wafers into finished devices. Some of the details of a particular transferred-electron oscillator program are given in Fig. 6. The efficiencies achieved in this program are the highest in the industry.

Microwave ferrite switches

The ferrite activity is attacking a problem that has plagued radar designers since the invention of pulse radar: how to use the same antenna for both receiving and transmitting. The traditional solution to this problem is to use gas T-R (transmit-receive) tubes. The difficulty with this solution is that gas T-R tubes occasionally misfunction, and a single misfunction can often cause severe damage to the receiver. The solution evolved by D. J. Blattner, Dr. W. W. Siekanowicz, and Dr. T. E. Walsh is to use high-power ferrite devices in the configuration shown in Fig. 7. The reliability of these ferrite devices, which are now being manufactured in Harrison for use in the RCA AVQ-30 weather radars, is expected to be many times as great as that of gas T-R tubes.

Conclusion

The Microwave Applied Research Laboratory has grown and prospered in the research atmosphere of the David Sarnoff Research Center, and has thus proven the wisdom of Microwave Management in establishing MAR as the first Applied Research Laboratory in Princeton. Much of the credit of MAR's success belongs to its many friends and supporters within RCA. Chief among these are H. K. Jenny, who has guided MAR since its inception; C. C. Simeral, G. W. Duckworth, W. G. Hartzell, and M. B. Shrader, who consistently provided MAR with the backing of the top management of the Microwave and Power Tube Operations; L. S. Nergaard, whose laboratory contributed innumerable new ideas and technical and financial support; and A. N. Curtiss, J. Hillier, and W. M. Webster, who have been ideal landlords.

New pencil tubes and cavities for air traffic control

E. Rose | O. Johnk

The increasing use of Air Traffic Control Beacon Systems (ATCRBS) has required the evolution of a new electron-tube technology to meet such critical system requirements as miniaturization, high reliability, fast warmup, super-active cathode emission, high-altitude voltage standoff, high-impact shock, long life, variable-frequency vibration, and high- and low-temperature operation. Present tube-manufacturing techniques integrate the tube with external circuitry in a sub-system module to satisfy these performance requirements and also reduce component costs by orders of magnitude. This paper describes the application of these techniques to pencil tubes and integral cavities for the ATCRBS market.

PENCIL TRIODES, which were developed by RCA, are ideally suited for operation at microwave frequencies. Because closely spaced coaxial electrodes are connected directly to terminals which comprise the body of the tube, a combination of low circuit capacitance and inductance is achieved. In addition, the stacking of concentric cylinders provides fast warmup (less than 10 seconds). The use of a cathode that completely surrounds the heater provides more efficient use of heater power and thus reduces the power drain—a necessity in aircraft equipment. Because concentric cylinders expand and contract radially, they maintain their relative spacing. Furthermore, the size, shape, and weight of pencil tubes are ideally suited for microwave circuits in aircraft applications.

Pencil tube design

Fig. 1 shows the basic construction of a pencil triode. The cathode, which determines the current capabilities and life of the tube, employs a careful selection of base metal and cathode spray materials. The base metal is chemically pure nickel which is vacuum-melted and tightly controlled for silicon content. A triple-carbonate oxide cathode coating is used to provide emission in excess of seven amperes per square centimeter. The cathodes are capable of peak emissions as high as fifteen amperes per square centimeter under very tightly controlled processing and environmental conditions; however for long-life operation, average emission should not exceed seven or eight amperes per square centimeter. Because of the need for extremely efficient use of heater power, heater location is carefully controlled to assure uniform heating, eliminate hot spots, and maintain good control of cathode temperature.

Aircraft power-supply regulation is limited because of cost, weight, and size restrictions. Therefore, the heater-cathode design of tubes for aircraft service must perform efficiently over variations of 10%. Fig. 2 shows a curve of warmup time required for plate current to reach 90% of its stable value in a typical pencil tube.

Pencil-tube grids are designed to assure maximum thermal conductivity and rigidity, and to provide tubes capable of withstanding 12 hours of continuous vibration at 20g acceleration from

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received the BSEE from Newark College of Engineering. He joined RCA as a specialized engineering trainee in 1955 and was subsequently assigned to the Electron Tube Division as a Test Engineer in the Industrial Receiving Tube activity. He later transferred to the Microwave Tube Applications activity where he has been responsible for the electrical and environmental testing and the engineering refinements of a variety of developmental pencil tubes. He is currently a Design Engineer in the Pencil-Tube Design and Development activity where he has been responsible for many of the designs in the RCA Integral Tube Cavity line. Mr Johnk is a member of IEEE.

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received the BSEE in June 1961 from Newark College of Engineering. Prior to receiving his degree, he worked as a foreman in Equipment Development, was a pencil-tube test engineer, and worked in applications and environmental test on magnetrons and traveling-wave tubes; he joined Microwave Operations in 1952. He was a production engineer on pencil tubes and integral tubes and cavities prior to his present assignment as applications and customer service engineer for pencil tubes and cavity devices. In this assignment he is responsible for customer liaison, evaluation, documentation, and quality control.

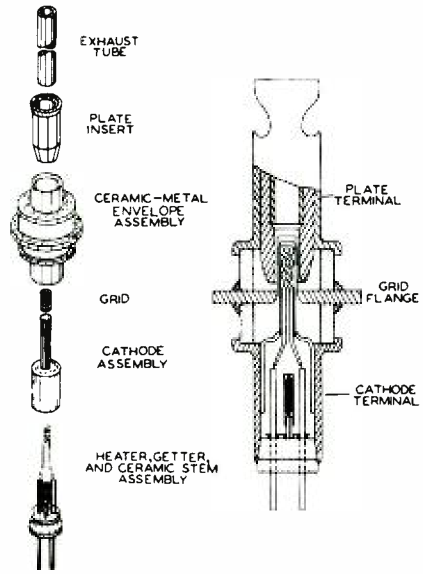

Fig. 1—Basic construction of the pencil tube.

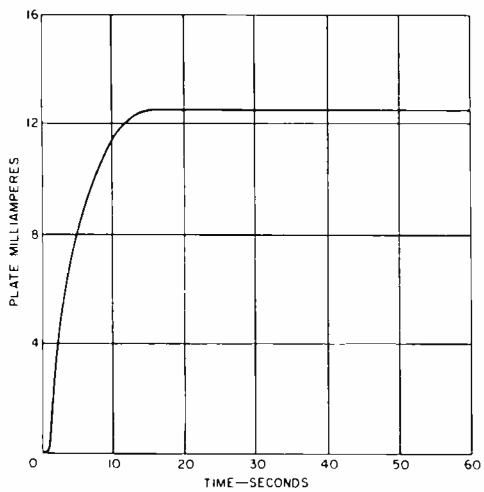

Fig. 2—Typical curve of plate current as a function of time.

50 to 2000 Hz. The grid structure for a typical ceramic pencil tube is shown in Fig. 3.

Plate (anode) materials were tested exhaustively to obtain a design which would withstand the environmental tests and prove thermally and mechanically suited for electron-tube manufacture. Titanium was selected because it possesses the required characteristics and also provides some additional gettering during life.

Improved processing and manufacturing techniques are also used for all pencil tubes, particularly in the areas relating to high-temperature bakeout, mechanical alignment, high vacuum, and super cleanliness. Interelectrode capacitances are monitored during manufacture, constant control is maintained over cathode base metal and spray, and washing and firing operations are kept under continual surveillance.

After fabrication, pencil tubes undergo severe stress and environment testing, and are then matched with oscillator or amplifier cavities. Fig. 4 shows an amplifier triode. These completed subsystems undergo a series of quality tests to determine their compatibility with actual system applications. Normal factory tests include all the tests usually associated with tube manufacture, plus additional screening for high-voltage standoff capability, high-voltage cutoff characteristics, cathode warmup time, cathode pulse-emission capabilities, and interelectrode capacitances. These tests are performed on 100% of the product manufactured. Other stress tests are destructive and are performed on a lot-sampling basis. These tests include mechanical and thermal shock, vibration, high-temperature life test, and dissection to assure good manufacturing practice throughout assembly.

Cavity design

RCA has had long experience with cw cavity oscillators, beginning with the weather sondes. Fig. 5 shows a typical 1680-MHz cw oscillator designed for weather-sonde operation. This weather-sonde experience provided the basis for development of the manufacturing techniques required for pulse cavities.

Fig. 6 shows the basic pencil-triode pulse oscillator design. The feedback path for RF energy in this oscillator is from the plate circuit past the grid circuit into the cathode circuit. The cathode circuit is tuned to provide the proper phase of feedback. Because the grid is at an RF potential, a quarter-wave choke made of RG-188 coaxial cable is used to provide RF isolation from the DC supply.

The circuit shown in Fig. 6 allows some control over pulse shape because the grid circuit has very low capacitance to ground. The lead inductance of the quarter-wave choke is sufficient to slow the rate of rise of grid current and thus provide the proper risetime for the RF pulse.

In addition, a compromise was necessary for the control of the amount of

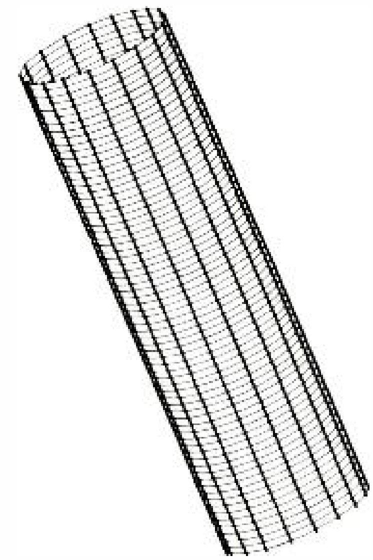
Fig. 3—Isometric view of the newly developed grid structure.

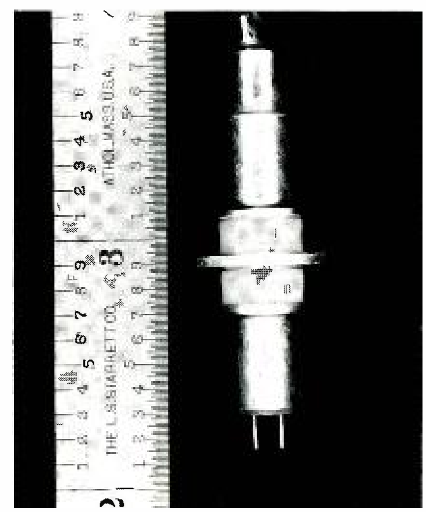
Fig. 4—Photo of an amplifier tube.

feedback because high-Q, low-feedback circuits are needed for proper pulse risetime and falltime, while, on the other hand, low-Q, high-feedback circuits are essential to minimize pulse leading-edge jitter and pulse-to-pulse jitter. The final oscillator design is capable of consistently meeting a ±10-ns jitter requirement.

This type of oscillator circuit is temperature-compensating; therefore, oscillator frequency drift is tightly controlled over wide ambient-temperature ranges. The frequency stability of any oscillator is affected by variations in temperature, output loading, and plate and heater voltage. Temperature effects on the cavity are further minimized by the use of Kovar for all cavity parts which would tend to expand and contract sufficiently under temperature extremes to affect the output frequency. The oscillator is capable of maintaining the frequency well within the specified deviation limits of ±3 MHz. Pencil-tube oscillators are much less susceptible than comparable planar designs to element-voltage changes that produce frequency modulation.

The oscillator is gated by low-level video circuits that have power-level requirements well within the capabilities of solid-state devices. It is capable of extremely high rates of modulation and narrow-pulse operation.

Because the oscillator basically establishes the frequency and shape of the pulse, oscillator stability is of paramount importance. Although pulse power outputs in excess of 500 watts are readily achieved with pencil-tube oscillators, frequency variation as a result of output loading of the antenna is a problem in the event of icing, rain, and dust. However, insertion of a buffer amplifier between the oscillator and the antenna provides enough isolation to eliminate the effects of such loading.

The amplifier is a grounded-grid configuration that uses a half-wave input circuit to allow for critical coupling adjustment. A quarter-wave output is used, and a heat sink is employed to improve tube life. Insertion of the buffer amplifier increases power-output capabilities, and also permits centering of system risetime when a small DC choke is included in the amplifier cathode circuit. System pulse stability is also enhanced by proper selection of

Table I—Typical operating conditions.

Heater voltage	6.3 V ±10%
Plate voltage	1000 V ±10%
Oscillator bias	−80 V
Amplifier bias	+25 V (on cathode)
Grid drive	Pulse osc. grid to 0 V
Load VSWR	1.5:1 (all phases)
Duty	1% (maximum)
Plate current (at 1% duty)	20 mA (maximum)
Nominal power output	700 W (peak)
Operating temperatures	−54°C to +165°C
Operating frequency	1090 ±15 MHz
Altitude (operating under no pressurization)	30,000 ft.
Vibration	20g (at 20 to 2000 Hz)
Shock	15g

inductance in the input circuit. Fig. 7 shows typical frequency deviation as a result of the cumulative effects of voltage, temperature, and load VSWR. The complete transmitter does not suffer from operation for short periods without a load.

Conclusion

Fig. 8 shows a typical transmitter chain which requires only the application of the necessary DC and gating voltages to provide the desired performance. Table I shows performance results of the transmitter. The comprehensive development program on pencil tubes and cavities has produced a tube-and-cavity design from which a new base has been formed to meet tighter objectives of environmental, electrical, and performance characteristics. A complete evaluation of each design modification has evolved high-volume designs which fulfill design objectives for Air Traffic Control Beacon Systems which previously were considered feasible only in laboratory designs.

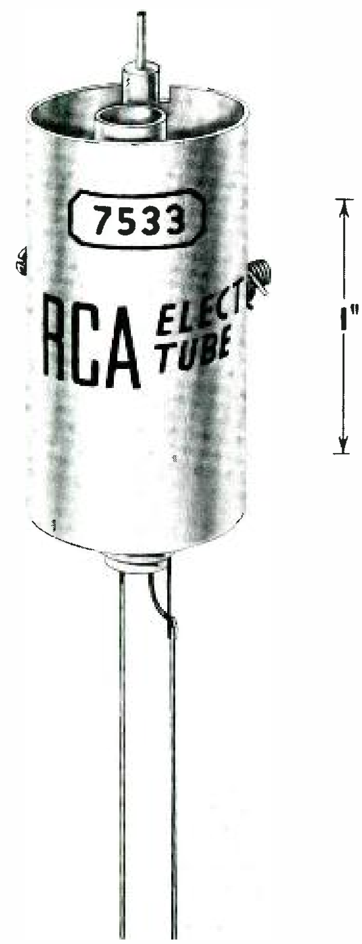

Fig. 5—Photo of the RCA type 7533 weathersonde oscillator tube.

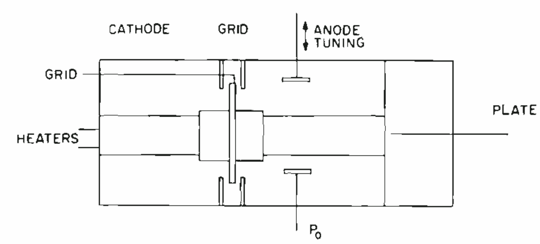

Fig. 6—Cross-section of an oscillator cavity.

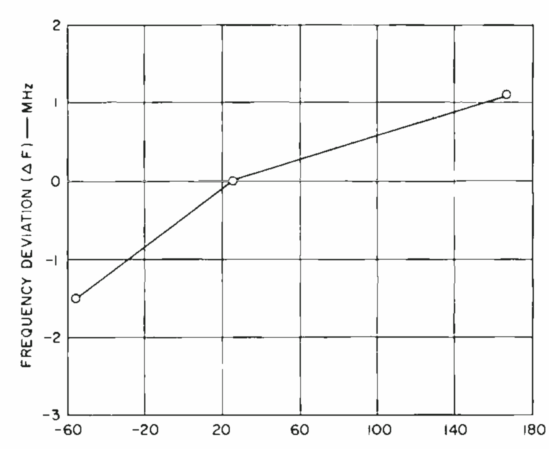

Fig. 7—Typical behavior of frequency stability as a function of ambient temperature.

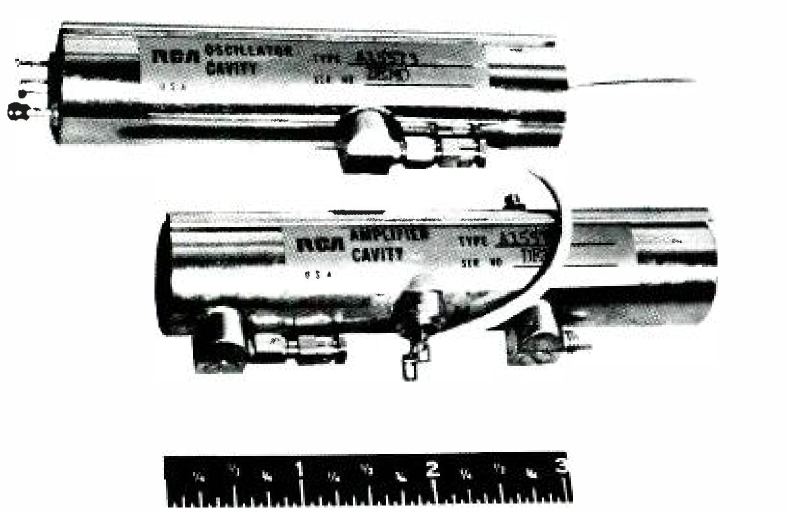

Fig. 8—A typical transmitter chain for Air Traffic Control Beacon Systems.

Microwave solid-state transmitters for rockets and projectiles

R. R. Lorentzen | R. E. Askew | A. Presser

Over the past few years, the constant improvements[1,2] in solid-state technology and their application to the challenges presented by the severe requirements of rocket- and projectile-borne systems have brought about advances in miniature solid-state transmitters—both those using transistors as the active devices and those using newer bulk-effect devices. Of particular significance for these systems is the promise of the newer devices: hybrid microwave integrated-circuit transistor oscillators, transferred-electron oscillators (TEO), and IMPATT (Impact Avalanche and Transit Time) devices. The possibility of placing the TEO and IMPATT devices in hybrid microwave IC's is also very promising.

The fact that these devices can function in hostile environments is at times quite surprising. This paper briefly describes some of the actual applications of these devices, and then describes the circuits and technology that have successfully been proven in these environments. A description is then given of devices which have the most promise for the future.

What kind of system functions require a small microwave transmitter? The two major applications so far have been 1) the telemetry of meteorological or scientific data by means of a transmitter that has been placed several hundred thousand feet above the earth by a fast-burning, high-thrust rocket, and 2) the telemetry of various functions that occur in an artillery shell during its flight by means of a transmitter that has survived the blast out of a cannon. In addition, a third, equally demanding possible application exists in the electronic fuzing of rockets, missiles, and shells by an on-board transmitter. The harshness of these environments is best illustrated by some actual examples.

Rocket and projectile applications

Meteorological sounding rockets are used to probe the earth's upper atmosphere to sample various environmental factors such as wind velocity, temperature, humidity, and other parameters by appropriate sensors and techniques. The information from the sensors modulates the payload L-band transistor transmitter and is received at ground stations for use in weather forecasting, for support missions in missile firings, or for other atmospheric research.

In one such meteorological rocket, the Loki-Dart, the rocket motor burns for about 1.8 seconds and propels the rocket and payload to an altitude of 5000 or 6000 feet while the rocket burns. After the motor is extinguished, the inertia and velocity of the rocket are sufficient for it to be carried to about 200,000 feet. When this altitude is reached, the payload is explosively ejected and parachutes back to earth, relaying the data generated by its sensors. The transmitter must operate on the launch pad and throughout the ascent and descent for a total time of perhaps an hour.

In another application, the transmitters have been tracked to an altitude of 500,000 feet and back again to earth, 100 miles away. During a test in a third application, a rocket motor exploded shortly after launch, but the transmitter survived. In still other applications, the devices are fired out of cannons and are subject to shocks up to 50,000 g's.

What kind of device can survive, and perform, in these environments? These devices are the subject of this paper.

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Lumped circuits—the transistor oscillator-multiplier[3]

The first RCA microwave solid-state transmitter for these applications was a transistor oscillator-multiplier (TOM). Several circuit and construction techniques were evaluated on a U.S. Army contract to develop a transmitter for radiosonde application which was mechanically tunable by ±10 MHz at 1680 MHz. This program resulted in a transistor-oscillator-multiplier circuit. In this approach, a single transistor is used as both an oscillator and a frequency tripler; the frequency multiplication is made possible by the strongly nonlinear, voltage-dependent, collector-to-base junction capacitance of certain overlay transistors. The circuit schematic of this transmitter, the RCA S170, is shown in Fig. 1; it uses lumped circuit elements, as shown in Fig. 2.

The transistor collector is connected directly to the transmitter chassis for good heat conduction. The transmitter can be both amplitude (ON-OFF) and frequency modulated. In frequency modulation, a frequency deviation of ±500 kHz is obtained for a 1-volt peak-to-peak input signal applied to the FM input terminal. The transmitter is compensated to reduce frequency changes with temperature.

The major characteristics are shown in the first column of Table I. The lumped-circuit approach of this transmitter is the major factor in its small size. The lumped elements have small mass and are selectively potted (for minimum RF circuit loading) to secure them against movement during shock and vibration.

The S170 has been successfully subjected to the following operating tests: 1600-g shock of 2-ms duration, 200-g shock of 11-ms duration, linear acceleration of 200 g's for two minutes, and vibration of 20 g's from 55 to 2000 Hz for the rocketsonde application. It will also see limited exposure to the artillery shell environment.

As shown in Table I, one disadvantage of this circuit is its subharmonics. A newer circuit approach, developed to overcome this difficulty, does not depend on the frequency-multiplication mode of operation.

Dual-cavity transistor oscillator[4]

Continued development under another U.S. Army contract led to a dual-cavity 1680-MHz transistor oscillator, a fundamental-frequency transmitter which replaces the earlier transistor-oscillator-multiplier (TOM) approach in rocketsonde systems. This transmitter, the RCA S190, performs as well as, and generally better than, the earlier circuit approach. It has the same power output (200 milliwatts minimum), inherently wider tuning range, higher efficiency, and, because it does not rely on frequency multiplication, reduced spurious-output performance and lower frequency pushing. The price paid for these advantages is slightly larger size (set by the dimensions of the resonant cavities). The TOM approach is still superior if smallest size, higher power output (some units have 400 milliwatts output), lowest voltage, or more ruggedization is a requirement. The TOM also has a concentric output RF connection, while the dual-cavity RF output is offset from the axis. The performance of this transmitter is shown in the second column of Table I.

The external view of the dual-cavity oscillator is shown in Fig. 3, and the circuit schematic in Fig. 4. The bias network is the same as in the earlier TOM circuit and, therefore, the amplitude- and frequency-modulation techniques are the same. This transmitter is also temperature-compensated. Fig. 5 shows the performance capability of one of these transmitters over the temperature range from −70 to +70° C.

The bias and modulation networks are potted against the rigors of the rocketsonde environment, and the center conductors of the coaxial cavities are supported by rexolite beads. The two cavities are, in turn, supported by potting and an external protective canister. This construction has consistently performed well under 200-g shock (11-ms), 250-g acceleration, and 20-g vibration.

The significant improvements that the dual-cavity, fundamental-frequency circuit accomplished are supplanted, to some degree, by the latest approach to the transistor source, the hybrid microwave integrated circuit. Indeed, this approach promises environmental performance capability that may surpass these earlier approaches.

Future devices—hybrid integrated circuits

The emphasis in the new generation of solid-state microwave sources for

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received the BSEE in 1961 and the MSEE in 1965 from Newark College of Engineering. He has also done a year of graduate work at Rutgers University. After working at Western Electric, Hewitt-Robins, and Federal Telephone and Radio, he joined what is now the RCA Microwave Devices Operations Department (MDOD) in 1956, in Equipment Development. In 1957, he entered the Microwave Applications Engineering Activity and worked on solving the technical intereface problems between RCA devices and customer systems. In 1963, he was assigned to the Microwave Engineering Programs Activity and was engaged in long-range planning of engineering programs. In July 1965, he became responsible for Research and Development Marketing for MDOD. Since January 1966, Mr. Lorentzen has been in Microwave Solid-State Applications engineering concerned with the device/systems problems for all Microwave Solid-State Devices Major emphasis has been in the area of solid-state radiosonde, rocketsonde, and shellsonde transmitters for the Army and the Air Force, tunnel-diode amplifiers for communications systems and weather radar receivers, transistor power amplifiers for communications systems, transistor and varactor devices for both microwave power sources and frequency multipliers for radar and transponder applications, gallium arsenide electro-optical infrared modulators for laser beam modulation applications, and applications work on transferred-electron devices, microwave integrated-circuit devices, and high-power microwave ferrite devices. Mr. Lorentzen has written papers on rocketsonde transmitters and microwave solid-state sources, and is a member of Eta Kappa Nu, Tau Beta Pi, and the IEEE.

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received the BEE from the Institute of Technology, Vienna, Austria, in 1950 and the MEE from the Polytechnic Institute of Brooklyn in 1961, where he is continuing studying for the DEE. In 1959, Mr. Presser joined the RCA Electron Tube Division and is now a member of the technical staff of the Microwave Applied Research group. As a member of the Microwave Electronics section in this group, he has been engaged in the development of various solid-state microwave devices. This work includes the design and development of parametric amplifiers, tunnel-diode amplifiers, tunnel-diode frequency converters, tunnel-diode oscillators, and transistor microwave oscillators. At the present time Mr. Presser is involved with the design and development of hybrid integrated microwave circuits that include radiosonde and telemetry transmitters and high-power transistor amplifiers.

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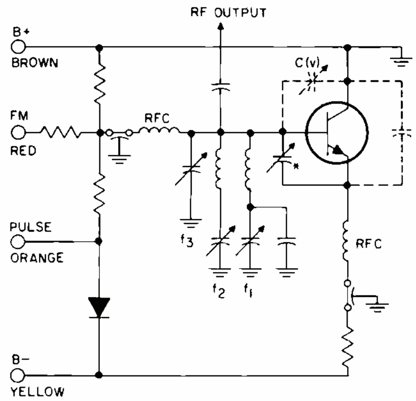
received the BSEE from Newark College of Engineering in 1963. From 1956 to 1961, he was employed by ITT Laboratories as a technician with the assignment of making measurements on microwave antenna systems. He joined the RCA Microwave Devices Operations Department in 1961 as a microwave engineering technician. In 1963, he was promoted to engineer, and was project engineer on the development of a pulsed pencil-tube-and-canity oscillator and on two other pencil-tube development programs. Early in 1965, Mr. Askew was assigned to the Advanced Product Development group and, later in the same year, to the Solid-State Design group where he is now working on the product design of a microwave integrated-circuit radiosonde transmitter. He has made important contributions to the development of RCA TOM's (Transistor-Oscillator-Multipliers) and low-cost rocket-sonde transmitters by improving environmental performance. He was product design engineer on the S190 dual-cavity radiosonde oscillator and also worked on a frequency-control loop used to linearize the tuning curve of a voltage-controlled oscillator. Mr. Askew has completed one year of graduate study at Newark College of Engineering. He is a member of the IEEE and the groups on Microwave Theory and Techniques and Electron Devices.



* EXTERNAL ADJUST. FOR TUNING

Fig. 1—At the frequency of oscillation (560 MHz) the transistor is terminated in a series resonant circuit. Another series resonant circuit is provided at the second harmonic (1120 MHz) of the frequency of oscillation to improve the efficiency; this is the idler circuit. An RF output greater than 200 mW is obtained at 1680 MHz, the third harmonic of the frequency of oscillation.

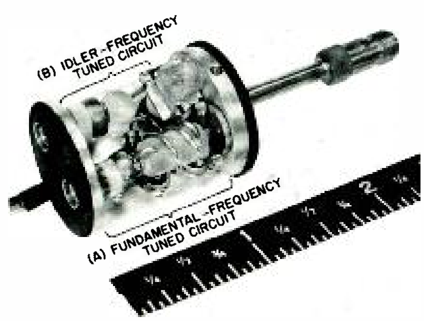


Fig. 2—S170 lumped-circuit transistor/oscillator/multiplier with cover removed to show lumped-circuit elements.

Fig. 3—RCA-S190 cavity oscillator.

radiosonde, telemetry, and proximity-fuze application is on low cost, small size, high stability, and extreme ruggedness. Microwave integrated-circuit techniques have opened the way for the development of solid-state oscillators that meet all these requirements. Two basic approaches are possible to integrated-circuit microwave transistor oscillators, monolithic and hybrid. Although silicon monolithic integration techniques would lead to the smallest size possible, the losses of these circuits are too high to make them useful. Hybrid integrated-circuit techniques are best for these applications because of their low-loss dielectric, as illustrated by the two examples presented in the following paragraphs. These examples describe the design and performance of an L-band oscillator for both balloon- and rocket-borne radiosonde and projectile telemetry applications.

Radiosonde oscillator

The fundamental-frequency RF oscillator uses a grounded-collector Colpitts circuit. The microstrip-transmission-line RF circuitry is formed on a 0.050-inch-thick high-density alumina substrate by use of thin-film technology and photolithographic and etching techniques. The transistor pellet is mounted on a molybdenum wafer directly to the baseplate of the housing for positive ground operation. The baseplate also serves as support for the ceramic RF circuit board. The RF circuit and the transistor pellet are interconnected by ultrasonic bounding. DC connections to the base and emitter are formed by quarter-wave, high-impedance transmission lines that are terminated in low-capacitive reactances. A high-Q half-wave resonator is coupled to the emitter-collector circuit to improve the load stability of the oscillator. The output power is line-coupled from the base-collector circuit. A photograph of the RF circuit of the oscillator is shown in Fig. 6.

Temperature compensation is used to reduce the changes in power output and frequency caused by changes in the transistor and the substrate dielectric constant with temperature. The pulling figure of the oscillator is approximately 2.5 MHz, and the efficiency is 10% (without the regulator).

A particular radiosonde application requires a modulator producing a 60 μs OFF pulse at a pulse repetition rate between 60 Hz and 1800 Hz that is governed by the changing resistance of the sensing element of the sonde. A suitable modulator consisting of a free-running, asymmetric multivibrator that switches the series-type voltage regulator for the oscillator was designed. The circuit diagram of the modulator is shown in Fig. 7. The modulator-regulator combination, which also includes the temperature-compensated bias network for the oscillator, is fabricated on a common ceramic substrate by use of thick-film technology. The transistors and diodes are pellet-mounted and interconnected by ultrasonic bonding. A completed modulator-regulator circuit board is shown in Fig. 8.

Projectile telemetry oscillator

The design and fabrication techniques for the projectile oscillator are similar to those used in the integrated-circuit radiosonde oscillator. The final package is slightly larger because of the lower frequency of operation (1470 MHz) and the more rugged housing construction necessitated by the severe environmental requirements (shock level of 50,000 g). The transistor pellet in this oscillator is mounted on a beryllia ceramic wafer to isolate the collector from ground and thus permit negative-ground operation as required. The thin-film rf circuit and a thick-film voltage regulator and bias network for the rf transistor are mounted back-to-back on a common steel disk. The rf section of the housing is hermetically sealed, and the voltage regulator and bias section is potted with an epoxy which has high thermal conductivity. This oscillator is provided with terminals for FM modulation, and has a modulation sensitivity of ±125 kHz per volt.

Although these transistor oscillators have different degrees of promise for these applications, in some areas other challengers, such as the TEO and IMPATT diode oscillator, are quickly outperforming these devices by orders of magnitude. These areas include very high pulsed power and high microwave frequencies. The advantages of these devices have their foundation in the gallium arsenide (GaAs) material they use.

TEO and IMPATT diodes

The search for semiconductor materials suitable for microwave use led naturally to GaAs because of its high electronic mobility. In addition, the bandgap in this material (1.4 eV) is higher than the bandgap in silicon (1.106 eV) or germanium (0.67 eV); this feature promised superior high-temperature performance. The discovery of a bulk negative resistance in GaAs at microwave frequencies gave further impetus to investigation to determine its use in microwave applications.

The mechanism of oscillation and amplification in bulk GaAs is generally explained in terms of a decrease in the mobility of the carriers (electrons) which accompanies the transfer of electrons into a higher-energy state when the applied electric field is increased; this action is the basis for the term transferred-electron oscillators, or TEO's. The first mode of operation was a transit-time phenomenon; i.e., the frequency of oscillation was a function of the transit time of domains of these carriers across the drift length of the device.

There are several different modes of operation in TEO's, including the pure transit-time mode, a quenched transit-time mode, and the LSA or Limited-Space-Charge-Accumulation mode. Most of the work in RCA's Microwave Device Operations Department has been in the quenched mode. In this mode, the frequency of oscillation is determined by the resonant circuit to which the GaAs diode is coupled.

The IMPATT (Impact Avalanche and Transit Time) diode is also a negative-resistance device, but the mechanism is generally hypothesized as resulting from two factors which add to produce a total phase shift between the voltage and current of the IMPATT diode that is between 90° and 270°. These two factors are 1) the delay (or phase shift) in the current waveform due to the inherent delay in the avalanche process, and 2) the delay due to transit time of the carriers through the diode. Only GaAs IMPATT devices are discussed in this paper because they appear to have substantially lower noise than either silicon or germanium IMPATT diodes.

Both the TEO and the IMPATT diode, and also some high-power varactor diodes, are being fabricated by use of the unique RCA vapor-hydride method of growing GaAs epitaxially;[5,6] this process yields material that is recognized in the industry as the best available GaAs material. In this process, the reactants used to form the material are in gaseous form and the growth of complicated doping profiles is accomplished by changes in flow valve settings. Material grown by the vapor-hydride process, in contrast to most bulk material, is uncompensated and thus has a positive temperature coefficient of resistance, a built-in safeguard against thermal runaway.

The diodes are fabricated from epitaxial wafers by use of photolithographic and/or mechanical techniques. These techniques have been designed to be true batch processes suitable for modern manufacturing requirements.

It is interesting to note that both transferred-electron diodes and IMPATT diodes can be used either as oscillators or as amplifiers, i.e., the same diode can be used in either function as determined by the external circuitry and the bias considerations. In addition, because the frequency of oscillation of both the TEO (in the quenched mode) and the IMPATT oscillator is determined by the circuit, both devices are readily tuned by either mechanical means or electronic means (e.g., by varactor tuning).

The results and objectives of active programs in the Microwave Devices Operations Department are shown in Table II. Since experiments[7,8,9] are continuously being carried out to study the effects of material and circuit parameters on the power,

Table I—Comparison of transistor transmitter characteristics.

Parameter	*RCA S170* TOM*	*RCA S190* Cavity Osc.*	*RCA Radiosonde Integrated Circuit*	*RCA Projectile Integrated Circuit*
Frequency (MHz)	1680	1680	1680	1470
Power output (mW)	200	200	125	150
Tuning range (MHz)	20	20	40	——
Frequency stability (MHz)	4 (0 to 70°C)	4 (0 to 70°C)	1 (−70 to +75°C)	7.5 (−40 to +60°C)
DC voltage (volts)	−20	−20	−24 to −28	+24 to +28
Pulling figure; VSWR=1.5:1 (MHz)	4	4	2.5	2
Pushing figure (MHz/volt)	2	0.5	integral voltage regulator	integral voltage regulator
Efficiency (%)	5 to 10	10 to 15	6% at −24 volts	6% at 24 volts
Vibration (g's)	20	20	20	20
Shock (g's)	200 (11 msec)	200 (11 msec)	75	50,000
Altitude (ft.)	300,000	300,000	300,000	300,000
Subharmonics—typical (dB)	−15	none	none	none
Size (in. diameter × in. length)	1×1.4	1.1×2.2	1.1×0.5	1.3×0.5
Weight (oz.)	2.5	3.0	1.0	2.5

* Many variants have been built at higher and lower frequencies, power outputs, and voltages, and with other special characteristics.

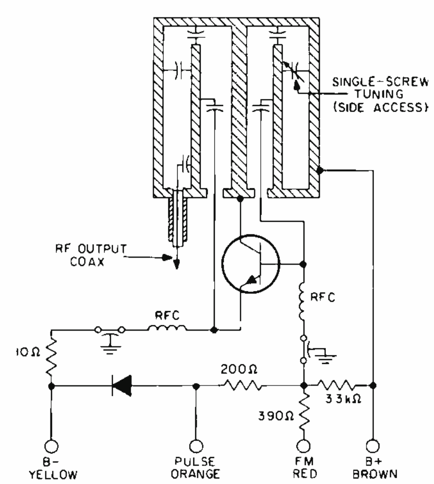


Fig. 4—Schematic diagram of S190 cavity oscillator.

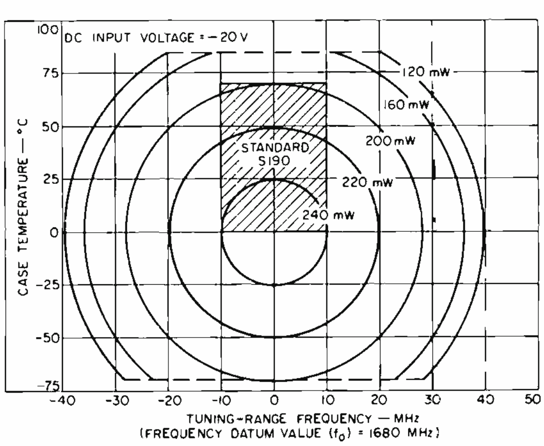


Fig. 5—Minimum power-output capability as a function of case temperature and tuning range for S190 variant.

Table II—TEO and IMPATT results and objectives.

Mode of operation		Pulsed				CW			
Frequency Band		L band	S band	C band	X band	C band	X band		Ku band
Type of device		TEO	TEO	TEO	TEO	TEO	TEO	IMPATT osc	TEO
Present performance	*Best performance*	P_o=220W η=32%	P_o=200W η=29%	P_o=30W η=10%	P_o=1.5W η=10%	P_o=300mW η=3%	P_o=500mW η=4%	P_o=60mW η=6%	P_o=50mW η=5%
	Region of peak yield	P_o=50W η=10%	Note 3	Note 3	Note 3	Note 3	P_o=50mW η=2%	Note 3	P_o=20mW η=2%
Objective (note 1)		P_o=1kW η=25%	Note 2	P_o=30W η=10%	P_o=1W η=5%	Note 2	P_o=500mW η=2.5%	Note 2	Note 2

Note 1—Projected performance in the lab at the end of 1969.

Note 2—The objective in these areas is to develop repeatability in material processes and device performance, and establish the limits of capability.

Note 3—No statistical data available.

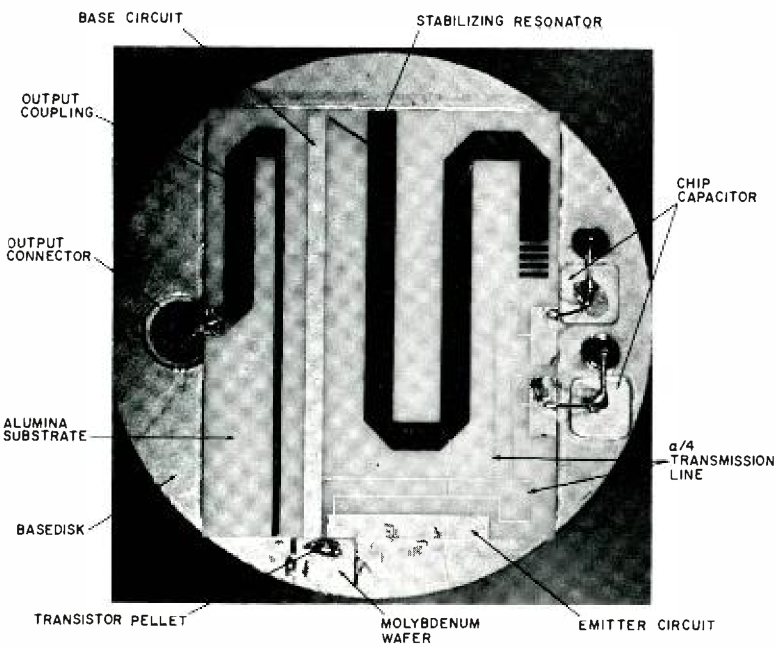


Fig. 6—Photograph of RF circuit of radiosonde oscillator.

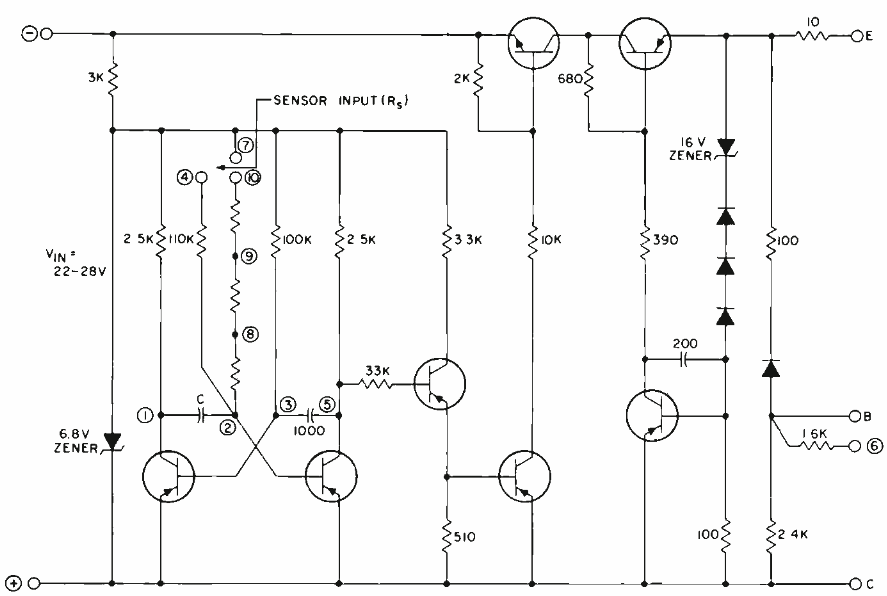


Fig. 7—Schematic diagram of modulator for radiosonde application.

efficiency, noise, temperature performance, electronic tunability, and modulation of these devices and the fabrication techniques are constantly advanced to improve the ruggedness and heat-sink capabilities of the devices, this information can quickly be outdated by new results. The fabrication techniques are also kept fully compatible with integrated techniques so that the same device may be used in both conventional circuits and hybrid microwave integrated circuits, and thus can be capable of extremely large shock and acceleration environments. The simplicity of these devices is illustrated by the simple cw X-band oscillator shown in Fig. 9; this oscillator is a simple coaxial cavity that produces an output power of 10 mW.

The noise performance of TEO and IMPATT devices appears to be comparable to that of good klystrons. For example, noise measurements on samples of the RCA developmental TEO type S229 over the sideband frequency range of 1 kHz to 155 kHz (the maximum frequency of the measurement), for a 1-kHz receiver bandwidth, show the AM noise to be about 117 dB below the carrier. A typical short-term frequency stability of 500-Hz carrier deviation (averaged over 1 millisecond) is achieved at 8.75 GHz with the S272 TEO. Both of these types are 10-to-30-mW TEO's. Noise measurements of an X-band reflection amplifier using GaAs IMPATT diodes have shown single-sideband noise figures of 17 dB.[10]

The temperature performance of these devices is also remarkable. As noted above, GaAs was expected to have good high-temperature performance because of its large bandgap. TEO's

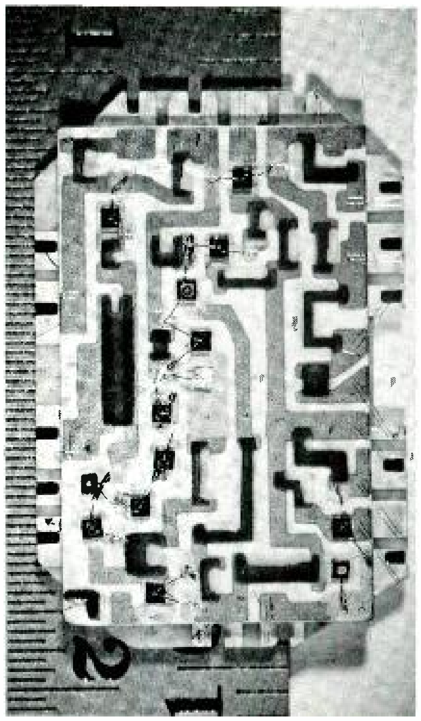


Fig. 8—Photograph of modulator-regulator circuit board.

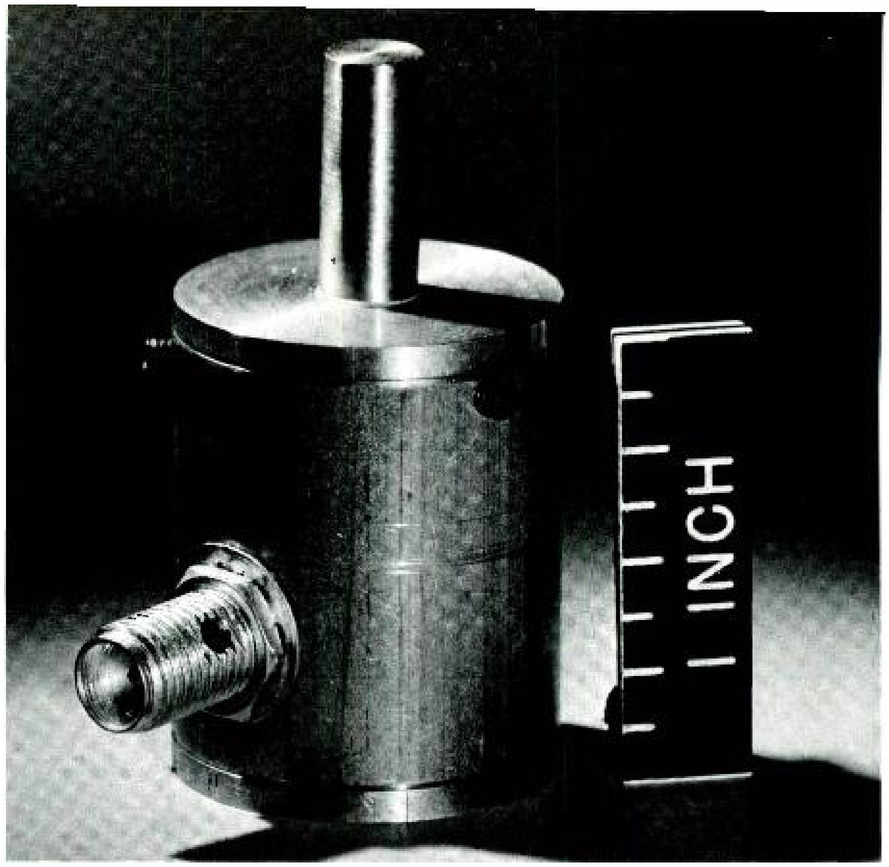


Fig. 9—Experimental X-band transferred-electron oscillator.

have now been operated over the −55°C to +135°C range with a total power variation of less than 2 dB and a total frequency change of about 15 MHz (at a center frequency of 1690 MHz). Although the power levels and efficiencies shown in Table II for these bulk-effect devices were unheard of for fundamental-frequency solid-state sources just a short while ago, they are very real today; the objectives listed appear to be readily attainable based on the continuing trends in these present programs.

Changes in future years can be just as dramatic and unforeseen. There are already many other recognized ways of using GaAs which are waiting for additional breakthroughs in material uniformity or properties to make the forecast in Table II obsolete. For example, power outputs of hundreds of kilowatts pulsed at X-band have been posed as a possibility using the LSA mode of the TEO.[11,12]

Based on today's results and today's technology, some of tomorrow's devices are already clearly taking shape.

Tomorrow's devices

This paper has followed the evolution of rocket and projectile transmitters from the transistor-oscillator/varactor-multiplier concept, to the transistor oscillator multiplier, to the hybrid microwave integrated-circuit transistor oscillator. In view of the rapid advances in TEO's and IMPATT's, it is not too difficult to forecast what the transmitters of the future are likely to be. They will use microwave integrated circuits, TEO and IMPATT devices, and, in many applications, integrated circuits and bulk-effect devices combined to produce miniature, powerful, efficient transmitters that will come quite close to being indestructible.

Acknowledgments

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The authors particularly acknowledge the contributions of the members of the Solid-State Electronics group of the Microwave Applied Research Laboratory, Princeton, N.J., whose work on TEO's and IMPATT's is reported in this paper and who provided much of the background on these devices.

References

1. Sterzer, F., "Microwave Solid-State Power Sources," *The Microwave Journal* (Feb 1968)
2. Lorentzen, R. R., "Microwave Solid-State Sources: Trends and Applications" presented at the IEEE Convention, NYC (Mar 18 and 20, 1968).
3. Askew, R. E., "An Economical Solid-State Rocketsonde Transmitter," *Electronic Communicator* (Jul-Aug 1966).
4. Lorentzen, R. R., "A New Low-Cost Fundamental-Frequency Rocketsonde Transmitter," *Electronic Communicator* (Mar-Apr 1968).
5. Tietjen, J. J., and Amick, J. A., "Preparation and Properties of Vapor-Deposited Epitaxial $GaAs_{1-x}P_x$ Using Arsine and Phosphine", *J. Electrochem. Soc.* vol. 113 (Jul 1966) pp. 724-728.
6. Enstrom, R. E., and Peterson, C. C., "Vapor-Phase Growth and Properties of GaAs Gunn Devices", *Trans. AIME* Vol. 239, No. 3 (Mar 1967) pp. 413-418.
7. Berson, B. E., and Narayan, S. Y., "L-Band Epitaxial Gunn Oscillators", *Proc. IEEE* vol. 55, No. 6 (Jun 1967) p. 1078.
8. Narayan, S. Y., and Berson, B. E., "High-Peak-Power Epitaxial GaAs Oscillators", *IEEE Trans. on Electron Devices* (Sep 1967).
9. Narayan, S. Y., Berson, B. E., and Reynolds, J. F., "Pulsed Epitaxial GaAs Gunn Oscillators", *NEREM Digest* (Nov 1967).
10. Kuno, H. J., Collard, J. R., Gobat, A. R., "Low-Noise Epitaxial GaAs Avalanche-Diode Amplifiers", presented at the International Electron Devices Meeting, Washington, D.C. (Oct 1968).
11. Copeland, J., "GaAs Bulk Oscillators Stir Millimeter Waves", *Electronics*, Vol. 40, No. 12 (Jun 12, 1967) pp. 91-96.
12. Kennedy, W. K., Jr., and Eastman, L. F., "High-Power Pulsed Microwave Generation in Gallium Arsenide", *Proc. IEEE*, Vol. 55, No. 3 (Mar 1967) pp. 434-435.

Traveling-wave tubes for electronic countermeasures

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Among the wide range of RCA-built traveling-wave tubes are those which satisfy the diverse and often contradictory demands of electronic countermeasures (ECM) systems. This paper introduces a typical active ECM system and then describes the design problems, and solutions, associated with the input and memory-storage TWT's used in such a system.

THE TRAVELING-WAVE TUBE (TWT) is uniquely suited for use as a wideband microwave amplifier. Its inherent capability to provide the highest gain-bandwidth product of any amplifying device over an octave in frequency makes it a key component for active ECM (electronic countermeasures) systems. For optimum effectiveness, active ECM systems must respond instantaneously to a wide band of "unfriendly" radar signals over extremes in environment (shipboard or airborne), and in turn retransmit deceptive and erroneous range information. Moreover, the system must operate over a wide range of frequency, signal strength, and pulse width without loss of its deceptive capabilities.

A simplified ECM chain which provides erroneous range information when illuminated by an unfriendly radar is shown in Fig. 1. Because of the widely different signal levels and signal-processing requirements imposed on each of the stages by the ECM system, specialized traveling-wave tubes have been designed for each of the major functions in the cascaded chain. These major functions include:

1) The low-level TWT amplifier stage,
2) The recirculating RF memory TWT stage,
3) The driver TWT stage, and
4) The final power-amplifier TWT stage(s).

RCA has developed an excellent design engineering and manufacturing capability which addresses itself to the traveling-wave tubes of the first three low-power stages of the typical ECM system indicated in Fig. 1. This capability, the result of many years of experience supplying TWT's for major ECM systems, has given RCA important insight into the required tube characteristics, associated operating interface, and signal-processing problems that must be resolved for each of the first three stages. The complexity and operating vagaries of these stages, therefore, warrant additional discussion.

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Simplified operation of the ECM system

A brief discussion of the simplified receiver/transmitter deceptive ECM chain (shown in Fig. 1) will provide some understanding of the functional requirements of each stage. Functionally, the ultimate output signal of the ECM system is a reasonable replica of the received radar signal, but subject to variable time delay before retransmission. This time delay is sufficient to deceive the radar with erroneous range information.

As indicated in Fig. 1, the input signal received from the illuminating radar is picked up by the receiving antenna of the ECM system. The amplifier chain of the system, which covers ½ to 1 octave depending on frequency, utilizes traveling-wave tubes for each of its amplifier stages. The received signal is amplified by the preamplifier stage, which has a noise figure low enough to accommodate the desired threshold or weakest signal.

The duration of the received signal, which is approximately equivalent to the reciprocal of the radar IF bandwidth, is designated τ. A portion of the preamplified signal then flows to the additional cascaded amplifier stages through a power splitter; the remaining preamplifier power is directed to the microwave storage memory circuit for signal processing. The recirculating memory TWT—the heart of the deceptive electronic countermeasures system—is described at length later. Briefly, however, its broad function, as shown in Fig. 1, is to sustain the received signal in the feedback loop so that the output-signal duration is many times ($N \times \tau$) the actual received signal. During the extension period of the memorized signal, the input low-level amplifier is gated off and the memory-loop TWT is turned on. The associated threshold and level-sensing circuits of the system determine the appropriate time—contingent on signal delay and amplitude—to put the system in the memory mode. The output of the memory-storage subsystem stretched out in duration ($N \times \tau$) is then amplified in the driver tube and the final power-amplifier stages. The grid (gate) pulse of this final stage is programmed to provide a variable time-positioned transmission window which turns the power amplifier "on" for the designated pulse duration (τ) over any portion of the total memory time. The variation of position of the output power pulse of the ECM system, relative to the incident received pulse, is the time delay that enables deceptive range information to be conveyed to the unfriendly radar.

For proper operation of the system, each amplifier stage must be capable of coping with the associated interface characteristics of adjacent stages. This criterion necessitates that each stage independently meet the following requirements:

1) A minimum small-signal gain requirement to insure that the threshold input signal will drive the final power tube to the minimum system power-output requirement;
2) Maximum small-signal gain limits, if cw operation is desired, to avoid

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received the BSEE in 1953, and has completed his work toward the MSEE at Newark College of Engineering. From 1948 to 1955, he worked in the Research Laboratories of National Union Electric Corporation. He joined RCA Microwave Tube Operations Department in 1955, where he worked on the design and development of traveling-wave tubes. In 1958, he became Engineering Leader in charge of the development of low-noise traveling-wave tubes. He was promoted to Manager, Traveling-Wave-Tube Design and Development, in 1961. In July 1964, as Manager, Microwave Advanced Product Development, he directed a group in advanced development and application work on traveling-wave tubes and pencil tubes. In August 1965, he became Manager of Traveling-Wave-Tube Product Design. Mr. Wolkstein has made many contributions to the design of traveling-wave tubes, periodic-permanent-magnet focusing structures, slow-wave structures, and electron guns. He was particularly instrumental in the development of the RCA family of ultra-low-noise traveling-wave tubes, memory-storage tubes, and the RCA tricoupler and multicoupler switching tubes. He has done notable work in the development of compact, solid-state microwave oscillators and frequency multipliers. Mr. Wolkstein has been awarded several patents in the electron-tube field. He is a member of the IEEE and the IEEE Groups on Electron Devices and Microwave Theory and Techniques.

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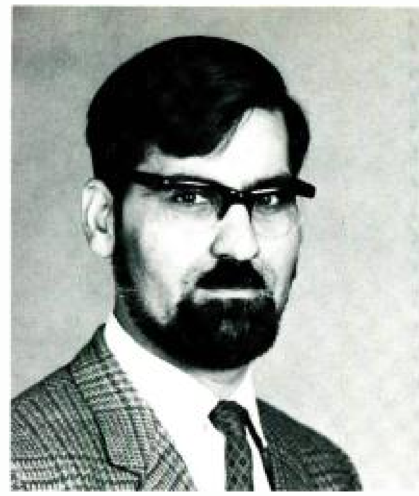
received the BA in Physics from New York University in 1953 and the MS in Applied Physics from Harvard University in 1954. From 1954 to 1957, he was a member of the Technical Staff of the Bell Telephone Laboratories. There he worked on microwave tubes including reflex klystrons operating at C-band for radio-relay applications, and at K-band for use in a circular-waveguide communications system. Mr. Freeling joined the RCA Microwave Tube Operations Department in 1957, where he has since been engaged in the development of PPM traveling-wave tubes. Among other programs, he participated in the design and development of the RCA Developmental Type A-1166 10-watt, S-band traveling-wave tube and a medium-power ppm traveling-wave tube for a radio-relay system. He has been engaged in the design and development of several memory-storage (recirculator) traveling-wave tubes for use in ECM systems. He has also done special design work on medium-low-noise PPM traveling-wave tubes and conducted a study of signal suppression in broadband traveling-wave-tube amplifiers. Mr. Freeling received the RCA Electronic Components and Devices 1963 Engineering Achievement Award for his work as a member of the team that developed the traveling-wave tubes for the orbiting Relay satellites.



Paul Puri
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studied radio engineering at the Indian Technical Institute, New Delhi, India and was transferred to the Aeronautical Communication School, Government of India, from which he graduated in 1949. He then joined the Aeronautical Communication Service, India, as a technical assistant and engaged in the development of radio communication and navigational aids. As a graduate student in 1954, Mr. Puri entered the research and development laboratories of Cossor Radar and Electronics, Ltd., London, England and joined its staff in 1956 as a development engineer. In 1958, he received the Dipla. Tech. in Electrical Engineering from Enfield College of Engineering, Enfield, England. From 1956 to 1960, Mr. Puri attended various post-graduate and other courses at Northern Polytechnic and Enfield College of Engineering (Univ. of London) in microwave physics, telecommunication engineering, and allied subjects. From 1960 to 1967, Mr. Puri was employed by MOV (General Electric Company, England) first as a senior development engineer and later as Technical Superintendent responsible for the design and development of various low-noise and low- and high-power communications tubes. Mr Puri joined RCA's Microwave Devices Operations Department in 1967 as a senior development engineer where he has been engaged in the design and development of a number of low- and medium-power traveling-wave tubes and special frequency-memory traveling-wave tubes.

antenna-to-antenna isolation problems (receiver to transmitter);
3) Minimum power output within the wide input-power overdrive range;
4) The overall performance criteria with power-supply deregulation of ±½ to ±2.0%;
5) The overall performance criteria over the temperature and environmental extremes (−85°C to +120°C, 70,000 feet, salt spray, humidity, etc.);
6) External mechanical requirements such as shock, vibration, acoustical noise, etc; and
7) RFI and stability requirements.

The input TWT

The typical input TWT of the ECM system must meet several diverse and opposing requirements. It must have a noise figure low enough to make the threshold signal discernible and establish the minimum signal-to-noise ratio of the system; it must simultaneously accommodate a wide range of input-signal levels (perhaps 30 to 50 dB beyond saturation) to meet minimum output-power requirements.

For the input traveling-wave tube, generally, a long input helix section is required for low noise figure, but a long output helix section is required for large input overdrive signals. To meet overdrive requirements, it is necessary that the active output helix section be equivalent in length (dB/cm) to the degree of overdrive input power beyond the saturation point of the tube. If the helix length is not adequate, additional input power drive causes sudden loss of output power as the saturation point of the tube moves to the input side of the decoupling attenuator sever. This condition is illustrated in Fig. 2 for drive level P4; the kinetic energy has been extracted out of the tube on the input helix, and no interaction energy is available for re-inducing the wave on the output helix.

It is also necessary to shape the output helix wave velocity as a function of frequency so that the generation of second-harmonic components is minimized. Fig. 3 illustrates the wide harmonic separation achieved with RCA tubes that use a special output helix taper. These characteristics are extremely important for ECM tubes and systems with wide drive ranges and octave or greater bandwidth performance.

RCA has designed medium-noise, PPM (periodic-permanent-magnet),

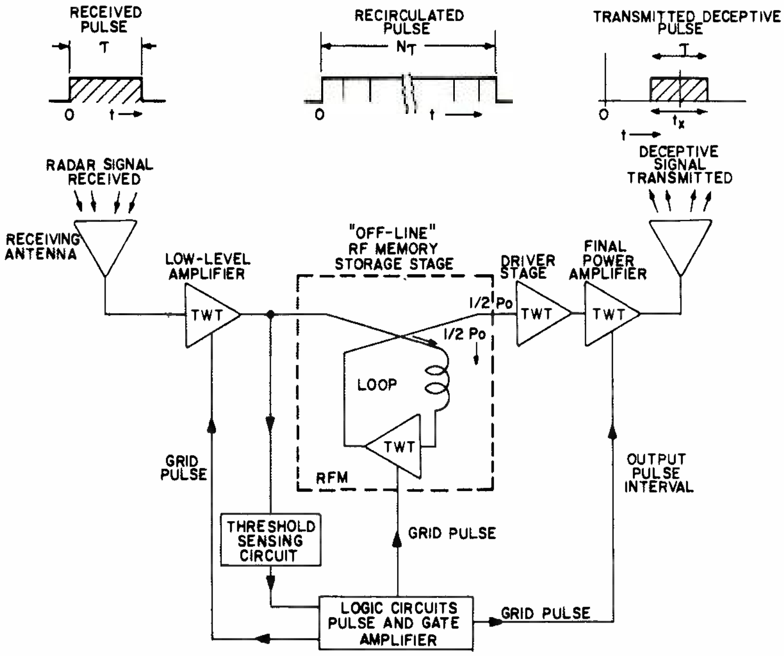

Fig. 1—ECM receiver/transmitter chain.

RCA dev. no.	Frequency (GHz)	Noise figure (aB)	Gain (min.) (dB)	Pulse grid	Power-output range (dBm)	Input-power range (dBm)	2nd-harmonic separation
A-1350	1 to 2.6	<12	30	x	0 to 20	−43 to −7	NA
A-1327	2 to 4	<17	36		+5 to +20	−32 to +2	−5 dBc
A-1381	2 to 3.8	~25	35	x	+1 to +20	−32 to +18	−5 dBc
A-1382	3.8 to 7.4	<20	28	x	−14 to +6	−38 to +6	−5 dBc
A-1383	7.4 to 12	<20	28	x	−14 to +9.5	−38 to +8.5	−5 dBc
A-1360	4 to 8	~15	33		−3 to +15	28 to 0	−5 dBc

Table I—RCA-built preamplifier TWT's.

traveling-wave tubes to meet customized system interface needs for a wide range of frequencies. In general, these tubes cover L to X band and have noise figures ranging from less than 12 dB to approximately 20 dB. The salient characteristics of these devices are shown in Table I.

Design of the memory-storage TWT

Operation of the storage TWT is obtained by feeding the output of the tube back into its input through an appropriate feedback circuit. Fig. 4 illustrates this technique for an "off-line" loop in which the initiating pulse does not undergo amplification by the loop TWT before being transmitted. The dynamic operation of this feedback loop, which consists of the TWT and a coaxial or waveguide delay line and other passive components, is so complex that the interrelationship of the various components must be fully understood before a satisfactory design criteria can be evolved.

To obtain memory performance and regeneration at any frequency in the band, the small-signal gain of the TWT in the feedback loop must be in excess of the feedback losses across the band. However, mere injection of a signal into the loop subsystem with the prerequisite gain is not sufficient to insure stable, long-term memory storage. Good operation of the memory traveling-wave tube and its feedback network requires that many dynamic RF parameters be simultaneously satisfied.

Overdrive equilibrium requirements

Operation of a loop memory tube can best be illustrated by reference to the dynamic overdrive and loop-loss curve shown in Fig. 5. For the example shown, application of the threshold signal (−30 dBm) to the loop subsystem provides a tube output power of +5 dBm (point A). The excess loop gain (~10 dB) after the first recirculation produces a new input power to the tube of −20 dBm (point B). This regeneration ideally occurs with each recirculation until the open-loop gain is equal to the loop loss and the system comes to rest at the equilibrium or quiescent storage point. Obviously, it is necessary to shape the overdrive curve properly to establish and to maintain stable memory operation' at the equilibrium point. An improperly shaped overdrive curve with overall power fall-off greater than 45 degrees beyond saturation will cause faulty recirculation and "homing" (bi-stable operating levels). This phenomenon is illlustrated in Fig. 6; the excess gain and the power curves start to converge toward a stable point and then diverge and repeat the cycle again so that power stability is not obtained.

Noise capture

The fact that the TWT and the feedback network are necessarily broadband assures that the white-noise power of the input TWT, enhanced by its gain and the excess gain of the memory circuit, will also be recirculated. This white noise can build up in each successive recirculation and virtually capture the memory system. Noise capture—one of the prevalent failure mechanisms in memory-storage traveling-wave tubes — generates an erroneous signal independent of the desired coherent input frequency and makes the memory inoperative.

Gain suppression

In the absence of an input signal, the noise recirculating in an active feedback loop is amplified with each successive recirculation. The excess gain, the power output, and the feedback phase relationship across the band determine the single frequency (or finite band of frequencies) which takes over, or captures the recirculating memory. In the presence of a desired input signal, however, this failure mode — noise capture — must be avoided for the required term of memory storage.

Random noise capture of a broadband feedback loop is inhibited by a phenomenon known as "gain suppression." Gain suppression manifests itself, as it does with all active devices, in the presence of a large overdriving signal, by compressing the small-signal gain everywhere in the band. Fig. 7 shows the input/output characteristics of a TWT in both the small-signal and saturation regions with varying levels of suppression signal elsewhere in the band. It is apparent that large

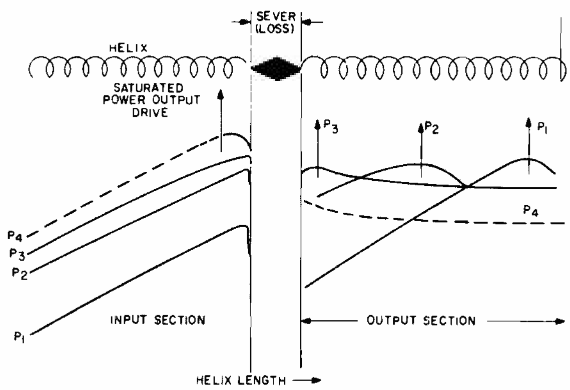

Fig. 2—Saturation position and power output as a function of input drive.

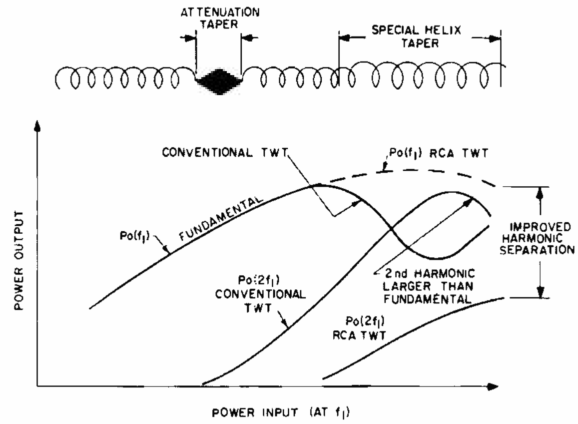

Fig. 3—Fundamental and second-harmonic power output as a function of power-input drive for conventional and improved RCA TWT's.

suppression signals reduce the small-signal gain appreciably.

In a feedback loop, as the operating point converges toward equilibrium after the initiation of an input pulse, the excess feedback gain is reduced to zero (i.e., the gain equals the losses). Obviously, the input power to the loop tube at equilibrium is sufficient to suppress the gain for all frequencies in the band. As a "rule-of-thumb," the degree of gain suppression for all noise frequencies is approximately equivalent to the gain suppression suffered by the coherent frequency itself in approaching its equilibrium point in the feedback circuit.

The suppression of gain in a well-designed broadband TWT by the larger coherent overdriving signal is sufficient to prevent build-up and capture of the memory by recirculating noise.

The delay line

A single recirculation delay time of the system is established largely by the average width of the varied radar pulses it must accommodate. For optimum performance, the total delay time for one recirculation must be approximately equivalent to the radar pulse duration. This delay time (150 to 250 nanoseconds, including the 12 to 20 nanoseconds delay of the TWT) typically may require 100 to 150 feet of coaxial cable length. After the cable length is established, the cable diameter and other parameters are determined.

Literally filling the feedback circuit with the weakest operating RF signal (signal threshold level) establishes the smallest prerequisite signal-to-noise ratio which enables operation. The absence of signal, or a signal below the operating threshold of the device during the pulse interval, allows "white" noise to recirculate and erroneous operation ensues.

The attenuation (or feedback loss) of a delay line of fixed length is an inverse function of cable diameter. The desire to minimize the size and weight of a cable is compromised by the more pressing need to keep the overall feedback loss substantially below the small-signal gain of the traveling-wave tube. The difference between small-signal gain and loss, 10 to 15 dB, is the excess gain of the feedback loop. Therefore, loop-attenuation problems must be balanced against size.

Loss equalization/temperature

The loss of the coaxial delay line increases linearly with frequency, as shown in Fig. 8. When this loss is subtracted from the typical small-signal gain characteristics of a TWT, an excess gain shape results which is generally convex or humped at center frequency. This gain shape, which is far from ideal, provides recirculating noise with the opportunity to build up at center band where the gain predominates (independent of the signal input frequency) and sometimes causes faulty RF memory operation.

To avoid noise capture due to relatively high excess gain at mid-band, a gain-shaping equalizer can be used in series with the delay line. The reciprocal loss characteristic introduced by

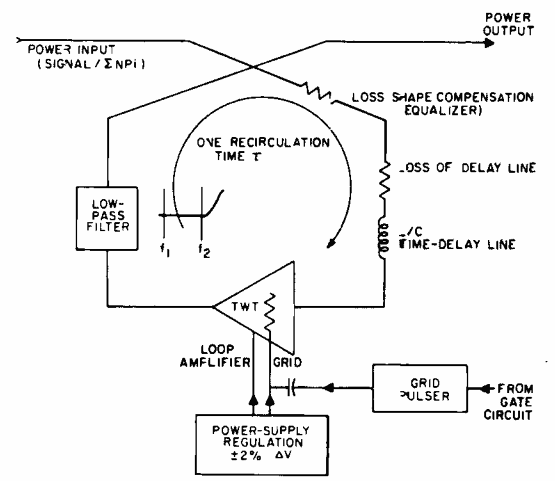

Fig. 4—Off-line recirculating RF memo y subsystem.

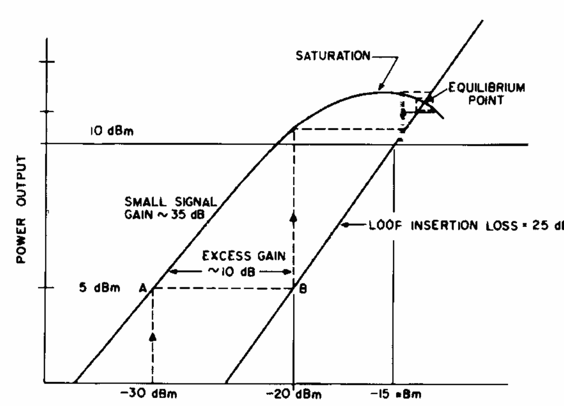

Fig. 5—Dynamic loop and TWT equilibrium operat ng point.

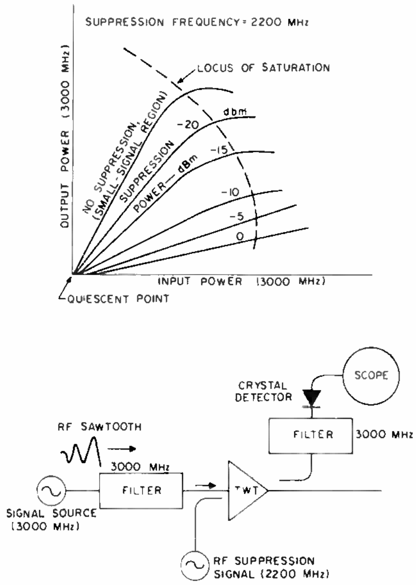

Fig. 7—Transfer characteristics of a traveling-wave tube in the presence of suppression signal at a fixed frequency.

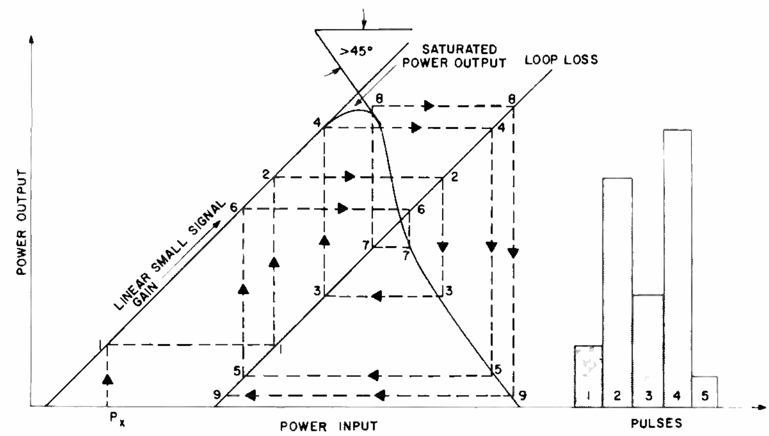

Fig. 6—Faulty (unstable) recirculation caused by poor overdrive slope.

Table II—RCA-built memory TWT's.

RCA dev. no.	*Performance mode*	*Frequency band*	*Grid gate*	*Storage time (μs)*	*Power level*	*Small-signal gain (dB)*
A-1220	Off-line	S	x	<5	10-80 mW	Not req'd
A-1361	Off-line	C	x	<5	3-16 dBm	Not req'd
A-1384	In-line	S	No	<5	~1 W	35
A-1385	In-line	C	No	<5	100 mW, ½ W	40
A-1386	In-line	X	No	<5	100 mW, ½ W	40

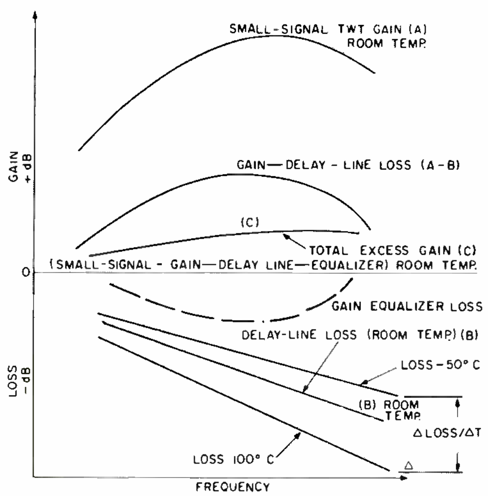

Fig. 8—Tube gain loop loss parameters as a function of frequency and temperature.

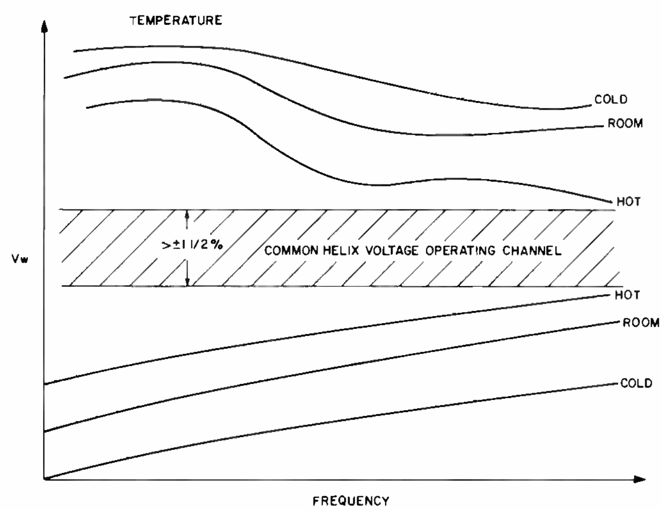

Fig. 9—Helix mode storage plot as a function of temperature.

the equalizer is designed to compensate for the dome-shaped excess-gain curve. The result at room temperature is a slightly rising excess-gain curve, as shown in Fig. 8 by curve C, which provides good memory-storage operation.

Maintaining the desired excess-gain shape is further complicated by the variations of delay-line loss with temperature. In general, delay-line losses track temperature linearly. An increase in temperature, therefore, causes losses to increase, while reduced temperature reduces losses. However, because the losses vary with frequency as well as temperature, the delay line, which covers an octave in frequency, is likely to suffer twice the loss change with temperature variation at high frequency as compared to the loss change at the low-frequency end of the band. Although the absolute change in loss can be tolerated with sufficient excess gain, the attendant change in loss shape with temperature is conducive to noise capture.

To overcome this problem on early delay lines with a characteristic 7 to 8 dB loss change over temperature extremes, methods were introduced to enable the gain of the tube to virtually track the loss of the loop. This temperature-compensation technique eliminates noise capture over the high-

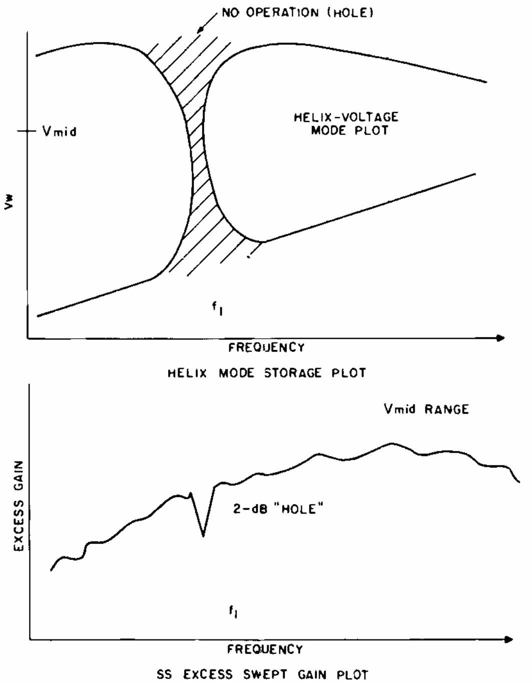

Fig. 10—Plots of helix mode storage (top) and small-signal excess swept gain (bottom).

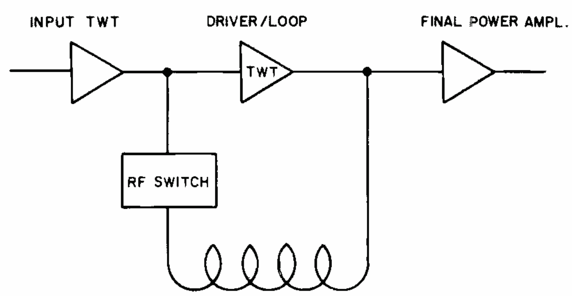

Fig. 11—In-line RF memory storage subsystem.

frequency portion of the band and the resulting memory failure.

Mode plots and performance

To test and demonstrate the capability of each loop TWT, complex measurements are made of RF storage capability over the range of conditions described above. These measurements indicate the common range of power-supply variation (helix voltage) that can be tolerated as a function of frequency without deterioration of power output and other parameters during the storage cycle. A typical "mode plot" indicating the loci of satisfactory performance is shown in Fig. 9. Measurements are repeated for hot and cold temperature and for extremes in the drive range. A tube is considered acceptable if it is able to meet the power-supply regulation requirements (~1 to 2% of helix voltage) as a common voltage corridor for all conditions of operation.

Perturbations in the small-signal gain curve of the TWT or in the feedback circuit can cause loss of memory over that frequency band. Fig. 10 illustrates an example of this failure mechanism which manifests itself as an "island" of inoperation. The corresponding excess or open-loop gain plot, shown also in Fig. 10, verifies that a "hole" exists over the same frequency band.

To inhibit failures similar to those shown, it is necessary to plot excess-gain curves of all tubes and associated loops to establish that the proper contour and fine-grain performance levels have been achieved.

When the proper controls have been imposed on both tube and passive circuit components for fine-grain response, VSWR, gain-loss contour, and overdrive, tubes can be made which provide the required memory storage with all loops over a reasonable spread of characteristics.

In-line RF memory storage

Loop memory storage tubes have been designed for specific systems in which the multiple functions of cw amplification and RF memory are combined in a single stage. This approach replaces the drive tube shown in Fig. 1 with the so called "in-line" loop TWT configuration shown in Fig. 11.

This circuit simplification reduces the complexities of the system, but imposes on the TWT all of the RF characteristics needed for pulse amplification as well as the sophisticated characteristics required for RF memory storage. The traveling-wave tube in this system must meet system minimum and maximum gain restraints, provide the proper input/output drive characteristics for the cw pulse, and enable RF memory storage approximately one magnitude higher in output power than that of the off-line TWT.

RCA memory tubes

RCA has built many different "in-line" and "off-line" traveling-wave tubes to meet a host of system requirements. For reference, some of the memory tubes are tabulated in Table II.

Prerequisites for memory storage

TWT's for loop memory subsystems must be designed to provide RF storage capability while operating with the required passive delay components in the feedback loop. To accomplish this objective, it is necessary for the TWT to meet the following prerequisites:

1) Produce a small-signal gain contour which complements the delay-line loss (~10 dB in excess of loop-loss contour);
2) Maintain excess-gain spread and gain contour with temperature variation over operating environment;
3) Provide storage operation over the memory period with power-supply (±2%) and temperature variations;
4) Meet the above requirements over the wide power ranges of the input pulses; and
5) For the in-line loop, meet the specific system interface characteristics as an amplifier between the input and final TWT's in the chain, as well as provide RF storage.

Microwave solid-state subsystems engineering

F. E. Vaccaro | J. J. Napoleon

This paper describes two typical "subsystems," each fairly complex, which illustrate the combination of microwave engineering skills with other engineering disciplines to satisfy a specialized systems need. Each of these subsystems forms a vital part of a larger system. The first subsystem described is a wide-range multiple-band voltage-tuned power source intended for local-oscillator application; the second is a frequency-multiplier chain used in several radar equipments in the LM Apollo vehicle.

THE MICROWAVE SOLID-STATE SUBSYSTEMS (MSSS) engineering group is concerned with the design and development of subassemblies that fill a specialized microwave-systems need. These devices or subsystems are generally unique or customized subassemblies that use discrete solid-state devices such as transistors or diodes combined with appropriate microwave and accessory circuits.

In many military and space electronic systems, there are advantages to a breakdown of the system into definable subsystems that perform specialized system functions and demand specialized microwave expertise. The combination of interrelated circuits or components can often improve the performance characteristics of a system by reducing the complexity of the interface between the components. Thus, it is often advantageous to consider a series of cascaded amplifier stages, or a chain of varactor multipliers, as a composite engineering problem rather than as a set of separate devices with multiple complex or indefinable interfaces that waste engineering effort. It is generally necessary to include in these subsystems several related microwave devices such as filters, isolators, and switches, together with appropriate lower-frequency circuits and often a rather demanding packaging concept.

In designing these subgroups of discrete devices, it is possible to focus all of the mechanical, thermal, and electronic engineering disciplines that are needed to satisfy complex systems needs as an efficient, integrated, and managed effort. The two typical subsystems described in this paper illustrate this fusion of engineering disciplines necessary for microwave subsystem design and development.

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Solid-state local oscillator

The function of the local oscillator (LO) in a superheterodyne receiver is to supply a signal to the mixer for conversion of the received signal to an intermediate frequency. The primary requirements of the LO signal are that it be stable in frequency and amplitude, relatively free of noise, and of sufficient level (a few milliwatts) to achieve good mixing. In many cases, these requirements can be fulfilled by a simple free-running oscillator. However, when the requirements are broadened to include

1) Electronic frequency tuning over portions of S, C, and X band;
2) High input impedance for tuning;
3) Good frequency stability over a wide range of environmental conditions; and
4) Packaging in a restricted volume,

the complexity of the LO is increased to that of a subsystem.

The block diagram of a solid-state local oscillator designed to meet these requirements is shown in Fig. 1. A photograph of a developmental unit is shown in Fig. 2. The basic configuration employs two varactor-tuned oscillators that drive three multiplier chains. The signal from the multipliers is filtered and channeled to a common port by a triplexer. Isolators are used to minimize frequency pulling of the oscillators and to isolate the multipliers from the output. Frequency changes resulting from ambient-temperature variations from −40° C to +80° C are reduced by placing the oscillators in an oven that maintains the temperature of the oscillator housing at 94 ±2° C and by temperature control of the isolators following the multipliers.

The output of oscillator *O2* (Fig. 1) can be switched between the *X4* multiplier chain *M2/M4* and the *X8* multiplier chain *M3/M5/M6* by the single-pole double-throw switch. A separate oscillator *O1* is used for the *X2* multiplier *M1* because the desired frequency bands are not integrally related. Both oscillators operate continuously to minimize frequency drift when band switching takes place. Band selection is accomplished by DC logic signals that actuate the SPDT switch and turn off the multiplier chains that are not in use.

Although there are a number of different ways such a system could be designed, the method shown best suits the special requirements. For instance, a low-power YIG-tuned oscillator followed by an amplifier was considered for the driver, but was rejected because of the tuning power required and the increased noise level resulting from the use of an amplifier stage. Another alternate considered was the use of three separate oscillators and elimination of the SPDT switch. This approach was not used because of the increased oven power that the additional oscillator would have required. Although higher-order multipliers might have been used in place of simple tandem doublers, it is difficult to make such devices operate over a broad band without spurious output.

Performance

The performance capability of the local-oscillator subsystem has been demonstrated on a large number of production units. Table I shows the typical performance achieved over the ambient-temperature range of −40° C to +80°C.

Multipliers and oscillators

In the diagram shown in Fig. 1, all multipliers are of the coupled rectangular-bar type[1,2] except *M6*, which utilizes a waveguide circuit because of the frequency. The rectangular bar configuration was selected because of its wide bandwidth capability and simplicity. Multipliers *M2/M4* and *M3/M5/M6* were constructed as single units without interconnecting cables to minimize space requirements and improve electrical performance. The size of these combined units was further reduced by circuit coupling from one varactor bar to the other without the use of an output or input bar. Thus, the combined units *M2/M5* and *M1/M4* use only four bars, as shown in Fig. 3a, instead of the six bars required for two connected doublers (Fig. 3b).

Fixed bias was used with a compensating thermistor network to minimize power change and eliminate spurious output over the complete temperature range.

Band selection is accomplished by use of the SPDT switch and application of a forward bias to the varactors of the chains not in use. A forward current of 2.5 mA through the diode of the doubler was found sufficient to reduce the multiplier output by 60 dB, provided that the second-harmonic content of the signal into the doubler was down at least 50 dB. This low harmonic level of the signal into *M3* was assured by use of a low-pass filter, as shown in the block diagram (Fig. 1). The oscillators are of a Clapp circuit design and utilize an RCA Dev. No. TA 7003 transistor with a grounded collector. Tuning is accomplished by use of two high-Q (Q-$4 = 1200$ at 50 MHz) varactors placed back-to-back to increase breakdown voltage. The power loss incurred as a result of the tuning varactors is approximately 1 dB. An additional 3-dB power is dissipated in a resistor shunting the output to reduce frequency pulling of the oscillator with changes in output loading. The maximum pulling due to a VSWR of 1.5 in the output line varying through all phases is 10 MHz. The power output is 250 mW, and is flat within $\pm 1/4$ dB.

Frequency-multiplier chains for LM radars

Four types of solid-state, transistor-amplifier/varactor-frequency-multiplier chains have been developed for use in the Apollo program. Since its inception in EC in 1963, this program has progressed from initial design through delivery of developmental pre-flight and environmentally qualified subassemblies suitable for use in manned lunar missions.

Application

The four frequency-multiplier chains described serve as the prime source

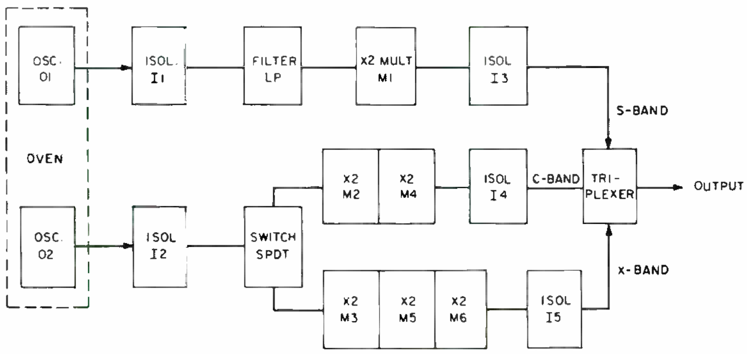

Fig. 1—Block Diagram of solid-state local oscillator.

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received the BSEE from the University of Tennessee in 1948, and the MSEE from the Stevens Institute of Technology in 1953. He joined RCA in 1948 and was assigned as a development engineer on the design and testing of magnetrons and traveling-wave-tube matching sections. In 1954, he was appointed a Member of the Technical Staff of the RCA Laboratories, and was assigned to the Microwave Applied Research group. In 1956, he was made Engineering Leader of the group. In 1958, he was made Manager, Microwave Applied Research, and given the responsibility for all applied-research and advanced-development work carried out by the Microwave Tube Operations. In 1963, he became Manager, Traveling-Wave Tube and Pencil-Tube Engineering at Harrison, New Jersey, and in 1965, he was made Engineering Leader of the Advanced Development group and did pioneering work on electrostatically focused traveling-wave tubes. Mr. Vaccaro has made major contributions to the microwave field. His applied-research studies on the characteristics of wide-range, high-power tunable magnetrons led to the development of a family of high-power tunable magnetrons with superior tuning, stability, and life characteristics This work is described in the book *Crossed-Field Microwave Devices*, published by Academic Press in 1961. Since 1966, Mr. Vaccaro has been Engineering Leader in the Solid-State Subsystems group. He received the 1967 RCA Electronic Components Engineering Achievement Award for valuable contributions to microwave circuits. Mr. Vaccaro is a Senior Member of the IEEE.

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Electronic Components
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received the BSEE from Newark College of Engineering in June 1958, and the MSEE from Rutgers in June 1960. He served two years with the United States Signal Corps (1953 to 1954) as an instructor for courses on electronic power supplies at the microwave branch of the Signal School at Fort Monmouth, New Jersey, and also in the capacity of maintenance technician on a microwave radio-relay station in Germany. He completed courses in radio and television engineering at the Jersey City Technical Institute (1950 to 1952) and was employed at the school as an assistant instructor during the period from 1955 to 1956. Mr. Napoleon was employed at RCA during the summer of 1957 as an engineer in the Microwave Engineering Test group, and joined Microwave Engineering Development in June 1958 to work on design of low-noise TWT's. In June 1960, he was assigned to the development of tunnel-diode oscillators. Mr. Napoleon has been a Project Engineer on several solid-state device developments including tunnel-diode oscillators, parametric amplifiers, and varactor frequency amplifiers, as well as lead engineer in the development and production of complex frequency multipliers used in missile tracking systems. The design of these frequency multipliers became the initial model for the LM frequency multiplier development. Mr. Napoleon has been directly assigned to the LM project since the spring of 1965, and has been responsible for the transfer of the multiplier design from Engineering to Manufacturing.

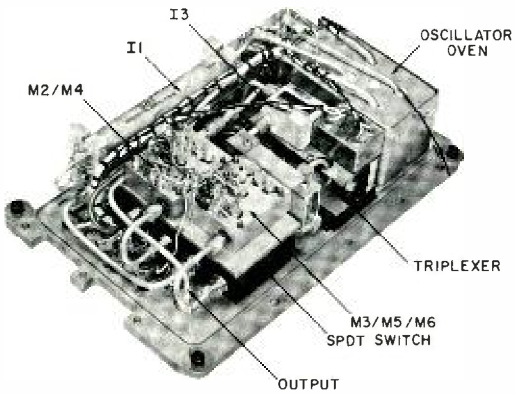


Fig. 2—Developmental Model of SSLO.

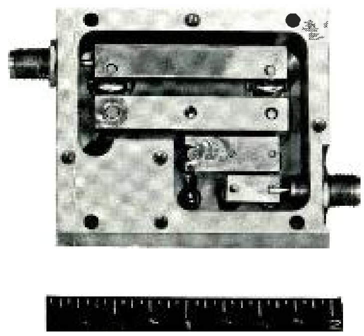


Fig. 3a—Multiplier M2/M4.

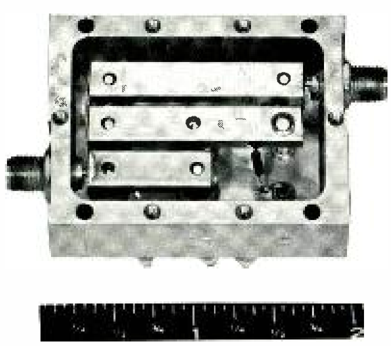


Fig. 3b—Multiplier M1.

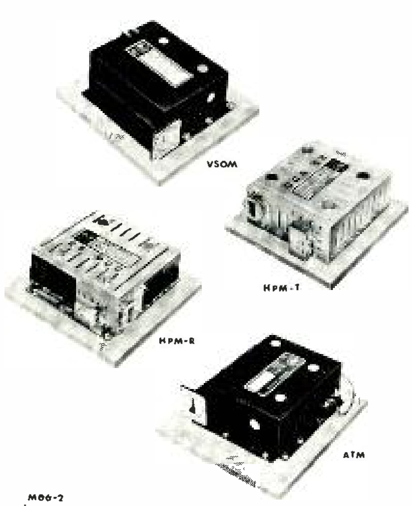


Fig. 4—LM frequency-multiplier subassemblies.

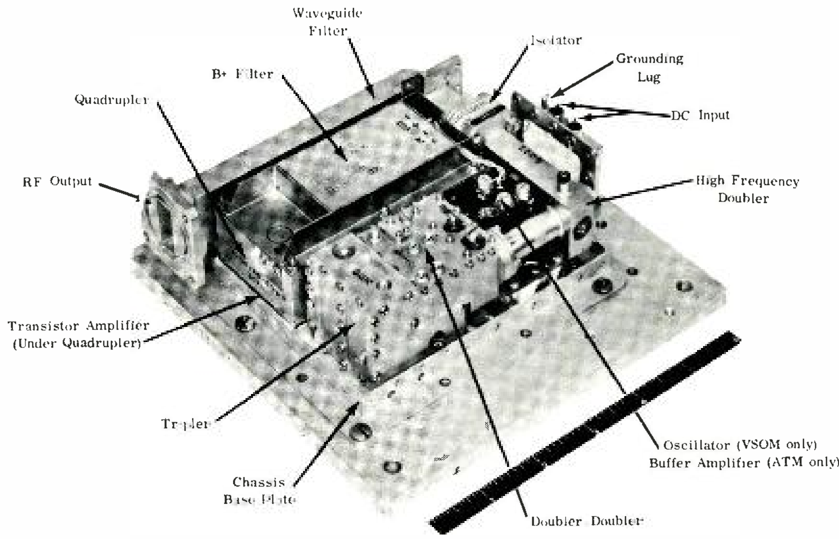
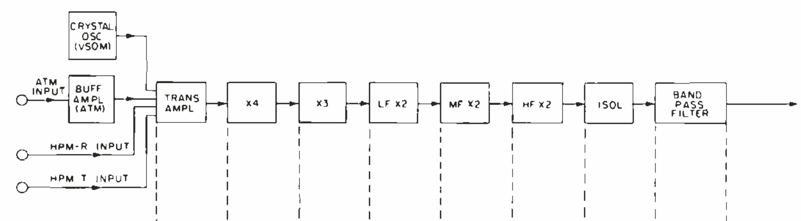


Fig. 5—LM frequency multiplier with chassis cover removed.



VSOM	109.5 MHz 24 mW	109.5 MHz 14 W	438 MHz 7 W	1314 MHz 3.8 W	2628 MHz 2.2 W	5255 MHz 1.1 W	10150 MHz 430 mW	-0.3 dB	-0.7 dB	340 mW
ATM	99.8 MHz 1.4 mW	99.8 MHz 6.5 W	399 MHz 4 W	1198 MHz 2.4 W	2395 MHz 1.5 W	4790 MHz 850 mW	9580 MHz 375 mW	-0.3 dB	-0.9 dB	280 mW
HPM-R	102.4 MHz 17 mW	102.4 MHz 16 W	410 MHz 8.5 W	1229 MHz 4.7 W	2458 MHz 2.8 W	4916 MHz 1.5 W	9832 MHz 590 mW	-0.3 dB	-0.4 dB	500 mW
HPM-T	102 MHz 15 mW	102 MHz 16 W	408 MHz 8.5 W	1224 MHz 4.7 W	2448 MHz 2.8 W	4896 MHz 1.5 W	9792 MHz 590 mW	-0.3 dB	-0.4 dB	500 mW

Fig. 6—LM frequency multiplier.

Table 1—Typical performance of solid-state local oscillator.

Parameter	*S-band*	*C-band*	*X-band*
Min. power output (mW)	8	7	5
Power flatness (dB)	3	3	2.5
Bandwidth (%)	24	8	8.6
Spurious output (dBc)	>60	>60	>60
Frequency repeatability (%)	0.08	0.06	0.06
Frequency reproducibility (%)	1.5	1.0	1.2
Short-term stability (%)	3×10^{-5}	3×10^{-5}	3×10^{-5}
Long-term stability (%)	0.002	0.0015	0.001
Tuning rate (MHz/V)	8 to 28	12 to 25	24 to 33
Tuning-voltage input impedance (ohms)	>10,000	>10,000	>10,000
Output VSWR	<1.5	<1.5	<1.5
Weight (lbs.)		6.7	
Size (inches; L×W×H)		10×6.5×2.7	

Definitions:

Min. power output is the lowest power measured throughout the frequency band as the ambient temperature is changed from −40° C to +80°C.

Power flatness is the ratio of maximum to minimum power (expressed in dB) measured in each band as the ambient temperature is cycled.

Bandwidth percentage is given by 100x $(f_h - f_l)/f_o$ where f_h, f_l, and f_o correspond to the high, low, and center frequency of each band.

Spurious output is the power level of discrete signals other than the carrier measured over the temperature range and expressed in terms of dB below carrier.

Frequency repeatability percentage is given by $(\nabla f/f)$ x 100, where ∇f is the maximum change in frequency measured over the entire ambient-temperature range for a constant tuning voltage.

Frequency reproducibility is the maximum percentage change in frequency for a fixed tuning voltage measured from unit to unit over the ambient-temperature range.

Short-term stability is the percentage change in frequency measured in a 10-second interval after the unit has reached a stable operating temperature.

Long-term stability is the percentage change in frequency measured in a 200-second interval after the unit has reached a stable operating temperature.

Tuning rate is the slope of the curve of tuning voltage as a function of output frequency. The two numbers given are for the high and low ends of each band, respectively.

Output VSWR is the voltage standing-wave ratio measured at the output of the unit.

of microwave power in the landing radars and rendezvous radar on the Lunar Module and the rendezvous radar and transponder located on the Command Module.

Two separate radar systems are used during the moon-landing operation. The Altimeter Radar (ATM) indicates the instantaneous elevation of the Lunar Module above the moon surface, and the Velocity Sensor (VSOM) measures the rate of descent of the Lunar Module.

During the subsequent rendevous of the Lunar Module with the Command Module, the Rendezvous Radar (HPM-R) and Transponder (HPM-T) serve as a tracking system which provides the crew of the Lunar Module with the relative position and velocity of this module with respect to the Command Module. The transponder aboard the Command Module serves as an active homing device which receives the signal transmitted by the Rendezvous Radar, processes the information contained on the signal, and then re-transmits to the Rendezvous Radar.[3]

Specifications

The performance requirements of the four multiplier chains are listed in Table II. The stringent reliability and environmental requirements have been achieved with no modification of the electrical or mechanical specifications.

Description

The four multiplier chains are almost identical in configuration and form factor. Slight differences prevail because of the specific output-power and frequency requirements for each chain. In addition, the VSOM chain is fitted with a self-contained crystal oscillator which provides the fundamental VHF signal for the chain. The HPM-R, HPM-T, and ATM chains are designed to operate from an external VHF driver signal.

A photograph of the fully packaged multiplier chains is shown in Fig. 4. Fig. 5 shows a photograph of a VSOM chain in which the outer cover has been removed.

The multiplier chain consists of a three-stage transistor amplifier which raises the fundamental VHF signal to a level of 15 watts, followed by a series of varactor frequency multipliers with a total frequency multiplication of 96 times. Fig. 6 shows a block diagram of the chains and lists the specific interstage frequency and power levels for each of the four types.

The detailed original design features of each of the stages have been presented in an earlier paper[3] and are not repeated here. It is instructive, however, to describe some of the redesign features and improvements which have resulted from three years of manufacturing and system experience which have dictated the required changes.

Redesign and improvements

The chassis baseplate (shown in Fig. 5) was redesigned to maintain a stringent flatness specification of 0.003 inch over the 5 by-5-inch surface. The flatness characteristic serves to minimize the thermal impedance between the multiplier chain and the system heat sink. The stiffness of the baseplate was enhanced by increasing the thickness of the baseplate and by installing brazed cross ribs within the chassis. A buffer amplifier was added at the input of the transistor amplifier in the altimeter frequency-multiplier chain to solve a system interface instability problem. The buffer amplifier is a single-stage common-emitter amplifier with unity gain; it contains a resistive pad at its input which provides 6-dB broadband isolation.

The transistor amplifier has been subjected to two redesign phases. The first phase was a change from the printed-circuit chassis used in the developmental models to a wired copper-clad phenolic chassis. This change eliminated many manufacturing problems (such as lifted pads) which degraded the reliability of the amplifier. A change in component layout was also made to permit electrical alignment of the amplifier after it was integrated with the frequency-multiplier stages of the chain.

The second redesign phase of the transistor amplifier was a major circuit redesign which was incorporated into the environmentally qualified chains. The circuit was redesigned to eliminate instabilities which were inherent in some of the pre-flight models. These instabilities dictated an alignment technique which was directed at the elimination of spurious outputs over a relatively narrow range of DC input voltage and RF input power and frequency. The new design features improve RF bypassing, decoupling, and broadband impedance termination and contribute to a systematic and positive alignment technique. In addition, the new design is characterized by a wide dynamic range in which the amplifier output is free of any spurious signals over the entire range of inputs of zero to 28 volts DC, zero to 30 mW RF drive, and drive frequency in excess of 600% of the required operating bandwidth. This wide design margin makes manufacturing and alignment easier.

The frequency-quadrupler stage has also been subjected to two redesign phases. The first phase was a change from a copper-clad phenolic wall structure with a printed-circuit chassis to solid metal walls with an integral metal chassis. As in the case of the amplifier, the printed-circuit chassis was abandoned to eliminate manufacturing problems which degraded the reliability of the quadrupler. In addition, the change to an integral solid-metal chassis/wall structure maintained the integrity of the component ground planes and thus assured performance repeatability.

The second redesign phase of the quadrupler was dictated by a mechanical limitation of its predecessor. Excessive spacing between the mounting screws which hold the cover on the quadrupler resulted in vibration-induced noise caused by a chatter between the cover and housing. The quadrupler housing and cover were completely redesigned to provide an increase in the number of tie-downs and decreased spacing between tie-downs from 1.8 inches to 0.6 inch. In addition, a change was made in the parts layout to simplify construction and repair; junctions to the variable capacitors were changed from rigid to semi-flexible to reduce the possibility of fracture of the capacitors due to thermal and vibration-induced stress; and some circuit changes were made to increase the stability and dynamic range of the quadrupler and thereby systemize and reduce the time required for electrical alignment.

The frequency-tripler stage was subjected to one redesign of major

Table II—Frequency-multiplier performance specifications.

	Limits			
	VSOM	ATM	HPM-R	HPM-T
Electrical				
Input data				
RF drive power (mW)	self-contained	14±2	17±4	15±2
RF drive frequency (MHz)	109.5	99.8	102.4	102.0
RF input impedance (ohms)	—	50±5±j5	50±10±j10	50±10±j10
DC voltage (V)	25.00±.25	25.00±.25	25.00±.25	25.00±.25
Max. DC power (W)	23.0	14.0	29.5	28.5
Output data				
Frequency (GHz)	10.510	9.580	9.833	9.792
RF power (mW)	210 min. 400 max.	185 min. 350 max.	320 min. 640 max.	320 min. 567 max.
Load VSWR	1.2:1	1.2:1	1.2:1	1.2:1
Minimum 1.0 dB bandwidth (MHz)	—	±25	±25	±25
Spurious output (dBc)	−50	−50	−50 to −117	−50 to −117
AM noise (dBc)				
with vibration	−92 to −130	−72 to −130	—	—
w/o vibration	−114 to −134	−100 to −132	−86 to −124	−86 to −124
FM noise (Hz, RMS)				
with vibration	5.0 to 440	6 to 570	—	—
w/o vibration	4 to 44	6 to 12	0.7 to 30	0.7 to 30
Warm-up time (sec)	75	75	75	75
Mechanical				
Max. weight (lbs)	2.25	2.10	2.21	2.05
Approx. dimensions (inches; L×W×H)	5×5×2	5×5×2	5×5×2	5×5×2
Environmental				
Operating temp. range (°C)	+10 to +63	+10 to +63	−12 to +63	0 to +63
Operating vib. level (g)	5	5	10	15
Oper. pressure range (mm Hg)	10^{-2} to 10^{-9}	10^{-2} to 10^{-9}	10^{-2} to 10^{-9}	10^{-2} to 10^{-9}
All-pressure design (mm Hg)	760 to 10^{-9}	760 to 10^{-9}	760 to 10^{-9}	760 to 10^{-9}

significance. An undesirably high rate of variable-capacitor breakage had prevailed in the existing design. The breakage was due to thermal and vibration-induced stress where parts were joined to the capacitors by rigid connections. The shrinkage rate was reduced to zero by changing all rigid connections to semi-flexible joints.

A final major redesign on the multiplier chains involved raising their performance capability to meet all performance specifications over all pressures from sea level to less than 10^{-9} mm Hg. The design changes required to achieve this goal are described below. Although not all planned flight models will contain this feature, results to date indicate that the goal can be met.

All-pressure redesign

The original performance specifications for the multiplier chains required that the units be capable of operating only in the high vacuum of deep space (see Table II). However, continued evaluation of the Apollo system and information obtained from other space programs revealed that pressures might be encountered which exceeded the specified upper limit of 10^{-2} mm Hg. The following factors could contribute to raising the pressure in the immediate vicinity of the multiplier chains:

1) A gaseous cloud develops and clings to a vehicle in deep space. The gas develops by virtue of the normal outgassing of materials when exposed to high vacuum and is captured by the gravitional force exerted by the space vehicle.

2) Exhaust gases generated by the descent engine and the reaction control jets on the Lunar Module during the moon landing phase are reflected from the moon surface back toward the Lunar Module.

3) Exhaust gases generated by the reaction control jets during the rendezvous of the Lunar Module with the Command Module create transient pressure fronts which may strike the rendezvous radar assembly.

Tests performed on multiplier chains through the pressure range from sea level to less than 10^{-6} mm Hg indicated that ionization breakdown occurred in the region from 10^{-1} mm Hg to 10^{+1} mm Hg in three of the stages in the chain: the quadrupler, the tripler, and the low-frequency doubler.

In the quadrupler and tripler, the regions which exhibited ionization breakdown were filled with an RTV Silicone potting compound. The compound, Eccosil 4659, is a new material (not available prior to 1968) which has good electrical properties and has proved useful in lumped-parameter circuits up through 1200 MHz.

Ionization had occurred in all three sections (input, idler, and output) of the quadrupler; therefore, the entire circuit was filled with the potting material. Small changes were required in some of the circuit inductances to compensate for the dielectric loading of the compound. The total reduction in the efficiency of the quadrupler due to the potting material was only 0.2 dB.

In the tripler stage, ionization was detected in the input section, the idler section, and the lumped-parameter portion of the output section. Again, small changes in the circuit inductances were made to compensate for the dielectric loading of the potting material; after potting, the total reduction in the tripler efficiency was less than 0.3 dB.

The low-frequency doubler is a distributed-parameter circuit which consists of three heavily loaded, coupled transmission lines. Ionization occurred between the center line, which supports both the fundamental frequency (1200 MHz) and its second harmonic (2400 MHz), and the adjacent circuitry. Any attempt to suppress this ionization by use of a dielectric other than air would result in a substantial change in the circuit geometry. The severe restrictions on the form factor of this stage prohibited such a change. The solution selected was to increase spacing in critical regions between the center line and the adjacent circuitry. This modification was achieved with no change in the efficiency of the stage. The redesign was achieved with no change in external form factor or degradation in operating specifications, and at a weight increase of less than 5%.

Summary of frequency-multiplier effort

In the three years which have elapsed since the original design and delivery of developmental subassemblies, a number of significant improvements have been made in the frequency-multiplier chains. The improvements reflect design changes which have been made to accommodate changes in system requirements, to facilitate manufacture, and to increase reliability. In addition, an all-pressure design has been completed which allows operation at pressures from sea level to less than 10^{-9} mm Hg.

References

1. Collard J., Sun S., and Walsh T. E., "High-Power Microwave Varactor Multipliers," WESCON (Aug 1966).
2. Sun C., "High-Power Varactor Multipliers," *NEREM Digest* (Nov 1967).
3. Bliss E., and Fromer M., "Design of Solid-State Frequency Multipliers for the LEM Radars," *RCA Reprints* PE-281, PE-282.

Microwave test-equipment design

M. Reiser | J. F. Kucera

This paper describes the several factors to be weighed in designing a test system for microwave components. A traveling-wave-tube test system is used as an actual example of how these various factors affect the design of the system.

THE DESIGN OF A MICROWAVE-DEVICE TEST SYSTEM begins when the product-line engineering personnel (the user) identify the device to be tested and the performance characteristics or parameters to be measured. At the same time, a choice is made as to the ultimate use of the equipment: whether it is to be used for production testing or for engineering evaluation. This choice represents a major constraint in the physical layout and design of the system. Although the integrity of the test data is of primary concern in either case, the alternative equipments are distinguished by the following features (listed in order of importance):

Engineering evaluation	*Production testing*
1) Physical layout and configuration is directed to provide easy modification to other configurations.	1) Biomechanics is the distinguishing design feature because of its large effect on production rate and the quality of test-operator performance.
2) Components are selected for their flexibility and adaptability to function in alternative future systems.	2) Automation techniques are used wherever possible.
3) Maintaining the integrity of test data is the responsibility of the user.	3) Maintaining the integrity of test data is the responsibility of lesser-skilled maintenance and calibration personnel; therefore, speed and accuracy of calibratoin are featured in the design.
4) Biomechanics (organization of the test system for ease of operation) is largely ignored.	4) The system is integrated and packaged in such a manner as to discourage modifications (intentional or unintentional) to the physical and/or operational configuration.

Most of these features are mutually exclusive; therefore, two "styles" of equipment result which, though performing the same electronic functions, are substantially different in physical and operational configuration.

The method of data acquisition is the next consideration. At this point, it is important to note that most microwave devices require an adjustment or optimization process before the final performance characteristics are measured. For economy, both these operations (optimization and data acquisition) are performed on the same test system because each process requires essentially the same equipment; independent implementation would

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received the BSEE *magna cum laude* from Newark College of Engineering in 1954. His early experience in the electrical industry was as a brazer for the General Electric Company from 1953 to 1956. In the latter year, he also graduated from the RCA Institutes with a V7 Certificate, and joined the RCA Microwave Tube Operations. His first assignment was as a technician in the construction, maintenance, calibration, and design of electrical test equipment. In 1964, he became an Associate Engineer in the design of electrical test equipment. During the next three years he continued this work and among other things was project leader of two million-dollar programs for designing and constructing equipment for testing traveling-wave tubes and solid-state devices. In 1967, he was appointed Manager of Test Equipment Services. Mr. Reiser is a member of the engineering honor societies, Tau Beta Pi and Eta Kappa Nu.

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received the BSEE from the University of Nebraska in 1952, and joined RCA as an Engineering Trainee. He was initially assigned to the Life Test and Rating Laboratory at Lancaster, where he developed methods of light output and contrast measurements on black and white picture tubes. From 1954 through 1961, he specialized in the development of life test methods and reliability prediction techniques for black and white and color television picture tubes. During the middle of 1954, he established an Extended Life Evaluation Program at the Laboratory in the Marion, Indiana plant. In 1962, Mr Kucera transferred to the Microwave Devices Operations Department in Harrison, New Jersey, as Manager, Quality and Reliability Assurance. In 1965, he became Manager, Engineering Services. In this assignment, he was responsible for the direction of Equipment Development, Standardizing and Technical Publications, the Chemical and Physical Laboratory, and the Life Test and Rating Laboratory. In 1967, Mr. Kucera assumed the responsibility for Technical Planning, Microwave and Special Components. He is a senior member of the American Society for Quality Control.

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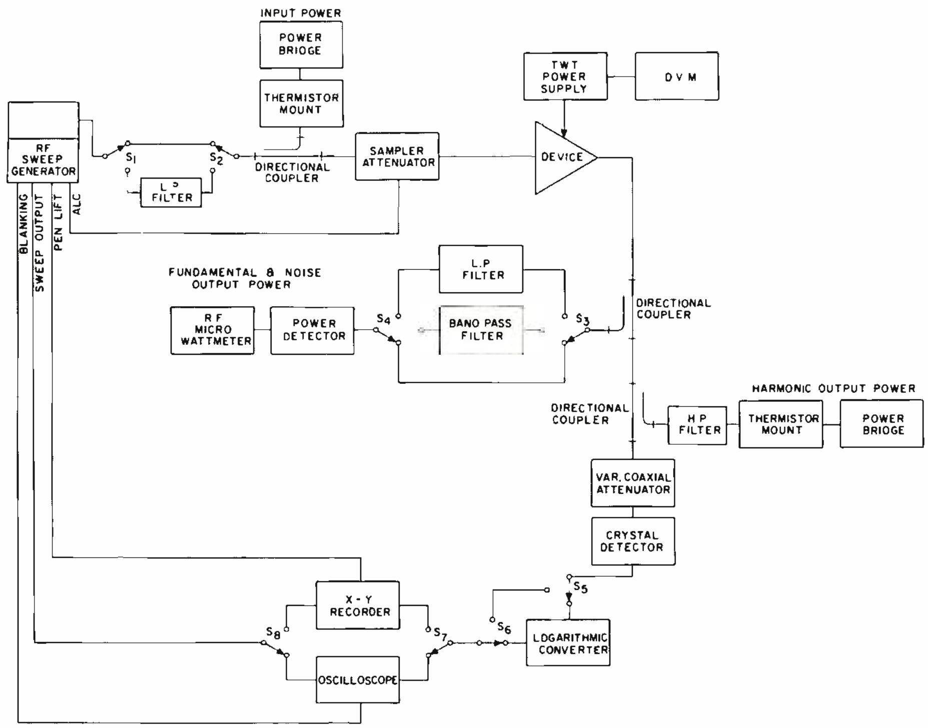

Fig. 1—Block diagram of TWT production test system.

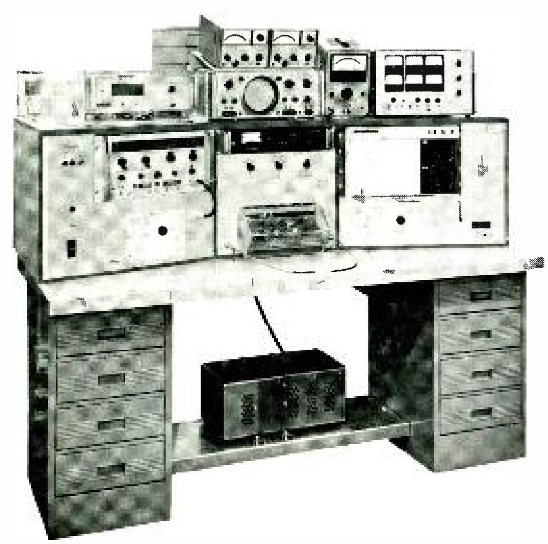

Fig. 2—TWT test system; note that the system is arranged for sit-down operation.

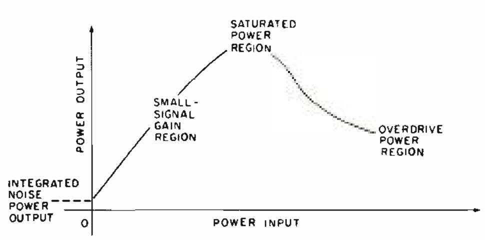

Fig. 3—Power output as a function of power input for a typical traveling-wave tube.

require twice the capital expenditure. In terms of system utilization, at least 50% of the total time on the system is generally used for the purpose of device optimization. Because microwave devices are broadband in nature, both operations are carried out over a range of frequencies. The system can be designed either to measure the device parameters at specific points on the frequency spectrum, or to sweep the frequency range for a given parameter and provide the data on a dynamic display—an oscilloscope or X-Y recorder. The distinguishing features of the two methods are listed below:

Swept frequency vs. devise parameter	*Fixed frequency vs. device parameter*
1) Optimization function is simplified and enhanced. Effect of any device change (impedance match, tuning, tube focusing, gain shaping, etc.) is dynamically displayed over the frequency range of interest.	1) Optimization function is laborious and subject to misleading results because the results of device changes are observable at discrete frequencies only.
2) Data acquisition can be simplified if wider measurement tolerance is accepted.	2) Data acquisition is laborious and subject to operator translation error because of operator meter interpretation, mental addition or subtraction, or system corrections, etc.
3) Initial cost of equipment is greater.	3) Initial cost of equipment is less.
4) Optimization time is reduced.	4) Optimization time is greater.
5) Calibration and methodizing of test equipment is more involved.	5) Calibation and methodizing of test equipment is less important.
6) Skill of test operator must be increased for proper test-set operation.	6) Less-skilled operator required.
7) Device under test is more rigorously tested as the dynamic display shows performance at all frequencies.	7) Because a device is tested, at discrete frequencies only, it is possible to accept a product that is out of specification.
8) Measurement tolerance is greater.	8) Test equipment is inherently more accurate.
9) Automatic permanent record of data can be made available.	9) Record of test data as interpreted by test operator is the only form possible.

The device parameters most often measured as functions of frequency in either method include reflected power, output power, cold VSWR, hot VSWR, insertion loss, noise figure, and gain. [NOTE: for the hot VSWR measurement, voltage is applied to the unit under test; for the cold VSWR measurement, no voltage is applied to the device under test.]

Either system can be automated to provide for the acquisition of repeatable data. The swept-frequency method provides data in analog form on a graph, while the point-by-point frequency method provides data in digital form from a printer. Of these two automatic data-collection methods, the point-by-point frequency system is more expensive and complicated because it requires sequential stepping and analog-to-digital converters for all the parameters mentioned above. When the type of test system and the method of data acquisition has been decided, the designer must be concerned with the specific details of the equipment design. A major consideration is that the normal range of frequencies is an octave or more, e.g. 1 to 2 GHz, 2 to 4 GHz, 4 to 8 GHz, and 8 to 12.4 GHz. In addition, coaxial microwave hardware is normally employed for microwave test equipment. The typical measurement requirements are as follows:

Parameter	*Dynamic range*
Gain	10 to 50 dB
Power input	+30 dBm to −40 dBm (restricted on any one device to ≃ 50 dB or less)
Power output	+36 dBm to −20 dBm (restricted on any one device to ≃ 35 dB or less)
VSWR	1.25:1 to 10:1
Insertion loss	0 to 30 dB
Noise figure	5 to > 30 dB (variation on any one device limited to ≃ 7 dB)

Thus, the designer must provide equipment that can supply the required RF input power to the device over a wide dynamic range; make measurements of input and output power over a wide dynamic range; and often make these measurements under simulated system conditions, i.e., with a phase-variable mismatch on the device.

TWT test set

A good example of the consideration given to the details of test equipment design is illustrated by the test system for traveling-wave-tube production. A block diagram of the system is shown in Fig. 1; Fig. 2 is a photograph of the system.

This test system is used to make the following measurements:

Measurement	*Conditions*	
Small-signal gain	Power input	≅ −40 dBm
	Gain (nominal)	≅ 33 dB
	Gain variation	≅ +12 dB
	Power output	≅ − 7 dBm
	Power-output-variation	≅ +12 dB
Saturated power	Power input (nominal)	= −25 dBm
	Power-input variation	= +24 dB, −15 dB
	Power-output (nominal)	= + 8 dBm
	Power output variation	= ±10 dB
Overdrive power	Power input (nominal)	= −16 dBm
	Power-input variation	= ±15 dB
	Power output (nominal)	= + 8 dBm
	Power-output variation	= ±10 dB
Stability	Power output (max.)	= −15 dBm
Integrated noise power output	Power output (max.)	= −23 dBm
	Tested with phase-variable 4:1 mismatches on device-under-test input and output ports.	
Noise figure	NF (nominal)	= 16 dB
	NF (variation)	= ± 4 dB
	Tested with an auxiliary piece of test equipment (noise-measurement cart).	

The *small-signal gain, saturated-power,* and *overdrive-power* regions are illustrated in the curve of power output as a function of power input for a typical traveling-wave tube shown in Fig. 3. All the measurements listed must be made at temperatures of −54°C, +20°C., and +120°C. The device is placed in an auxiliary environmental chamber for tests at high and low temperature extremes.

Accuracy

Input and output 0- to 50-dB variable coaxial attenuators are used to calibrate the system and to set power-input and power-output levels. Therefore, the attainable measurement accuracy is directly related to four factors:

1) The attenuator accuracy and attenuation variation with frequency (specification ±0.5 dB or ±4%, whichever is greater);
2) The attenuation tracking of the input and output attenuators;
3) The measurement ambiguity due to test-system mismatches and their interaction with the device mismatch; and
4) The accuracy of the power-measuring meters.

When measurements are made point by point, accuracies are in the order of ±0.5 to ±1.0 dB. Swept-frequency accuracies are in the order of ±0.75 to ±1.5 dB. The measurement accuracy is a function of the dynamic range of measurement. Care must be exercised to maintain these accuracies. The test operator must be sensitive to attenuator backlash, power-meter drift, oscilloscope DC drift, X-Y recorder DC drift, and cable connections for possible undesirable mismatches.

Repeatability

The repeatability of measurements is a function of the care of the test operator and the inherent capability of the components for the test system. The factors under the control of the operator were mentioned above; those under the control of the test-equipment design engineer are as follows:

1) Repeatability of coaxial switch VSWR and insertion-loss characteristics;
2) Regulation and stability of power supplies;
3) Frequency stability and repeatability of RF generator;
4) Repeatability of attenuation of input and output attenuators;
5) Accuracy of digital voltmeter, power meters, and other meters;

Calibration and maintenance

Ease of calibration and maintenance is aided by the modular construction of the test equipment. This type of construction allows any major instrument to be quickly removed for calibration or maintenance.

On a periodic cycle, individual instruments are calibrated to manufacturer's specification; the VSWR of input and output ports and the insertion loss between input and output tests ports to the power-monitoring ports are also calibrated periodically. [*Note:* Referring to Fig. 1, the VSWR is calibrated looking into ports 1 and 3, and the insertion loss is measured from ports 1 to 2, 3 to 4, and 3 to 5].

Maintainability is aided by several features:

1) Modular construction;
2) Quick-disconnect rear panels which, when removed, open the entire interior of the test system for ease of servicing;
3) Use of common parts; and
4) Test-system documentation.

The documentation made available to the calibration personnel includes an operating manual (complemented by 1-hour lectures by the design engineer) and a complete set of schematics which are on file in the maintenance and calibration center.

Biomechanics

The consideration given to biomechanics can be demonstrated by review of the layout shown in Fig. 2. The test system is arranged for sit-down operation and is panoramic in configuration. Because the system is used for optimization as well as data acquisition, adequate test-bench space is provided for the device and for the test operator's use. In addition, the primary viewing area (eye level of 48 inches) is allocated to power meters, digital voltmeter, and oscilloscope. The primary control area is allocated to switching functions (DVM, measurement-mode, and test-mode switches). All controls, including the secondary controls in the peripheral control area, are within the operator's reach and captioned in readily understandable terms.

Conclusion

The design of microwave-device test equipment is dictated principally by the choice of either an engineering or a production-type test system, and secondly by selection of either a point-by-point or a swept-frequency data-acquisition configuration. When these choices have been made, the designer considers the parameters to be measured and the dynamic range of measurement, and chooses the instrumentation to implement the tests required with due consideration to accuracy, repeatability, calibration, and maintainability. Finally, the test system is configured with the operator in mind, and the trade-offs which are always required are made.

Gallium arsenide for microwave integrated circuits

Dr. R. H. Dean

Gallium arsenide has some outstanding features which make it well suited for microwave integrated circuits. A single monolithic structure composed of layers of semi-insulating *GaAs*, N+-*GaAs*, N-*GaAs*, P+-*GaAs*, aluminum oxide and aluminum, stacked atop one another in that order, might be used to host a remarkable variety of devices. These include a number of passive components, three different kinds of microwave oscillators, a field-effect transistor, and a unidirectional high-frequency amplifier with a built-in voltage-controlled phase-shifting capability. The structure and the performance of many of these devices are still in an initial stage of study.

Microwave integrated circuits have received increased attention in recent years because of their small size and weight, and because of the reliability that can be obtained by paralleling a large number of identical systems.[1] As integration drives the unit cost down, the day approaches when microwave systems will move into the consumer market. Silicon, no doubt, will continue to hold a commanding position at frequencies on the lower end of the spectrum, but it is clear that *GaAs* offers several advantages in the microwave regime. As the material quality improves and more individual devices are perfected, the gallium arsenide microwave integrated circuit becomes more and more attractive.

In this article, we will be speculating on how a number of different devices, now in the early developmental stage, might be fabricated on a common substrate of gallium arsenide. We will begin by delineating some of the advantages of *GaAs*, and then we will propose a common structure on which different devices can be fabricated. Finally, we will describe a variety of devices which are especially well-suited for this structure.

Most of the devices considered in this paper have been demonstrated in some form.[2-10] For the most part, these devices have been studied on an individual basis, with a specialized structure and a specialized circuit for each device. In general these different devices have *not* been studied on a common structure which is appropriate for integrated circuits. The structure that we will be considering is still in a very early stage of its development, and much work needs to be done to evaluate the performances of the various devices in this new structure.

Advantages of GaAs

In view of the technological lead held by silicon, one may well ask, "Why gallium arsenide?" Gallium arsenide has many advantages:

1) *High temperature capability* — Because of its wider band-gap and positive thermal coefficient of resistivity, devices made of epitaxial GaAs can be utilized at higher ambient temperatures and driven harder than similar devices made of silicon.

2) *High maximum drift velocity and low fields required to attain this velocity* — The maximum electron drift velocity in epitaxial GaAs (2×10^7 cm/sec) is a factor of two or so higher than it is in silicon. Gallium arsenide requires a field of about 3 kV/cm to attain its maximum drift velocity whereas silicon requires a field of about 20 kV/cm. Thus, for a fixed-geometry device whose gain-bandwidth product depends on transit time, one expects to be able to operate at higher frequencies when the material is *GaAs*.

3) *Quiet avalanching process*—Recent experimental results indicate that *GaAs* avalanche diode microwave oscillators are significantly quieter than silicon ones. This difference is very important, since the noise produced in silicon avalanche diode oscillators is a major impediment in applications.

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received the BSEE (highest distinction) from the University of Kansas in 1958. He was elected into the activities honorary society, Omicron Delta Kappa, and served as president of the local chapter of Tau Beta Pi. He satisfied his military obligation as a technical liaison officer at the Defense Atomic Support Agency in Albuquerque, New Mexico, where he monitored the design and development of electro-mechanical fusing and firing components. In 1960, he entered MIT on an N.S.F. fellowship, and one year later he received the MSEE. For the next two years he was engaged as a professional engineer in the design of high-velocity air conditioning systems, and he developed a digital computer program for such design. In 1963, he joined the staff at Midwest Research Institute and participated in research on *MnBi* magnetic thin films. The following year he entered the PhD program at Princeton University, on an N.S.F. fellowship, majoring in solid-state device physics and minoring in plasma physics. His dissertation, which was completed in June, 1968, treated the transient double injection of an electron-hole plasma into a semiconductor. At RCA he is engaged in research on the transferred-electron effect in *GaAs*. He is a member of the IEEE.

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4) *Piezoelectric effects*—Since *GaAs* is piezoelectric, in principle one is able to couple electrical signals to acoustic waves. The latter are of interest because they can be used to produce long delays.

5) *Electroluminescent effects*—Because *GaAs* is a direct band-gap material it can be used to make luminescent and laser diodes.

6) *Transferred-electron effects*—For our purposes, one of the more important special features of *GaAs* is the transferred-electron effect.[2] This effect produces a bulk negative resistance which can be employed in high-frequency two-terminal oscillators or in a broad-band traveling-wave amplifier. The latter device (which is now in the early-research stage) offers the exciting possibilities of unidirectional amplification at high frequencies and relatively simple voltage-controlled phase shifting with constant gain, also at high frequencies.

Gallium arsenide looms up as perhaps the most versatile single material for making semiconductor devices. The sheer multiplicity of advantages and special features make it appear very attractive, and the outstanding microwave devices which it yields recommend it highly for microwave integrated circuits.

Possible material building blocks

Our hypothetical integrated circuits are made out of several different material components, all of which are laid down by vapor transport or evaporative processes. By using a sequence of depositions and photographically defined etches, one "constructs" his own desired circuit by etching patterns in the various material layers as they are built up on a common substrate of gallium arsenide. Since the individual devices in the structure are *not* separately fabricated, the final configuration can be termed "monolithic". For specificity, we will consider a very particular combination of material layers. Other combinations and dimensions are also possible.

Our common substrate is a slab of semi-insulating GaAs (Fig. 1). After suitable SiO_2 masking, and possibly some shallow planar etching, a 5-micron layer of N^+ is grown in appropriate spots to provide low-resistance conduction. At this point, a light lapping can be employed to reflatten the surface. The next step is to deposit a 2-micron layer of one ohm-cm N-type gallium arsenide. This layer serves as the interaction layer for most of the active devices. Desired patterns can be defined in this layer by SiO_2 masking before the deposition or photo-masking and etching after the deposition. The final epitaxial deposition is a 3-micron P^+ layer. Parts of this P^+ layer can be removed later with an electrolytic etch, which does not attack the N-type material beneath. The crucial part of this structure is the lightly-doped N-layer.

The N^+, N, and P^+ layers can be contacted separately by evaporating and sintering various alloys using baked photoresist for masking. For N-type material, a suitable alloy is 90% silver with 5% germanium and 5% indium.

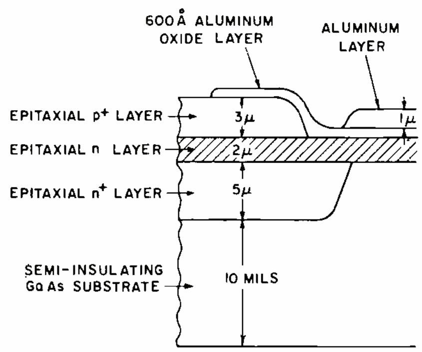

Fig. 1—Material building blocks.

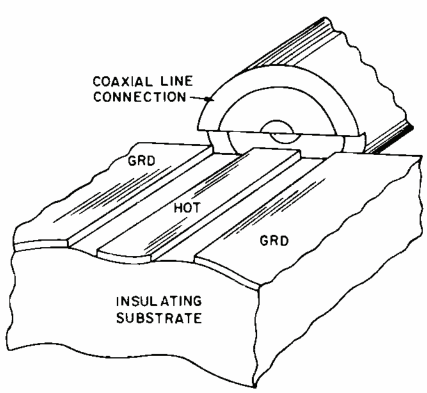

Fig. 2—Coplanar waveguide (after C.P. Wen).

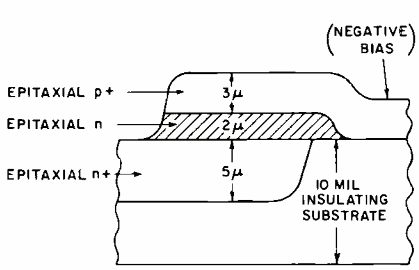

Fig. 3—Varactor diode or avalanche diode oscillator.

For P-type material, a suitable alloy is 96% silver with 4% manganese. These combinations result in relatively low-resistance, ohmic contacts.

Aluminum oxide is used for insulation. It has a dielectric constant not too different from that of *GaAs*, and it can be deposited, pinhole-free, in thin layers (approx. 600 Å) with relatively high breakdown strength (~50 V). The aluminum oxide is etched with hot phosphoric acid, which does not bother the other materials.

For the final conduction electrodes, we choose aluminum. It adheres well to the aluminum oxide and can be etched with *HCl*, which does not seriously bother the other materials employed. One must be careful that the aluminum electrodes are continuous over steps in the surface.

Waveguides and passive components

For conducting connections and tuning stubs, one can employ either N^+ or P^+ *GaAs*, any of the alloys used to make ohmic contacts to these layers, or aluminum, or any combination of these materials. The waveguide structures may be patterned around either of two forms:

1) Conventional microstrip, with aluminum oxide as the insulator, is appropriate for small, low impedance lines and high-Q tuning sections. A somewhat higher impedance is obtained by back biasing the P^+-N-N^+ structure to punch through.

2) A special co-planar waveguide[3] shown in Fig. 2, is appropriate for other applications. The co-planar waveguide is conveniently coupled to external co-axial lines. It is easily tapered for size and impedance transformations, and since all of the conductors lie in the same plane, a single layer of conducting material can be used for the entire line. If the conducting material for the line is not taken from the final aluminum layer, tuning of the line can be achieved by capping the subsequent aluminum oxide layer with a suitably situated aluminum pad.

The material elements can be combined in various ways to obtain passive components. The lightly-doped one ohm-cm N-layer can be used for resistors. Capacitors can be made with the aluminum oxide or with back-biased N^+-P^+ junctions. Lower capacitance P^+-N junction varactors (Fig.

3) can be used for rectification, detection, mixing, multiplying, and voltage-controlled tuning. Schottky-barrier diodes are also possible.[4]

Oscillators

The varactor diodes indicated in Fig. 3 can also be made to serve as avalanche diode oscillators, operating in the "punch through" configuration. Silicon avalanche diodes of this sort have been studied in considerable detail[5], and recent experiments show that *GaAs* gives qualitatively similar results, with somewhat less noise.[6] These oscillators are expected to operate best in the frequency range of 10 to 25 GHz.

A sandwich-type transferred-electron oscillator is obtained by removing the P^+ layer and making an alloy ohmic contact directly to the lightly-doped N-layer (Fig. 4). With the doping density and thickness specified, spontaneous Gunn-type oscillations do not occur but a high-frequency negative resistance will exist in the 25-to-50-GHz frequency range. This negative resistance has been employed in reflection-type amplifiers,[7] and with the proper load impedance, it can be made to produce oscillations.

When both the N^+ and P^+ layers are absent, it is still possible to build a transferred-electron oscillator, by going to a co-planar geometry[8] similar to that shown in Fig. 5. This particular geometry is well-adapted to the coplanar-type stripline, shown in Fig. 2, since both the ohmic contacts are on the same plane. With proper tuning, this configuration can be made to produce oscillations in the 1-to-10-GHz range.

Finally, it is worth noting that any of the three oscillators mentioned above can be distributed over several electromagnetic-wave wavelengths[11] for increased power level. In this case, the anode and cathode electrodes double as a built-in distributed tuning circuit. Fig. 6 shows a one-half wavelength oscillator built into a low-impedance stripline. From the oscillator's point-of-view, the two ends look almost open-circuited and a large amount of positive feedback is possible. From the external circuit's point-of-view, the impedance level is transformed, and good matching is possible.

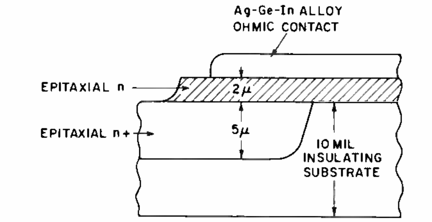

Fig. 4—Sandwich-type transferred-electron oscillator.

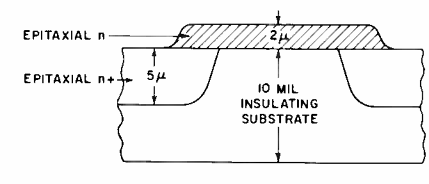

Fig. 5—Coplanar-type transferred-electron oscillator.

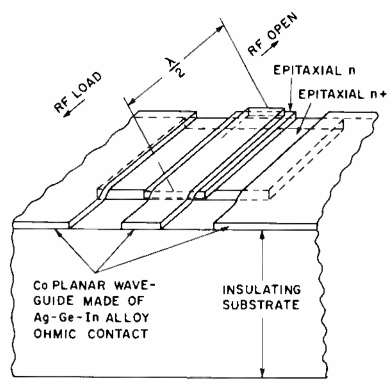

Fig. 6—Distributed oscillator (electromagnetic-wave wavelength, λ, based on dielectric constant on N-material, including electrons).

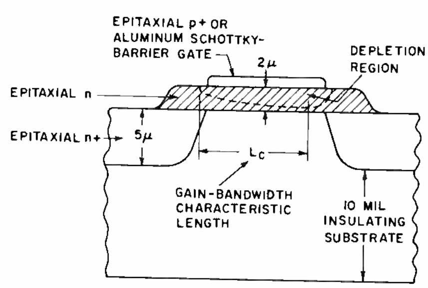

Fig. 7—Field-effect transistor.

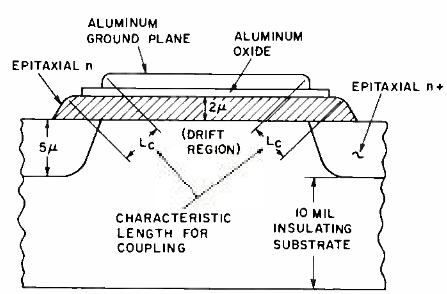

Fig. 8—Traveling-wave amplifier and voltage-controlled phase shifter.

Field-effect transistor

Field-effect transistors have been produced[9] on lightly-doped N-type layers of *GaAs*. A common approach is to use the lightly-doped N-layer directly on an insulating substrate. The source and drain are alloyed ohmic contacts, and one or more Schottky-barrier gates are laid down in the region between.

A somewhat different scheme is shown in Fig. 7. The N^+ material on the bottom provides the ohmic source and drain contacts, and the P^+ material on the top serves as the gate. Aluminum with a Schottky barrier is an alternate possibility for the gate. The latter is probably more practical for low-capacitance or multiple-gate geometries. If there were aluminum oxide between the lightly-doped N-layer and the gate, interface traps would shield the gate from the channel and seriously reduce the low-frequency gain. Thus, a back-biased junction is required for the gate insulation.

Good high-frequency performance calls for a small gate, a short distance between source and drain, and a high bias voltage for a high drift velocity. With ideal majority-carrier injecting contacts, the gain-bandwidth product is approximately

$$Gf \approx \frac{V_d}{2\pi L}\left[\frac{C_{ins}}{(C_{ins}+C_{stray})}\right],$$

where G is I_D/I_G or current gain; f is frequency; C_{ins} is gate insulation capacitance; C_{stray} is stray gate-to-source capacitance; V_d is particle drift velocity; and L is characteristic length ($\approx$ source-to-drain spacing).

This formula indicates that a 2-micron *GaAs* device with a capacitance ratio of ½ might be made to yield net gain for frequencies up to about 8 GHz.

Traveling-wave amplifier and voltage-controlled phase shifter

For a high-frequency traveling-wave amplifier, we start with the field-effect transistor configuration and perform some modifications as shown in Fig. 8. The source (cathode) and drain (anode) electrodes serve as the microwave input and output lines, respectively. The transistor gate becomes the microwave ground plane. For insulation between this plane and the lightly-doped N-layer, we replace the P-N junction depletion layer by aluminum oxide. This way, the traps in the aluminum oxide/gallium arsenide interface act as a low-frequency screen and prevent unwanted channel depletion near the anode. (The trap density could be enhanced if necessary). These same traps should be ineffective at microwave frequencies. Now the structure looks like a pair of upside-down microstrip lines, with the hot lines skewed off to the sides of the common ground plane.

A positive bias is applied to the output electrode. This voltage is high enough to saturate the drift velocity and activate the transferred-electron effect in the lightly-doped N-layer. A microwave signal on the cathode input injects bunches of electrons. As these bunches drift toward the anode, the transferred-electron effect causes them to grow in amplitude. When they finally arrive at the anode, they induce an amplified voltage on the output electrode.

For frequencies and dimensions of interest to us, there are several cycles of phase shift in the drift region between the cathode and anode. If the drift velocity simply saturated, there would be a net loss and the phase shift would be constant with applied voltage. But the drift velocity does *not* simply saturate. Above the threshold for the transferred-electron effect, the average drift velocity starts going *down*. This drop has two effects: 1) It causes space-charge bunches to grow, resulting in gain, and 2) it causes the drift velocity to drop with increased voltage, resulting in a voltage-controlled phase shift. In *GaAs*, the velocity-field curve fortuitously has a very convenient shape. The shape is such that if the electric field is above the transferred-electron-effect threshold throughout the entire drift region, the total gain is independent of the applied voltage, and the change in the phase shift is directly proportional to applied voltage.[10] Thus we have the possibility of a voltage-controlled phase shifter with constant gain.

The coupling mechanism in this device is similar to the charge injection mechanism in the field-effect transistor. The transistor formula above indicates a loss at high frequencies. This loss can be offset, however, by the large gain in the drift region, thereby greatly enhancing the overall gain-bandwidth product. Experimental results on low-frequency variations of this device indicate that net gains of 20 to 30 dB are reasonable[12], and linear phase-shift variations in excess of 360° have been obtained.[10] A 50-micron-long device is expected[13] to exhibit this sort of performance for frequencies in the range of 20 to 50 GHz, although so far our prediction has not been verified experimentally.

Conclusion

We have seen that a wide variety of devices might be fabricated on a common structure of *GaAs*. The proposed structure is built up on a semi-insulating *GaAs* substrate as follows: The first three layers are epitaxial *GaAs*. The bottom one is approximately 5 microns of highly conducting N-type material. The second and most crucial one is approximately 2 microns of lightly-doped N-type material. The third one is approximately 3 microns of highly-conducting P-type material. Ohmic alloy contacts are applied where appropriate. Several hundred Angstroms of aluminum oxide serve as insulation, and a final layer of aluminum can be used for conducting electrodes.

Passive components that can be constructed include resistors, capacitors, two kinds of diodes, and two kinds of striplines. For oscillation, there is a relatively quiet avalanche diode for frequencies in the range of 10 to 25 GHz; a transferred-electron oscillator for frequencies in the range of 1 to 10 GHz; and another transferred-electron oscillator for frequencies in the range of 25 to 50 GHz. A field-effect transistor provides amplification (or oscillation) for frequencies up to several GHz. Amplification at higher frequencies (up to 50 GHz) calls for a transferred-electron-effect traveling-wave amplifier. The latter device might also be used for high-frequency phase shifting.

The growing of the various epitaxial layers, especially the lighter doped N-layer is still a fine art and strongly dependent on the quality of the raw materials. Some of the devices, like the traveling-wave amplifier, are still at a very early stage of their development. Other parts of the structure and most of the other devices have been proven, however, and in the years ahead we may well find that *GaAs* will play an important role as the key material in microwave integrated circuits.

Acknowledgments

The ideas in this article have been accumulated from interaction with many people at the RCA Laboratories. M. C. Steele promoted the idea of a *GaAs* monolithic microwave integrated circuit. C. P. Wen has generalized the stripline concept. The idea of a distributed oscillator was developed by R. D. Larrabee. H. von Philipsborn and A. Triano have contributed much to the art of growing very thin lightly-doped N-layers of epitaxial *GaAs*, and M. Duffy has developed a technique for depositing high-quality layers of aluminum oxide. J. F. Kaminski and A. Young have improved our integrated-circuit processing capabilities. J. Hughes and L. Napoli have provided valuable information on the design of high-frequency circuits and devices.

References

1. Webster, W. M., "Integrated Microwave Modules—A Prospectus," *IEEE Trans. Electron Devices* ED-15 (1968) p. 446.
2. Sterzer, F., "Microwave Solid-State Power Sources," *Microwave Journal*, (Feb 1968).
3. Wen, C. P., "Coplanar Waveguide, A Surface Strip Transmission Line Suitable for Non-Reciprocal Gyromagnetic Device Applications," 1969 International Microwave Symposium, Dallas, Texas (May 5, 1969).
4. Mehal, E. W., and Wacker, R. W., "GaAs Integrated Microwave Circuits," *IEEE Trans. Electron Devices* ED-15, (1968) p. 513.
5. Misawa, T., "Negative Resistance in P-N Junctions Under Avalanche Breakdown Conditions, Part II." *IEEE Trans. Electron Devices* ED-13 (1966) p. 143.
6. Levine, P. A., *private communication.*
7. Thim, H. W., and Barber, M. R., "Microwave Amplification in a GaAs Bulk Semiconductor," *IEEE Trans. Electron Devices* ED-13 (1966) p. 110.
8. Dienst, J. F., Dean, R., Enstrom, R., and Kokkas, A., "Coplanar-Contact Gunn-Effect Devices," *RCA Review, 28*, (1967) p. 585.
9. Becke, H. W., and White, J. P., "Gallium Arsenide FET's Outperform Conventional Silicon MOS Devices" *Electronics, 40* (Jun 12, 1967) p. 82.
10. Robson, P. N., Kino, G. S., and Fay, B., "Two-Port Microwave Amplification in Long Samples of GaAs," *IEEE Trans. Electron Devices* ED-14 (1967) p. 612.
11. Larrabee, R. D., *private communication.*
12. Preliminary experimental results in frequency range 1-5 GHz, by others.
13. Dean, R. H., "Optimum Design of Thin-Layer GaAs Amplifiers," *to be published in Trans. IEEE (correspondence).*

Resonators compatible with microwave integrated circuits

A. Schwarzmann

Integrated modules for duplex communications systems require filters of high selectivity and low insertion loss as receiver preselectors and transmitter postselectors. The conventional microstrip transmission line resonator has low *Q* and new resonator techniques are needed. The following resonators were compared theoretically and experimentally: a microstrip resonator, a disk resonator, conventional waveguide cavities, and dielectric loaded cavities. The latter technique was chosen for the construction of multi-resonator filters. Compared to conventional waveguide resonators, the dielectric resonators reduced volume 30 to 1 while increasing losses 3 to 1.

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attended electrical power engineering school in Germany, and received the BS in Physics from LaSalle College of Philadelphia. Mr. Schwarzmann joined RCA in 1956 as a Design and Development Engineer at Moorestown where he contributed to the development of the high power transmitters. Since 1960 he has been engaged in advanced research and development of solid state devices and microwave integrated circuits at RCA's Advanced Technology Laboratories in Camden. Mr. Schwarzmann has published several papers in the microwave solid state field. He has one patent and several applications pending in the field of varactor multipliers and mixers. He is a member of IEEE.

ACCEPTABLE REQUIREMENTS for a microelectronics communications system operating at X-band are 60 dB rejection of the transmitter signal by the receiver while attenuation of the received signal is less than 1 dB. The bandwidth of the system is near 1%, and the receiver and transmitter frequency separation is near 10%. This relates to a single-resonator unloaded *Q* of greater than 2000. In addition, microwave-integrated-circuit modules for a transmitter and receiver are less than one cubic inch in size. Therefore, a compatible duplexer cannot be greater if phased arrays are to be constructed. The investigation began with single resonators of compatible types and then progressed to the most suitable multi-resonator filters.

Microstrip resonator

Because of its simplicity, the microstrip resonator could not be overlooked. Its resonant wavelength is a function of the effective dielectric constant, $\lambda_0 = l\sqrt{\varepsilon_{eff}}$, foreshortened by the coupling and end-capacitance effect.

For a commonly used substrate of $\varepsilon_r = 9.6$ and a thickness of 0.025 inch with copper conductors at 50 ohms impedance, $Q_u = 120\sqrt{f}$. From this it can be seen that the unloaded *Q* obtainable from microstrip falls far short of the requirement (Fig. 1). The microstrip unloaded *Q* was measured first on resonant rings as to eliminate the losses introduced by the foreshortening end-capacitance; a sample test circuit is shown in Fig. 2. The sample shown in Fig. 3 was used to determine unloaded *Q*'s with the end-capacitance losses. As frequency increases, the foreshortening increases, and for open-end microstrip resonators, the losses increase.

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Glossary
λ_0 = resonant wavelength
l = length of line
ε_{eff} = effective dielectric constant
Q_u = unloaded *Q*
f = frequency (GHz)
ε_r = relative dielectric constant
h = thickness of dielectric
D = diameter of disk

Resonant disk on a substrate

The resonant disk has a fundamental mode approaching a half wavelength in the diameter *D* with an *E*-field distribution along its diameter similar to the just described microstrip resonator. Its resonant wavelength is $\lambda_0 = 1.7\sqrt{\varepsilon_r}D$ when taking the disks fringe capacitance into account.

The unloaded *Q* of the disk resonator is that of a cavity resonator in a pseudo-TE010 mode with a near-perfect *H*-barrier perpendicular to the edge of the disk. The unloaded *Q* for this model is approximately $200\sqrt{f}$ on a 25-mil Alumina substrate. The actual values are still far below the required unloaded *Q* for the duplexer design.

The second-order mode of resonance of a disk appears when the diameter of the disk approaches a full wavelength foreshortened by the fringe capacitance of the edge. Fig. 4 shows experimental data on the latter resonance. Fig. 5 is a photograph of a sample test circuit.

The quality of the shape of the resonance curves was poor beginning at 25 dB down from resonance and leveled off at 35 dB for the disk resonator as well as the microstrip resonator. A duplexer design on a substrate using these types of resonators would show serious limitations in the required isolation of 60 dB and less than 1-dB insertion loss in the bandpass.

Rectangular dielectric loaded waveguide resonator

The waveguide theory in use for conventional designs is applicable directly for any other low loss, higher and homogeneous dielectric. The linear dimensions, the wavelength and the unloaded *Q* decrease by $1/\sqrt{\varepsilon_r}$.

A desirable characteristic of the dielectric is a high enough relative dielectric constant to result in a significant reduction in size. The *Q* of the dielectric should be at least an order of magnitude higher than the required. The change in dielectric constant with temperature should be very small as should the linear coefficient of expansion. Alpha-alumina has a dielectric constant

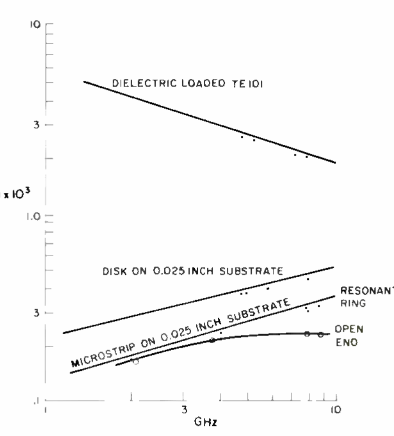

Fig. 1—Q_u of resonators compatible with microwave integrated circuit for alumina dielectric.

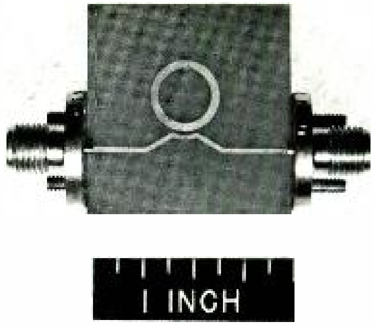

Fig. 2—Sample of resonant ring in microstrip form.

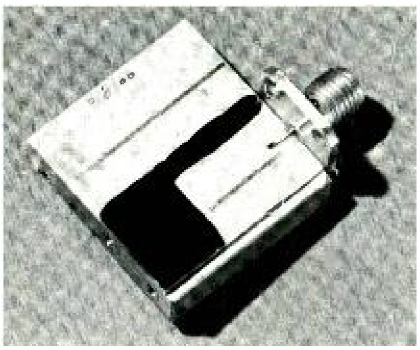

Fig. 3—Sample of open-end microstrip resonator on 0.025-inch-thick alumina substrate.

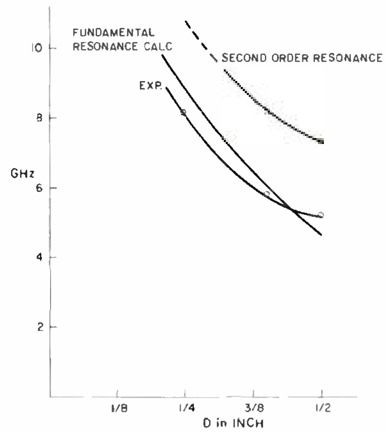

Fig. 4—Resonances of a disk on a 0.025-inch alumina substrate.

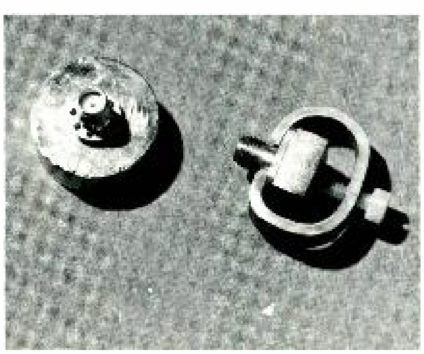

Fig. 5—Test circuits for dielectric-loaded resonant disk.

of 9.9 and a loss tangent of 0.000025 at X-band and was the best choice for this application. The linear coefficient of expansion is equal to that of Kovar. Also, the change in dielectric constant with temperature is one of the smallest of all the ceramics (Table I).

Table I—Characteristics of dielectrics at X-band.

Type	ε	*tan* α	$\frac{dl}{dt}$ *for* °C	$\frac{d\varepsilon}{dt}$ *for* °C
α-alumina	9.9	.00002	5×10^{-6}	$+1\times10^{-4}$
Fused quartz	3.8	.0001	$.5\times10^{-6}$	$+1.6\times10^{-5}$
Beryl. oxide	6	.0001	6×10^{-6}	$+1.5\times10^{-4}$
TiO_2	100	.0002	9×10^{-6}	-8×10^{-4}

Notes: ε is relative dielectric constant; tan α is loss tangent; dl/dt is linear coefficient of expansion; and $d\varepsilon/dt$ is change of dielectric constant with temperature.

The resonators were machined out of large ceramic plates. The machining included the coax-to-waveguide transitions. Before metalizing all surfaces by Electroless Copper, the device was subjected to a deglazing process for best possible adhesion of the copper.

The unloaded Q measurements were made by the swept reflectometer method[1]. The measured values are plotted against the calculated values in Fig. 1. The measured unloaded Q of 2040 was sufficiently high to meet the requirements. The resonant frequencies were within one part per thousand of the calculated, reflecting the machining error. A set of dielectric loaded resonators constructed for the purpose of these measurements is shown in Fig. 5.

Multi-resonator filters

Having tested the theory and established a satisfactory construction for dielectric resonators, the iris-coupled rectangular waveguide filters[2] were designed in the dielectric form. Fig. 6 shows a three-resonator section filter in its stages of construction. Fig. 7 illustrates the size reduction between filters of the same requirements.

The response of a two-section filter presented in Fig. 8 is compared to the theoretical response curve. The insertion loss of the flat part of the curve is 0.6 dB including the coax-to-waveguide transition losses.

Concluding remarks

High quality microwave resonators and filters can be constructed in dielectric loaded form to be compatible with microwave integrated circuits. Transitions to microstrip are made via a perpendicular round rod through the substrate into the loaded waveguide device. A method of trimming resonators has been demonstrated. The approach is similar to conventional methods. A small dielectric slug changed tuning by 1% whereas a metal slug changed resonance by 20%.

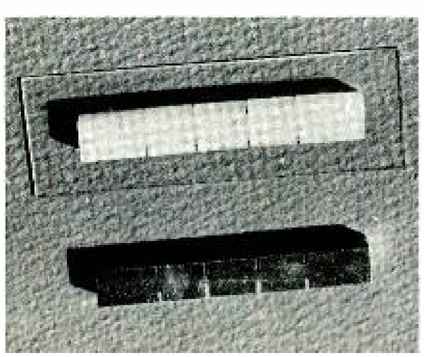

Fig. 6—Three-resonator iris-coupled filter in the machined and metalized stages of construction.

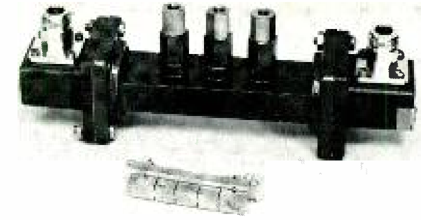

Fig. 7—Three-resonator iris-coupled filter of the same requirements in conventional and dielectric loaded form.

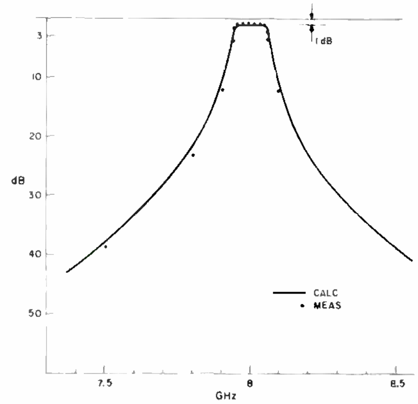

Fig. 8—Response of two-resonator iris-coupled dielectric-loaded waveguide filter.

The tests on the two-section waveguide filter were extended to include temperature characteristics. The fractional frequency change of the alumina dielectric loaded filter is -5×10^{-5}/°C. This reflects the linear coefficient of expansion and the dependence of the dielectric constant of the alpha alumina upon temperature. No measurable change in bandwidth and insertion loss was detected for a 130°C change in temperature.

In a similar test on a Quartz-dielectric loaded resonator the fractional change in frequency was measured at -2×10^{-6}/°C. This characteristic of Quartz may influence some future dielectric loaded filter designs.

Acknowledgment

The expert crafsmanship of Mr. R. Distefano and W. Dimitruk in machining and metalizing made this work possible.

References

1. Sucher, M., *Handbook of Microwave Measurements*, Vol. II, (Polytechnic Press).
2. Matthai, G. L., Yound, L., Jones, E.M.T., *Microwave Filters Impedance Matching Network and Coupling Structures* (McGraw Hill, 1964).

New technique for combining solid-state sources

D. Staiman | M. E. Breese | Dr. W. T. Patton

The advent of many new moderate-power solid-state devices has created a renewed interest in the techniques for combining these devices to achieve even higher powers. This paper describes a new technique for combining large numbers of energy sources by using a dense array of radiating elements. The impedance of the radiating elements, as determined theoretically and confirmed using an array simulator, may be well matched over a large bandwidth. A transfer array utilizing this concept to parallel one hundred transistor amplifiers has a net gain of 4.75 dB at 410 MHz with 100 watts output. Tests in which individual failures were simulated indicate that array elements were well isolated from each other.

THE ADVENT of many new microwave solid-state devices, such as RF transistors and bulk-effect devices, has created a renewed interest in the techniques for combining energy sources to achieve high powers. Although existing techniques are satisfactory for paralleling moderate numbers of devices, these techniques are severely bandwidth limited and excessively lossy when very large numbers are paralleled.

This paper describes a new low-loss technique for combining the power of very large numbers of moderate power devices over large (up to an octave) bandwidths, especially suitable for high-power transmitters. Power is summed by using an array of very small radiating elements, closely packed together, each element fed by an active device as shown in Fig. 1. The output power of each device is radiated, and power combination occurs in free space. Typical packing densities of the radiators are greater than 240 elements/square wavelength.

Impedance of radiating element

For efficient operation of the array, there must be a good impedance match between the radiating elements and the transmitter device. Prior theoretical work on closely-spaced array elements in which the current distribution was assumed to be sinusoidal has indicated that they are highly reactive and have a correspondingly narrow bandwidth. However, preliminary work with a waveguide array simulator[2] has shown that if the collinear dipoles are contiguous (as shown in Fig. 1), with no gap between adjacent elements, the reactance of the dipoles (whose current distribution is uniform) is very small.

A theoretical program and additional experiments were conducted to determine the impedance of a dipole with a uniform current distribution in a large array; the impedance of a dipole with a sinusoidal current distribution was also evaluated to provide a convenient check point against previous theoretical work[3].

The impedance of a dipole in a large array is obtained using a mathematical model of an array extended to infinity. The impedance of central dipoles in a large array is well approximated by the infinite array impedance since the coupling between the central and peripheral elements is negligible. The results of the theoretical study are presented here without the detailed mathematical derivation.

The impedance of a dipole with a uniform current distribution is an infinite array of dipoles, with uniform current and phase excitation, spaced a distance d above a reflecting ground plane is given by

$$Z=\frac{\eta L^2 k}{2ab}\sum_{m=-\infty}^{+\infty}\cos\beta_m\sigma\left[\frac{1-\exp(-j2d\zeta_{nm})}{\zeta_{nm}}\right] \quad (1)$$

For thin dipoles ($\sigma << 1$), the real component of Eq. 1 is given by

$$R=\eta\frac{a}{b}\left[\frac{L}{a}\right]^2\left[\frac{1-\exp(-j2dk)}{2}\right] \quad (2)$$

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Glossary

- a Height of elemental array aperture (see Fig. 1)
- b Width of elemental array aperture (see Fig. 1)
- L Dipole length (see Fig. 1)
- Z Element impedance
- η Free space impedance (377 ohms)
- R Real part of element impedance
- σ Dipole radius
- h Effective height of the antenna
- ζ_{nm} $[k^2-\beta_m^2-\alpha_n^2]^{1/2}$

  where, for $\sqrt{\mu^2}=\mu$ and $\sqrt{-\mu^2}=-j\mu$

  $|k^2-\beta_m^2-\alpha_n^2|=\mu^2$
- k 2π
- η $\sqrt{\mu/\varepsilon}$
- α_n $2\pi n/a$
- β_m $2\pi m/b$
- $I(x)$ Axial current distribution of the dipole where the dependent variable, x, is taken along the direction of dipole length, L.

when $a < 1$ and $b < 1$. Although these equations are completely valid in practice, a uniform current distribution is obtained only when the radiator length L is much smaller than a wavelength.

The impedance of a dipole with a sinusoidal current distribution in an infinite array of dipoles, with uniform amplitude and phase excitation, spaced distance d above a ground plane is given by

$$Z=-\frac{2k\eta}{ab\sin^2(kL/2)}\left[\sum_{n=-\infty}^{+\infty}\left(\cos\frac{\alpha_n L}{2}-\cos\frac{kL}{2}\right)^2/(\alpha_n^2-k^2)\right]\cdot\left[\sum_{m=-\infty}^{\infty}\cos\beta_m\sigma\frac{(1-\exp(-j2d\zeta_{nm})}{\zeta_{nm}}\right] \quad (3)$$

For thin dipoles ($\sigma << 1$), the real component of equation is given by

$$R=\eta\left(\frac{a}{b}\right)\left(\frac{h}{a}\right)^2\left(\frac{1-\exp(-j2dk)}{2}\right) \quad (4)$$

when $a < 1$ and $b < 1$; h, the effective height of the antenna, is given by

$$h=\frac{1}{I(0)}\int_{-L/2}^{+L/2}I(x)\,dx=\frac{2}{k}\frac{[1-\cos(kL/2)]}{\sin(kL/2)} \quad (5)$$

when $I(x) = I(0)\sin(L-|x|)$. Eq. 2 and 5 are in agreement with results previously obtained by Wheeler[4].

The resistance of the uniform current dipole given by Eq. 2 is summarized in Fig. 2 for a specific example. This figure presents the resistance of the dipole as a function of the cell param-

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eters a and b when the dipole radius $\sigma = 0.001$, $d = 0.25$; the dipole height is the same as the cell height, $L = a$. Fig. 3 presents a similar set of curves for the sinusoidal current dipole. Fig. 4 presents a comparison of the reactance of the uniform and sinusoidal current dipoles for these same parameters. Note that in the case of the sinusoidal current distribution, the dipole is resonant in the vicinity of $a = \lambda/2$ and becomes large and negative when its height is reduced to zero. This behavior is expected since an isolated sinusoidal current dipole is resonant when its length is approximately $\lambda/2$. In contrast, the reactance of the uniform current dipole is linearly proportional to its height, and is thus very small for short fractional-wavelength dipoles. This behavior is analogous to the isolated fractional-wavelength dipole with capacitive top loading; it is resonant when its length is much smaller than a wavelength and its current distribution is uniform. Hence it is evident that fractional-wavelength radiators in an array may be configured to achieve broad-band matching of the cell impedance to that of the transmitter device.

Array simulator

To provide experimental confirmation of the theoretical results presented, a novel single element array simulator was constructed and tested. Its basis of operation is derived from the mathematical model used for the impedance calculation. Fig. 5 shows an infinite array of dipoles with the horizontal and vertical planes of symmetry indicated by dashed lines. For broadside radiation, the electromagnetic boundary conditions are not affected if ideal magnetic and electrical walls are constructed perpendicular to the array coincident with the vertical and horizontal planes of symmetry, respectively. In the region in front of the array, these define identical transmission-line cells emanating from each radiator. Hence the impedance of a dipole is determined by evaluating its impedance feeding an ideal TEM-mode transmission-line cell. Fig. 6a is the cross-sectional view of one of these cells fed by a radiator. The radiating element shown in this figure is fed at its end rather than at its center since this configuration more closely simulates that of the test array described later in this paper.

In the case of the uniform current distribution, the impedance of the radiator is not a function of the point at which it is being fed. The electric field lines are shown extending from the top to the bottom walls, and the magnetic field lines extend from one sidewall to the other. To provide a terminal resistance of 50 ohms, the unit cell width and height are 0.177 and 0.0234 wavelengths, respectively. For this specific case, in which the unit cell height is much smaller than its width and both are small fractions of a wavelength, the removal of the magnetic walls does not appreciably affect the internal electromagnetic field configuration. Although some fringing does occur at the edges of the cell, as shown in Fig. 6b, the impedance of the monopole feeding the resultant parallel plate structure provides a very good estimate of the monopole impedance feeding an

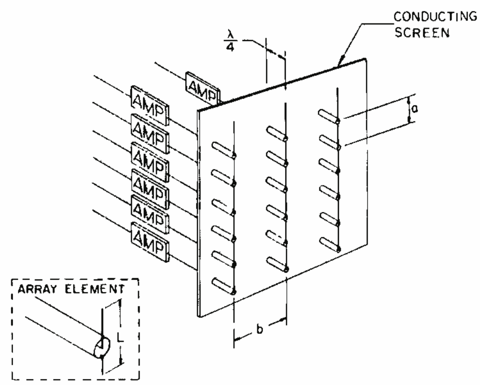

Fig. 1—RF power combination in free space using an array of individually fed, closely spaced dipoles.

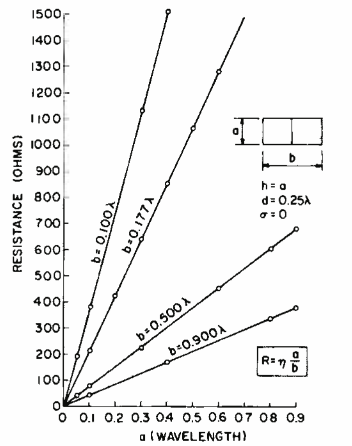

Fig. 2—Radiation resistance of uniform current dipole in infinite array; $L=a$; $d=0.25$; $\sigma=0.001$.

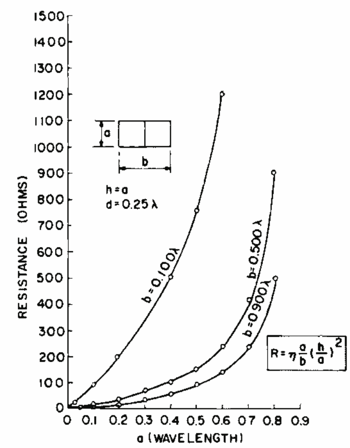

Fig. 3—Radiation resistance of sinusoidal current dipole in infinite array; $L=a$; $d=0.25$.

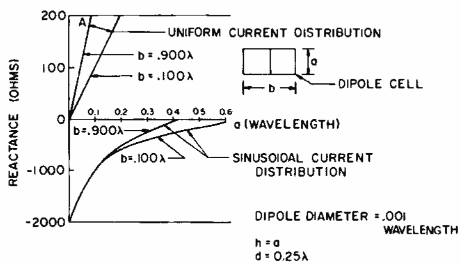

Fig. 4—Radiation reactance of uniform and sinusoidal current dipoles in infinite array; $L=a$; $d=0.25$.

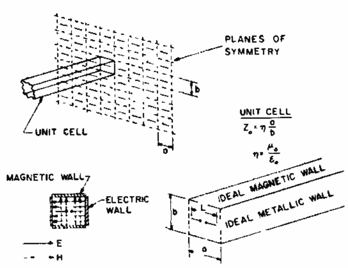

Fig. 5—Unit cell of dipole array.

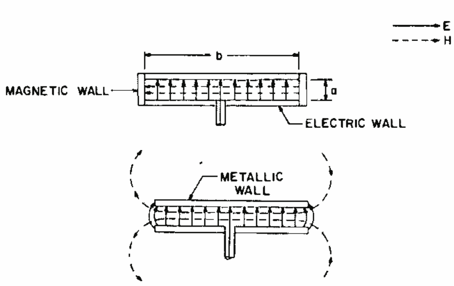

Fig. 6—a) Electromagnetic field configuration in unit cell; b) electromagnetic field configuration in single-element array simulator.

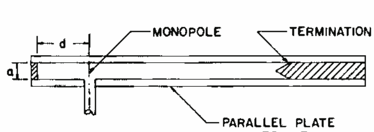

Fig. 7—Single-element array simulator.

ideal unit cell, thereby providing the impedance of the central elements in a large array. A simulator based upon this approximation to the unit cell was constructed from two metal beams as shown in Fig. 7. A short circuit located a distance d from the monopole simulates the reflecting ground plane in an array; absorbing material at the other end of the simulator terminates the line. The simulator was designed to work in the vicinity of 410 MHz.

Fig. 8 is a graph showing a comparison of the measured impedances of the simulator against the theoretically predicted values over a large band of frequencies extending from 300 to 800 MHz; the similarity of these curves provides confirmation for the theoretical analysis within the limits imposed by experimental error. It is also evident from Fig. 8 that the closely spaced element configuration has good broadband behavior. The frequency locus (if centered) would yield less than 1.6 VSWR over an octave bandwidth. This could be facilitated by impedance matching the element at its input and by increasing the dipole diameter to further reduce its radiation reactance.

Experimental array

A receive-transmit array composed of 100 elements employing the closely spaced element concept, with each element equipped with an amplifier, was constructed and tested. The system shown in Fig. 9, has identical receiving and transmitting arrays composed of elements arranged 4 per row, 25 per column. The spacing between elements is 0.0234 and 0.177 wavelengths in the vertical and horizontal dimensions, respectively. The monopole elements are located 0.25 wavelengths from a reflecting ground plane, which also serves as a shield between the amplifier and antenna regions. Metal-clad (1-mil copper on one side and 1/32-aluminum plate on the other) dielectric boards (polyolefin, inch) extending perpendicularly from the ground plane serve to mechanically support the monopole in place and to provide its electrical excitation. They do not affect the TEM-wave radiating from the array since they are thin and perpendicular to the electric field. The monopoles are fed by strip transmission lines that are printed internally on the dielectric sheets extending to the monopole; a right-angle connection to this transmission line feeds the monopole. The dipole is also held in place by the connection that it makes to the metal aluminum plate above it. A small spongelike metallic bottom (fuzz button) serves to maintain pressure at the feed connection to hold the monopole in position. The dielectric spacers shown in the Figure maintain the height between adjacent plates; experiments have demonstrated that their effect on antenna performance is negligible.

Fig. 10 is a photograph of one layer of the antenna with monopoles removed. The layer consists of a single board on which is printed four identical amplifier circuits and their associated input and output lines. The amplifier circuitry in the assembly, located between the two metal shields, is composed of

RF microstrip transmission-line elements plus several lumped capacitors. The amplifier, designed around a 2N3866 RCA overlay transistor, has a power output of 1 watt with a 7-dB gain, and an efficiency that lies between 26 to 43% at the 410-MHz operating frequency. The gain and transmission phase of the 100 amplifiers was measured and found to have a spread given by 0.35 dB RMS and 5.6° RMS, respectively. The antenna region, as described, consists of two dielectric boards that are used to form the strip transmission-line feed networks. A bus wire shown connecting all the amplifiers provides the collector voltage to the transistors through biasing networks, and is connected to a terminal board mounted on the side of the array.

The assembled array is excited by a uniform plane wave incident on its receive aperture. This excitation was obtained by placing the array over the central portion of a large oversize waveguide. Although the field intensity variation in a waveguide is sinusoidal, the variation of the field near its center is relatively low. To reduce this variation, a disturbance was introduced into the taper feeding the oversize waveguide, causing a third order mode to be excited with amplitude and phase such that it canceled part of the variation in the dominant-mode field intensity. Fig. 11 is a photograph of the array situated on top of this oversize waveguide; those portions of the waveguide not feeding the array are terminated with absorber blocks. The entire array and feed assembly are mounted vertically in a hole in a large ground screen.

Antenna patterns were measured by recording the field intensity sampled by an antenna mounted on a boom that travels in a vertical arc in the plane of the array. The receive-transmit array was evaluated by a comparison of the **E**-plane and **H**-plane antenna patterns of the array with an aperture having the same geometry. These patterns together with relative power measurements show that the net gain of the receive-transmit module was 4.75 dB. Tests of individual amplifiers prior to assembly showed an average gain of approximately 7.0 dB. The disparity between this gain figure and that of the array module is attributed principally to the small size of the array. Even in a large array, elements near the periphery do not see the same physical environment as elements near the central portion of the module, and hence have a driving-point impedance substantially different from that approximated by an infinite array. The small size of the test array, 0.416 square wavelengths, although adequate for testing feasibility, does not provide a good estimate of the efficiency since more than 50% of the elements are edge elements, and even the interior elements are in a decidedly noninfinite array environment.

Several additional experiments were made with the array to determine its sensitivity to isolated failures. Various combinations of amplifiers were disabled by disconnecting the collector supply lines. Tests were made with a single disabled element, a disabled layer of elements, and several combinations of disabled layers, including the series of cases in which 124 out of the total number of 25 layers were disabled. In all these tests no transistor failure occurred, and the array, when completely reconnected, showed no signs of any malfunction. These preliminary tests indicate that this paralleling scheme is comparable in reliability to the cascaded hybrid junction combining schemes.

Conclusions

The impedance of radiating elements in a dense array has been theoretically determined and experimentally confirmed. Large arrays of elements may be configured to have an impedance that is suitable for matching to many transmitter devices over large bandwidths. Tests of a 100-element receive-transmit array have demonstrated the feasibility of the closely spaced element concept and have underscored the reliability of this paralleling scheme.

References

1. Allen J. L. and Diamond B. L., *Mutual coupling in array antennas*, M.I.T. Lincoln Lab., Tech. Rept. 424 (Oct 4, 1966) p. 10.
2. Hannan P. W., Meier P. J., and Balfour M. A., "Simulation of phased array antenna impedance in waveguide;" *IEEE Trans. on Antennas and Propagation*, vol. AP-13 (May 1965) pp. 342-353.
3. Stark L., *Radiation impedance of dipoles in infinite arrays*, Hughes Aircraft Co., Tech. Rept. FL60-230 (1960).
4. Wheeler H. A., "The radiation resistance of an antenna in an infinite array or waveguide," *Proc. IRE*, vol. 36 (1948) pp. 478-487.

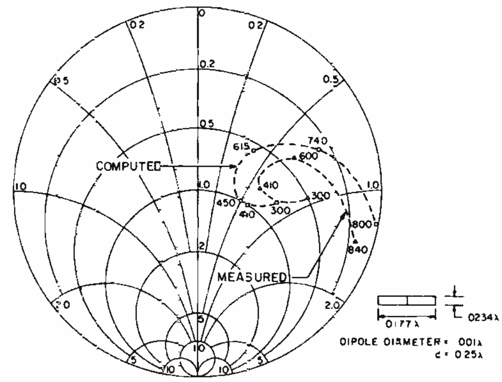

Fig. 8—Impedance of single element array simulator.

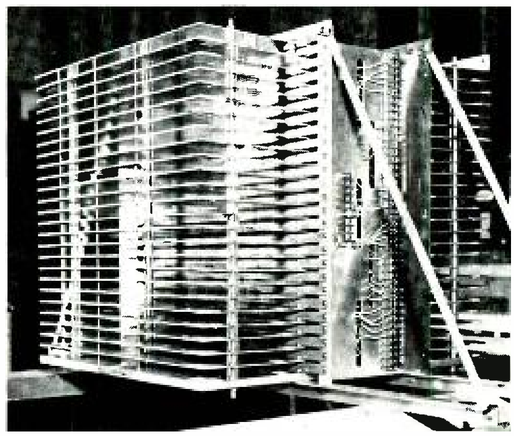
Fig. 9—Photograph of 100-element transfer array.

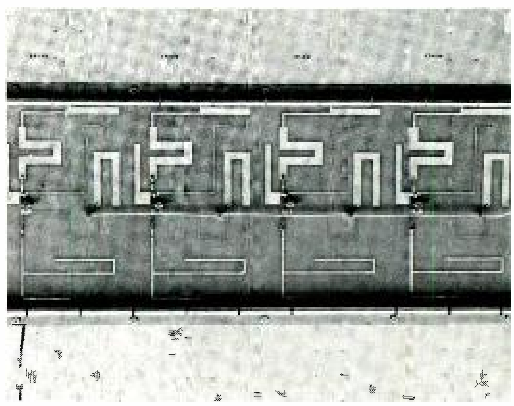
Fig. 10—Photograph of single layer of 100-element transfer array.

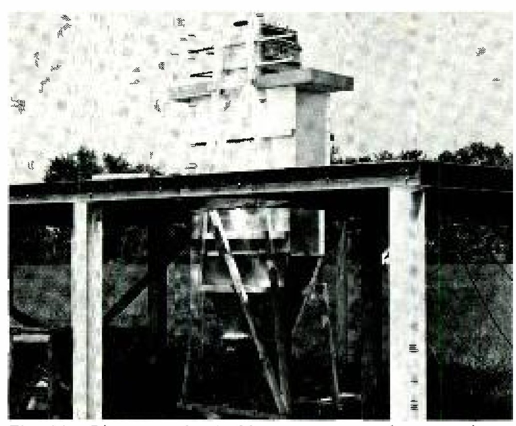
Fig. 11—Photograph of 100-element transfer array in test configuration.

The sandwich pack

J. Croft

This paper describes a packaging technique used extensively by the Astro-Electronics Division to protect spacecraft hardware and other valuable equipment during handling. The unique feature of the system is that it can easily be adapted to several equipment configurations.

THE ASTRO-ELECTRONICS DIVISION produces low-volume, high-reliability equipment that requires in-process handling protection to a level almost the same as that for out-of-plant shipment. When an item leaves one operation for the next, it may be delayed for several hours or for several months. It may be diverted to (and through) Engineering, Quality Control, or other departments for various reasons, and it may be subjected to numerous types of stresses in handling.

In the past, the manufacturing operator or stockroom attendant had to improvise adequate in-process handling methods using plastic bags, plastic boxes, or one of several other means available.

The Technology Engineering Section at the Astro-Electronics Division has invented a new packaging concept that eliminates improvised packaging and provides maximum protection. This new concept is called a *sandwich pack* and is composed of a container having three separate parts (as shown in Fig. 1): a top and bottom made of a soft material (e.g., polyurethane foam) which is bonded to a hard backing (such as phenolic sheet or plywood) and an inner frame. With these three parts, equipment can be packaged without the necessity for a dunnage filler or a custom-made nest to immobilize and cushion it. This is accomplished by compressing the item between the top and bottom foam-lined parts and fastening the package together. By keeping the top and bottom parts separate, extreme versatility is achieved with regard to the size of the item that can be accommodated in any one package.

A closed package, secured by strips of Velcro tape, is shown in Fig. 2; the tapes are bonded to the hard backing

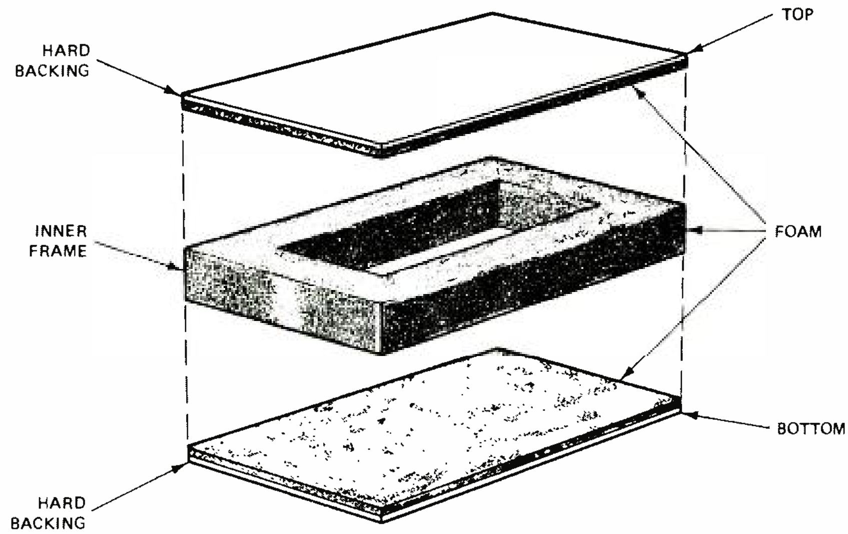

Fig. 1—The sandwich pack consists of three separate parts: cushioning material, rigid backing, and an inner frame.

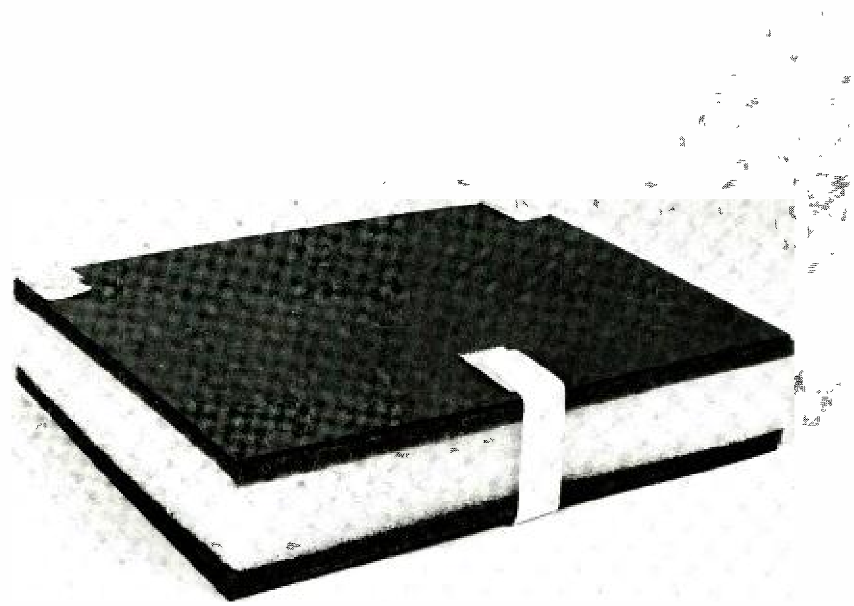

Fig. 2—The assembled sandwich pack is held together with Velcro tape.

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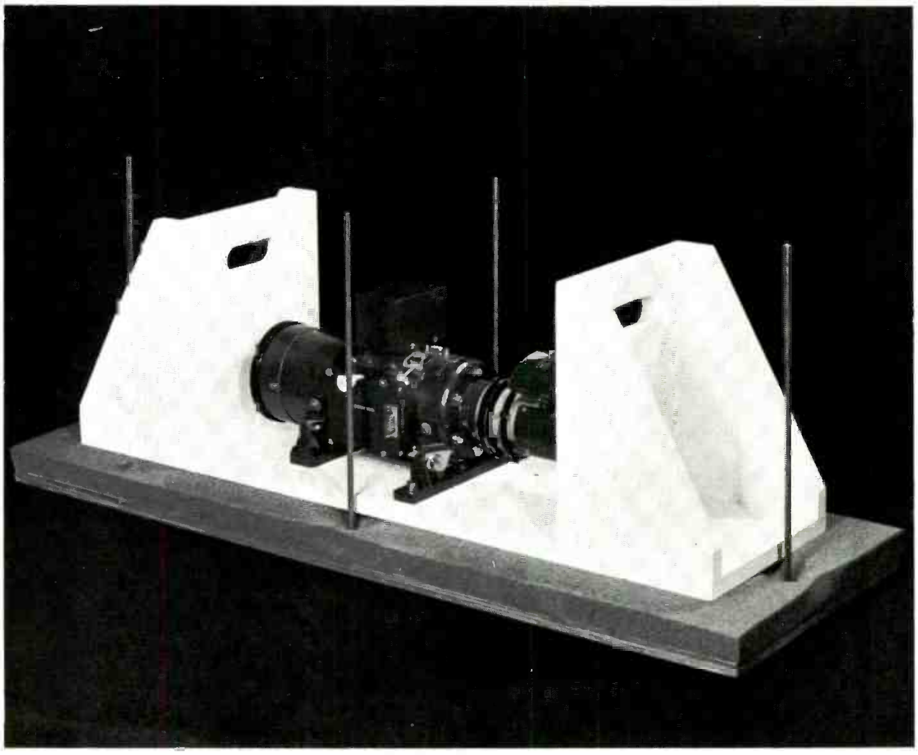

Fig. 3—A satellite camera mounted on the baseboard and lower cushioning material of the sandwich pack.

Fig. 4—The inner frame and plywood top and sides are added to the frame shown in Fig. 3 to form a complete shipping container.

material. Different heights can be accommodated by inserting additional inner frames and using longer tapes.

The key to the sandwich-pack principle is the separate inner frames. By keeping this part separate, the height of the package can be tailored to the contents; inner frames are added until they are at the approximate height of the equipment being packaged. When the frame height is a little less than that of the equipment, it can be held securely by compressing the foam backing when the package is closed. If the frames are slightly higher than the item, this compression is accomplished by positioning a separate piece of foam over the item before closing the package.

The sandwich-pack concept can also be applied to the design of shipping containers. Figs. 3 and 4 show a container designed for inter-plant handling of a satellite camera; the camera is mounted to an inner frame which, in turn, is packaged and held secure by compression in the same manner as previously described. Note again, that by keeping the inner frame (this time of plywood) separate, the container can be used on items of varying size simply by substituting a frame to meet the height requirement.

The Astro-Electronics Division has found the sandwich-pack system extremely valuable in solving its handling problems. For further information regarding the application or utilization of the system, contact J. E. Croft at Astro-Electronics Division, P.O. Box 800, Princeton, N.J. 08540.

Acoustic surface-wave devices

Dr. D. A. Gandolfo

Acoustic surface-wave devices offer attractive solutions to many signal-processing problems at frequencies from tens to thousands of megahertz. Presently, RCA Advanced Technology Laboratories is actively engaged in a program to investigate surface-wave phenomena and to apply these phenomena to microwave devices. This paper will give a brief review of the state of the art in acoustic surface-wave devices and of the promise which these devices hold. RCA efforts up to the present and the direction of future programs will be discussed. The acoustic surface waves as described here are primarily Rayleigh waves such as the frequently observed waves on the surface of a body of water. In such a wave, the motion of the particles in the medium is elliptical, that is, it contains components parallel to and perpendicular to the direction of propagation. The amplitude of the waves decays exponentially with distance from the surface.

COMPACT ACOUSTIC SURFACE-WAVE DELAY DEVICES afford a convenient technique for achieving time delay in the microsecond range. The surface waves, like other acoustic waves in solid media, propagate with a velocity smaller by five orders of magnitude than that of electromagnetic waves in free space. Thus the required path length for a delay of a few microseconds is reduced from a kilometer to approximately one centimeter. Experiments demonstrating time delay through surface-wave techniques have been conducted at frequencies from a few megahertz up to about 1 GHZ, and time delays of up to 10 μs have been observed. Both dispersive and nondispersive delay lines have been built. Variable delay lines with delay variation being achieved through mechanical displacement of the output transducer have also been constructed. However, the truly significant aspect of acoustic surface waves is that the wave energy is localized within about one wavelength of the free surface, a distance of the order of a few micrometers at 1 GHz, and this energy can be easily extracted for signal processing. This behavior makes possible the development of tapped delay lines and other signal processing functions which may be realized through surface-wave techniques. These functions include matched filtering (as in pulse compression), auto-correlation, cross-correlation, and coding.

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A number of different single-crystal piezoelectric materials have served as media for the propagation of surface waves. These include quartz, *ZnO* and $LiNbO_3$. We usually wish to convert an electromagnetic signal into an acoustic signal directly at the surface of the propagation medium and in this case, a material such as $LiNbO_3$ which has a large electromechanical coupling coefficient has an obvious advantage. However, if simultaneous propagation in several different directions is desired, a material such as *ZnO* may be more useful. *ZnO* has a smaller electromechanical coupling coefficient, but exhibits transverse isotropy on a *Z*-cut plate. Thus, the velocity is independent of the direction of propagation on the surface. *CdS* also possesses good electromechanical coupling and transverse isotropy in a plane normal to the *c*-axis. However the velocity is so small, approximately 1.73 x 10^5cm/s that the consequent wavelength reduction may make the construction of microwave frequency transducers unduly difficult. Quartz has been widely used because of its ready availability, but it is not a satisfactory material because of its weak electromechanical coupling. It might serve as the propagation medium if the electromechanical conversion occurred in another material.

Acoustic attenuation of surface waves has been measured in several of the materials mentioned above. Slobodnik and Carr have studied $LiNbO_3$ and found losses on the order of 3 dB/cm at about 1 GHz and at room tempera-

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received the BS in Physics from Saint Joseph's College in 1956 and the MS and PhD in Physics at Temple University in 1963 and 1967, respectively Since joining RCA Applied Research in 1960, he has worked in microwaves, cryogenics, plasma physics, and radiation damage. He has conducted experimental programs in which various microwaves delay techniques were studied. These include acoustic surface-wave devices, YIG devices, and superconductive slow-wave structures. His cryogenics experience includes the design and fabrication of superconductive maser magnets and operation of these magnets in liquid helium baths as well as in closed-cycle refrigerators. In the area of plasma physics, Dr. Gandolfo has studied the interaction of electromagnetic waves with rocket exhaust plasma and the effects of this interaction on radar and telemetry systems. He has also experimented with a coaxial-rail gun plasma accelerator. In radiation damage studies, he has measured and analyzed the effects of neutron and gamma irradiation on semiconductor devices. He also analyzed the effects of high-energy proton bombardment on transistors. Dr. Gandolfo is a member of the American Physical Society.

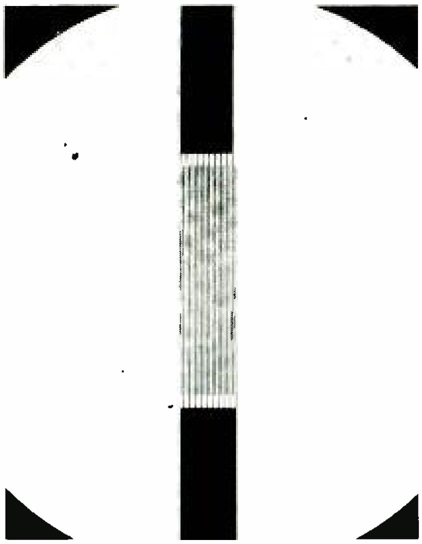

Fig. 1—Transducer pattern used in 425-MHz delay device. The fine line electrodes are 2 microns wide placed on 4-micron centers.

ture.[1] In the UHF range, propagation losses are negligible. Salzmann et al. made a systematic study of attenuation on quartz as a function of frequency and temperature.[2] They found that, at temperatures from about 50°K up to room temperature, attenuation is essentially independent of temperature and proportional to f^2. At room temperature, the losses were about 1 dB/cm at 316 MHz and about 10 dB/cm at 1047 MHz. This latter figure is approximately three times greater than the losses in $LiNbO_3$ under similar conditions. In either case, these losses are probably tolerable for time delays of up to a few microseconds in the microwave range.

Surface waves have been launched by a variety of transducers including piezoelectric plates, wedges, metallic plates with comb profile, and interdigital electrodes. Most of these techniques lead to the conversion of a large amount of energy into bulk waves and are therefore inefficient generators of surface waves. The transducer which has proven to be the most efficient, most versatile, and probably the simplest to implement is the interdigital electrode transducer. In this transducer, an electrode structure is formed directly on the surface of propagation. This type of transducer was built and operated by R. M. White,[3] among others, and has been analytically treated by Coquin and Tiersten,[4] and Tseng.[5] A typical member of the class is shown in Fig. 1. This transducer was designed at the DEP Advanced Technology Laboratories, and made at the Defense Microelectronic facility in Somerville using photomasks prepared by personnel at RCA Laboratories and DEP Central Engineering. It consists of two interdigital combs formed on the surface of a piezoelectric crystal by phototech techniques. The center-to-center distance between adjacent lines must be equal to one-half the acoustic wavelength at the operating frequency and, for maximum efficiency, the lines should be one-quarter wavelength in width. The transducer in Fig. 1 has 2-μm wide lines on 4-μm centers. The RF signal is applied to the large area pads at top and bottom in Fig. 1, and the RF electric fields extending between the fingers couple piezoelectrically to the crystal. One such transducer on a $LiNbO_3$ substrate has been operated at a frequency of 100 MHz with a conversion loss of only a few dB. Similar transducers have been operated at frequencies up to approximately 1 GHz in fundamental mode and up to about 3 GHz at third harmonic. These transducers permit a tradeoff between coupling strength and bandwidth by adjustment of the number of fingers. By forming the appropriate electrode pattern, one may accomplish a variety of signal processing tasks. In our opinion, the interdigital or periodic electrode transducer is by far the best transducer for Rayleigh wave generation, and it is the one which is receiving the most attention during our present acoustic surface-wave program. At the Advanced Technology Laboratories, we have operated delay devices using interdigital transducers on ZnO and $LiNbO_3$ substrates.

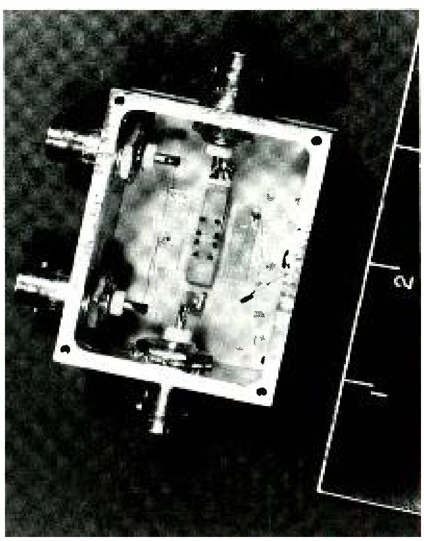

Fig. 2—Acoustic surface-wave delay device employing single-pair transducers on ZnO.

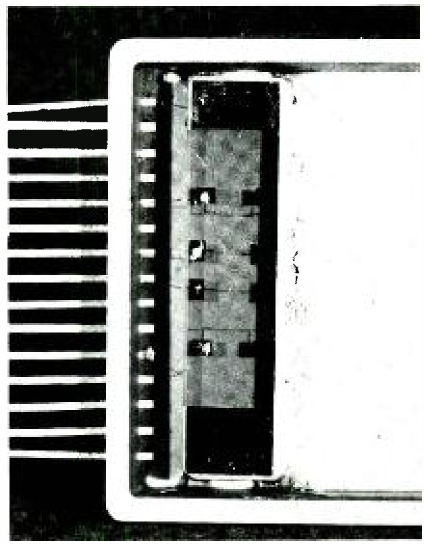

Fig. 3—An experimental acoustic surface-wave delay device employing single-pair transducers on $LiNbO_3$ substrate. The device is mounted in an integrated-circuit flat pack, emphasizing the compatibility of surface-wave and microelectronic technology.

Because the energy of surface waves is confined to the free surface, signals may be operated upon while still in acoustic form. D. L. White has shown that Rayleigh waves can be guided by means of metal strips formed on the surface.[6] (The materials of the strip and the substrate must be such that the acoustic velocities in the strip are smaller than those in the substrate.) These strips must be about $\lambda/2$ in width. Guiding occurs because the velocity of propagation is smaller under the strips than it is on the free surface. One may envision devices such as directional couplers, power dividers, and hybrid couplers with

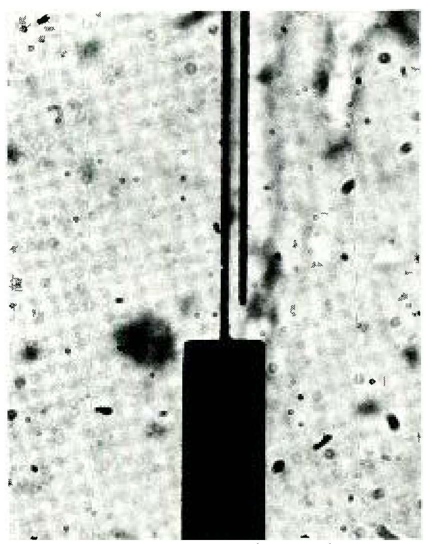

Fig. 4—Single electrode pair transducer configuration.

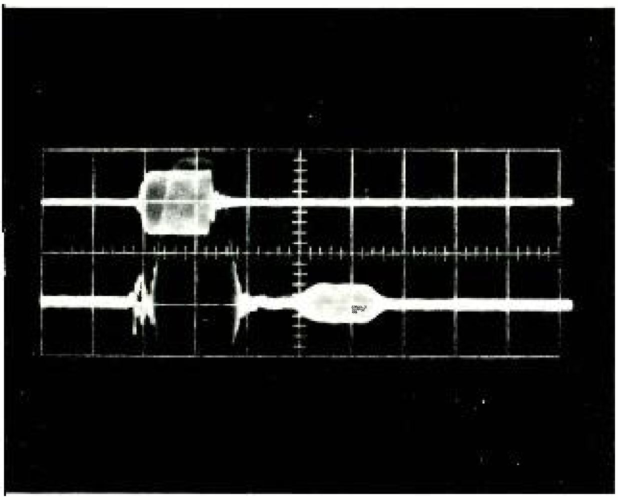

Fig. 5—Measurements of time delay—input signals on upper traces and output signals on lower traces.

configurations similar to stripline components but reduced in size by a factor approximately equal to the ratio of the electromagnetic to the acoustic wavelength. Since metal strips change the velocity of the surface waves, one may also deflect energy out of a primary beam by means of a grating consisting of a periodic array of metal lines.

Recently Collins and Lakin at Stanford University constructed an acoustic surface-wave amplifier that exhibited net terminal gain at a frequency of 100 MHz.[7] This device employed the interdigital transducers on a $LiNbO_3$ substrate to transmit and receive the surface waves. The electric field in the direction of propagation, required for traveling wave amplification, was applied to a block of silicon which was placed at a very short distance, on the order of a micrometer, from the surface.

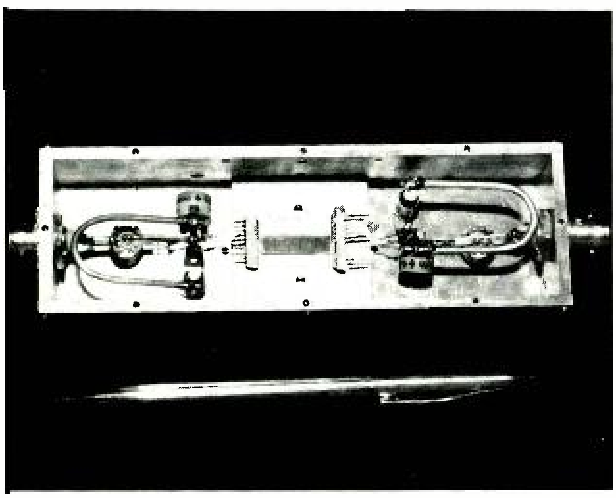

Fig. 6—The 425 MHz delay device.

RCA efforts up to the present

Advanced Technology Laboratories has designed and evaluated the surface wave delay devices shown in Figs. 2 and 3. These devices were fabricated at RCA Laboratories in Princeton and Defense Microelectronics in Somerville. Both of these devices employ the simplest type of periodic electrode transducer, that is, the two-element, or single-pair transducer. These transducers are of interest because of their potential utility in tapped delay line applications. In these applications one may wish to use a large number of transducers along the propagation path, separated from each other by small distances, with each transducer extracting only a small amount of energy from the surface wave. Since they contain only two elements, they extend only about one wavelength in the direction of propagation and interact weakly with the surface wave.

We have performed experiments in the range of 45 to 55 MHz using chrome-gold transducer-electrodes on a *ZnO* substrate and in the range of 180 to 200 MHz using aluminum transducer-electrodes on a $LiNbO_3$ substrate. The *ZnO* sample (Fig. 2) was a high resistivity single crystal with the hexagonal-axis normal to the surface on which propagation occurred. The $LiNbO_3$ sample (Fig. 3) was also single crystal material and was oriented so that propagation occurred along the *X*-axis on a surface normal to the *Z*-axis. The transducers were formed on these surfaces by the usual photoetch process. The lower frequency transducers consisted of lines 12.5-μm wide on 25-μm centers while the higher frequency units had 4-μm-wide lines on 10-μm centers. In both cases, the lines were 2-mm long. A close-up view of a portion of the transducer pattern is shown in Fig. 4. In our experiments, we measured time delay and insertion loss of a signal consisting of an RF burst about 0.5 μs in duration. Both the input and output transducers were operated in a tuned and matched configuration.

The capacity of the transducers was tuned out at the operating frequency by means of a series inductor. This series-resonant combination presented a real impedance of a few ohms so that a large ratio impedance transformation had to be accomplished in order to effect a match to the 50-ohm coaxial input and output lines. No attempt was made to optimize the tuning-matching networks, so that some mismatch still existed.

Some typical results are shown in Fig. 5, an oscilloscope photograph of the input and output signals. The input signal (after a 20-dB reduction) is on the upper trace while the output signal (after about 20-dB amplification) is shown on the lower trace. The first signal on the lower trace is the direct, undelayed, RF feedthrough—the result of capacitive coupling between input and output transducers. The second signal is the delayed signal which has experienced conversion from electromagnetic to acoustic and back to electromagnetic form. The velocity of propagation obtained from the measurement of time delay is 2.7×10^5 cm/s on the basal plane of *ZnO*, in agreement with the value given by Tseng,[9] and 3.6×10^5 cm/sec for *Z*-cut, *X*-propagating $LiNbO_3$. The apparent bandwidth limitation in the photos is the result of the relatively high *Q* of the input and output circuits which in turn is indicative of a rather small radiation resistance which we expect for a 2-element transducer.

Most recently we have operated a delay device that employs multi-element transducers (Fig. 1) on a *Y*-cut, *Z*-oriented $LiNbO_3$ plate. The center frequency for this device is 425 MHz and the 3-dB bandwidth is about 5%. Total insertion loss at center frequency is 16 dB for 3 μs of time delay. In addition to the electromechanical conversion loss, this total includes propagation, ohmic and mismatch losses, and losses caused by the bidirectionality of the transducers, which radiate equal energy in both directions. The actual conversion loss is only a few dB, resulting in a very high conversion efficiency. This device is shown in Fig. 6. The package contains the input and output tuning-matching networks as well as the $LiNbO_3$ crystal. Although the present package is very compact, it is expected that a significant reduction in overall size can be easily achieved.

Important work on surface wave devices has also been performed at RCA Laboratories, Princeton and at M&SR,

Moorestown. At RCA Laboratories, Schnitzler has carried out an extensive theoretical-experimental investigation of the propagation of acoustic waves at the interface between a semi-infinite medium and a thin (compared to one-wavelength) layer.[10] Wen, Mayo and Schnitzler have demonstrated a surface wave delay device in which variation of time delay is accomplished by mechanical motion of one transducer.[11] Talamini at M&SR, in conjunction with RCA Laboratories personnel, has demonstrated pulse expansion and compression—both important radar signal processing techniques—by means of dispersive surface-wave transducers.[12] Leibowitz at the RCA Laboratories is presently investigating surface wave amplification techniques employing deposited piezoelectric and semiconducting films on a quartz substrate, bearing transducers formed by photoetch.[13]

ATL present and future efforts

We are experimenting at present with a device which is expected to operate at a frequency of 2.5 GHz. This device will use 10-element transducers on a $LiNbO_3$ substrate. The lines are 0.34-μm wide and are placed on 0.68-μm centers. These dimensions are beyond the capability of the usual photoetch process which uses optical exposure of a photoresist. The transducer patterns were formed in the photoresist by means of a scanning electron microscope. A photo of this pattern is shown in Fig. 7. The use of the electron microscope represents a significant advance in the state of the art of acoustic surface-wave devices and one which is necessary if the use of these devices is to be extended to the region beyond 1 GHz. Our 2.5-GHz delay device will be used in an experimental recirculating delay subsystem which in turn may be used in a frequency memory. Frequency-memory devices are important in electronic warfare applications.

As noted earlier, acoustic surface waves may be guided by means of metal strips or layers formed on the surface. Guidance occurs because the metal structures modify the surface wave velocity. The phenomenon will permit us to realize surface-wave devices such as directional couplers and power dividers. Since the size of these devices is usually determined by the wavelength of the propagating signal, and since the acoustic wavelengths are quite small—of the order of a few micrometers at 1 GHz—truly miniature devices are possible. One may envision matched filter applications in which a tapped delay line (conveniently realized in the form of a surface-wave device) feeds an array of couplers, with coupling coefficients adjusted to accomplish the desired weighting function.

An experiment now being conducted at Advanced Technology Laboratories will provide information about the parameters required for design of such devices as directonal couplers. A typical sample is shown in Fig. 8. There are three basic areas of concern in the construction of a surface wave guide device:

1) How does one make the transition from an acoustic beam many wavelengths wide into a waveguide which is only one-half wavelength wide?
2) What are the propagation characteristics; i.e., surface wave velocity and attenuation in the waveguides?
3) How does coupling from one waveguide into an adjacent waveguide depend on the separation between guides and the size of the coupling region?

It can be seen that the experiment depicted in Fig. 8 will shed light on all these areas.

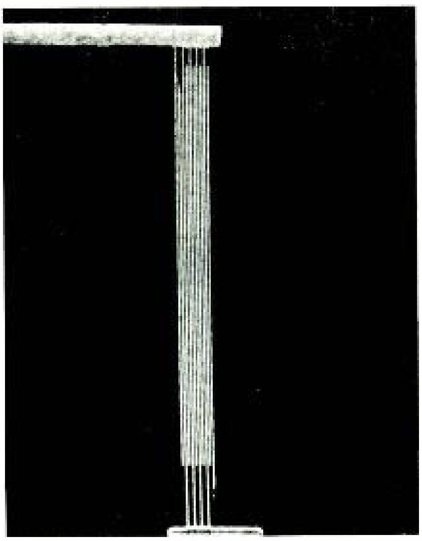

Fig. 7—Transducer pattern formed in photoresist by scanning electron microscope. The lines are 0.34 micron wide placed on 0.68 micron centers.

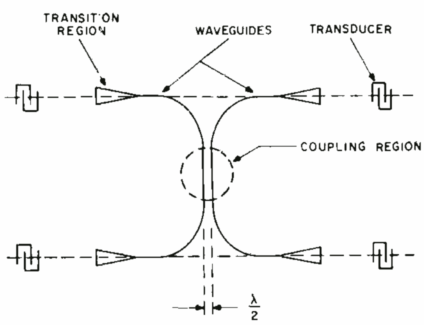

Fig. 8—Surface wave guiding and coupling experiment.

Conclusion

The acoustic surface-wave devices represent an important new area of technology for RCA. These compact devices may be used to perform many signal processing tasks—particularly those based upon delay lines and tapped delay lines—better than components now in use.

Acknowledgment

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References

1. Slobodnik, Jr., A. J., and Carr, P. H., "Microwave frequency acoustic surface waves," 1968 IEEE Ultrasonics Symposium, New York City.
2. Salzmann, E., Plieninger, T., and Dransfeld, K., "Attenuation of elastic surface waves in quartz at frequencies of 316 MHz and 1047 MHz," *Appl. Phys. Letters*, vol. 13 (July 1, 1968) p. 14.
3. White, R. M., "Direct piezoelectric coupling to surface elastic waves," *Appl. Phys. Letters*, vol. 7 (Dec 15, 1965) p. 316.
4. Coquin, G. A., and Tiersten, H. F., "Analysis of the excitation and detection of piezoelectric surface in quartz by means of surface electrodes," *J. Acoustical Soc. America*, vol. 41 (Apr 1967) p. 921.
5. Tseng, C. C., "Frequency response of an interdigital transducer for excitation of surface elastic waves," *IEEE Trans. on Electron Devices*, vol. ED-15, 586 (Aug 1968).
6. White, D. L., "Ultrasonic waveguide system for surface waves," 1967 Ultrasonics Symposium, Vancouver, B. C.
7. Collins, J. H., and Lakin, K. M., Announcement by Auld, B. A., 1968 IEEE Ultrasonics Symposium, New York City. (Also, see *Microwaves*, vol. 7, pp.14, 21 (Nov 1968) and *IEEE 1969 International Convention Digest*).
8. Mathews, H., "Nonreciprocal surface wave devices," *NEREM*, 1968, Boston, Mass.
9. Tseng, C. C., "Elastic surface waves on free surface and metallized surface of Cds, ZnO and PZT-4," *J. Appl. Phys.*, vol. 38 (Oct 1967) p. 4281.
10. Schnitzler, Paul, "Elastic surface wave velocities in a layered system of cadmium sulfide on germanium," *Appl. Phys. Letters*, vol. 11 (1967) p. 273.
11. Wen, C. P., Mayo, R. F., and Schnitzler, P., "Mechanically variable acoustic surface wave delay device," *J. Acoustical Soc. America*, vol. 41 (1967) p. 1372.
12. Talamini, A. J., M&SR, *private communication*.
13. Leibowitz, D., RCA Laboratories, *private communication*.

Diversity techniques and coding for troposcatter

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The protection of high-rate digital traffic over tropo links against "flat" Rayleigh fading, multipath distortion, and long bursts of errors due to interference has proven to be a difficult task. System requirements for lightweight and short setup time complicate the problem further. A combination of time diversity and multi-level frequency coding with phase modulation provides great relief for the situation. A scheme which has been termed the Tropomod 4-4 has been devised. The functional design of the modem has been completed by RCA with remarkable results. The goal is a 1 Mbps traffic in a 5- to 10-MHz band with an average bit error rate of 10^{-5} or better.

THE TROPOMOD 4-4 scheme has been conceived by RCA in an effort to meet the demand, particularly for tactical applications with a minimum of hardware complexity. Space diversity has been used successfully to achieve some of the tropo-link objectives but these achievements were partially offset by the need for additional antennas, receivers, and diversity combiners. Also, a longer setup time is needed for more than one antenna. The concept of an "in-band" frequency diversity is extremely attractive for tactical environments because of its potential ability to achieve performance equivalent to space diversity with only one antenna, one transmitter, and one receiver per site. Modulation, demodulation, and diversity combining functions are performed by a modem; thus size, weight, and setup time are reduced. The price that must be paid for the in-band frequency diversity is bandwidth, since diversity is obtained by transmitting information redundantly. A combination of FSK (frequency-shift keying) and DPSK (differential phase-shift keying) used in the TROPOMOD 4-4 scheme, reduces the bandwidth to the minimum.

Description

The TROPOMOD 4-4 scheme features a novel combination of proven techniques designed to overcome both natural and aircraft-produced fading of the tropo medium with a high grade of digital transmission capability, a high degree of flexibility, and a minimum bandwidth. A combination of FSK and DPSK is employed to provide orthogonal transmission of symbols.

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The FSK may be thought of as a frequency-time code, in which there are four possible in-band frequencies and four possible time slots. Every time slot is filled with one and only one frequency, so that the transmitted output appears as a frequency-shift-keyed CW signal.

Four mutually exclusive sequences are chosen for the transmission of the FSK, as follows:

$$f_1\ f_2\ f_3\ f_4$$
$$f_2\ f_4\ f_1\ f_3$$
$$f_3\ f_1\ f_4\ f_2$$
$$f_4\ f_3\ f_2\ f_1$$

Inspection will show that, once framing is achieved, the identity of any sequence can be established if any one of the frequencies is received, even if the other three have been lost due to fading. This is true because the location of each frequency in the frame is unique to the corresponding sequence.

Quaternary DPSK modulation is applied to each frequency pulse transmitted. Consider for the moment only f_1, which is being transmitted in successive frames. Although f_1 may appear in different time slots of each frame, its relative phase would remain constant from frame to frame in the absence of phase modulation. The quaternary DPSK modulation shifts this phase by 0°, 90°, 180°, or 270° from its relative position in the previous frame.

Each frequency is treated separately but in the same manner, so that if f_1 is shifted 90° from its previous phase, f_2 will also be shifted 90° from its previous phase, etc. The transmitted phase information can be received if only one frequency is present and three have faded.

The foregoing establishes 16 possible symbols formed by four possible sequences in combination with four possible phases. These sixteen symbols can carry 4 bits of information. Accordingly, the incoming data stream is arbitrarily divided into four-bit frames, each frame being comprised of 2 two-bit words. The first two-bit word is encoded into one of the four frequency sequences; the second two-bit word is encoded into one of the four possible phase shifts to be applied as quaternary DPSK.

Since both the FSK and DPSK information are transmitted with 4th order redundancy, the system has an intrinsic 4th order diversity capability. The degree to which this can be realized depends on how much bandwidth can be used to obtain uncorrelated signals.

Advantages

Diversity

TROPOMOD 4-4 has an intrinsic capability of 4th order diversity. An analysis has shown that in the situation where bandwidth is limited from 5 to 10 MHz, as is probably the case, most of the attainable diversity gain is achieved with a four-frequency system. Very little additional improvement can be obtained by squeezing more than four frequencies into the fixed band, since the behavior of the channels becomes increasingly correlated. This reasoning applies to any tropo system depending on the frequency diversity effect in a fixed bandwidth.

100% transmission efficiency

The TROPOMOD 4-4 has a transmission rate that is the same as the incoming data rate. No added bits are required for synchronization or other supervisory functions. The entire bandwidth utilization is expended in information transmission. Several modes of operation are possible at various bit rates, and various degrees of diversity can be traded off with bandwidth.

Response to fades and phase reversals

An extremely important consideration is the ability of the system to cope with rapid phase reversals and deep fades caused by the medium. Since transmission of information is accomplished by two modulation techniques, each is treated separately.

Detection of the sequence depends on equal-gain combining after amplitude detection of the individual frequencies. Deep fades will not cause errors unless all four frequencies fade simultaneously (diversity fails). Phase reversals do not affect the amplitude detection. In addition to the two information bits per frame, timing is extracted from the sequence detection.

Detection of DPSK is accomplished in a pseudo-coherent manner by comparing the received phase of each symbol with that of the corresponding symbol in the previous frame. The detection does not depend on maintaining a long-term phase-coherent local oscillator. For this reason, a phase reversal in the medium may cause a single bit error, but would not produce a burst of errors during the time required for a local oscillator to recover its reference phase position. Even the single bit error may not occur, since the phase decision is based on equal gain combining of phase information from four in-phase and four quadrature signals.

The system is open loop and does not require a sequence of actions such as instruction, acknowledgement, and execution before information transmission can begin.

Timing is, of course, required. Since this depends only on amplitude detection, it enjoys the advantage of diversity reception, and can readily be made immune to momentary loss of signal by locking a local timing source to the received timing, this function can be expected to operate reliably in

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received the BSEE from Worcester Polytechnic Institute in 1944 and later completed several graduate-level courses at Drexel in 1954-1956. He started his engineering career in the Transmitter Design group in 1946 after serving two years in the Signal Corps. His early experience was concentrated in design of various medium-power UHF transmitters for FM, data link, and TV service, as well as a high accuracy Loran receiver. As group leader he has been responsible for design of high power UHF transmitters, including a 20 KW exciter for BMEWS, and several Tropo Scatter transmitters. He has subsequently worked on RADAS, Minuteman Data Processing, LEM, Minuteman TAPS, and a digital frequency synthesizer for modern multipurpose airborne communications radios. He is currently engaged in advanced technique development in microwave components and data modems. Mr. Allen is a Senior Member of IEEE and a registered Professional Engineer in New Jersey. He holds a patent on a Loran Receiver circuit.

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was graduated from the University of Kaunas, Lithuania in 1943 with the BS and from the University of Pennsylvania in 1954 with the MA; he also did additional graduate work in Electrical Engineering and Math. at the University of Maryland and the University of Pennsylvania. He joined RCA's Communications Systems Division in 1961 and began work on passive satellite communications studies. Later, his assignments included satellite and tropo systems analysis, electrical and optical correlation techniques, antijam techniques, analog and digital modulation, and filtering methods. Prior to his RCA employment, he was a Project Engineer on communications systems and performed airborne weapons system analysis and airborne radar performance analysis at Westinghouse. From 1943 to 1949, he taught mathematics and physics at European secondary schools. Mr. Volertas is a member of the Institute of Electrical and Electronics Engineers and the American Mathematical Society.

any environment in which usable data can be transmitted.

It is recognized that different operational requirements may exist within the framework of a given tactical environment. Although the prime objective of the Tropomod 4-4 is to approach 4th-order diversity transmission at 1.152 Mbps data-transmission rate for path lengths up to approximately 100 miles, the equipment design can incorporate several other modes of operation. The degree of diversity and bit rate may be traded off with transmission bandwidth.

The Tropomod 4-4 modem

The modem is designed to interface with existing tropo transmitters and receivers through a standard 70-MHz modulator output and demodulator input. Other interfaces include receiver AGC, data, and timing inputs and outputs.

The modulator block diagram is shown in Fig. 1. Incoming data is shifted through the four-bit input register, and a parallel read out of the register is initiated. The readout of the first two bits is fed to the frequency sequence encoder. The frequency sequence encoder has four timing inputs and four control outputs. The timing inputs each have pulses of one bit duration at one-fourth the incoming bit rate, and the outputs occur in a continuous, fixed sequence. The sequence in which timing appears on the output lines depends on the incoming data.

In a similar manner, the second two bits in the input register control four outputs of the phase encoder. Here, however, logic is provided to chose absolute phase in such a way that the output is differentially phase shifted. In this case, the length of the pulse on each control line is one frame, or four bit periods.

The gating matrix selects two of the eight outputs for each symbol to be transmitted. These two are always the quadrature components of the same frequency for a given symbol. The outputs are modulated with quadrature components of a 70-MHz local oscillator and are summed in the SSB Generator and Frequency Translator. This process generates a single-sideband signal whose frequency is 70 MHz plus or minus the modulating frequency. The composite 70-MHz signal output has the desired constant envelope, with frequency shift keying and with DPSK of each frequency.

Timing of the modulator can be self generated, or can be extracted from a timing input or from the data. A local oscillator maintains stability. Framing and other timing signals are generated based on the bit timing.

The demodulation process is comprised of the following major steps:

1) Frame pulse detection,
2) Frame and bit timing synchronization,
3) Sequence detection,
4) Phase detection, and
5) Data readout.

The demodulator block diagram is shown in Fig. 2. The 70-MHz input from the receiver is routed to a bank of four filters and detectors. Each filter is tuned to one of the four FSK frequencies. Each time the incoming carrier is keyed to one of these four frequencies, a pulse will appear at the corresponding detector output.

The sequence detector utilizes four delay lines and four summing networks to obtain a correlated output for each of the four valid sequences.

Each valid sequence is treated in a like manner, so that one of the sequence detector outputs will contain a pulse each frame. The four outputs drive a maximum decider circuit in the Framing and Bit Timing unit. This circuit generates a received frame pulse which is used to lock a stable local oscillator. The latter provides frame and bit timing to all the circuits of the demodulator and to the external devices which are to be driven by the demodulator output data.

In addition to frame and bit timing, the sequence detector outputs drive the sequence decoder, which converts the information into a form that can be read into the first two bits of the output register each frame.

Sequence decoding is required to establish which time slot should be examined for phase information for each frequency in each frame. This is indicated in the block diagram of Fig. 2 by the connection between the sequence decoder and each of the phase detectors.

Examination will show that operation of the phase detector will provide differential phase shift demodulation without the necessity for long term stability of phase of the local oscillator. All that is required is that the phase drift be small compared to 90° over a two-frame interval.

The sine and cosine outputs of differential phase so detected are summed with similar contributions from detection of f_2, f_3, and f_4 phase. Each output will be plus, minus, or zero. When one output is plus or minus, the other is zero. These two signals are decoded to form the last two bits of each frame,

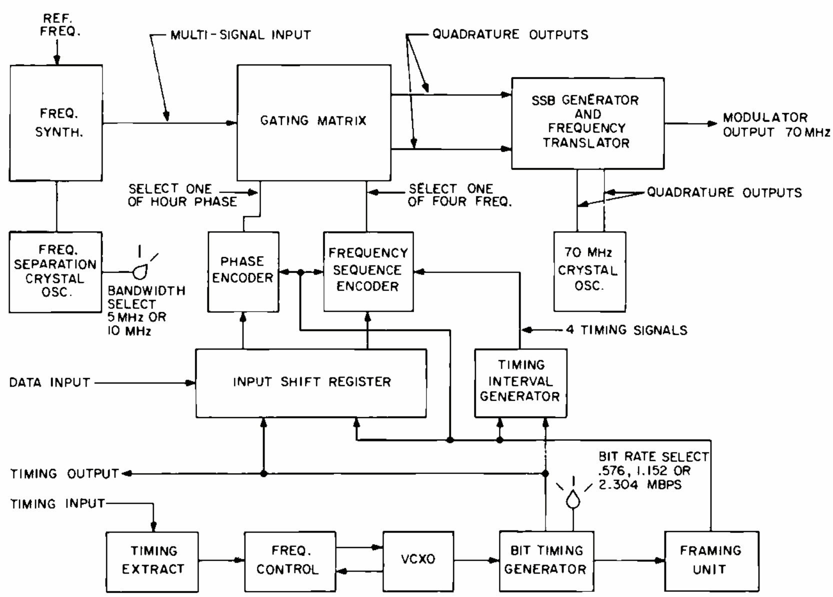

Fig. 1—Modulator block diagram.

and are read into the appropriate stages of the output register. The data is then shifted out serially.

Analysis of functional design

To establish the best implementation, the intersymbol interference as a function of received signal-to-noise ratio and the multipath effects were examined in detail.

The analysis of intersymbol interference predicts levels of error rate for various conditions which are a function of the mode chosen (bit rate, frequency spacing, etc.). Frequency spacings may be chosen so that the information spectrum about each of the frequency "channels" is either overlapping, or essentially non-overlapping. Error rates for modes where the channel spectrums are non-overlapping are quite acceptable. If overlapping spectra is implemented, error rates may be marginal for data transmission, but would probably be acceptable for digitized voice. If overlapping spectra does give adequate performance for some modes and some transmission paths, its use is attractive in terms of bandwidth required. Experimental measurements are needed to establish the final decision as to what modes should be selectable.

Multi-path effects will result in intersymbol interference unless some guard time is provided. As a result of investigation it was decided to allow approximately 100 nsec guard time. This is to be implemented in the receiver integrate and dump circuits. Transmission will remain as a CW type of signal.

If guard time were not required, some advantage in spectrum width could be obtained by making the switching among frequency channels phase coherent within the frame (4 bit periods). However, it is considered far more important to provide the protection against multipath afforded by guard time, than to obtain the small advantage of phase-coherent switching. In any event, phase coherence would not be maintained from frame to frame because of the DPSK modulation.

The addition of guard time requires that the frequency spacings be slightly increased in order to maintain orthogonality, which is needed to minimize intersymbol interference. This is accomplished by making the integrate time an exact multiple of the number of cycles appearing at the integrator input from adjacent channels. The integral of these signals is, therefore, zero.

Optimum phase detection of the received signals requires true multipliers (analog signal *A* times analog signal *B*). However, some difficulties might be experienced in building multipliers for use at high rates. Therefore, an analysis was done of the relative system performance with the multipliers replaced by a hard-limiting amplifier and balanced modulators. The degradation in performance was found to be small, and because of the relative ease of implementation, the decision was made to use limiting and balanced modulators.

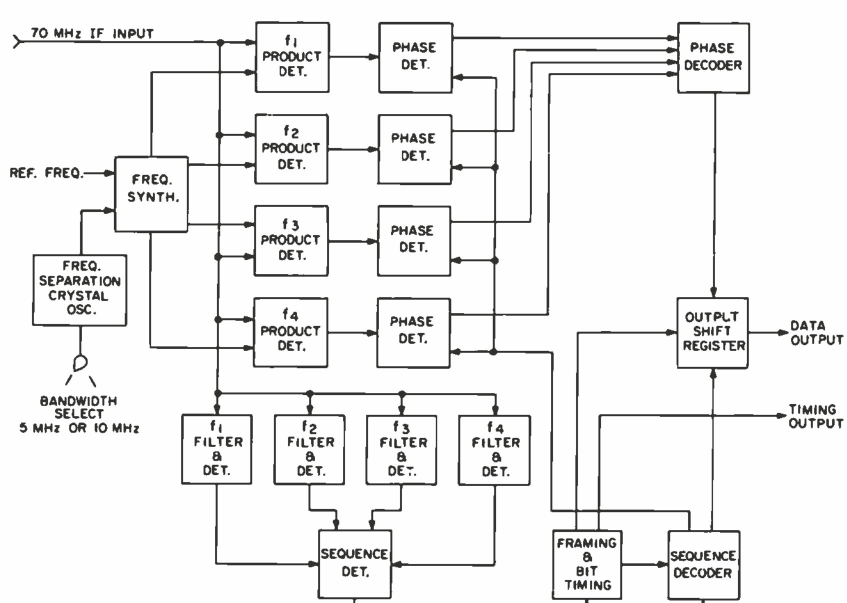

Fig. 2—Demodulator block diagram.

The initial approach to design of the frequency synthesizer utilized a phasing method to generate SSB outputs. Each sideband corresponded to one of the frequency channels. The method contemplated switching at baseband with direct mixing to IF of quadrature signals. At the IF output, the sideband chosen would depend on the phase of the baseband signals switched into the mixers.

With the dismissal of phase-coherent keying as a requirement, a much more straightforward synthesis approach has been adopted. One oscillator with associated digital dividers and enabling gates provides all frequencies required to establish several selectable frequency spacings. A second oscillator provides the basic IF center frequency. These signals are modulated in balanced mixers and the sidebands (corresponding to the frequency channels) are separated with upper and lower sideband filters. This method provides considerable flexibility for coarse or fine adjustments of the frequency spacings. This will be needed to evaluate the optimum performance for various Tropo paths.

Sequence information may be extracted either from the integrate and dump circuits of the phase detector or by AM detection after channel filtering. If the system achieved perfect framing and ideal operation of the matched filters (integrate and dump circuits), a slight advantage in performance could be obtained by extracting sequence information from these circuits. Since the ideal conditions cannot be expected to prevail in a practical implementation, and because a considerable simplification of circuitry is realized, the use of filters and AM detection is the currently favored approach to sequence detection.

Status of development

Functional design of the modem has been completed. Key circuits of the modulator have been breadboarded for evaluation, and the digital portion of the modulator has been constructed. Work is continuing toward completion of the Modem design and construction.

High power L-band avalanche diodes and their applications

K. K. N. Chang | H. J. Prager

Based on results of several experiments, "anomalous" avalanche diodes are excellent possibilities for high-power pulsed microwave sources in the 200 to 1500-MHz frequency range. This paper describes the anomalous high-power, high-efficiency avalanche diodes and the experimental results obtained with them and discusses briefly the device application in radar.

In the past decade, two solid-state devices—the tunnel diode and transistor—have found application in microwave power-generating systems because of their small size, modest voltage requirements and long life. The powers involved are, however, limited to a few watts. Besides, they are mainly cw devices.

For pulse applications, electron tubes have remained supreme because of their huge power handling capacity. During the last few years, two new solid-state devices—the Gunn diode and the avalanche diode—have been developed which yield results in power generation that begin to challenge the electron tube in several applications. To date, these two devices can generate about 100 times the power of cw tunnel diodes or transistors. The avalanche diode is particularly interesting because it is usually constructed of silicon, a material for which the technology is very well advanced.

The silicon avalanche diode has become even more interesting with the discovery at RCA Laboratories of an "anomalous" mode diode that is capable of generating pulse powers of hundreds of watts at over 25% efficiency. While the work on this diode is still in what might be considered an exploratory phase, hundreds of diodes have already been built and tested in a variety of circuits. Among these diodes, many have achieved efficiencies exceeding 40%, and two have accumulated thousands of hours of continuous life test. Both the efficiency and the long life are vitally important for applications requiring high peak power.

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Microwave oscillations in silicon avalanche diodes

Semiconductors are known to exhibit breakdown in the presence of high electrical field. Such fields may be reached in a reverse biased P-N junction diode. The work of McKay[1] in 1954, first experimentally established an ionization rate for silicon diodes at breakdown as a function of the electrical field.

Based on the experimental data on electron-hole-pair generation, Read[2] proposed a N^+PIP^+ structure and predicted microwave oscillation in such a diode. The model is straight-forward. A $\pi/2$ radian phase shift occurs between the electrical field and the carrier current during ionization and another $\pi/2$ radian shift results from the transit-time effect of the moving carriers through a properly designed I region of the diode. The total shift by π radians leads to a negative resistance which is responsible for the microwave oscillation. In spite of the analytically derived prediction such an oscillation did not materialize until a similar transit-time oscillation was found in an avalanching P^+NN^+ diode.[3] Since then many IMPATT avalanche transit-time diodes have been developed at X-band or higher frequencies. These diodes give, typically, cw power outputs of less than a watt at efficiencies of a few percent. Practically no diodes were available for the lower-frequency range of UHF and L-band.

A new mode of operation of avalanche diodes

In 1967, Prager, Chang, and Weisbrod of RCA Laboratories discovered a new mode[4] of operation that dramatically deviated from the IMPATT mode and opened up the possibility of high power at efficiencies in the lower-frequency range. To obtain such lower-frequency operation, the conventional avalanche diode was modified in its doping profiles and physical junction dimensions. In the course of this work, we procured from RCA Electronic Components Division at Somerville some experimental varactor diodes [H. Kressel designed the varactor diode and A. Pikor developed the process specifications.] which were similar to our avalanche-diode design. One of these diodes gave 280 watts peak power at 1.05 GHz with an efficiency of 43%. Other diodes from the batch gave frequencies ranging from 425 to 1400 MHz, peak powers from 150 to 435 watts, and efficiencies from 25% to 40%. Since that time, several hundred of these diodes have been made at RCA Laboratories. A summary of selected data on such diodes is given in Table I.

Table 1—Selected data on anomalous avalanche diodes.

P_o (watts)	Eff. (%)	Freq. (MHz)
435	22	425
280	22.5	425
200	25	420
420	32.5	1050
280	43	1050
177	59	820
180	60	775

Subsequent to our observation of this new mode of operation, Johnston, Scharfetter and Bartelink[5] observed it at 40% efficiency in germanium avalanche diode oscillators. More recently, Snapp, Hoefflinger[6], Grace and Gibbons[7] have also achieved this mode with silicon diodes.

Diode fabrication

The anomalous diode is a P^+NN^+ structure where the N-region has a resistivity of about 5 ohms/cm. The depletion layer sweeps across the N-region and the diode "punches through" before reaching the point of avalanche breakdown. Typically, the N-region is 8 to 10 microns wide with a breakdown voltage of 160 V at a punch-through voltage of 75 V. The P^+ region of the mesa diode is obtained through a boron deposition and diffusion upon the N-layer. The diffused P^+N junction is of a nearly-abrupt type.

An important step in diode processing

is to produce the mesas by photoresist masking and chemical etching. [More recently, we have had the help of J. Assour who processed several wafers with his facilities.] An array of mesa diodes before dicing is shown in Fig. 1. Diced diodes are mounted in standard "varactor packages" as shown in Fig. 2.

Circuit design

A tunable coaxial cavity (Fig. 3) was chosen as one of the first circuits used for our tests. This circuit has the advantage of a wide tuning range. Diodes operated in this circuit were usually found to exhibit AM noise for the duration of the RF pulse. The noise could sometimes be minimized by proper adjustment of a stub tuner.

In addition to the coaxial cavity, the G-R coaxial line, stripline, and lumped circuit have also been attempted and they all function with proper adjustment. A very simple and yet very successful circuit is the combined coaxial-lumped circuit[8] (Fig. 4) which produced a pulse power output of 180 watts at 1.3 GHz with an efficiency of 40%. The circuit has a movable short-circuit and a tunable capacitor for impedance matching. Continuous frequency tuning from 1.0 GHz to 1.7 GHz with a variation in power output of less than 1 dB has been obtained by adjusting the settings of the short circuit and capacitor.

Performance evaluation

Risetime

Fig. 5 shows oscilloscope tracings of pulse voltage, pulse current, and RF power output when the diode is in an oscillating condition. Trace B shows a typical pulse voltage. One observes first a very steep rise to the reverse breakdown voltage of the diode and then, after a few hundred nanoseconds, an abrupt decrease to a lower level. Trace A shows the pulse current which rises gradually to a certain level until a sharp increase occurs, simultaneously with the sharp decrease in the pulse voltage. When the pulse current has reached the level where it shows the sharp increase, an RF power output can be observed as shown in trace D. (Trace C is a repetition of A). When the circuit is detuned, the steep changes in the voltage and current pulse disappear as does the power output.

The RF pulse risetime is dependent to a large extent on the circuit and to a lesser extent on the particular diode. Good risetimes were obtained with both cavity and lumped circuits. Well-fabricated diodes, operated in a properly-tuned circuit, exhibit a typical rise-time between 50 nsec and 100 nsec. Fig. 6 shows the RF pulse shape and the DC current pulse. The corresponding output spectrum is shown in Fig. 7.

Delay time

The delay time (i.e., time from start of current pulse to onset of RF oscillation) appears to be almost entirely a function of the pulser and the bias network used to drive the device. With the pulsers and biasing schemes used during these experiments, the measured delay times ranged from 50 nsec to 200 nsec.

Variations with temperature

A check of the variation of diode per-

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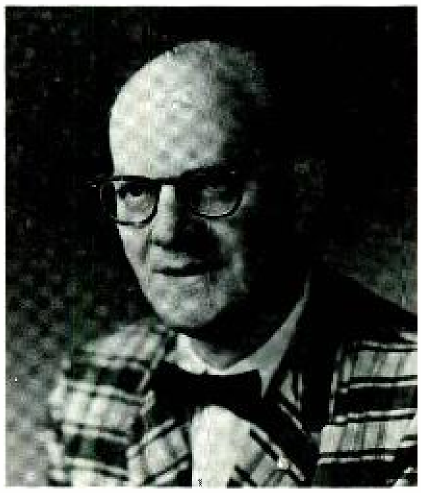
received the BS from National Central University Chunking-Nanking, China, in 1940, the MSEE from the University of Michigan in 1948, and the PhD from the Polytechnic Institute of Brooklyn in 1954. From 1940 to 1945, he was associated with the Central Radio Manufacturing Works, Kumming, China, working on radio receivers; and from 1945 to 1947, he was a radio instructor in the Office of Strategic Services, U.S. Army, China Theatre. Since 1948, Dr. Chang has been a member of the technical staff at RCA Laboratories, Princeton, New Jersey. He has been engaged in research on magnetrons, traveling-wave tubes, beam-focusing devices, parametric ampliers, tunnel-diode devices, solid-state bulk-effect devices, and IR devices. In 1953 he did original work on periodic field focusing for traveling-wave tubes, which has culminated in an RCA commercial line of TWT's. In 1957 he was one of the pioneers who explored the principle of parametric amplifier and converter. Presently, his field of interest is superconducting, semiconductor amplifiers and oscillators. Dr. Chang is the author of fifty original technical papers and holds thirty patents in the field of microwave tubes and solid-state devices. He is the author of the book *Parametric and Tunnel Diodes*, Prentice-Hall, Inc. He was the recipient of 1956 and 1960 RCA Achievement Awards for outstanding theoretical and experimental research on electron-beam focusing and on parametric and tunnel diode devices. He was also the 1964 achievement award winner of the Chinese Institute of Engineers, New York, Inc. for his outstanding contribution in the field of electron devices. In 1967, he received one of the David Sarnoff Outstanding Achievement Awards in Science for "original contribution to the basic understandng of microwave phenomena and the invention and development of superior microwave components." Also in 1967, he was appointed a Fellow of the RCA Laboratories. He is a member of Sigma Xi and has been selected for listing in the "American Men of Science."



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received the BSEE from the University of Vienna, Austria in 1938, and the MSEE from the University of Michigan, Ann Arbor, in 1940. From 1940 to 1942 he was associated with the Research Laboratory of the Detroit Edison Co., Detroit, Michigan. In 1943 he joined the Electron Tube Division of RCA in Harrison, New Jersey as a production engineer of small power and receiving tubes. In 1944 he transferred to the Receiving Tube Development Group where he worked as Design Engineer, Technical Coordinator, and Unit Leader until 1959. His assignments during that time included the design of several entertainment-type receiving tubes, as well as premium industrial tubes, gas-filled tubes and UHF pencil tubes. From 1954 until 1959 he served as a member of the JETEC-12 Committee, and was an Evening Instructor at the Newark College of Engineering, Newark, New Jersey. In 1959 he became a Member of the Technical Staff at RCA Laboratories, Princeton, New Jersey assigned to the Microwave Research Laboratory. He has since been engaged in various duties on microwave semiconductor devices, such as varactors, tunnel diodes, Hall effect devices, solid state optical devices and avalanche diodes. In 1960 he was co-recipient of an RCA Achievement Award for team work on research leading to the first tunnel diode amplifier and down-converter. In 1967 he was again presented with an RCA Laboratories Achievement Award for outstanding team performance "in the development of greatly improved avalanche-diode oscillators". Mr. Prager is a member of the IEEE.

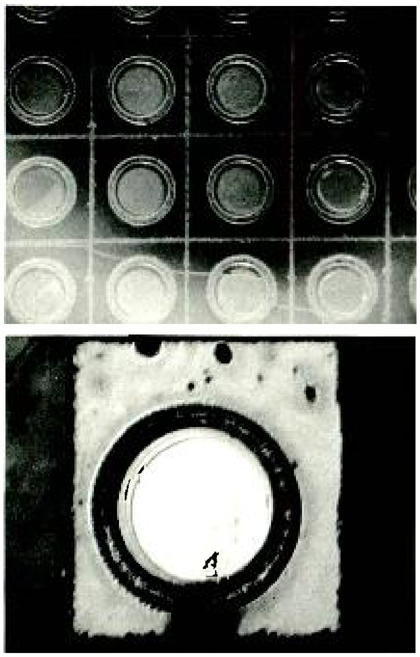

Fig. 1—Arrays of mesa diodes (top) under 16x magnification; and a single diode (bottom) under 50x magnification.

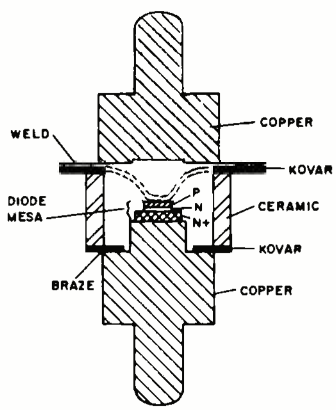

Fig. 2—Avalanche diode package.

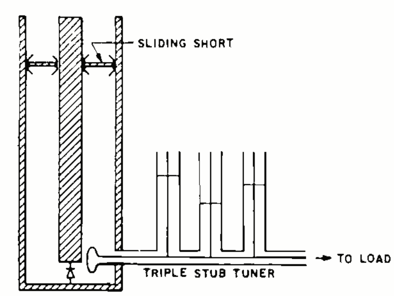

Fig. 3—Coaxial cavity with loop coupling.

formance with temperature showed that only the diode breakdown voltage was significantly affected. The tests covered the temperature range from −61°C to 150°C. The change in the breakdown voltage, E_B, followed the expected theoretical variation given by,

$$E_B(T)=E_B(T_o)[1+\beta(T-T_o)]$$

where $\beta=4.4\times10^{-4}$/°C.

When the pulse voltage was changed to allow for the change in the breakdown voltage, the power was found to vary less than 1 dB over this temperature range. The frequency change over this range was approximately 2 MHz. (The operating frequency was 760 MHz).

The peak transient temperature rise of the diode, due to the energy of the individual pulse rather than the average dissipated power, depends on the thermal constant and on the thermal resistance and capacitance of the diode structure. With this in mind we have briefly investigated the potential application of the anomalous avalanche diode as a solid-state transmitter for the AIMS AN/APX-70 type of transponder. Such an application requires high-power pulse bursts in a variety of coded patterns, with duty factors of up to 50% for short periods of time. In a simulated transponder test we operated these diodes with up to 56-pulse bursts, each 1 microsecond in duration and spaced 1½ microseconds. Fig. 8 shows the first 14 of these pulses; both the RF output power (of about 50 watts) and the corresponding current pulse are recorded.

Power supply variations

Once the bias current and the circuit are adjusted for an optimum output at a particular frequency, small variations in bias current will not cause a severe shift in frequency. The power output, however, has a more critical dependence on current level. Tests on a typical diode operating at 1.055 GHz, showed that a 20% change in the bias current caused only a 0.2% change in frequency, whereas the power changed by 47%. Although there are variations from diode to diode, these numbers are typical of diodes to date and represent the type of variations usually encountered.

Power and efficiency

We have observed two distinct regimes with respect to power and efficiency. Diodes with abrupt junctions tend to give the largest output powers and highest efficiencies. Graded junctions, on the other hand, yield lower power and efficiency but are much less susceptible to burn out. It is extremely difficult to strike the delicate balance between a junction which is sufficiently abrupt to yield high powers but not so abrupt as to cause it to burn out at low current levels. Typical output power for the abrupt junctions which were successful was in the range of 100 to 400 watts. Efficiencies for these diodes ranged from 22 to 60%. For the graded junctions, typical power levels were 20 to 150 watts at efficiencies ranging from 15 to 45%.

To realize high powers, series and parallel operations of diodes have been attempted.[8] A four-stacked series unit has produced 500 W at 1.14 GHz with an efficiency of 25%, while a single diode gives about 125 W with approximately the same efficiency. A parallel unit has also yielded similar results.

Reliability

Two diodes were placed on life test in September, 1967. One diode started at an output of 172 watts with 50% efficiency at a frequency of 740 MHz. The other diode started at 90 watts with 15% efficiency at 1020 MHz. As of March 12, these diodes had accumulated 12,200 and 12,400 hours, respectively, without degradation in power output or change in frequency. The duty cycles are 0.04% and 0.02% respectively.

Recently another life test was added to evaluate the diodes at a higher duty factor. The diode is operated at an output power of 90 watts, an efficiency of 21% at 1040 MHz, and with a duty

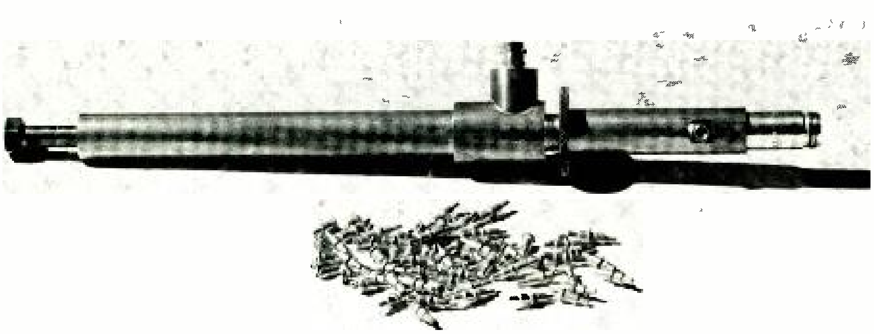

Fig. 4—Coaxial lumped circuit.

a)

b)

c)

d)

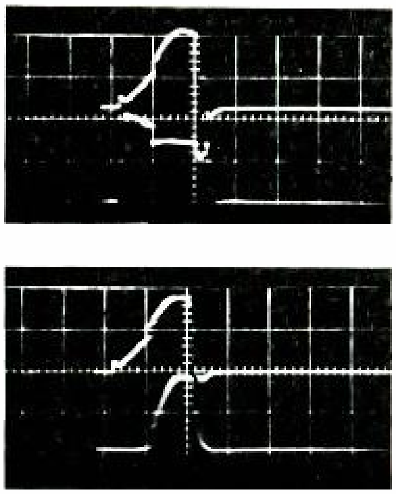

Fig. 5a—Pulse current at 5 amperes/division; b) Pulse voltage at 100 volts/division; c) same as a); and d) RF output power at 150 watts/division. Horizontal time scale for all four tracings is 0.5μs/division.

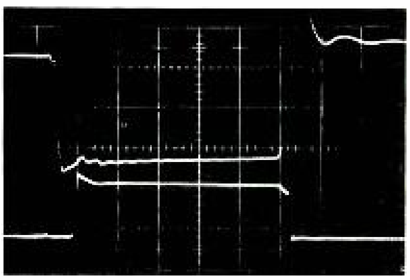

Fig. 6—Top, pulse current at 1 ampere/division; bottom, RF output power at 50 watts/division. Horizontal time scale is 100 ns/division.

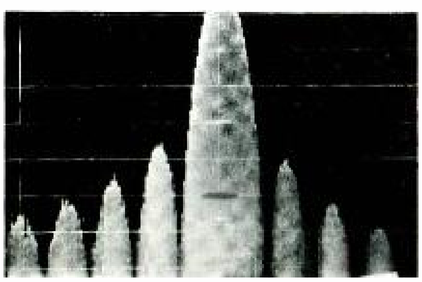

Fig. 7—Output spectrum.

factor of 0.5%. So far, 3140 hours have elapsed without failure.

Sample application

Encouraged by these preliminary results, the RCA Laboratories in collaboration with the RCA Missile and Surface Radar Division set up an experiment to demonstrate the feasibility of avalanche diodes in radar applications. The outcome was so successful that it became one of the featured attractions at the "Open House Exhibit" of the 25th Anniversary of RCA Laboratories in October 1967. In this experiment a medium-range search radar (AN/UPS-1A) was retrofitted by replacing the magnetron (QK 358) of

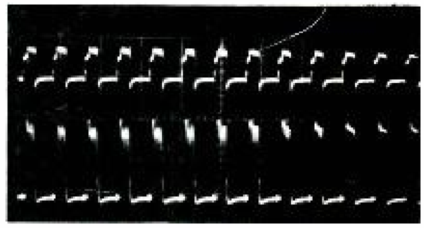

Fig. 8—Multiple pulse bursts: top, pulse current at 5 amperes/division; bottom, RF output power at 150 watts/division. Horizontal time scale is 2 μs/division.

the transmitting unit with a single "anomalous" avalanche diode. The diode was mounted in a mechanically tunable coaxial cavity, which had a frequency range from 1250 to 1350 MHz. The pulse width was 1 microsecond and the repetition rate 800 pulses per second. The peak power under these conditions was held to about 100 watts—a conservative value. Using the regular antenna and receiver of the radar set, this output was sufficient to cover a normal operational range of at least 15 miles radius. The PPI displayed a clear picture of stationary objects and moving aircraft within this range. Fig. 9 shows the detail of the diode-cavity with a triple-stub tuner, and some of the accessory equipment.

Amplifier

Preliminary experiments have also been performed on the possible applications of the high-efficiency diodes in amplifiers. During the course of these experiments, we have observed phase locking, a phenomenon that in itself has several possible applications.

One of the observations was made with a diode yielding 25 watts of peak pulse power at a frequency of 1090 MHz. A locking signal that was pulsed on in synchronization with the diode oscillator was injected through a circulator, and the resultant signal observed on a spectrum analyzer. Results thus far obtained show a locking range of 10 MHz at a center frequency of 1090 MHz, with a locking gain of 10 dB.

In another amplifier mode of operation, which is still under study, a power gain of 10 dB at an output level of 30 watts at UHF has been observed. The amplifier is found to be linear up to 20 watts. At low levels, however, the output contains broadband noise and is extremely noisy. One of the more interesting findings is that no

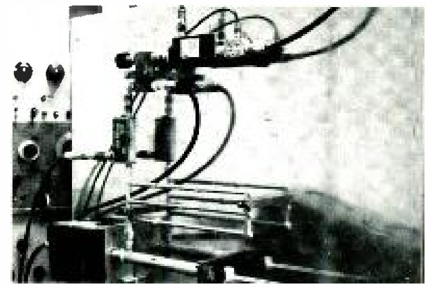

Fig. 9—Detail of radar set with diode cavity.

measurable harmonics or subharmonics have been noticed.

Conclusions

The experimental results already achieved show that the anomalous avalanche diode has excellent potential as a high-power pulsed microwave source for operation from 200 to 1500 MHz. A considerable amount of information has been obtained about the circuit requirements of these diode oscillators. However, further research, particularly to reach full understanding of the mode of operation, is needed to achieve the full potential of the diode, and this research is being vigorously pursued.

Acknowledgement

A. S. Clorfeine, R. J. Ikola, P. Levine, and S. G. Liu ably assisted by R. D. Hughes, J. J. Risko and S. Weisbrod have all participated in the experimental work reported here. Special credit is due to M. Breese, B. Hamman, J. Kiss and P. Ray of the Missile and Surface Radar Division, Moorestown, New Jersey for their help in realizing the retrofit of the AN/UPS-1A radar set.

References

1. McKay, K. G., "Avalanche Breakdown in Silicon," *Phys. Rev.* 94, 877 (1954).
2. Read, T., "Proposed High-Frequency Negative Resistance Diode," *BSTJ*, 37, 401 (1958).
3. Johnston, R. L., DeLoach, Jr., B. C., and Cohen, B. G., "Silicon Diode Microwave Oscillator," *BSTJ*, pp. 369-372, (1965).
4. Prager, H. J., Chang, K. K. N., and Weisbrod, S., "High-Power, High-Efficiency Silicon Avalanche Diodes at Ultra High-frequencies," *Proc. of IEEE*, p. 586 April 1967.
5. Johnston, R. L., Scharfetter, D. L., and Bartelink, D. J., "High-efficiency Oscillators Ingermanium Avalanche Diodes Below Transit-time Frequency," *Proc. of IEEE*, p. 1611 October 1968.
6. Snapp, C. P. and Hoefflinger, B., "An Efficient Multriesonant Avalanche Diode Oscillator in the 1.5 to 11 gHz Range," Proc. IEEE (Letters) Vol. 56, p. 2054, November 1968.
7. Grace, M. I. and Gibbons, G., "High-efficiency Microwave Oscillations from Si Avalanche Diodes," *Electronic Letters*, Vol. 4, No. 25 p. 564, December 1968.
8. Liu, S. G. and Risko, J. J., "Tunable L-Band High-Power Avalanche Diode Oscillator," IEEE Solid-State Circuit Conference, *Conference Digest* 12, p. 84 (1969).

Advances in Nb_3Sn superconductors and their applications

E. R. Schrader | H. C. Schindler | F. R. Nyman

The requirement that superconductors operate at a temperature near absolute zero introduces a composite of design and operational techniques which are unique and for which the RCA Superconductive Operations Department is geared. This three-part paper reviews the properties of superconductors, the design and fabrication of RCA superconductive ribbon, and the practical considerations in the design of superconductor magnets.

Superconductive technology has entered a phase in which it is challenging the design of electromagnetic devices using conventional conductors. Superconductors offer the unique capability of conducting current with insignificant power loss. High-field magnets for research applications are now almost exclusively fabricated with superconductors,[1] and much effort is being directed toward introducing the technology into more sophisticated high-energy-physics devices.

Properties of superconductors

Idealized superconductors have been extensively discussed in the literature and can be described by a three-dimensional graph of magnetic field, critical current, and temperature. Fig. 1 shows the phase boundary of a typical superconductor. Within the boundaries, the material exhibits superconductivity; outside the boundaries, the material exhibits normal conduction. All superconductors exhibit this type of characteristic behavior, but the coordinate intercepts—H_{co}, I_{co}, T_{co}—vary over wide ranges for specific superconductors. For superconductors used in high-field devices, the axial intercepts are necessarily very high.

For a superconductor to have reasonable current-carrying ability in a high-field device, the critical fields and currents must be high. The values for the four most important high-field superconductors are given in Table I[2-4]. These values and the resulting critical currents vary somewhat depending on the relative amounts of the constituent metals and the means of preparation.

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At the present time, niobium-tin and niobium-titanium are the only materials used to any extent in commercial devices. Niobium-zirconium, the first "practical" high-field superconductor, has gradually disappeared from commercial use and has been replaced by niobium-titanium and niobium-tin. Vanadium-gallium is presently under developmental evaluation.

Low-field instability

A limitation of superconductors that has prevented their practical application has been a form of instability that occurs in the presence of magnetic fields and causes degradation of the critical characteristics.[5] The instability occurs while the field is going through a change. Any conductor that is subject to a changing magnetic field has currents induced in it which tend to form an opposing field. This phenomenon occurs in superconductors, as well as in normal conductors such as copper. The induced currents in copper continually decay as a result of dissipation through the intrinsic resistance. In a superconductor, the induced currents do not of themselves dissipate because the superconductor has zero resistance. These induced currents, called shielding or magnetization currents, are contiguous to the immediate conductor and no externally completed circuit is necessary for their existence. Therefore, any device containing a superconductor which is under the influence of a magnetic field is subject to the presence of these shielding currents.

In a device such as a superconductive solenoid, the useful magnetic field in the bore results from the regular transport current in the turns caused by an applied potential at the magnet terminals. However, as the transport current is increased, magnetic fields are generated throughout the volume of the solenoid windings as well as in the bore. There is, then, in each superconductive turn a useful transport current plus a multitude of locally induced shielding currents which act to keep the changing magnetic field from penetrating the body of the superconductor.

As the result of the rapid buildup and sudden breakdown of these shielding currents as they exceed the critical surface (Fig. 1) in a superconductor exposed to changing magnetic flux, the flux penetrates in discrete bundles causing "flux jumps". These perturbations can be picked up as a noise-like pattern of voltage spikes appearing throughout a magnet while subject to a changing field. As with a normal conductor, the magnitude of shielding currents in the superconductor depends on the geometry of the conductor as well as its inherent current-carrying and heat-dissipating capabilities. The quantitative details of the buildup and breakdown of these shielding currents are not fully understood, but the end result is a local, finite dissipation of energy in the form of heat. There is little doubt that this mechanism is responsible for the premature normalcy of superconductive devices, referred to earlier as device degradation[6,7,8].

The overall result of having unstable currents is that less than the maximum operating current is attained in the superconductor. Essentially combinations of two principles are used to control the amount of device degradation caused by induced shielding currents. In one approach, a conventional conductor, such as silver or copper, is intimately bonded to the superconductor (i.e., by plating or cladding). The normal metal electrically parallels the superconductor and is capable of carrying the transport (operating) current when a local superconductor goes prematurely normal for any reason. In the second approach, the triggering mechanism which initiates shielding-current breakdown is minimized by conductor design until an acceptably high current density is obtained in the superconductor windings.[9] Although the first method results in a very stable mode of operation, the presence of the required amount of normal metal and space for optimum cooling decreases the effective cross-sectional area of the superconductor and thus reduces the current density, sometimes below a useful level. Use of the second approach, with far less normal metal, provides a high-current-density superconductor in a partially stable mode of operation. The practical consequences of the two approaches are both low- and high-current-density superconductive magnets. A refinement of this approach currently under wide investigation is to drastically reduce the shielding currents by dividing the superconductor into very finely divided strands. Such conductors theoretically promise to yield high stability with high current densities.

Low-current-density magnets

In low-current-density superconductive magnets, enough normal metal is affixed to the superconductor to carry the full design current in the event that the superconductor goes normal. In addition, the joule heat created during these intervals is dissipated by means of liquid helium in intimate contact with each turn of the magnet. The necessity for the use of normal metal and for providing cooling passages at each turn can result in a large and very costly magnet. A typical application is a large-bore (order of feet) low-field bubble-chamber magnet for high-energy particle accelerators, in which the magnets are a relatively small part of the total machine, and extreme reliability and predictability of performance is essential to success and economy. Effects of shielding-current breakdown and dependence on charging rates are virtually eliminated. As a general rule, this type of magnet design should be approached as closely as system size and cost requirements permit.

Because the low-current-density approach applies primarily to larger magnets which require correspondingly large conductors, RCA makes a ½-inch-wide conductor series with varying thicknesses of copper cladding to provide degrees of stability consistent with the cooling means determined by the magnet designer. A brief understanding of the important parameters involved in the design of this type of magnet shows the importance of the thickness of the copper cladding in the use of this conductor.

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received the BChE from Cooper Union in 1955, and the MS in Physics from the Stevens Institute of Technology in 1959. Mr. Schindler was employed for four years at Picatinny Arsenal where he formulated and tested rockets and jet devices. Subsequently, he joined General Instrument Corporation as a senior engineer in developing semiconductor devices. In June 1962, Mr Schindler was engaged by the RCA Superconductor Materials and Devices Laboratory of the Special Electronic Components Division at Princeton, N.J. He participated in the development of the niobiumtin vapor deposition process and studies of the effect of the physical, chemical, and electrical properties of Nb_3Sn films. As a result of this work, he received the RCA Laboratory Outstanding Achievement Award. In April 1964, Mr. Schindler transferred to the RCA Superconductive Products Operation He was initially involved with the development and electromagnetic evaluation of superconductive ribbons for magnet applications In 1968, he assumed the full responsibility in the design and assembly of all commercial magnets systems. He has just recently been assigned to additional responsibility for ribbon development and pilot line production. Mr Schindler is a member of the American Physical Society.

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received the BA in Physics from Columbia University in 1950 and the MS in Physics from the Polytechnic Institute of Brooklyn in 1953. Mr. Schrader was associated with the American Museum of Natural History in oceanographic exploration in 1950 and was subsequently employed as a project engineer in aircraft instrument research by the Sperry Gyroscope Company. In 1954 he joined the RCA Tube Division in Harrison, New Jersey, where he studied the effects of tube materials upon tube performance. On July 1, 1962, Mr. Schrader was appointed to head the Magnet and Measurements Group of the newly established RCA Superconductor Materials and Devices Laboratory located in Princeton, New Jersey. He has been the Senior Project Engineer on four contracts with the Lewis Research Center, NASA, in which studies were made of the feasibility of designing and constructing large-bore, high-field superconductive magnets. Mr Schrader is a member of the American Physical Society, Sigma Xi, and a Senior Member of the IEEE. He originally had the responsibility for magnet design and development and made RCA's first commercial magnets. He is an Engineering Leader now responsible for a new advanced products group.

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received the BS in Chemistry from Wagner College in 1954. From 1954 to 1956 he performed research on selective chlorination of titanium-bearing ores and zirconium ores at the research laboratories of the National Lead Company. While in the U.S. Army between 1956 and 1959, he was attached to the U.S. Army Ballistic Missile Agency, Huntsville, Alabama, where he performed research on thermal properties of materials for use in missile and satellite programs. Mr. Nyman joined the RCA Semiconductor and Materials Division in March, 1959 and performed research for the development and pilot manufacture of miniature-size tantalum solid electrolytic capacitors. In November, 1962, Mr Nyman first became associated with the Superconductor Materials and Devices Laboratory at Princeton where he was responsible for the process development of Nb_3Sn films on ceramic and metal substrates. In connection with this work, he received an RCA Laboratory Outstanding Achievement Award. From June 1964 to December 1968 he was responsible for ribbon development and pilot production facilities at EC&D, Harrison, New Jersey In January 1969, Mr. Nyman joined the Cryoelectric Devices Laboratory at the RCA Laboratories where he will be working on the development of permaloy plated wire for use in computer memories.

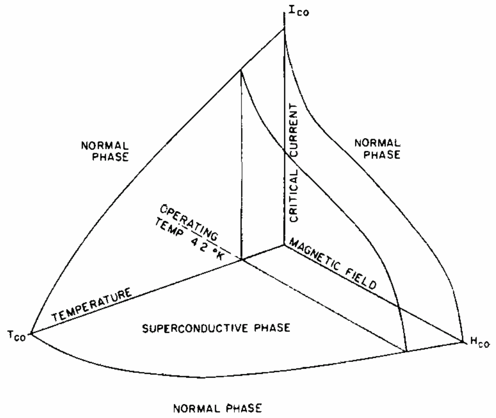

Fig. 1—The generalized critical surface of a high-field superconductor.

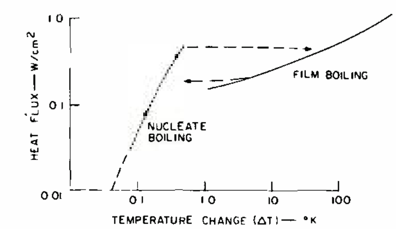

Fig. 2—Heat-flux transfer to liquid helium.

Table I—Critical fields for the four major superconductors.

Superconductor	*Critical field, H_{co} at 4.2° (kG)*	*Transition temperature, T_{co} (°K)*
Niobium stannide, *Nb_3Sn* (Niobium Tin)	225	18.3
Vanadium gallium, *V_3Ga*	195	14.0
Niobium-titanium, *Nb-Ti* (alloy)	122	8.4
Niobium-zirconium, *Nb-Zr* (alloy)	83	10.8

A temporarily normal superconductor recovers its superconductivity if the temperature of its immediate surroundings is maintained below its critical range, as shown in Fig. 1. This requirement is met when the heat generated per unit length of conductor by all the current in the adjacent copper is transferred to the liquid helium without raising the temperature of the superconductor above the critical value. Fig. 2 shows typical values of the heat transfer coefficient for a metal surface in liquid helium[10]. Because it is desirable to work in the more efficient nucleate boiling range of liquid helium, the conductor must be designed to keep the temperature difference between the surface of the conductor and the liquid helium less than a few tenths of a degree.

With the selection of an acceptable design value for the heat-transfer coefficient and the actual perimeter of the conductor in contact with the liquid helium, the cross-sectional area of normal (copper) conductor required to carry the current is selected. Because the resistivity of the copper varies as a function of magnetic field, being over five times higher at 100 kilogauss than at zero field, the proper copper thickness will have a field dependence. Since the choice of conductor parameters greatly depends on other magnet fabrication requirements, such as the forces and the possible means of holding the conductor, actual design involves much iteration of all quantities.

Fig. 3 shows an idealized voltage/current diagram for two superconductors with the same current-carrying capability but with different thicknesses of copper cladding. Equal conditions of background magnetic field and cooling by direct contact with liquid helium are assumed. The superconductors can carry a current up to its full critical current I_c, after which any excess current transfers to the copper cladding. For the lesser-stabilized case, the copper cladding alone at 4.2°K has a resistance shown by the slope of line *A*. In a typical test, the current can be increased to I_c with zero voltage developed across the superconductor. At higher currents (between points a_1 to a_2) the current is shared between the superconductor and the copper. Assuming no heat inputs other than that caused by the joule heating in the copper, the temperature of the composite conductor rises until, at point a_2, the temperature for nucleate boiling is exceeded and the conductor jumps to the film boiling region (a_2 to a_3). The temperature is then high enough so that the superconductor goes completely normal and no longer shares any portion of the current, all of it being carried in the copper. The only way to reduce the temperature is to reduce the current until the heat transfer is favorable for recovery into the nucleate boiling region (a_3 to a_4). At this point, the composite conductor again becomes superconductive (a_5). Such a conductor is fully stable to currents represented by point a_1 because it is always in the nucleate boiling region below this current. However, for most practical purposes the conductor can be operated in a quasi-stable state to currents represented by point a_4.

In a second case, the copper has twice the thickness and half the resistance, as represented by the slope of line *B* in Fig. 3. With the same dissipation characteristics assumed, the current/voltage relation follows the path b_1 (same as a_1), b_2, b_3, b_4, b_5; for this case, the conductor is fully stable to a current level represented by point b_5, which is above the critical current in the superconductor. The case of higher stability (case *B*) generally results in a lower-current-density magnet than case *A* because of the extra volume of windings used for stabilizing copper. The only advantage of the use of the extra thickness of copper in a design is the ability of the superconductor to reversibly recover from a higher takeoff current (point b_2).

Actual voltage/current characteristics of superconductors are more complex than those shown in Fig. 3 because of the presence of heat and field perturbations (flux jumping) and non-ideal power-transfer characteristics. The specifications for ½-inch-wide superconductors marketed by RCA to satisfy the requirements for fully stable low-current-density applications are described below. The ½-inch ribbons are also used for very-high-current-density applications by use of silver plating or thin copper cladding on the ribbon in place of the heavier copper cladding. In these cases, the operation of the ribbon is similar to that under high-current-density conditions, and diagrams such as those shown in Fig. 3 do not apply.

High-current-density superconductive magnets

Although the low-current-density approach is attractive from a design and operational point of view, it presents an inherent limitation on the range of magnet types which can be built. A second, more subtle approach actively pursued by RCA is to regulate the initial "triggering" mechanism so that propagating normalcies are not nucleated until an acceptably high current density is achieved in the magnet. As described earlier, the initial stages of normalcy are caused by the local heating of the superconductor when "shielding" currents suddenly break down. The addition of relatively minor amounts of normal metal, such as copper or silver, provides enough of a local sink for the energy released to prevent the propagation of a normalcy up to some acceptably high transport current. As a result, greater amounts of released energy can be safely tolerated and the magnets can be raised to higher currents before an irreversible normalcy occurs. Once normalcy begins at one spot in the windings and begins to propagate, however, the condition is enhanced by continued dissipation due to transport current and collapsing magnetic-field energy, and the heat sinks are not capable of removing this energy. Therefore, the superconductor does not recover until the total energy has been dissipated to the liquid helium at the coil extremities. By minimizing the initial triggering effects, relatively high currents can be attained with only minor additions to the superconductive volume by the inclusion of normal-metal energy sinks. This partially stable mode of operation is subject to additional degradation by further alterations in the energy balance, such as faster device charging rates. Therefore, these higher-current-density magnets usually have restrictions with regard to modes of operation, speed of charging, and limitations on AC power-supply ripple. By tightly packing the windings (no helium flow at conductors) and using other published techniques,[1,5,6] practical high current densities (15 to 35 kA/cm^2) have been achieved in a vast range of high-field commercial and research magnets, both by RCA and others.

The initial problems involved with lack of full predictability of the critical currents expected with the high-current-density approach have been reduced to an engineering level such that a practical design is usually within 5% of anticipated performance. As a result, even higher-current-density magnets (40 to 60 kA/cm^2) are being developed for use in particle accelerators in places such as Brookhaven and Argonne National Laboratories. These devices use the RCA ½-inch wide superconductive ribbon.

Design and fabrication of RCA superconductive ribbons

All RCA ribbons are composite structures consisting of a strength-bearing substrate, the vapor-deposited Nb_3Sn, and a layer of silver or copper to stabilize the superconductor. Each portion of the composite can be individually modified to meet a specific requirement in the design of a superconductive device. RCA manufactures a series of commercial and developmental conductors in this general configuration to meet the needs of the industry. Because the processes used to fabricate these conductors has been adequately described elsewhere,[11,12,13] they are only briefly discussed here. Instead, the role of each member of the composite that makes up the conductor is discussed and examples are given of its respective contribution to the performance of the entire conductor.

Substrate ribbon

The primary role of the substrate in the ribbon is to provide a high-strength support for the somewhat brittle Nb_3Sn superconductive layer. The use of this substrate makes possible the winding and rewinding of the ribbon without fear of damage to its superconductive properties. The material selected for use as the substrate must have a high yield strength, in excess of 75,000 psi, to withstand the large hoop stress forces generated during operation of a magnet. It must also be chemically inert to the chloride atmosphere of the Nb_3Sn vapor-deposition process and have a coefficient of thermal expansion closely matching that of the Nb_3Sn. The Hastelloy alloys best meet these requirements; in particular, Hastelloy *B* is used as the substrate material for all RCA commercial ribbons. [Hastelloy is a trademark of Hanes-Stellite Co.] The substrate dimensions should be as small as possible consistent with the above requirements because excess substrate volume reduces the space available for the actual Nb_3Sn conducting layer and normal metal. Ideally, the substrate dimensions should be varied to meet the different hoop-stress force requirements of each section of a magnet. A 140-kilogauss, 6-inch-bore magnet made for NASA, for example, uses 1.8-, 2.5-, and 3-mil-thick Hastelloy ribbons. For small magnets, however, a single-size substrate ribbon can be used throughout the windings because the hoop-stress forces are only in the order of several pounds.

In the case of very large devices operating at several hundred to several thousand amperes, the tensile forces

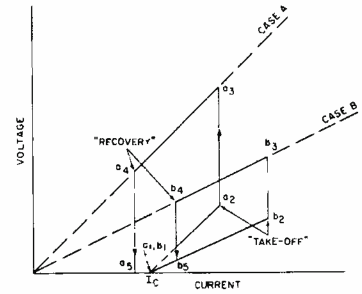

Fig. 3—Idealized voltage-current diagram for a composite superconductor.

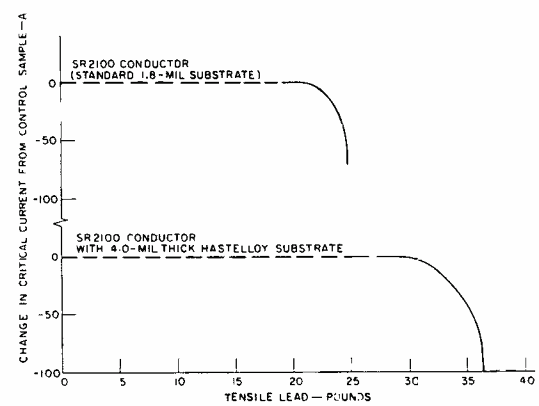

Fig. 4—Critical current of two superconductors as a function of tensile load.

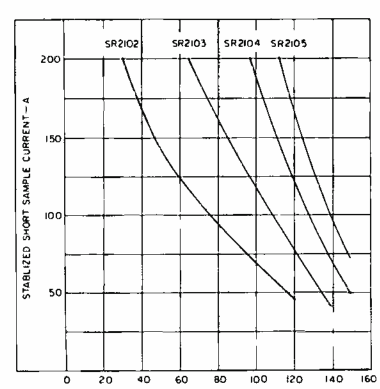

Fig. 5—H_c-I_c characteristics of fully stabilized 90-mil ribbons.

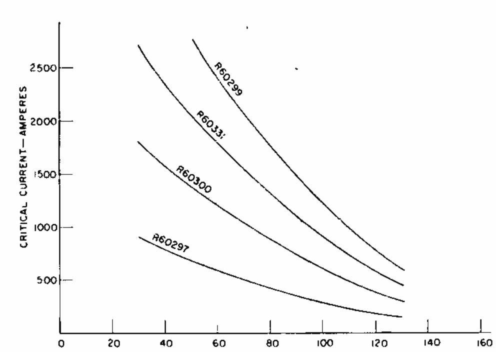

Fig. 6—H_c-I_c characteristics of fully stabilized ½-inch wide ribbons.

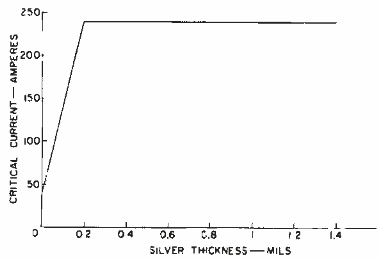

Fig. 7—Effect of silver-plating thickness on short-sample I_c.

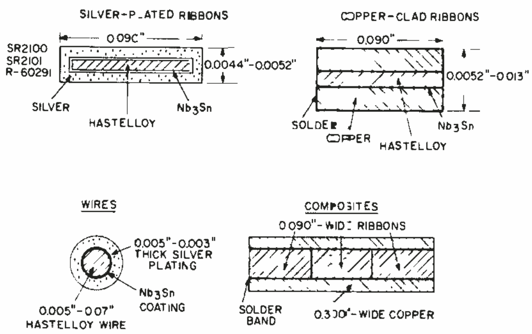

Fig. 8—Typical conductor cross-sections.

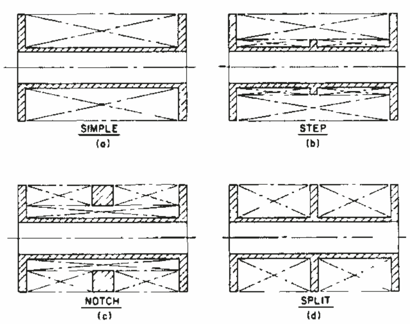

Fig. 9—Construction techniques used to achieve high homogeneity in magnets.

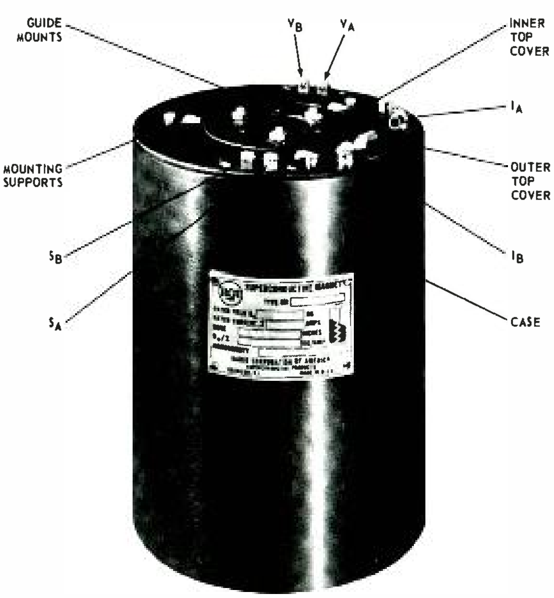

Fig. 10—Two-section, high-field magnet.

on the ribbon may reach 200 pounds or more. The ½-inch-wide family of conductors with 5.5 times the strength and critical-current capability are used in these devices, frequently with additional strength-bearing members bonded to the Hastelloy—Nb_3Sn composite. In the case of large, low-current-density magnets for use in bubble chambers, the large amount of normal metal added to the superconductor-substrate composite for electromagnetic stability provides part of the mechanical strength needed in the conductor composite.

The Nb_3Sn superconductive layer begins to lose its ability to carry supercurrents when the hoop-stress forces on the conductor exceed the yield point of the Hastelloy ribbon. This point can be determined experimentally by tensile-loading the sample to various levels in liquid helium and determining the load at which the critical current begins to decrease. Fig. 4 shows the critical current as a function of tensile load for Type SR2100 conductors having two different value of substrate thickness. The dashed portion of the curves represents the strength contributed by the Hastelloy ribbon, with its yield point at the end of the dashes. The critical current of the Nb_3Sn-Hastelloy composite does not begin to drop until slightly beyond the yield point of the Hastelloy alone, indicating that the composite is stronger. In normal design practice, the substrate thickness is selected so that the hoop stress to which it would be exposed in the device is less than 90% of the Hastelloy yield point.

Nb_3Sn superconducting layer

The vapor-deposition process for the production of Nb_3Sn is based on the simultaneous hydrogen reduction of the mixed chlorides of niobium and tin at the substrate to form the intermetallic compound without the formation of the free metals. The process is performed at temperatures between 900°C and 1200°C according to the following chemical reaction:

$$3NbCl_4 + SnCl_2 + 7H_2 \rightarrow Nb_3Sn + 14HCl$$

In practice, this process is carefully controlled to produce a Nb_3Sn product which exhibits a specific critical-current characteristic for a given cross-sectional area of Nb_3Sn. It is possible to change the cross-sectional area of Nb_3Sn and therefore the critical current, I_c, of the material at a given field to meet the needs of a magnet designer. As in the case of substrate thickness, the thickness of the Nb_3Sn could ideally be graduated in an almost continuous way to meet the $H_c - I_c$ requirements of each turn in the magnet. Because this specification is not practical, ribbons are made to cover certain ranges of the $H_c - I_c$ characteristics. All magnets, however, can be built with either the RCA 90-mil-wide, ¼- or ½-inch-wide family of ribbons.

The family of 90-mil-wide ribbons is designed for the fabrication of small-size high-current-density research-type magnets normally operated at currents of 80 to 120 amperes to develop fields of 50 to 150 kilogauss. The specific conductors are made by applying different thicknesses of Nb_3Sn to the substrate to obtain critical currents in the range from 80 to 120 amperes for use in specific field regions of the magnet. The inherent short-sample critical-current capability of the family of narrow ribbons is shown in Fig. 5 as a function of magnetic field. These ribbons are offered as a commercial line of silver-plated ribbons and as a developmental line of copper-clad ribbons. In the latter case, OFHC copper has been soldered to each side of the ribbon to provide increased conductor stabilization, as discussed previously. Selection of ribbons is based on the desired operating current. For operation at 100 amperes, for example, SR2102 would be used to about 70 kilogauss, SR2103 to about 110 kilogauss, SR 2104 to about 125 kilogauss, and SR2105 to about 140 kilogauss. If higher fields are desired, specialized ribbons are available.

For larger devices and high-current operation of the coil (several hundred to several thousand amperes), RCA manufactures a series of developmental ½-inch-wide conductors having a minimum guaranteed short-sample rating of 300, 600, 900, and 1200 amperes at a 100-kilogauss field environment. These current levels are achieved by depositing a specified thickness of Nb_3Sn on the Hastelloy substrate for each given performance level. The inherent short-sample critical current of these materials as a function of field is shown in Fig. 6. As in the narrow ribbons, these materials are offered in both silver-plated and copper-clad versions

Table II—RCA superconductive ribbon products.

	Min. guaranteed short-sample performance Current (A)	Field (kG)	*Recommended coil-design parameters* Field (kG)	Operating Current (A)	Width (in.)	*Ribbon constituents—typical dimensions* Hastelloy Thickness (in.)	Nb_3Sn Layer Thickness (in.)	Copper* Thickness (in./side)	Total* Conductor Thickness (in.)
Commercial types									
SR2102	120	65	0-75	90-110	0.090	0.0010	0.0025	0.002	0.0063
SR2103	120	100	55-100	90-110	0.090	0.0018	0.0038	0.002	0.0074
SR2104	110	125	70-125	90-110	0.090	0.0018	0.0065	0.002	0.0080
SR2105	100	140	100-140	90-110	0.090	0.0018	0.0090	0.002	0.0088
Developmental types									
R60381	150	100	0-75	180-250	0.250	0.0010	0.0025	0.002	0.0063
R60382	300	100	55-110	180-250	0.250	0.0018	0.0038	0.002	0.0074
R60383	450	100	70-125	180-250	0.250	0.0018	0.0065	0.002	0.0080
R60384	600	100	100-140	180-250	0.250	0.0018	0.0090	0.002	0.0088
R60297	300	100	Unspecified to allow freedom		0.500	0.0010	0.0025	0.002	0.007
R60300	600	100	of design for different		0.500	0.0018	0.0038	0.002	0.008
R60331	900	100	degrees of cooling in magnet		0.500	0.0018	0.0065	0.002	0.0086
R60299	1200	100	configurations		0.500	0.0018	0.0090	0.002	0.0094

* Thickness of copper ranging from 0.001 to 0.004 inch available. Total conductor thickness would be modified accordingly.

Fig. 11—Two-inch-bore, 100-kilogauss magnet.

to provide different stabilization levels from which the coil designer may select. Table II summarizes the specifications for these ribbons.

Stabilization layer

The critical-current/critical-field relationships shown in Figs. 5 and 6 hold quite well for fully stabilized small samples of conductor immersed in liquid helium. When these materials are tested as a Nb_3Sn-coated substrate without the presence of the stabilizing normal metal, however, critical currents are considerably lower than the values shown in the Figures. These results point out the importance of the stabilizing metal in achieving high currents. As stated earlier, the normal metal must have extremely low electrical resistance at liquid-helium temperatures. Generally, the lower the resistance, the greater the stabilizing influence a given amount of normal metal has on the superconductor. The normal metals are often plated on the Nb_3Sn-coated ribbon under conditions which minimize contamination and structural defects, the presence of which produce a high resistance in the normal metal. For copper-clad ribbons, only OFHC copper which has been fully annealed is used. A typical effect of the thickness of the normal-metal layer on performance is shown in Fig. 7, where the critical current of a short sample is plotted as a function of the thickness of silver-plated layers having the same resistance ratio. The critical currents obtained increase from about 40 amperes for unplated ribbon to about 240 amperes for a 0.2-mil-thick plating. At this point, the maximum current-carrying capacity of the Nb_3Sn layer is reached, and the critical current remains constant for increasing thicknesses of silver plating. For coil use, where thermal and electromagnetic characteristics are different, this amount of silver is insufficient and a minimum of 1 mil must be used.

RCA superconductive ribbon products

The above principles and design concepts have been successfully applied to the design of families of ribbons for use in fabricating superconductive magnets. Two families are offered as a standard commercial product line. The others are offered as developmental ribbons for use by scientists and engineers working on magnetic development programs in government, university, and industrial laboratories. Table II contains information on short-sample performance criteria and recommended applications ranges for the commercial ribbons and similar information on typical developmental ribbons. Schematic cross-sections of the various conductors are shown in Fig. 8, including some configurations made for special applications.

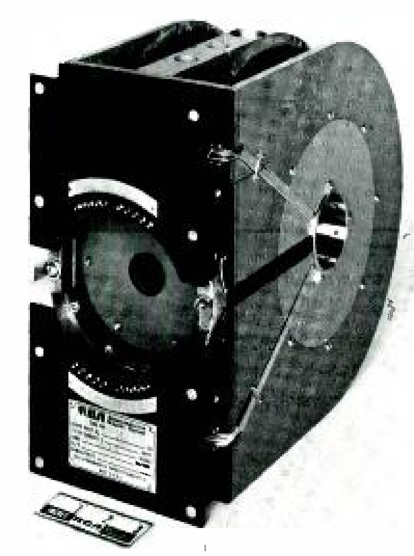

Fig. 12—"Split-pair" magnet with 2.4-inch bore and 1½-inch separation between windings.

Superconductive magnets

The magnetic field intensity, H, at the geometry center of a magnet is given by

$$H = \frac{Fa_1 I}{A} = Fa_1 J$$

where F is a geometric factor; a_1 is the inner winding radius; A is the area per conductor; and I is the current through the conductor. From the definition of A and I, it is clear that J is the current density. This relationship shows that, for a given geometry, the field generated in the magnet is proportional to the current density in the windings.

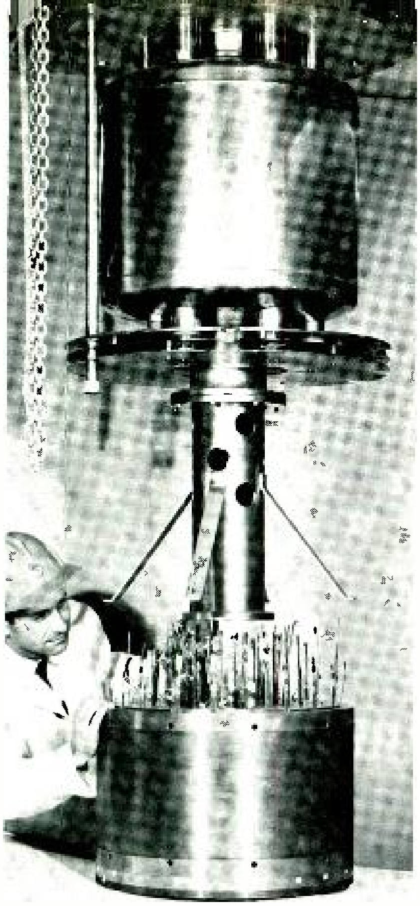

Fig. 13—Six-inch-bore, 140-kilogauss magnet.

Therefore, current density is a very important design factor.

In the fully stabilized low-current-density approach to the design of superconductive magnets, the current density in the windings is approximately 4,000 to 6,000 amperes per square centimeter. By way of contrast, devices designed using the high-current-density approach normally operate at current densities ranging from 15,000 to 25,000 amperes per square centimeter and, in special cases, sometimes reach as high as 60,000 A/cm^2. This high current density is achieved by operating the magnet in the partially stabilized mode, i.e., by winding the turns without providing any liquid cooling passages. In addition, less copper or silver is used on the Nb_3Sn than would be used if the design were for stable operation. These features permit considerable savings in space and result in high current densities. The ability to develop high current densities in the windings provides some degree of freedom in optimizing other desirable characteristics of magnets, as discussed in the paragraphs that follow.

In the design of a magnet, the following interrelated parameters are often of primary importance:

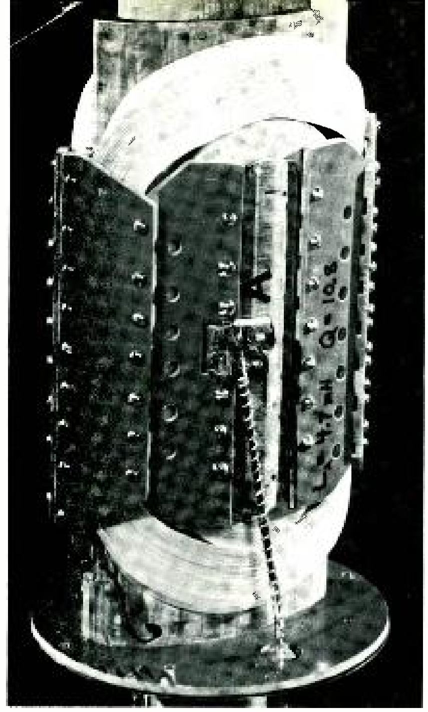

Fig. 14—Elliptical dipole magnet.

Maximum magnetic field,
Bore diameter,
Homogeneity within a specified volume in the bore,
Time to reach maximum rated field, and
Electrical time constant of the magnet.

The first design factor has readily been achieved with the family of superconductor ribbons developed by RCA over the past few years, which include both the silver-plated and copper-clad ribbons previously discussed. This family of ribbons spans the range of field intensities up to 150 kilogauss.

The second parameter is readily fed into the computer computations used to establish the magnet design. In general, as the bore diameter increases, the amount of ribbon required goes up nonlinearly and magnet costs rise rapidly. Consequently, bore size is frequently limited by budget.

Homogeneity of the magnetic field over a specified bore volume has generally been achieved by use of the four magnet designs shown in Fig. 9. The cross-hatched sections indicate the areas where there are no ribbon windings. The windings have been removed in the regions to achieve the desired homogeneity by preferentially obtaining field contributions from other areas.

The time to reach the maximum designed field is related to the equivalent circuitry of the magnet as specified by the distributed inductances and resistances, as well as the degree of stability designed into the superconductor. For a completely stabilized magnet, the time may be a matter of a few seconds; for a partially stabilized magnet, the time may be minutes. However, compromises such as magnet weight, magnet size, and the added quantity of ribbon indicate use of as little normal metal as possible to meet this requirement.

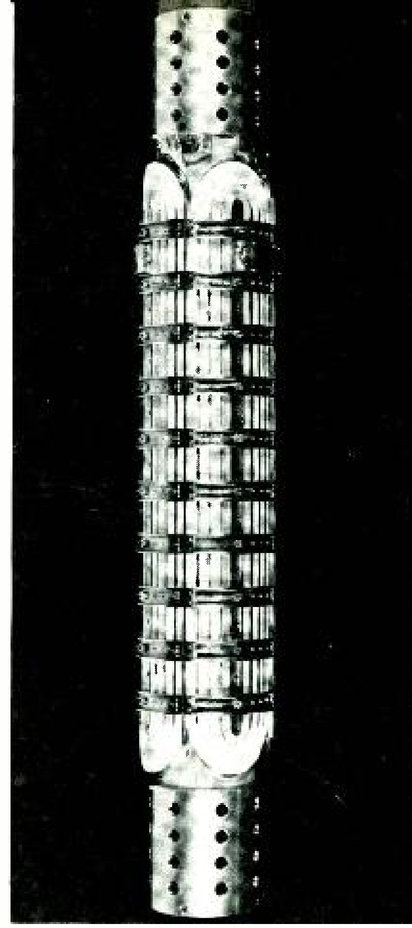

Fig. 15—Four-inch-bore quadrupole magnet.

The electrical time constant is related to the resistance of the shorting strips used in the magnet. These strips are electrically in parallel with the inductive windings of the magnet. The ratio of the inductance of the magnet to the total parallel resistance of the magnet is defined as the magnet time constant. To limit peak voltages on normalcy, shorting strips of varying electrical resistance are sometimes used in winding of the RCA ribbons. The effective shorting resistance is related to the combination of the resistance of the normal metal at 4.2°K in contact with the superconductor, as well as to the type of metal in the strip. For example, with no background field and with a 0.001-inch-per-side silver plating on the ribbon, the electrical resistance of the conductor at liquid helium temperature is approximately 1.5×10^{-4} ohms per inch, and copper or phosphor-bronze shorting strips have been used. With a 0.001-inch-per-side copper cladding on

Table III—List of typical RCA superconductive magnets and systems in service or in process.

Magnet Type	Type No.	Rated field (kG)	Clear bore (inches)	Homogeneity (in a DSV*)	Date delivered	Customer
Simple solenoid	SM 2814	18	12.125	Not applicable	fall 1966	Midwestern univ. Res. Assoc.
Simple solenoid	SM 2801	50	1.125	1% in 1⅛ inches	mid 1965	RCA Labs, Princeton
Split coil	SM 2819	50	1.000	0.4% in 1 cm	early 1967	Andonian Associates
Simple solenoid	SM 2801-V1	70	1.125	1% in 1⅛ inches	mid 1966	RCA Labs, Tokyo
Simple solenoid	SM 2813	80	1.000	3% in 1 inch	early 1967	Tokyo University
Simple solenoid	SM 2827	80	1.50	1% in ¾ inch	mid 1968	RCA Lab—Switzerland
Simple solenoid	SM 2803	100	1.000	1% in 1 inch	early 1966	CERL, England
Compound solenoid	SM 2802	100	1.280	1% in 1 inch	mid 1966	Gen. Motors Corp.
Simple solenoid	SM 2804	100	1.000	0.5% in ½ x ½" cyl.	fall 1966	Ames Lab, Iowa
Simple solenoid	SM 2815	100	2.500	0.2% in 1 inch	mid 1967	NASA-Lewis Res. Center
Split coil	SM 2818	100	2.500	0.4% over 1 cm	mid 1968	Ames Lab, Iowa
Split coil	SM 2829	100	2.500	0.4% over 1 cm	early 1969	Wright Patterson Air Force Base
Simple solenoid	SM 2826	100	2.100	0.75% in 1 x ½" cyl.	fall 1968	Bell Telephone Labs.
Split coil	SM 2820	100	2.136	1% in 2 inches	mid 1967	Bell Telephone Labs.
Simple solenoid	SM 2806	125	1.000	1% in 1 inch	mid 1967	Rutgers Univ.
Simple solenoid	SM 2816	134	1.500	0.2% in ½ inch	fall 1968	Douglas Adv. Res. Lab.
Compound solenoid	SM 2805	137	1.930	¼% in 1 inch	mid 1966	RCA Elec. Comp. & Devices
Compound solenoid	SM 2821	140	6.000	Not applicable	early 1967	NASA-Lewis Res. Center

* diameter spherical volume

the ribbon having resistivity at 4.2°K of approximately 2.0×10^{-5} ohm-cm, both phosphor-bronze and stainless-steel shorting strips have been used. For a superconductor with 0.002-inch copper per side having an electrical resistivity at 4.2°K of approximately 1×10^{-8} ohms-cm, either stainless-steel or no shorting strips have been used. When no shorting strips are used, the electrical time constant of the magnet is only limited by the internal resistance of the power supply and the effective resistance of any inductively coupled circuits such as metallic coil forms or the like.

The effects of these different construction techniques can be illustrated by measuring the time required for the voltage across a magnet to decay to $1/e$ of its original value when a fixed current has been reached. Typical times for 1-inch-bore, 100-kilogauss magnets are as follows:

Shorting strip	Resistivity at 100 kG and 4.2°K (ohm-cm)	Time
Copper	4.5×10^{-8}	6 min.
Phosphor-Bronze	3×10^{-5}	54 sec.
Hastelloy	150×10^{-6}	11 sec.
None	supply resistance limited only by power	

Actual devices

By use of the high-current-density approach, many notable 'firsts' in magnets were achieved by RCA for the government, such as the construction and testing of a 6-inch-bore, 140-kilogauss magnet for NASA Lewis Research Center. In addition, many types of 100-kilogauss magnets having bore sizes from 1 to 2½ inches have been constructed for commercial sale. Fig. 10 shows the flexibility achieved by use of a two-section, high-field magnet. With the insert in place, the magnet generates 100 kilogauss in a 1.28-inch bore. With the insert removed, the magnet generates 60 kilogauss in a 3.3-inch bore. The magnet in Fig. 11 is a 2-inch-bore, 100-kilogauss magnet. The separation of the windings at the center is made to obtain greater homogeneity of the field in the bore.

Fig. 12 shows a 2.4-inch-bore, 100-kilogauss magnet with a 1¼-inch separation between the windings. Such "split-pair" magnets present difficult fabrication problems because of very large axial forces with which the two magnet halves are drawn together when operated. When the magnet is powered, the edges of the windings are bearing against the central separator which contains the access holes for the samples under test and electromagnetic radiation.

The magnet shown in Fig. 13 was constructed as part of a plasma-physics research project for the NASA Lewis Research Center. It develops 140 kilogauss in a 6-inch bore, contains over 90 kilometers of 90-mil-wide Nb_3Sn ribbon, and has a magnetic-field energy of two megajoules. The magnet is internally constructed as separate modules in which the module walls bear the forces and distribute the axial loads. The structure at the top of the Figure is the magnet support and dewar cover.

Table III shows the specifications for a variety of magnets made by RCA. The wide range in magnetic field, bore size, and bore homogeneity should be noted. At the present time, 100-kilogauss, 2-inch-bore magnets are relatively routine items of manufacture, and a 150-kilogauss 1.5-inch-bore magnet has just been successfully completed. Devices developing fields of this magnitude will satisfy most commercial needs in the near future, and the immediate trend will be to achieve higher homogenities and faster operation times.

A somewhat different area of effort is the development of dipole and quadrupole magnets by the National Laboratories for use on particle accelerators. These windings are as shown in Figs. 14 and 15, where the radical departure from cylindrical symmetry is seen. RCA is very active in supplying ribbons to satisfy the different requirements and fabrication techniques typical of these beam-handling devices.

References

1. Schrader, E. R., "Design and Construction on Nb_3Sn Superconductive Magnets," RCA reprint, PE-331, (Jan. 1967).
2. Cooper, J. L. "Transition Temperature of Niobium Stannide," *RCA Review*, Vol. XXV, (Sep. 1964), p. 405.
3. Saur, E., Wizgall, H., "*Edition du Centre National de la Resherche Scientifique*," Conference on Intense Magnetic Fields, Grenoble, (1966), paper c. 8; Conference *Proceedings* (1967) p. 223.
4. Hulm, J. K., Blaugher, R. D., "Superconducting Solid Solution Alloys of the Transition Elements" *Physical Review* 123 (1961) p. 1569.
5. Schrader, E. R., Kolondra, F., "Analysis of Degradation Effects in Superconductive Niobium Stannide Solenoids," *RCA Review*, 25, 582 (1964).
6. Chester, P. F., "Superconductive Magnets," Reports of Progress in Physics v 30 pt 2 (1967)
7. Hancox, R., "Enthalpy Stabilized Superconducting Magnets, UK Atomic Energy Authority" Research Report CLM-p 1963 (1968).
8. Hale, R., "The Transient Stabilization of Nb_3Sn Composite Ribbon Magnets," *J. of Applied Physics*, Vol. 30, No. 6 (May 1968) p. 2634.
9. Schrader, E. R., Thompson, P. A., "Use of Superconductors with Varied Characteristics for Optimized Design of Large-Bore High-Field Magnets" *IEEE Transactions on Magnetics* (Sep. 1966).
10. Lyon, D. N., *Advances in Cryogenic Engineering*, 11 (Plenum Press) p. 652.
11. Hanak, J. J., Strater, K., Cullen, G. W., "Preparation and Properties of Vapor Deposited Niobium-Stannide," *RCA Review*, Vol XXV (Sep. 1964), p. 342.
12. Nyman, F. R., "Vapor Deposition of Niobium Stannide—A Versatile Process," RCA reprint, PE-331, (Jan. 1967).
13. Schindler, H. C., Green, R., "Improved Stability of Nb_3Sn Ribbon by Plating or Cladding with a High-Conductivity Metal," RCA Reprint PE-331, (Jan. 1967).

Silicon-on-sapphire devices

Dr. C. W. Mueller | Dr. F. P. Heiman

The excellent mechanical and electrical properties of sapphire coupled with techniques of epitaxially growing one micron thick single-crystal silicon on the sapphire have allowed reductions of 10 to 100 in device and integrated circuit capacitance. Measurements on a CMOS memory circuit have shown 1.5 to 2.0 nanoseconds pair delay with a power consumption in the microwatt range. Thin-film silicon bipolar transistors and 14,000 volt integrated rectifier strings have been made.

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received the BSc (magna cum laude) from Notre Dame University in 1934, the MSEE and the ScD from Massachusetts Institute of Technology in 1936 and 1942. Between 1936 and 1938 he worked on electron tubes at the Raytheon Production Corporation and, at MIT, he worked on tubes for computing purposes. His doctoral work was in physical electronics and involved fundamental measurements on secondary-electron emission. Since 1942, he has been with RCA Laboratories. Dr. Mueller worked on beam-deflection tubes for operation up to 1200 MHz. A grid-controlled secondary-emission tube was also developed. He then worked in the field of junction transistors and was responsible for the alloy-junction technique used in many commercial types. He developed the first alloy junction transistor for higher-frequency operation. He developed the thyristor type switching transistor. He supervised the work leading to a parametric diode and the development of a low inductance ceramic enclosure for diodes. He participated in the development of tunnel diodes for which he was one of the recipients of the David Sarnoff Team Achievement Award in Science. More recently he has been working on the growth of single-crystal silicon films on sapphire and the use of these films for electron devices and integrated circuits. He holds many patents in the fields of electron tube and solid state devices. In 1961-62 Dr. Mueller held the RCA European Study Fellowship and spent the year on special studies in the field of solid state physics at the Swiss Federal Institute of Technology in Zurich, Switzerland. Dr. Mueller was awarded the David Sarnoff Outstanding Achievement Award in Science in 1966 with the citation "for outstanding contributions to semiconductor devices and circuits." He is a Fellow of the IEEE, a Fellow on the RCA Laboratories Staff, and a member of the American Physical Society and Sigma Xi.

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received the BSEE (summa cum laude) from the City College of New York in 1960 and the MSE and PhD from Princeton University in 1962 and 1964, respectively, under a David Sarnoff Fellowship. Since he joined RCA Laboratories in 1960, he worked in the fields of silicon devices and surface physics. In collaboration with Dr. S. R. Hofstein, he developed the silicon insulated-gate field-effect transistor and was co-recipient of an RCA Laboratories Achievement Award in 1963 and the IEEE Browder J. Thompson award in 1965 for his work. In 1964 he was awarded the David Sarnoff Outstanding Achievement Team Award in Science for his contributions to silicon-based integrated electronics. He has studied the properties of devices fabricated in thin silicon films epitaxially deposited on sapphire and was co-recipient of an RCA Laboratories Achievement Award in 1967 for the development of a complementary MOS transistor integrated memory cell. At present he is investigating electron-beam addressed diode arrays for television camera applications. Dr. Heiman is a member of Eta Kappa Nu, Sigma Xi, and a senior member of the IEEE. He was Publicity Chairman for the Princeton IEEE Section and is now Vice-President of the N.J. Chapter of the CCNY Alumni Association.

*Since this paper was written, Dr. Heiman has become a Vice President of Princeton Electronic Products, Inc.

IN THE CONSTRUCTION of monolithic integrated circuits, isolation between elements is necessary. There are several ways of obtaining isolation; most use single-crystal silicon grown in bulk form and obtain isolation by means of P-N junctions or by etching away the bulk silicon where isolation is desired. In some cases the silicon is then supported by glass or a combination of SiO_2 and polycrystalline silicon. The volume of active *Si* that is necessary for devices in the finished circuit is quite small. A direct approach to the problem of isolation is to start with an insulator and use the silicon only where it is actually needed. This paper discusses the advantages of this approach and summarizes the results that have been obtained on several devices built in the RCA Laboratories.

Sapphire substrate

The substrate, of course, must have a definite match[1] to silicon crystal structure so that single-crystal silicon can be grown on it. High mobility material is readily produced and other papers have discussed in detail its electrical properties.[2]

One of the outstanding properties of sapphire over glass is its good heat conductivity. Page[3] has recently shown that 10^4 watts/cm^2 could be dissipated through sapphire whereas only 2×10^2 watts/cm^2 could be dissipated through glass under the same conditions (a factor of 50 difference).

The Table I lists some of the advantages of silicon-on-sapphire when compared with other techniques. Each item, of course, does not apply to all possible techniques.

Table I—Advantages of the silicon-on-sapphire technique.

Electrical Advantages

Excellent isolation ($\rho > 10^{11}$ ohm-cm)
Good high frequency performance (loss tan $< 10^{-4}$ at 800 MHz)
Extremely low capacitance devices and circuits
No possibility of "4-layer latch-up"
No allowance necessary for space-charge spread
Considerably greater resistance to transient radiation

Mechanical Advantages

Ability to withstand regular Si processing, temperature of diffusion, chemical etches, etc.
High strength, especially at high temperatures
Good heat conductivity (50X glass)
Smoothness, no voids
Very high packing density (10^5 complementary devices per square inch)
For many circuits fewer processing steps are required

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Silicon-on-sapphire has the disadvantage of poorer crystal quality; e.g., 75% of bulk mobility at low doping concentrations. Early disadvantages of size, cost, and new technology have been steadily reduced over the past few years and in many cases are no longer serious barriers.

One cannot describe all the devices that can be made on silicon-on-sapphire (SOS) in a short paper nor would there be much point to it. So this discussion will be confined to:

1) An application readily and advantageously adapted to the SOS technology (complementary MOS devices and circuits);
2) Linear UHF amplifiers;
3) A difficult device to make (the bipolar transistor);
4) High voltage diode stacks; and
5) A new visible-light emitting plasma phenomenon.

Complementary MOS memory cell

Fig. 1a shows a complementary MOS memory cell circuit and Fig. 1b its integrated form.[4] There are 6 N-type transistors in one row and 4 P-type transistors in the other. Note that all the parts and interconnections are on sapphire and consequently have very low capacitance.

Fig. 2a shows a cross section illustrating the construction. At the left is the conventional N-channel MOS on P-type material. At the right you see a deep-depletion transistor[6] made on the same P-type silicon. This transistor is normally cut-off at zero bias because the P-type film is depleted all the way through due to the contact potential difference between silicon and the gate metal. Applying a voltage to the gate then causes current to flow and forms an enhancement MOS transistor. The magnitude of the threshold of both transistors is 1 ±0.5 volt.

The cross-over technique is shown in Fig. 2b. A strip of silicon is doped to degeneracy during the source diffusion and then oxidized. A metal strip is then evaporated across the oxide forming a cross-over.

The fact that there is no silicon under any of the junctions reduces the capacitance of source, drain and cross-over regions by about 2 orders of magnitude.

The important question now is how fast can these circuits be made to work. In the thin film we can conservatively get ¾ of the mobility obtained on bulk silicon devices. However, we can make the capacitance so low that the figure of merit is increased considerably. Fig. 3 shows the switching performance of the memory cell. One can see that the elapsed time between applying the input write signal and observing the output sense signal is 6 ns. The quiescent power dissipation of the circuit was 7 μ-watts. Complementary-pair ring oscillators were also constructed that operated with a pair delay of 2 ns. In this complementary MOS circuit, we have demonstrated a very fast circuit with a very low power consumption.

Linear UHF amplifiers

The use of thin silicon films in linear circuits[7] is more difficult than in digital applications. The major advantage of an insulating substrate lies in the high frequency range where device and circuit capacitance is a major problem and must be minimized. At 500 MHz and above, best results are obtained by using the tetrode or double gate structure (Fig. 4). The second gate shields the control gate from the drain and reduces feed-back capacitance while the low drain capacitance due to the absence of a conducting substrate reduces the output admittance which is nearly constant to 900 MHz. Fig. 5 shows the gain of a thin-film tetrode as a function of frequency indicating that useful gain can be obtained in the UHF frequency range.

Monolithic integrated circuits with inductors and capacitors in the UHF frequency range are possible, however, economic considerations determined largely by yield, at the present state of the art, do not justify their use where the silicon chip approach is feasible. Future monolithic integration can undoubtedly be handled when desirable after some technology improvements in passive components are developed.

Bipolar transistors

Although a great deal of integrated circuit work is performed by staying completely in the MOS world, engineers would like to have bipolar transistors on the same chip to shift impedance or voltage level or to do some things most easily done by bipolar devices. The bipolar transistors[5] is more difficult to make than the MOS transistor because it requires minority carrier lifetime

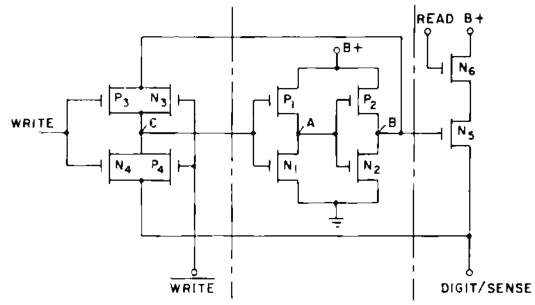

Fig. 1a—Electrical circuit of memory cell.

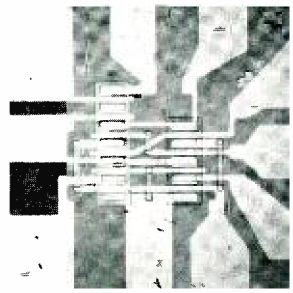

Fig. 1b—Integrated memory circuit.

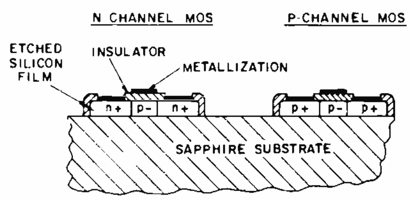

Fig. 2a—Cross section of complementary MOS transistors.

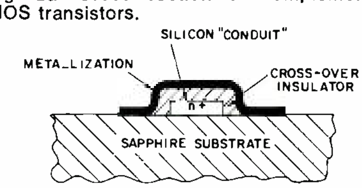

Fig. 2b—Cross section of cross-over technique.

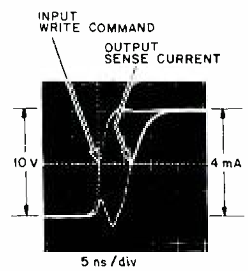

Fig. 3—Total delay from write command to sense current.

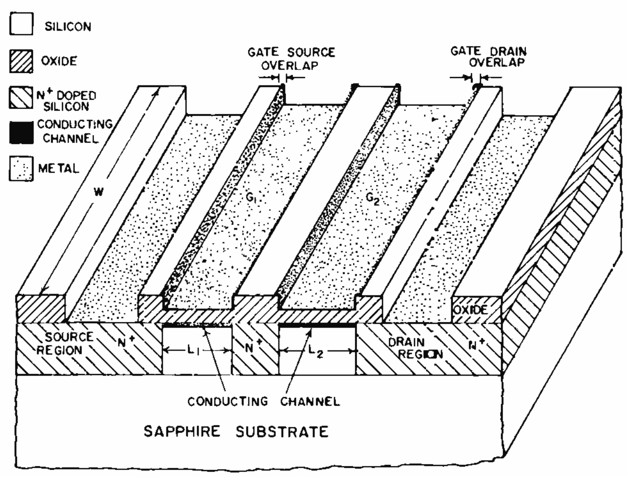

Fig. 4—Cross section of tetrode transistor.

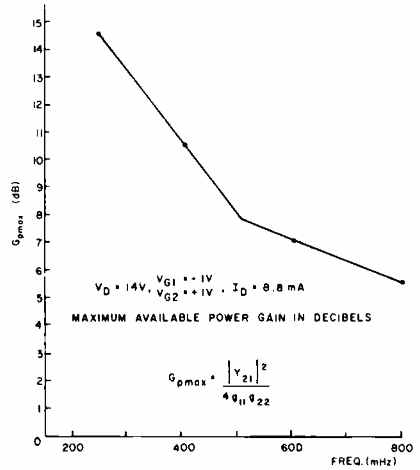

Fig. 5—High-frequency measurements of tetrode.

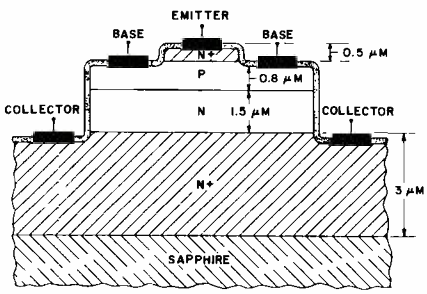

Fig. 6—Cross section through all-epitaxial thin-film bipolar transistor.

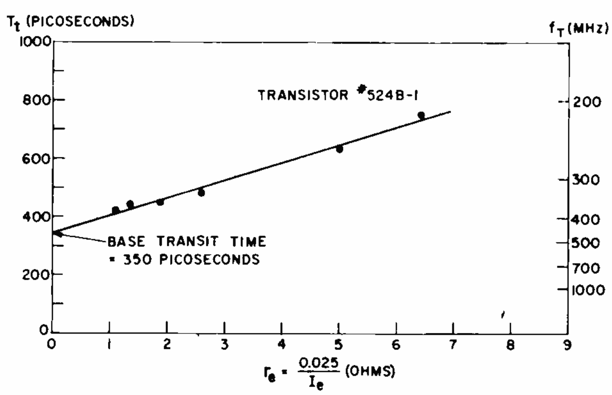

Fig. 7—High-frequency transistor measurements.

and/or closely spaced junctions. This means a higher degree of perfection in the single crystal silicon film.

After experiments with several methods of making bipolar transistors including vertical junctions, an epitaxially grown junction version[5] was chosen. By consecutively growing N^+NPN^+ layers quickly, difficulties with diffusion spikes are minimized. A mesa type transistor is then constructed from this type of grown multilayer structure (Fig. 6).

With transistors of this type, a current gain of 25 to 30 has been achieved with a base width of 0.8μm. High frequency measurements (Fig. 7) show an f_T of 350 MHz at 15 mA. Since high speed circuits are the major goal of sos work, close-spaced transistors as described are useful. However, to provide margins of safety an improvement in current gain is desirable. This means an improvement of material and minority carrier lifetime. Several promising methods of improving lifetime are under development such as the use of spinnel as a substrate and the use of getters to remove heavy metal ions. Improvements of a factor of 20 to 40 in lifetime have been achieved so far in single layer films.

High voltage rectifier strings and diode circuits

The processing of diodes in silicon-on-sapphire is simple and straight-forward with no difficult problems.[8] With the sos construction there is no possibility of breakdown to the substrate and cooling is efficient. Consequently, high voltage operation is possible. Fig. 8 shows a combination of the parallel connection of several series strings of 50 diodes that gives a high degree of redundancy and consequently a high yield of usable devices. This combination when operated as a high voltage rectifier will withstand 14,000 volts reverse bias and deliver several milliamps in the forward direction.

An adjustable read-only diode memory is now being designed at the request of the computer memory group in Camden. The sos technology is necessary to meet the speed requirements. One place where isolated diodes on an insulating substrate can do things that cannot be done conveniently by other means is in the addressing of liquid-crystal displays. An integrated circuit consisting of diodes and capacitors has been designed to address a liquid crystal display and is being constructed. [*Editor's note:* the paper by Dr. G. Heilmeier in this issue, describes the liquid crystal effect].

Plasma emission of light

An interesting new phenomenon has been observed: the emission of visible light from an extended plasma[9] formed in silicon-on-sapphire diodes. If the diodes in the string previously shown (Fig. 8) are reverse biased and the reverse voltage is gradually increased the usual microplasma breakdown is observed as shown in Fig. 9a. As the reverse voltage is increased, the light emitting region continually increases until it extends from the cathode to the anode as shown in Fig. 9b. The emitted light is white and is easily visible in room illumination. The extended plasma is formed when the diode goes into what is called "second breakdown", as is evident from V-I oscillograph traces. The emission of light shows a lag of 1μs, which is about the thermal time constant of the diodes. The light goes off in nanoseconds, i.e. as quickly as the "second breakdown" current decays. The light-emitting plasma is stable and we have run it over a weekend with no noticeable change. It is interesting that this mode is stable whereas in ordinary transistors destruction usually occurs. The plasma can be stable in silicon-on-sapphire because of the cooling provided by the sapphire and the current limiting due to the resistance of the film. The light is bright because most of it can get out whereas in the usual bulk device it is absorbed by the surrounding silicon.

The phenomenon can be used in any place where a small high-speed visible light source is desired that can be formed into strings or integrated into various shapes for print-out or similar applications.

The most significant results of the studies of the light-emitting plasma may very likely be contributions to the understanding and controlling of "second breakdown" in silicon. "Second breakdown" is an important limitation in all high voltage transistors. The silicon-on-sapphire construction allows one to dissect and examine in detail the physics of "second breakdown" under controlled conditions. Normally, "second breakdown" is a destructive phenomenon hidden inside a regular transistor and direct observation of what is happening is very difficult.

Present technical status

Silicon films 2μm thick at a doping density of about $10^{16}/cm^3$ with a hole mobility of 250 cm^2/volt-sec and an electron mobility of 750 cm^2/volt-sec can be reproducibly grown. At a thickness of 6 μm hole mobility increases to 350 cm^2/volt-sec. The silicon films have been continually improved and good, controlled-resistivity films are now available from G. Gottlieb and G. Cullen of the Process and Materials Applied Research Laboratory. The low

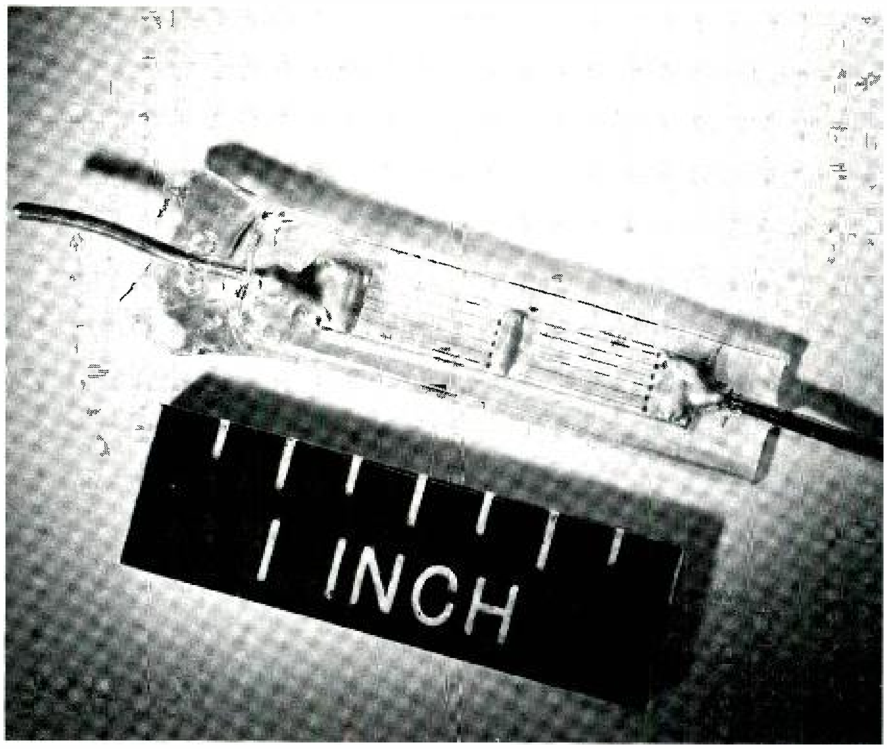

Fig. 8—14,000-volt rectifier.

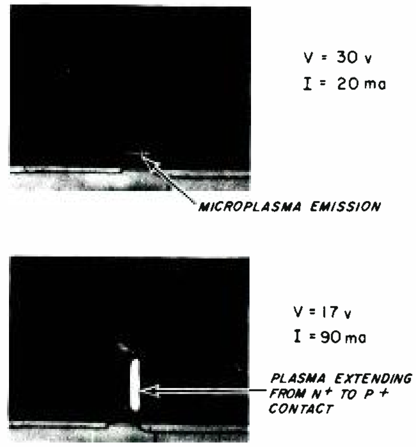

Fig. 9—Microplasma and extended plasma light emission.

temperature processing developed by J. Scott of the Integrated Circuit Facility produces good complementary MOS devices with considerably fewer operational steps than are used in bulk silicon devices. Because the mobility is usually within 25% of bulk silicon values and the capacitance is from 1 to 2 orders of magnitude less, faster circuits can be made than by any other process by a factor of three minimum.[10]

The major factor that still causes trouble is that shorts occur when thin metal strip interconnections pass over oxidized steps in the silicon film. This difficulty is related to etching and photo-resist technology at the steps. Several approaches are being worked on to solve this problem and it does not appear to be a fundamental or insolvable problem. Consequently the status appears to be one in which techniques are available that give results not attainable by other means but with initial costs that may be higher. (Finished product and not wafer costs are the factors that must be compared). Consequently applications must be such that the user will pay for the increased performance.

Economics and future applications

For advice on what the customer will pay for, we rely on the guidance of the Laboratories' personnel in the Data Processing Applied Research section who in turn are in contact with the appropriate product divisions. It is their opinion that a computer user will want and pay for the additional speed. This is especially important because of the increased use of time sharing methods.

The economic factors governing SOS circuits are not easy to evaluate exactly. Since the amount of silicon actually used for active devices is very small the process of growing a large crystal, cutting, polishing, growing epitaxial layers, diffusion of deep wells of opposite conductivity type, and diffusing isolation strips seems an extremely round-about process that grew up because no one knew how to grow good silicon on a good insulator. At present we can grow four epitaxial layers (N^+NPN) directly on sapphire or spinel. The cost of sapphire has been steadily decreasing and since polishing is about 80% of the cost, the use of spinel in quantity will greatly reduce costs.

One should not compare only initial cost, of course, because the silicon-on-sapphire film requires no additional polishing as well as fewer and shorter device processing steps. High voltage devices can be placed closer together. Actual costs will have to be evaluated when more data on such factors as yield of good circuits becomes available. In fact, present indications are that cost will be set by yield rather than by materials cost as is so frequently the case for complicated circuits.

References

1. Manasevit, H. M., Miller, A., Morritz, F. L., and Nolder, R., "Heteroepitaxial silicon-aluminum oxide interface. Part 1—Experimental evidence for epitaxial relationships of single-crystal silicon on sapphire; an overview of the gross mechanism" *Trans. Met. Soc. AIME* 233 (1965) p. 540; Nolden, R., and Cadoff, I., "Heteroepitaxial silicon-aluminum oxide interface. Part 2—Orientation Relations of single-crystal silicon on alpha aluminum oxide" *Trans. Met. Soc. AIME* 233 (1965) p. 549; Joyce, B. A., Bennett, R. J., Bicknell, R. W., and Etter, P. J. "Epitaxial deposition on quartz and aluminum" *Trans. Met. Soc. AIME* 233 (1956) p. 556.
2. Dumin, D. J., and Robinson, P. H., "Carrier transport in thin-silicon films" *J. Appl. Phys.* 39 (1968) p. 2759.
3. Page, D. J., "Thermal Limitations of the thin-film transistor," *Solid State Electronics* 11 (1968) p. 87.
4. Allison, J. F. Heiman, F. P., and Burns, J. R., "Silicon-on-sapphire complementary MOS memory cells" *IEEE J. of Solid State Circuits* 2 (1967) p. 208.
5. Heiman F. P., and Robinson P. H., "Silicon-on-sapphire epitaxial bipolar transistors," *Solid State Electronics* 11 (1968) p. 411.
6. Heiman, F. P., "Thin-film silicon on sapphire deep depletion MOS transistors" *IEEE Trans. Electron Devices* ED-13 (1966) p. 855.
7. Mueller, C. W., Robinson, P. H., and Rosenblum, R. S., "Compatible active thin-film integrated structures" *Technical Report AFAL-TR-67-331.*
8. Dumin, D. J., and Silver, R. S., "Diffused diode in silicon-on-sapphire," *Solid State Electronics* 11 (1968) p. 353.
9. Dumin, D. J., "Emission of visible radiation from extended plasmas in silicon diodes during second breakdown" (to be published).
10. Burns, J. *private communications.*

Acknowledgment

The research described here is the work of many persons at the RCA Laboratories and especially those listed in the references.

High resolution television images from space

M. V. Sullivan | F. H. Eastman III

This paper describes a television system capable of producing images with 5000 TV lines resolution. A proposed application for this system is in the Earth Resources Observation Satellite where three cameras will observe the earth to provide high resolution multispectral TV pictures of world resources. The key components in this high-resolution TV system are the 2-inch return-beam-vidicon (RBV) camera for space-born use and the laser-beam image reproducer (LBIR) for ground recording on film. The primary assets of the RBV are improved signal-to-noise ratio, higher sensitivity, and greatly improved resolution. Since the scanning spot of present cathode ray tubes is not small enough with sufficient brightness to produce an image of 5000 TV lines, a laser-beam image reproducer was developed. The LBIR is an electro-optical-mechanical device for recording images on 9½-inch film.

TIROS, RANGER, NIMBUS, AND ESSA spacecraft have successfully obtained television images from space using 1-inch vidicon cameras. On the ground, the video signal is displayed on a cathode ray tube and photographed with a film camera. The resolution obtained in these systems is 800 TV lines.

The Earth Resources Observation Satellite is a proposed program to investigate the earth's surface through the use of ultra-high resolution television imaging systems.[1] This satellite is intended to serve as an aid in the discovery, development, and conservation of world resources, thus furthering technology in agriculture, forestry, geology, geography, oceanography, and hydrology around the globe. Such a system must be able to resolve small ground details in the order of 100 feet per TV element in a field of 100 x 100 miles from an altitude of approximately 500 miles.

To accomplish this task, the sensor used must have resolution and sensitivity characteristics an order of magnitude greater than the sensors used in current programs. The return beam vidicon (RBV), which is a type of image sensing vacuum tube that converts optical images into varying electrical signals, is capable of producing the resolution required in this program. For the ground display facility, a laser-beam image reproducer (LBIR) has been developed to record on film all of the video data from the RBV camera without compromise in resolution.[2,3] A diagram of this proposed space imaging system is presented in Fig. 1.

To obtain multispectral information, three shuttered cameras would simultaneously image the same area of earth at different portions of the spectral band: green, red, and near infrared filters should be used. Each shutter is a focal-plane mechanical type that is electronically triggered. Five-inch f/2.8 lenses are used in the camera optics. The vidicon photoconductors store the images while each camera is read out sequentially. Video signals can then be transmitted directly to ground or stored in the wideband tape recorder for later playback.

Return beam vidicon

The primary assets of the 2-inch RBV camera are improved signal-to-noise ratio, higher sensitivity, and greatly improved resolution. The 2-inch diameter of the tube provides a large target area (1 inch square) and the modulated return beam provides the signal. The sensor operates with a shuttered lens and the high image retention characteristic of the photoconductor makes possible the slow scan readout of a high definition nonsmeared image.

The RBV utilizes a standard *ASOS* vidicon photoconductor and a multiplier gun structure similar to that of the image orthicon (Fig. 2). The electron gun consists of a thermionic cathode, a control grid (*G1*), and an accelerating grid (*G2*). The stream of electrons emitted by the cathode produces a low velocity electron beam

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which is deflected vertically and horizontally across the photoconductor by external transverse electromagnetic fields. The electron beam is focused on the sensing layer by a combination of the electrostatic field formed by the wall (*G4*) electrode and the axial electromagnetic field produced by the external focusing coil.

The *G5* electrode adjusts the shape of the decelerating field to obtain uniform landing of the electrons over the sensing layer. Major variations in beam angle may be corrected for by use of an external alignment coil which produces two transverse magnetic fields at a 90° angle over the gun aperture. A fine screen, high transmission decelerator mesh, spaced close to the target, is used to create a high-gradient decelerating field between the mesh and sensing layer. This field eliminates the varying radial components which the beam may experience in different parts of the scanning raster, thus providing an orthogonal beam landing angle.

The sensing layer (target) consists of an optically flat glass faceplate, a transparent metallic conducting film called the signal plate, and the photoconductor. The photoconductor is a light sensitive substance which may be analyzed as a number of discrete elements, each consisting of an incremental capacitance shunted by a variable resistance. The low lateral leakage of the surface permits a high definition pattern to be retained on the photoconductor surface. The magnitude of the shunt resistance is inversely proportional to the incident light on the photoconductor surface, approaching an open circuit for no light and a short circuit for high intensity illumination. A typical storage characteristic of the RBV is presented in Fig. 3 (the storage time can be modified if desired). The spectral sensitivity of the *ASOS* photoconductor is shown in Fig. 4. Superimposed on the curve are the three spectral regions of interest.

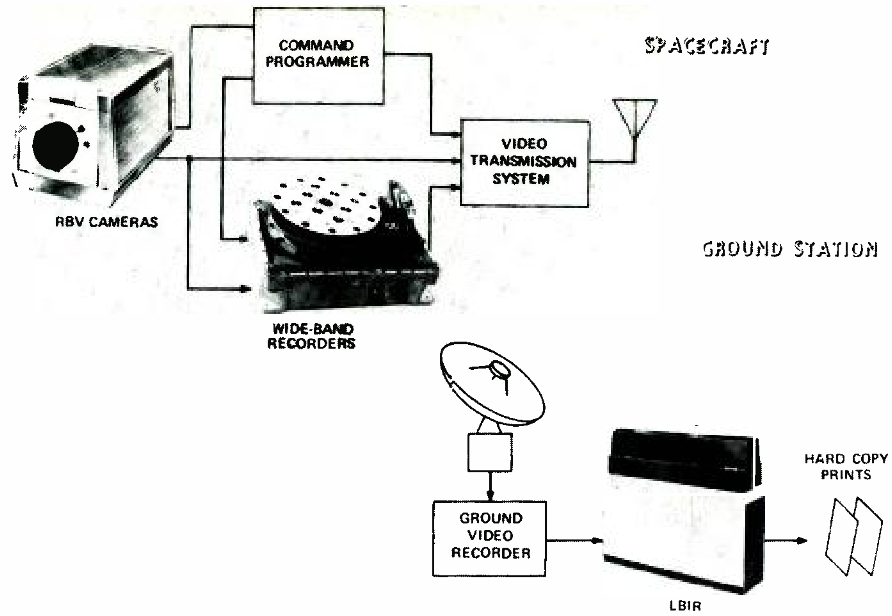


Fig. 1—High-resolution television imaging system.

RBV operation

Before exposure, the photoconductor surface undergoes a preparation cycle whereby any residual image is removed. This is accomplished by flooding the photoconductor with light and scanning with maximum beam current to impress a charge across the photoconductor. The beam deposits electrons on the scanned surface charging it down to gun cathode potential.

The beam is cut off, and, typically, the photoconductor is exposed for 1.5 to 5 ms. During exposure, the imaged optical pattern is transformed into a charged pattern on the gun side of the photoconductor. The dark areas remain at cathode potential while the highlight areas discharge towards the more positive target potential.

During the read cycle, the beam scans the target and charges each incremental element toward cathode potential. In the dark areas, the target acts like an electron mirror reflecting all impinging electrons. In areas where the target potential is higher due to the image charge pattern, the target becomes partially absorbent and the electrons land. This absorption causes a negative amplitude modulation of the return beam, which is greatest in the highlight areas of the pattern.

The modulated return beam is collected at the first dynode of a secondary emission electron multiplier (Fig. 2). The modulated portion of the amplified return beam out of the five-stage multiplier becomes the video signal.

Signal-to-noise ratio

In normal vidicon operation, the electrons absorbed by the sensing layer produce a signal current which is sensed through a load resistor. At low light levels, the signal current is exceedingly small and the sensitivity of the device is limited by the noise of the preamplifier. Even the low-noise-figure field-effect-transistor preamplifiers in use today produce a fixed noise current, which is significantly greater than the signal current at the light levels of interest. However, in the RBV, the signal-to-noise (S/N) is primarily determed by the shot noise of the modulated return beam. Several factors affecting the magnitude of the beam current must be considered.

Although a low velocity beam (for which the secondary emission ratio is less than one) is used to scan the photoconductor, some electron scattering occurs at the sensing layer due to beam-landing errors and the irregular photoconductor surface. These electrons contribute to the total beam current collected at the dynode, but not to the signal current.

The percentage of beam (signal) current absorbed is a function of the charge on the photoconductor. Also, if the fact is considered that, even in the case of a totally reflected dark current beam, not all the electrons are collected by the multiplier, then it becomes apparent that the usable signal current is only a small percentage of the total return beam. Thus, when all factors are considered, the total gain in signal amplitude through the multiplier section, when compared to that of the signal present at the photoconductor, is equal to the product of the multiplier gain, the mesh transmission, and the percent beam modulation. Typical values for these parameters are as follows:

Mesh transmission	40%
Return beam modulation	10 to 30%
Multiplier gain	100

Therefore, the peak-to-peak signal at the anode of the multiplier is approxi-

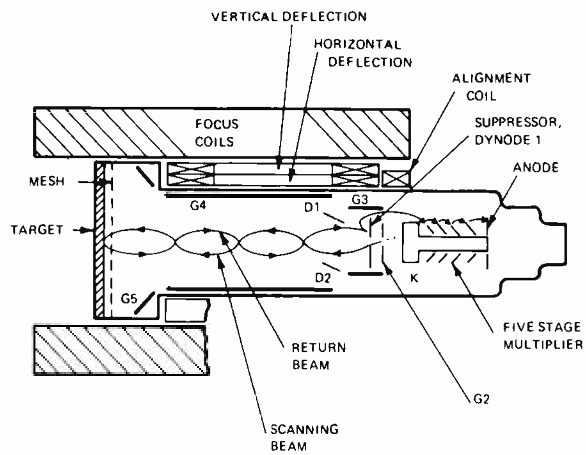


Fig. 2—Return beam vidicon (RBV) schematic diagram.

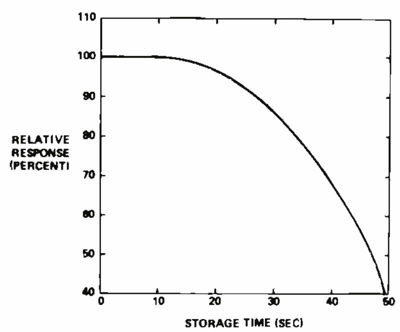


Fig. 3—2-inch RBV storage characteristics.

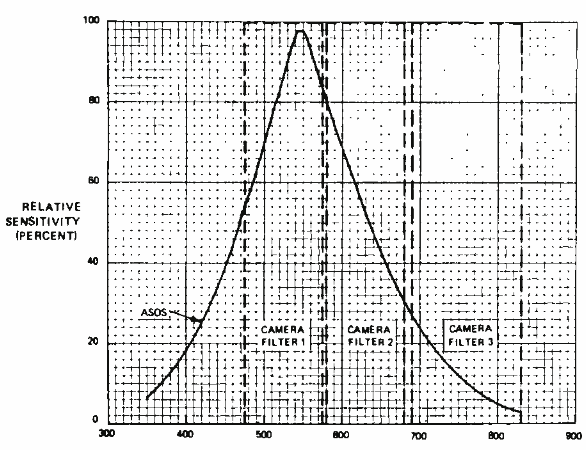


Fig. 4—Spectral sensitivity of ASOS photoconductor.

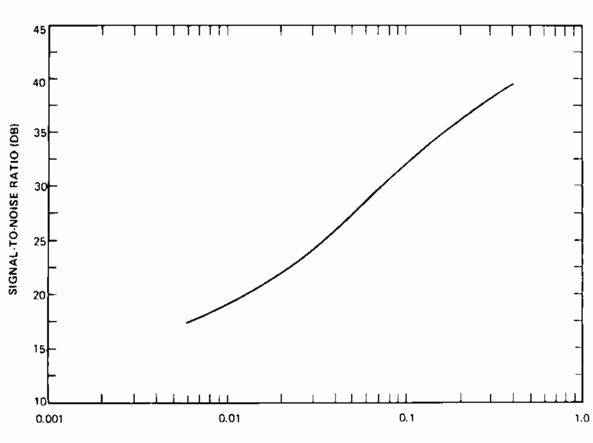


Fig. 5—S/N vs exposure for RBV camera.

mately ten times the signal present at the sensing element.

The shot noise of the return beam becomes the major portion of noise, and the RBV S/N is proportional to $I_s/I_b^{1/2}$, where I_s is the useful signal current and I_b is the total beam current.

Any technique which reduces the total beam current results in improved S/N. The slow scan mode of operation offers one method of reducing the beam current since less beam current density is required to discharge the highlights at slow scanning rates.

The mere presence of the multiplier results in greater sensitivity at any given illumination. Again, this permits further reduction of the beam current and a corresponding increase in S/N as less illumination is required for a given output signal. Fig. 5 presents a curve of S/N versus exposure for the 2-inch RBV camera.

Resolution

The high resolution capability of the *ASOS* target can only be realized by obtaining a precise relationship between the beam and the electron optics. If resolution is defined as the number of black and white lines which can occur in either the horizontal or vertical dimension of the format, then the ultimate number of lines which can be resolved is limited by the spot size of the beam. The spot size is in turn dependent on the focusing ability of the electron optics, the diameter of the aperture in the accelerating grid, and the current density available in the beam for discharging the highlights.

Dr. O. H. Schade, Sr.[4] has demonstrated that the size of the scanning beam is directly proportional to the beam current. The peak signal current is proportional to the number of electrons which land and discharge the highlights on a given incremental element. Slow-scan operation permits the beam current to be reduced while maintaining the number of landing electrons constant. Thus, a smaller spot and higher resolution can be obtained.

The resolution of the 2-inch RBV is specified as 4500 TV lines with 80% corner resolution. In the laboratory, 6000 lines have been measured on some tubes. These numbers reflect limiting resolution when the measurements are made with high contrast test patterns. The modulation transfer function (MTF) of the camera, with response plotted against spatial frequency, is shown in Fig. 6. This curve is the result of measurements made on one return beam vidicon using white light. The response of the Tropel test lens is included in the MTF curve. The performance characteristics of the 2-inch RBV camera are tabulated below:

Resolution	4500 TV lines
Horizontal rate	1200 lines/sec
Vertical time	5 seconds
Video bandwidth	4 MHz
Dynamic range	100 to 1
Aspect ratio	1 to 1
Shutter time	0.0015 to 0.01 seconds
High light exposure	0.1 foot-candle seconds

Laser-beam image reproducer

To record the high resolution image produced by the RBV, a laser-beam image reproducer (LBIR) has been developed.[3] The scanning spot of present cathode ray tubes is not small enough with sufficient brightness to produce an image of 5000 TV lines. The LBIR is an electro-optical-mechanical device for recording television images on film. A block diagram of the LBIR is shown in Fig. 7; the LBIR performance specifications are tabulated below:

Image format	9 x 9 inch image Single frame
Image quality	
Resolution	75% response at 6000 lines
Tone reproduction	13 √2 gray steps
Density uniformity	2%
Linearity	0.5%
Recording rate	
scanning	1200 lines/ second
frequency response	5 MHz within ±0.5 dB

Basically, the LBIR consists of a light source, a modulator that modulates the intensity of the light with the video signal, optics to focus the beam on the film, a mechanical-optic scanner to deflect the beam and to produce horizontal scan lines, and a transport to obtain the vertical movement of the film.

The light is generated by a 20-mW Helium-Neon gas laser, and it is a coherent red light at 6328 Å. The polarized 1-mm diameter beam of light passes through a crystal modulator that is driven by the amplified video signal.

The light modulator consists of a pair of ferro-electric ADP crystals. The application of an electrostatic field essentially causes a rotation of the polarization of the light passing through the crystals. The degree of polarization rotation is dependent on the voltage applied. The light then passes through a fixed polarizer (analyzer), and the resulting intensity is a function of the degree of polarization rotation experienced in the light modulator.

The transfer modulation characteristic of the modulator is that of a cosine-squared function. Thus, video signal processing is provided to compensate for this nonlinearity as well as correcting for the gamma of the camera and film.

After modulation, the beam is collected, enlarged, deflected 90° from the optical axis, scanned, and focused on the film as an 0.8-mil high density recording spot. The scanning device is a four-sided pyramidal beryllium mirror that is fastened to the shaft of a synchronous motor. The beam is enlarged to fill the entire area of the scanning mirror to obtain negligible shading. The imaging lens has a 1.5-inch diameter and an f-number of 8.5. The laser beam is deflected perpendicular to the axis of rotation by each of the four mirror faces, which form a 45° angle with the axis of rotation. The image plane is curved, and conforms to a portion of a cylinder with a radius of approximately 6 inches. Cut film 9½ by 9½ inches is located in the cylinder section, which serves as the transport for the film, and is held in place by vacuum.

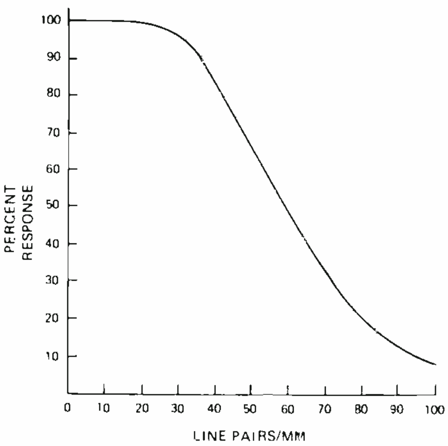


Fig. 6—Modulation transfer function of RBV including lens.

The rotating scanning mirror moves the spot across the width of the film to form a horizontal scan line. As one line is completed, the next line is produced from the adjacent mirror face. The scanning drive is an air bearing hysteresis-type synchronous motor that runs at 18,000 r/min; it is servo-controlled to synchronize the scanning lines to the video signals. The film carriage is synchronized to the video frame and is moved at a constant velocity to provide vertical scan. The carriage is an air table moved by a

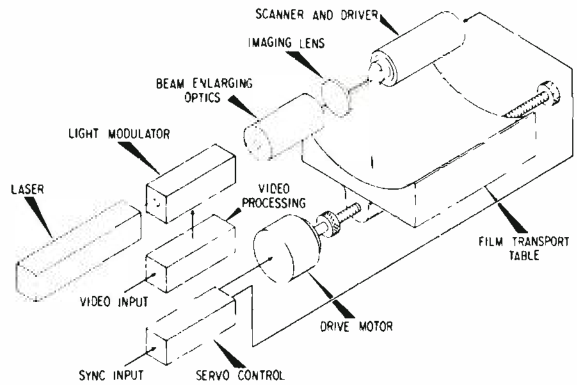


Fig. 7—Laser beam image reproducer.

precision ball-screw and nut driven by a servo-controlled motor.

Conclusions

The 2-inch RBV and LBIR combination provides a means of obtaining television images with resolution far in excess of what has been possible in the past. Fig. 8, which is a picture taken through the RBV and LBIR systems, illustrates the effectiveness of the combined systems.

The current 4500 TV line capability of the RBV/LBIR system has demonstrated the feasibility of this new approach to high resolution imagery. Further improvement in the RBV is certainly a possibility, for larger sensors are presently under investigation to obtain even greater resolution. Concurrently, since the spot size of the LBIR can readily be reduced, and techniques are available for handling greater bandwidths; the performance of the LBIR can also be improved. Plans are underway to incorporate a completely automatic continuous motion film unit including processing into the LBIR.

Acknowledgments

The authors are indebted to Dr. O. H. Schade, Sr. for his initial work in the development of the RBV cameras, to D. Woywood and G. Burton for the development of the LBIR, and to the many other members of the RCA team that developed this high resolution television system.

References

1. Gurk, H. M., Miller, B. P., "An earth resources satellite," RCA ENGINEER, Vol. 14, No. 5 (Dec 1968-Jan 1969) pp. 78 to 82.
2. Burton, G. T., *Laser-beam image reproducer*, second annual wideband analog recording symposium, Technical Report No. RADC-TR-68-201, Vol. 1 (Jun 1968) pp. 75 to 85.
3. Woywood, D. J., "Laser recording systems," RCA ENGINEER, Vol. 13, No. 6 (Apr-May 1968) pp. 58 to 61.
4. Schade, O. H., Sr., "The resolving power functions and quantum processes of television cameras" *RCA Review* Vol. 28, No. 3 (Sep 1967).

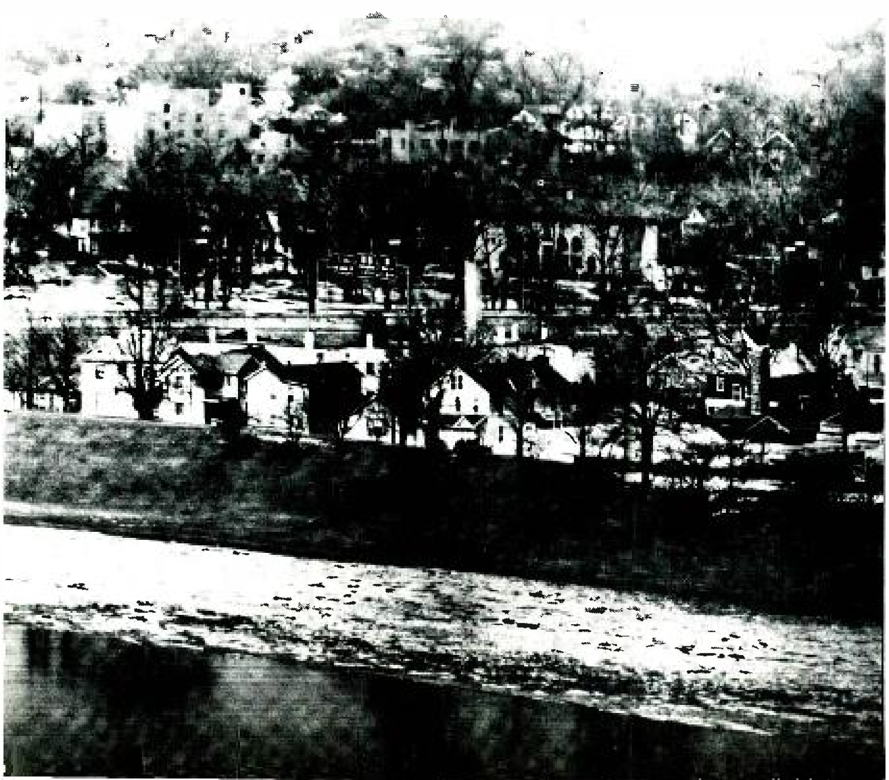
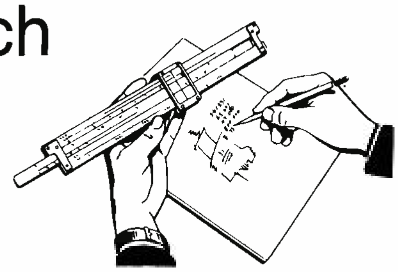


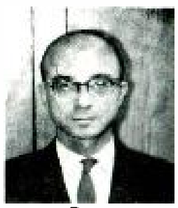
Fig. 8—An outdoor city scene taken from the 15th floor window of a building in Dayton, Ohio.

Engineering and Research Notes



Brief Technical Papers of Current Interest

Integrated parametric amplifiers with IMPATT-diode pumping


Bura


Pan


Yuan

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Hybrid integrated parametric amplifiers (paramps) have been developed for different S-band frequencies. The amplifier circuits were etched on a 1×1-in. copper-on-alumina substrate. Voltage gain-bandwidth products of 800 MHz and noise figures as low as 1.2 dB were measured. An IMPATT-diode oscillator was used as the pump source. The paramp noise problem due to the IMPATT oscillator was determined and remedied.

Microwave integrated circuits, using microstrip on an alumina dielectric, offer considerable size and cost reductions in the construction of parametric amplifiers, without any sacrifice in performance.

A hybrid integrated 1.8-GHz paramp was first described by P. Bura, et al.[1] The design equations are:[2]

$$G=(R_g+\beta-R_1)/(R_g-\beta+R_1) \qquad (1)$$

Glossary

- G Available power gain (reflection type);
- R_g Generator resistance at varactor terminals;
- R_1 Signal circuit resistance, including varactor series resistance R_s;
- m_1 Elastance modulation ratio;
- f_c, f_s, f_i Cutoff, signal, and idler frequencies, respectively
- R_2 Idler circuit resistance
- β $\dfrac{m_1^2 f_c^2 R_s^2}{f_s f_i R_2}$

For any required gain, G, the required varactor loading resistance, R_g, can be found as a function of the varactor and circuit parameters and the operating frequencies. The bandwidth, B, is given by:

$$B=\frac{R_1+R_g-\beta}{\dfrac{R_1+R_g}{B_s}+\dfrac{\beta}{B_i}} \qquad (2)$$

where B_s and B_i are the loaded signal and idler bandwidths, respectively. The noise-figure expression is given by:

$$F=1+\{(G-1)/G\}\{[(f_s/f_i)\beta+R_1]/(\beta-R_1)\} \qquad (3)$$

The design requirements are then summarized by:

1) Resonate the varactors at the signal, idler, and pump frequencies;
2) Provide correct loading, R_g, at the signal frequency;
3) Provide a ground return for the idler current;
4) Match the pump source to the varactor; and
5) Isolate the three circuits from each other.

The design of the 1.8-GHz paramp is shown in Fig. 1. It was designed for low-power pump operation, which was achieved by operation with zero bias on the varactor. Pump power requirements in all designs described are low enough to permit use of an IMPATT-diode source. The idler frequency was chosen to be the self-resonant frequency of the varactor. The idler current was returned to ground through a $\lambda/4$ open-circuited stub. This insured, in addition, that no idler current leaked into the signal and pump circuits. The signal circuit was resonated by means of a line length and two capacitive stubs. One of the stubs was $3\lambda/4$ long at the pump frequency, thus preventing pump leakage. The amplifier can be operated with as little as 2-mW pump power for 4-dB gain and a noise figure below 2 dB. For larger pump power, higher gain and a noise as low as 1.2 dB were measured.

Fig. 2 shows the design for a wideband paramp operating at a signal frequency of 2.25 GHz. Bandwidth improvement is achieved by eliminating the idler return stub and using low-impedance stubs in the signal circuit. The idler current return is accomplished by adjusting the distance between the varactor and the pump filter, which appears as an open circuit to the idler frequency. Bandwidths in excess of 150 MHz with 13-dB gain were measured. Further increase in bandwidth can be achieved by double-tuning the signal-input circuit. The noise figure was below 2 dB.

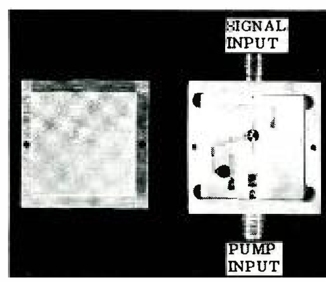

Fig. 1—1.8-GHz amplifier; noise figure = 1.3dB; 3-dB bandwidth = 50 MHz; gain = 16dB; pump frequency = 8.5 GHz; pump power = 5mW.

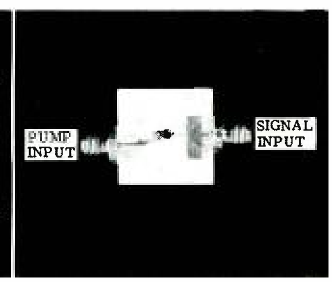

Fig. 2—2.25-GHz wideband parametric amplifier; noise figure = 2.0dB; 3-dB bandwidth = 150 MHz; gain = 12dB; pump frequency = 8.7 GHz; pump power = 16mW.

Fig. 3 shows a 3.5-GHz paramp. It uses a design similar to that of the 2.25-GHz paramp, but since wide bandwidth was not required, higher-impedance stubs were used in the signal circuit. And, since a self-resonant idler circuit again was used, a correspondingly higher pump frequency, 11.5 GHz, was used. A noise figure of 2.5 dB was measured, which included the circulator loss and the contribution of the following mixer stage. Pump power required was 30 mW.

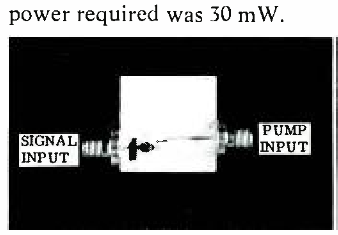

Fig. 3—3.5-GHz amplifier; noise figure = 2.5dB; 3-dB bandwidth = 60 MHz; gain = 13dB; pump frequency = 11.5 GHz; pump power = 30mW.


Fig. 4—3.5-GHz amplifier with IMPATT pump source.

Fig. 4 shows a combined 3.5-GHz amplifier and pump source package. Less than 1 W DC power was required to operate the amplifier.

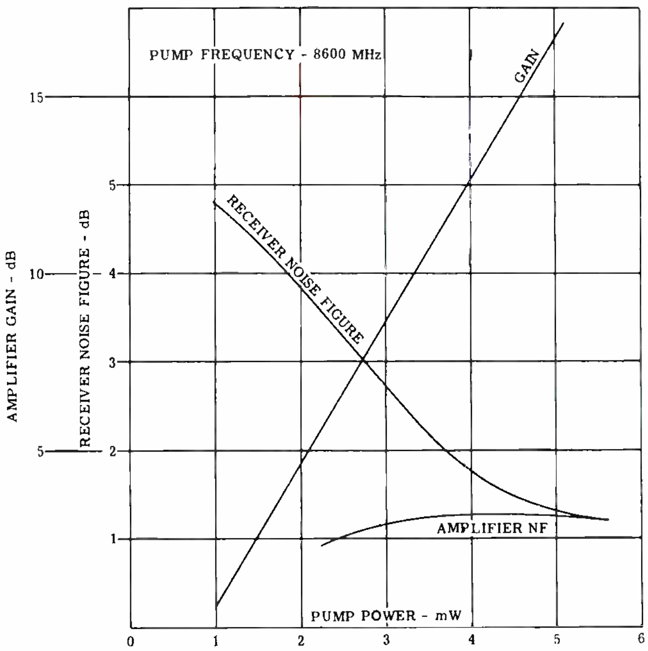

Fig. 5—Gain and noise figure of 1.8-GHz amplifier.

Figs. 5 and 6 show the performance curves of the 1.8 GHz amplifier. The receiver noise figure, as low as 1.2 dB, was measured with a mixer with a 7.0-dB noise figure. To check whether the IMPATT-diode current had any effect on the amplifier noise figure, it was measured at different current values and with an attenuator adjusted to feed a constant 4 mW of pump power to the amplifier. Negligible variation in the noise figure was observed with change in the current, as shown in Fig. 6.

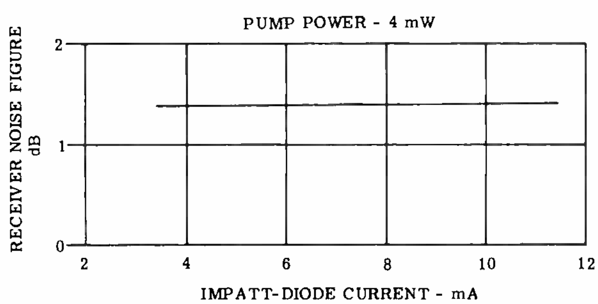

Fig. 6—Noise figure as a function of IMPATT current.

When the IMPATT-diode source was connected directly to the paramp, as in Fig. 4, amplifier performance became very noisy at some local-oscillator (LO) frequencies. This was traced to LO leakage into the paramp, which then produced a corresponding idler frequency. These two components together, through the nonlinear varactor capacitance, influenced the IMPATT-diode oscillator, resulting in "noisy" performance. By improving LO matching in the mixer, or providing additional isolation between mixer and paramp, large noise-figure variations were avoided, resulting in a noise figure as low as that measured with a klystron pump. Similar "quiet" performance was achieved by incorporating isolation between the IMPATT-diode oscillator and the amplifier pump-input port.

References

1. P. Bura, et al, "Design Considerations for an Integrated 1.8 GHz Parametric Amplifier," *IEEE Journal of Solid State Circuits*, Vol. SC-3 (Jun 1968) p. 86.
2. Penfield and Rafuse, *Varactor Applications* (MIT Press, Cambridge, Mass., 1962).

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200-watt solid-state UHF amplifier

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Staiman

Breese

A high power transistor amplifier with an output of 200 W peak at a center frequency of 432 MHz is described. Eight TRW 2N5177 transistors are operated in parallel by means of a network of split-tee hybrid junctions as shown in Fig. 1. The individual amplifier circuits, as well as the hybrid junction network, are etched microstrip circuits on high purity alumina substrates.

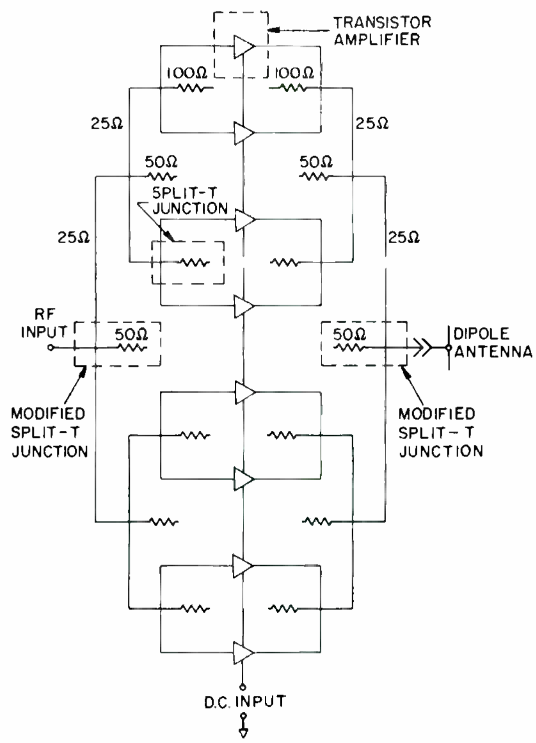
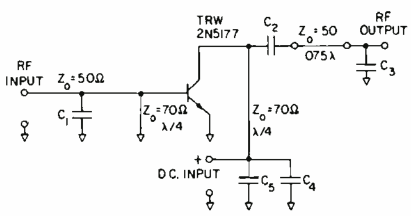


Fig. 1—200-watt amplifier schematic.

The circuit for the individual amplifiers was designed by determining the generator and load impedances required for maximum gain and bandwidth[1], and designing circuits to present these impedances at the transistor terminals. Several iterations are necessary in this procedure since the transistors are operated in a class-C mode to attain high power and efficiency, and the resulting non-linearity causes significant variations in apparent impedance as the operating point is changed. The final circuit is shown schematically in Fig. 2. An important feature of the design is the elimination of tuning adjustments.

Alsimag 772 was selected as a substrate material, with a thickness of 0.025 inch to permit an adequate range of characteristic impedances to be realized with practical widths and tolerable loss. The metallization consisted of vacuum deposited chromium, covered with vacuum deposited gold, and finally electroplated gold to a thickness of approximately 0.0005 inch. To minimize interconnections, substrates of both 1×4- and 4×4-inch dimensions were utilized. A completed 200-W amplifier is shown in Fig. 3. As can be readily observed, in a more refined version, many of the circuit paths could be folded to occupy less area, permitting the use of much smaller substrates. The input matching networks for four transistors, along with three hybrid junc-



C_1 - CAPACITIVE STUB - 33 pF
C_2 - JFD UNICERAM 300 W.V (UYO2121J)-120 pF
C_3 - CAPACITIVE STUB - 15.6 pF
C_4 - SPRAGUE GMV-TYPE BUTTONHEAD (BH240)-1000 pF
C_5 - ELECTROLYTIC 60 WV (CL65CK040KP3)- 4 μF

Fig. 2—Microstrip amplifier schematic.

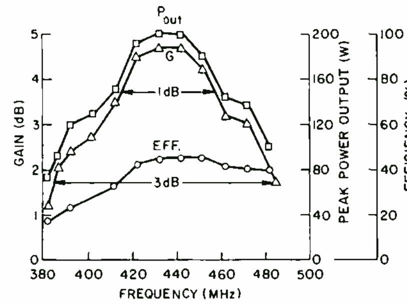


Fig. 4—200-watt amplifier performance.

tions, are etched on a 4×4-inch substrate. Two such substrates together with a 1×4-inch substrate for the input hybrid junction complete the input circuit from a 3-mm connector. The output is similarly formed by three separate substrates. The interconnecting lines in the power dividing/combining networks have a characteristic impedance of 25 ohms to reduce losses and permit tighter control of tolerance. The input and output hybrid junctions are of modified design, including a half-wavelength line to the resistive termination, to provide a symmetrical circuit while permitting the utilization of separate substrates as shown. The terminating resistors and the blocking capacitors in the output are mounted on the microstrip circuit by soldering to small pads. The output connection is by means of a right-angle coaxial adapter, with the center conductor penetrating a small hole in the ceramic, in order to facilitate driving a dipole on the opposite side of the common ground plane structure.

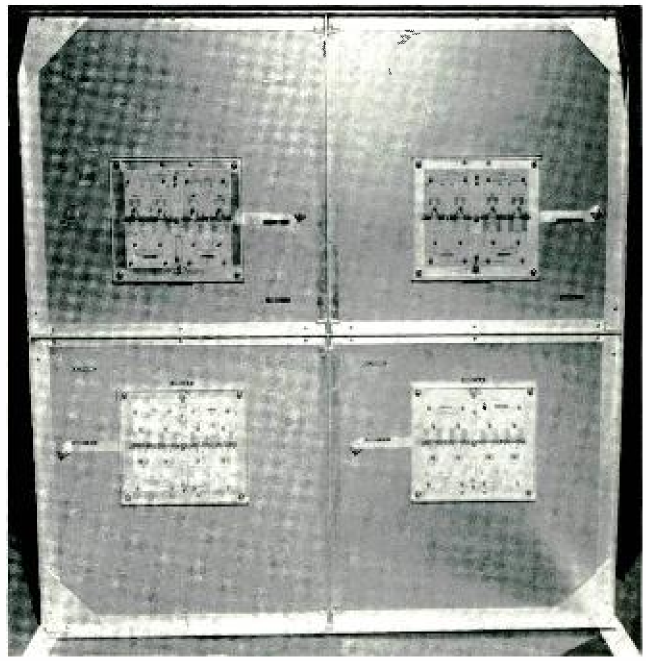


Fig. 5—800-watt array.

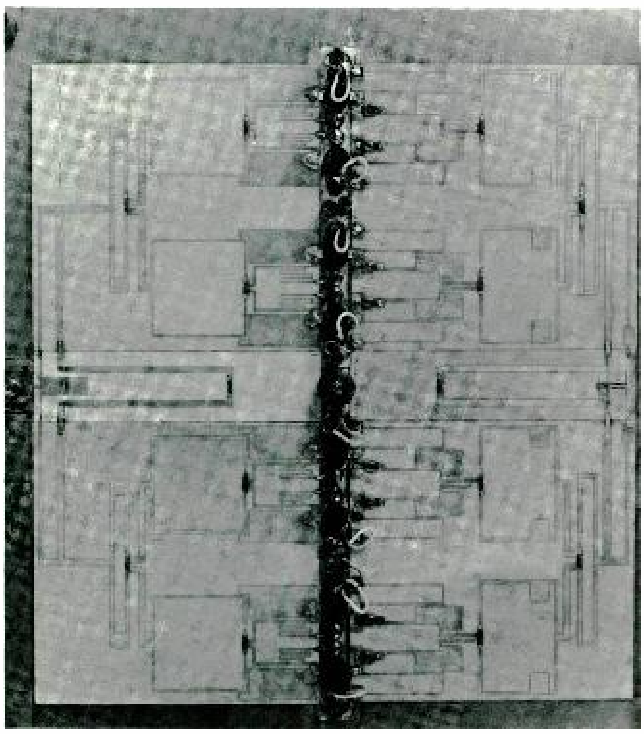


Fig. 3—200-watt amplifier.

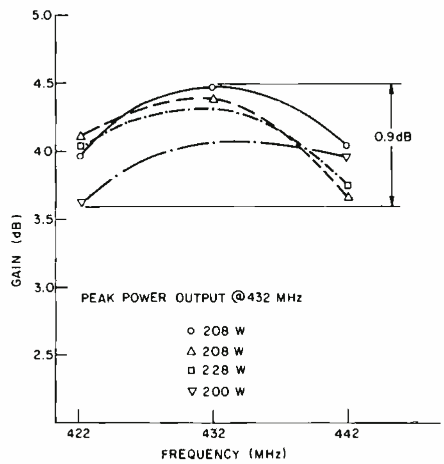


Fig. 6—Comparison of four amplifiers.

The data obtained from a breadboard amplifier are shown in Fig. 4. The 1-dB bandwidth exceeds 35 MHz, with a 3 dB bandwidth of nearly 100 MHz. The DC to RF conversion efficiency is over 40% at center frequency. These data were measured at a pulse width of 50 μs and a repetition rate of 500/second. One of the advantages of the design is the capability to utilize an unmodulated collector voltage and obtain the pulsed output by simply using a pulsed drive signal. The transistors were operated at a collector voltage of 36V.

Four 200-W amplifiers were fabricated and assembled as a broad side transmitting array as shown in Fig. 5. The radiating elements are half-wavelength dipoles spaced slightly less than one wavelength for maximum gain. The four amplifiers were measured individually with the results shown in Fig. 6. Over the design band of 422 to 442 MHz all exhibit gain within a total spread of 0.9 dB. (The difference in measured output power was due to difficulty in exactly re-setting the drive power level.) Gain for the amplifiers operating in the four-element array was measured by far field intensity measurements relative to an identical array without amplifiers. This gain was 4.38 dB at 432 MHz, demonstrating excellent phase uniformity.

Acknowledgment

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Reference

1. H. C. Lee "Microwave Power Transistors", WESCON, 1966.

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High-power solid-state TR switch

W. W. Siekanowicz
D. J. Blattner
T. E. Walsh
R. W. Paglione
Electronic Components
Princeton, New Jersey

From left to right are Walsh, Paglione, Blattner, and Siekanowicz.

A new type of transmit-receive (TR) switch that improves the noise figure, life, and reliability of radar receivers has been developed by the Microwave Applied Research[1] group of Electronic Components. These improvements result from the use of ferrite phase shifters, instead of a gas discharge tube, in the new device. The new switch, which operates at C-band, provides

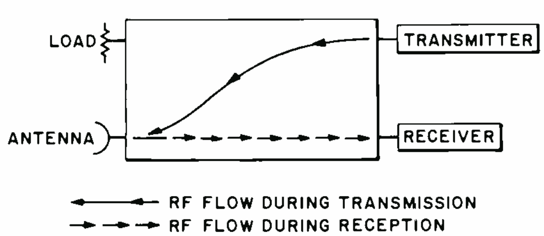


Fig. 1—Simplified schematic diagram of TR switch.

essentially constant isolation and insertion loss over a wide temperature range, independence of isolation and loss with respect to power at levels up to 130 kw, and full receiver protection against driver failure or antenna breakdown.

The switch consists of a 3-dB waveguide power divider, followed by a dual waveguide containing the ferrite phase shifters and a second 3-dB coupler for reconstitution of the output signal. When the ferrites are latched to the desired phase, RF signals are made to travel either straight through or diagonally through the switch, as illustrated in Fig. 1. The ferrites are latched to carry power diagonally through the switch when the transmitter is to be connected to the antenna. When the receiver is to be connected to the antenna, the ferrites are latched to permit power flow directly through the switch. This latching is performed in less than a microsecond by application of a short pulse of current through a wire threading the ferrites. The energy required to switch from one condition to the other is only about 150 microjoules.

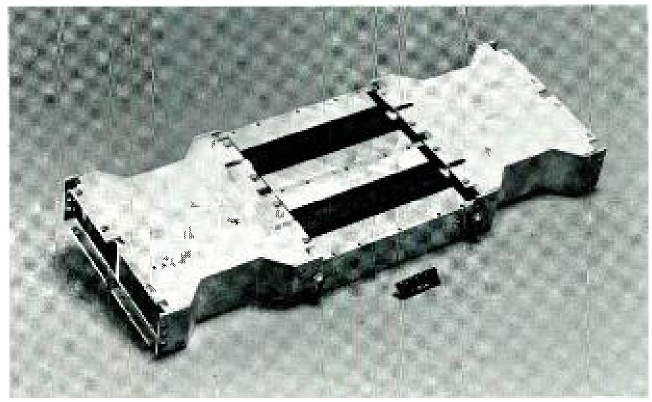


Fig. 2—TR switch with cover removed.

Fig. 2 is a photograph of the switch with its cover removed to show the ferrite-loaded dual waveguide section. The width of the waveguide is reduced in the toroid region to eliminate spurious modes. For receiver isolation of 40 dB, the VSWR at the ferrite must be 1.02 or less. Such low reflections are achieved by a combination of quarter-wavelength impedance transformers and trimming screws. (The screws are not visible in Fig. 2.)

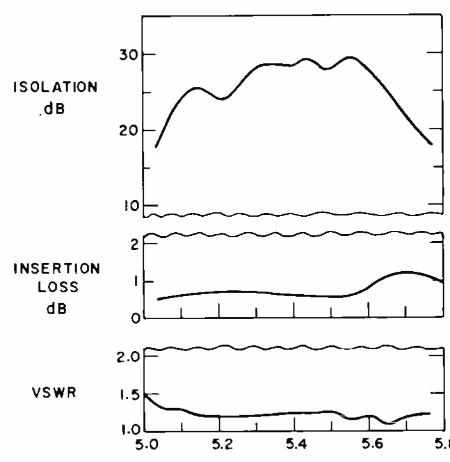


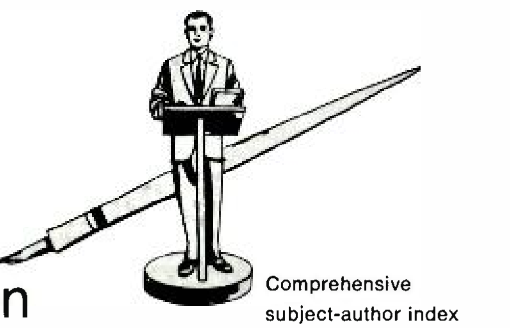
Fig. 3—TR switch performance.

The performance of the switch is shown in Fig. 3: isolation is greater than 20 dB, insertion loss less than 1 dB, and VSWR below 1.5 over a 12% bandwidth. Temperature-chamber measurements have shown that isolation varies less than 3 dB, and insertion loss remains unchanged, over the temperature range from −40°C to +75°C. Further details of the design and performance of this TR unit are reported elsewhere.[2] Its development was supported and encouraged by the RCA Aviation Equipment Department.

References

1. Sterzer, F., "The Microwave Applied Research Laboratory", *this issue.*
2. Siekanowicz, W. W., Blattner, D. J., Walsh, T. E., Paglione, R. W., "A temperature-stable, Fail Safe, Latching Ferrite TR Switch", *IEEE Trans. on MTT.*

Repr nt RE-15-2-29 (ST-4003) | Final manuscript received May 6, 1969.



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SEALED-OFF He^3-Cd^{114} LASER, Characteristics of a—J. R. Fendley, I. Gorog, K. G. Hernqvist, C. Sun (EC, Pr) IEEE Laser Applications Conf., Washington, D.C.; 5/26-28/69

SINGLE-FREQUENCY ARGON LASER—L. Gorog, F. W. Spong (Labs., Pr) *RCA Review*, Vol. 30, No. 2; 6/69

SMALL-OBSTACLE DETECTION SYSTEM for High Speed Train Roadbeds, An Automatic Laser—B. Clay, E. Kornstein, N. Luce, H. Wetzstein (ASD, Burl) F. Bernstein, L. Conant, J. Heck (Labs., Pr) 1969 IEEE Conf. on Laser Engrg. and Applications, Washington, D.C.; 5/27/69

THREE-TERMINAL GUNN DEVICES by Optical Means, Frequency Modulation of—F. P. Califano (Labs., Pr) *IEEE Trans. on Electron Devices*, Vol. ED-16, No. 1; 1/69

UNDERWATER LASER COMMUNICATIONS—H. Wetzstein (ASD, Burl) *Oceanology Yearbook*, 1969

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PUBLISHING THE RESULTS OF RESEARCH A. From the Viewpoint of the Scientist. B. From the Viewpoint of Management—C. W. Sall (Labs., Pr) American Management Association, New York; 5/6/69

TECHNOLOGY GAP through R & D, How Canada can Close the—M. P. Bachynski (RCA Ltd., Montreal) *Science Forum*, Vol. 2, No. 1; 2/69

TOTAL SYSTEM MANUFACTURING—G. A. McAlpine (CESD, Ply., Mich) ASTME, Chicago, Ill.; 5/7/69

VENDOR AWARD PROGRAM, RCA's—W. E. Shaw (CED, Indpls) American Society for Zero Defects, 2nd Annual National Symposium, Bedford, New Hampshire; 5/20/69

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PLASMA FORMATION in Avalanche Diodes, Theory of—L. S. Napoli, R. J. Ikola, A. S. Clorfeine (Labs., Pr) 1969 Device Research Conference. Rochester, New York; 6/23-26/69

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EPITAXIAL SILICON, Substrate Use of Spinel for—C. C. Wang (Labs., Pr) Electrochemical Society Meeting, New York City; 5/4-9/69

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MIXED LIQUID CRYSTAL SYSTEMS, Electric Field Induced Cholesteric-Nematic Phase Changes in—G. H. Heilmeier, J. E. Goldmacher (Labs., Pr) 1969 Device Research Conference, Rochester, N.Y. 6/23-26/69

NEW SINGLE-CRYSTALLINE PHASES in the System Cu-Nb-S, Vapour Growth of—R. Nitsche, P. Wild (Labs., Pr) *J. of Crystal Growth*, Vol. 3, No. 4; 1968

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TERNARY METAL OXIDES by Chemical Transport, Crystal Growth of—F. P. Emmenegger (Labs., Pr) *J. of Crystal Growth*, Vol. 3, No. 4; 1968

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THIN-FILM MICROELECTRONIC Components, Transition Metal Oxide—C. C. Wang, K. H. Zaininger (Labs., Pr) 1969 Electronic Component Conference, Washington, D.C.; 5/1/69

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IONIZING RADIATION in MIS Devices: a Review, The Effects of—K. H. Zaininger (Labs., Pr) Metal Insulator Semiconductor Conference, Grenoble, France; 6/18/69

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Dischert, W. A. communications components
Stachejko, V. communications components
Stachejko, V. reliability
Staiman, D. circuits, integrated
Staiman, D. communications components

MISSILE TEST PROJECT

Simpson, J. communications systems
Trimble, G. radar

RCA LIMITED, MONTREAL

Almey, E. N. optics
Bachynski, M. P. Management
Carswell, A. I. optics
Chitre, N. K. M. filters, electric
Kudsia, C. M. filters, electric
Richard, C. optics

SYSTEMS, ENGINEERING, EVALUATION AND RESEARCH

Barnla, J. D. communications systems
Mitchell, M. W. communications systems
Tangradi, L. J. communications systems

LABORATORIES

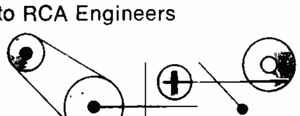
Abrahams, M. S. properties, molecular
Alig, R. C. properties, acoustic
Amarel, S. logic theory
Amarel, S. mathematics
Amick, J. A. properties, chemical
Amith, A. properties, electrical
Amith, A. properties, thermal
Anderson, C. H. properties, atomic
Arlett, R. H. properties, molecular
Bassani, F. properties, optical
Berger, S. B. properties, magnetic
Bernstein, F. lasers
Blanc, J. properties, molecular
Botnick, E. M. computer applications
Botnick, E. M. laboratory techniques
Brunner, H. properties, molecular
Busanovich, C. J. properties, surface
Busanovich, C. J. circuit analysis
Califano, F. P. solid-state devices
Califano, F. P. lasers
Califano, F. P. optics
Castellano, J. A. properties, molecular
Caulton, M. amplification
Caulton, M. circuits, integrated
Caulton, M. communications components
Caulton, M. circuits, integrated
Caulton, M. communications components
Chang, K. K. N. amplification
Chang, K. K. N. solid-state devices
Conant, L. lasers
Clorfeine, A. S. solid-state devices
Clorfeine, A. S. plasma physics
Clorfeine, A. S. solid-state devices
Clorfeine, A. S. communications components
Clough, R. B. properties, molecular
Clough, R. B. properties, chemical
Cohen, R. W. superconductivity
Crane, R. L. circuit analysis
Cuicchi, C. J. properties, molecular
Cullen, G. W. properties, surface
Curtis, B. J. properties, molecular
Dean, R. H. properties, molecular
Dresner, J. properties, optical
Dumin, D. J. properties, surface
Emmenegger, F. P. properties, molecular
Emmenegger, F. P. properties, surface
Firester, A. H. electro-optics
Firester, A. H. optics
Fischbeck, K. H. graphic arts
Fischer, A. G. properties, optical
Fischer, A. G. solid-state devices
Gittleman, J. I. superconductivity
Goldmacher, J. E. properties, molecular
Goldmacher, J. E. displays
Goldmacher, J. E. optics
Goldstein, B. properties, surface
Gordon, I. properties, mechanical
Gottlieb, G. E. properties, surface
Greenaway, D. L. properties, optical
Hanak, J. J. superconductivity
Harbeke, G. properties, optical
Heck, J. lasers
Heilmeier, G. H. properties, molecular
Heilmeier, G. H. displays
Heilmeier, G. H. optics
Heiman, F. P. solid-state devices
Heiman, F. P. properties, surface
Hershenov, B. properties, molecular
Hershenov, B. circuits, integrated
Hershenov, B. communications components
Heyman, P. M. properties, optical
Honig, R. E. properties, mechanical
Hughes, J. J. transmission lines
Ikola, R. J. plasma physics
Ikola, R. J. solid-state devices
Ikola, R. J. solid-state devices
Kern, W. properties, chemical
Kiss, Z. J. properties, electrical
Klein, R. properties, acoustics
Klein, R. mathematics
Knight, S. P. circuits, integrated
Knight, S. P. communications components
Kochen, M. linguistics
Korenjak, A. J. computers, programming
Korenjak, A. J. information theory
Kramer, D. A. properties, mechanical
Kressel, H. properties, molecular
Kressel, H. lasers
Larrabee, R. D. solid-state devices
Latta, J. N. displays
Larach, S. properties, optical
Larach, S. laboratory techniques
Lechner, B. J. displays
Lehmann, H. W. properties, surface
Levin, E. R. laboratory techniques
Levine, J. D. properties, surface
Levy, S. Y. computers, programming
Liu, S. G. circuits, integrated
Liu, S. G. communications components
Liu, S. G. solid-state devices
Liu, S. G. circuit analysis
Maruska, H. P. properties, chemical
McFarlane, S. H. properties, surface
Meyerhofer, D. graphic arts
Mezrich, R. S. displays
Moore, R. M. solid-state devices
Moore, R. M. circuit analysis
Moore, R. M. properties, surface
Mueller, C. W. properties, surface
Napoli, L. S. circuits, integrated
Napoli, L. S. communications components
Napoli, L. S. solid-state devices
Napoli, L. S. plasma physics
Napoli, L. S. transmission lines
Nelson, H. lasers
Nitsche, R. properties, molecular
Nuese, C. J. properties, optical
Nuese, C. J. solid-state devices
Paull, M. C. information theory
Pinch, H. L. properties, molecular
Poole, W. E. amplification
Poole, W. E. circuits, integrated
Poole, W. E. communications components
Prager, H. J. amplification
Prager, H. J. solid-state devices
Pruss, T. V. properties, mechanical
Pruss, T. V. superconductivity
Rajchman, J. A. computer storage
Revesz, A. G. properties, surface
Richamn, D. properties, molecular
Riley, G. A. properties, chemical
Risko, J. J. solid-state devices
Robinson, P. H. solid-state devices
Ross, E. C. solid-state devices
Sabisky, E. S. properties, atomic
Sahm, P. R. properties, mechanical
Sahm, P. R. superconductivity
Sall, C. W. documentation
Sall, C. W. management
Schade, H. properties, optical
Schade, H. solid-state devices
Schiff, L. communications systems
Schiff, L. information theory
Scott, J. H. solid-state devices
Shahbender, R. recording, audio
Shrader, R. E. laboratory techniques
Shrader, R. E. properties, optical
Simhony, M. properties, chemical
Spong, F. W. lasers
Srinivasan, C. V. computers, programming
Staebler, D. L. properties, electrical
Staras, H. communications systems
Staras, H. antennas
Steele, M. C. solid-state devices
Stephens, A. W. graphic arts
Taylor, B. N. mathematics
Tietjen, J. J. properties, molecular
Tietjen, J. J. properties, chemical
Toda, M. properties, surface
Tosatti, E. properties, optical
Tosima, S. properties, surface
Unger, S. H. information theory
Von Philipsborn, H. properties, molecular
Wallmark, J. T. solid-state devices
Walsh, J. J. graphic arts
Walters, D. information theory
Wang, C. C. properties, molecular
Wang, C. C. properties, surface
Wang, C. C. communications components
Wehner, R. K. properties, molecular
Wehner, R. K. mathematics
Weisberg, L. R. properties, molecular
Weisbrod, S. amplification
Weisbrod, S. solid-state devices
Wen, C. P. transmission lines
Wen, C. P. properties, molecular
Wilm, P. properties, molecular
Williams, R. properties, molecular
Williams, R. properties, surface
Wiliams, R. properties, chemical
Winder, R. O. logic theory
Wolf, J. K. information theory
Woolston, J. R. computer applications
Woolston, J. R. laboratory techniques
Wronski, C. R. properties, electrical
Yocom, P. N. properties, optical
Zaininger, K. H. properties, surface
Zaininger, K. H. communications components
Zaininger, K. H. radiation effects

DEFENSE ADVANCED COMMUNICATIONS LABORATORY

Beinart, J. logic theory
Hampel, D. logic theory
Prost, K. logic theory

Patents Granted

to RCA Engineers



As reported by RCA Domestic Patents, Princeton

COMMERCIAL ELECTRONIC SYSTEMS DIVISION

Coordinated sensitivity and amplification control system—R. A. Dischert, N. L. Hobson (CESD, Cam) U.S. Pat. 3,445,590; May 20, 1969

ELECTRONIC COMPONENTS

High speed controlled rectifiers with deep level dopants—T. J. Desmond, L. S. Greenberg, H. Weisberg (EC, Mntp) U.S. Pat. 3,445,735; May 20, 1969

Semiconductor device having increased resistance to second breakdown—F. Cohen (EC, Som) U.S. Pat. 3,448,354; June 3, 1969

Shaped-loss attenuator for equalizing the gain of a traveling wave tube amplifier—H. J. Wolkstein (EC, Hr) U.S. Pat. 3,440,-555; April 22, 1969

Television deflection circuits—C. F. Wheatley (EC, Som) U.S. Pat. 3,449,622; June 10, 1969

Remote cutoff junction gate field effect transistor—J. H. Scott, J. A. Olmstead (EC, Som) U.S. Pat. 3,449,647; June 10, 1969

Television scanning and power supply system—M. B. Knight (EC, Som) U.S. Pat. 3,450,936; June 17, 1969

LABORATORIES

Thermal feedback for stabilization of differential amplifier unbalance—J. J. Amodei (Labs., Pr) U.S. Pat. 3,445,777; May 20, 1969

Differential amplifier—H. R. Beelitz (Labs., Pr) U.S. Pat. 3,445,780

Half wavelength monopole antenna with spaced loading coils—R. F. Sanford (Labs., Pr) U.S. Pat. 3,445,849; May 20, 1969

Laser digital device—W. F. Kosonocky (Labs., Pr) U.S. Pat. 3,430,160; February 25, 1969; Assigned to U.S. Government

Luminescent materials and apparatus for generating coherent radiation—Z. J. Kiss (Labs., Pr) U.S. Pat. 3,447,097

Light deflecting apparatus—W. H. Barkow, D. Brasen (Labs., Pr) U.S. Pat. 3,447,853; June 3, 1969

Method for pressing particulate material—H. I. Moss, W. P. Stollar (Labs., Pr) U.S. Pat. 3,448,184; June 3, 1969

Semiconductor laser components for digital logic—W. F. Kosonocky (Labs., Pr) U.S. Pat. 3,439,289; April 15, 1969

Wire handling apparatus—H. D. G. Scheffer (Labs., Pr) U.S. Pat. 3,448,777; June 10, 1969

Logic circuits employing complementary pairs of field-effect transistors—J. J. Gibson, J. R. Burns (Labs., Pr) U.S. Pat. 3,449,594; June 10, 1969

Probe assembly for testing semiconductor wafers including a wafer vibrator for effecting good connections—W. L. Oates (Labs., Pr) U.S. Pat. 3,453,545; July 1, 1969

Grooved bulk semiconductor oscillator—G. A. Swartz (Labs., Pr) U.S. Pat. 3,453,-560; July 1, 1969

Method for preparing a ferroelectric body and devices—G. H. Heilmeier, L. A. Zanoni (Labs., Pr) U.S. Pat. 3,449,824; June 17, 1969

Ferroelectric insulated gate field effect device—S. S. Perlman. R. S. Silver (Labs., Pr) U.S. Pat. 3,450,966; June 17, 1969

Luminescent material and laser apparatus utilizing said material—D. L. Ross (Labs., Pr) U.S. Pat. 3,451,009; June 17, 1969

DEFENSE ELECTRONIC PRODUCTS

Printer with print bars supported by parallelogram linkage arrangement—E. D. Simshauser (Labs., Pr) U.S. Pat. 3,444,975; May 20, 1969

ELECTROMAGNETIC AND AVIATION SYSTEMS DIVISION

Current limiting voltage regulator—F. C. Easter (EASD, Van Nuys) U.S. Pat. 3,445,-751; May 20, 1969

DEFENSE MICROELECTRONICS

Phase splitting circuit for a direct coupled push-pull amplifier—A. J. Leidich (DME, Som) U.S. Pat. 3,445,776; May 20, 1969

INFORMATION SYSTEMS DIVISION

Memory accessing system—R. S. Y. Yen (ISD, Cam) U.S. Pat. 3,445,818; May 20, 1969

Conversion from self-clocking code to NRZ code—J. A. Vallee (ISD, Palm Beach) U.S. Pat. 3,448,445; June 3, 1969

PARTS & ACCESSORIES

Antenna—J. D. Callaghan (P&A, Dept.) U.S. Pat. 3,445,854; May 20, 1969

ASTRO-ELECTRONICS DIVISION

Connector strips—C. R. Peek, L. E. Boodley (AED, Pr) U.S. Pat. 3,422,213; January 14, 1969; Assigned to the U.S. Government

Helical coaxial resonator RF filter—W. M. Myron (AED, Pr) U.S. Pat. 3,437,959; April 8, 1969

DEFENSE COMMUNICATIONS SYSTEMS DIVISION

Input buffer—R. S. Klein (DCSD, Cam) U.S. Pat. 3,407,389; October 22, 1968; Assigned to the U.S. Government

Capacitor anode holder—S. Lynn, W. C. Ries (DCSD, Cam) U.S. Pat. 3,449,650; June 10, 1969

AEROSPACE SYSTEMS DIVISION

Stepping switch employing chain of logic gates having means for locking a gate in a given state—W. Henn (ASD, Burl) U.S. Pat. 3,450,897; June 17, 1969

HOME INSTRUMENTS

Protection circuit—N. W. Hursh (HI, Indpls) U.S. Pat 3,450,935; June 17, 1969

Television kinescope voltage cable assembly—R. C. Owens (HI, Indpls) U.S. Pat. 3,448,323; June 3, 1969

Electron beam deflection circuit—W. F. W. Dietz (HI, Indpls) U.S. Pat. 3,449,623; June 10, 1969

ADVANCED TECHNOLOGY LABORATORIES

Magneto-optic display system—H. E. Haynes, K. C. Hudson (ATL, Cam) U.S. Pat. 3,448,211; June 3, 1969

Circuit that analyzes transient signals in both the time and frequency domains—G. J. Dusheck (ATL, Cam) U.S. Pat. 3,453,540; July 1, 1969

MISSILE AND SURFACE RADAR DIVISION

Monostable wide range multivibrator—A. A. Gorski (M&SR, Mrstn) U.S. Pat. 3,428,902; February 18, 1969

Contradirectional waveguide coupler—J. S. Daglian, J. W. Grace, C. P. Clasen (M&SR, Mrstn) U.S. Pat. 3,427,570; February 11, 1969

Electronic crowbar—W. H. Cheever (M&SR, Mrstn) U.S. Pat. 3,418,530; December 24, 1968; Assigned to the U.S. Government

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Professional Meetings

Dates and Deadlines

Be sure deadlines are met—consult your Technical Publications Administrator or your Editorial Representative for the lead time necessary to obtain RCA approvals (and government approvals, if applicable). Remember, abstracts and manuscripts must be so approved BEFORE sending them to the meeting committee.

Calls For Papers

JAN. 19-21, 1970: **AIAA 8th Aerospace Sciences Meeting,** Statler-Hilton Hotel, New York, New York. **Deadline info: (abst), 8/18/69; 12/8/69 (papers to:** Robert A. Gross. School of Engineering and Applied Science, Columbia University, New York, N.Y. 10027.

JAN. 25-30, 1970: **Winter Power Mtg.,** Statler Hilton Hotel, New York, N.Y. **Deadline info: 9/15/69 (papers) to:** IEEE Hdqs., Tech. Conf. Svcs., 345 E. 47th St., New York, N.Y. 10017.

JAN. 27-29, 1969: **Reliability Symposium,** Ambassador Hotel, Los Angeles, Calif. **Deadline info: (abst.) 5/1/69, (papers) 8/15/69 to:** W. R. Abbott, D60-01/B104, Lockheed Miss. & Space Co., POB 504, Sunnyvale, Cal.

FEB. 4-6, 1970: **AIAA Advanced Space Transportation Meeting,** Cocoa Beach, Fla. **Deadline info: 9/4/69 (abst); 10/15/69 (ms) to:** Alfred C. Draper, Air Force Flight Dynamics Lab. (FDM), Wright-Patterson Air Force Base, Ohio 45433.

MARCH 6-7, 1970: **AIAA Fighter Aircraft Conference,** St. Louis, Missouri. **Deadline info: (abst.) 10/30/69, (ms) 1/12/70 to:** Robert W. Bratt, Advanced Aircraft Systems, Norair/Northrop Corp., 3901 West Broadway, Hawthorne, Calif.

MARCH 17-20, 1970: **Symposium on Management & Economics in the Electronics Industry,** Univ. of Edinburg, Edinburg, Scotland. **Deadline info: (syn.) 5/1/69 to:** IEEE. Savoy Place, London W. C. 2 England.

APRIL 1-3, 1970: **AIAA Test Effectiveness in the 70's Conference,** Palo Alto, Calif. **Deadline info: (abst.) 11/3/69 to:** Co. Frank Borman USAF, Room 342, Building CB, NASA Manned Spacecraft Center, Houston, Texas 77058.

APRIL 6-8, 1970: **AIAA 3rd Communications Satellite Systems Conference,** International Hotel, Los Angeles, Calif. **Deadline info: 2/2/1970 (papers) to:** Nathaniel E. Feldman, The Rand Corporation, 1700 Main Street, Santa Monica, Calif. 90406.

APRIL 16-18, 1970: **1970 Carnahan Conference on Electronic Crime Countermeasures,** Carnahan House, University of Kentucky, Lexington, Kentucky. **Deadline info: (abst.) 11/15/69, (papers) 2/15/70 to:** Prof. J. S. Jackson, Department of Electrical Engineering, University of Kentucky, Lexington, Kentucky 40506.

APRIL 22-24, 1970: **AIAA/ASME 11th Structures, Structural Dynamics, and Materials Conference,** Denver, Colo. **Deadline info: (abst.) 9/12/69, (ms) 3/9/70 to: Structures,** Roger A. Anderson. Structures Research Division, Mail Stop 188, NASA Langley Research Center, Langley Station, Hampton, Va. 23365; **Materials,** Dr. Edward Epremian. Carbon Products Division, Union Carbide Corp., 270 Park Avenue, New York, N.Y. 10017; **Structural Dynamics,** Dr. H. M. Voss, Mail Stop 8R-34, **The** Boeing Co., P. O. Box 3999, Seattle, Washington 98124; **Other areas,** Dr. H. M. Voss, Mail Stop 8R-34, The Boeing Co., P. O. Box 3999, Seattle, Wash. 98124.

MAY 4-5, 1970: **Transducer Conference, Nat'l Bureau of Standards,** Washington, D. C. **Deadline info: (papers) 11/1/69, (ms) 2/15/70 to:** Dr. Robert B. Spooner, IMPAC Instrument Service, 201 East Carson Street, Pittsburgh, Pennsylvania 15219.

MAY 4-6, 1970: **AIAA/Navy Marine Systems, Propulsion, and ASW Meeting,** Newport, R.I. **Deadline info: (abst.) 9/19/69 to:** Gerald G. Gould, Technical Director, Naval Underwater Weapons Research and Engineering Station, Newport, R.I. 02840.

MAY 4-7, 1970: **4th Conference on Aerospace Meteorology (AMS/AIAA/IES),** Las Vegas, Nev. **Deadline info: (abst.) 9/1/69, (papers) 12/15/69 to:** Norman Sissenwine, AFCRL (CREW), L. G. Hanscom Field, Bedford, Mass. 01730- **meteorological studies;** William W. Vaughan, NASA Marshall Space Flight Center, Code: S&E-AERO-Y, Huntsville, Ala. 35812-**engineering studies.**

MAY 5-6, 1970: **Appliance Technical Conference,** Leland Motor Hotel, Mansfield, Ohio. **Deadline info:** R. G. LaBudde. Westinghouse Elec. Corp., 246 E. 4th Street, Mansfield, Ohio 44902.

MAY 13-15, 1970: **AIAA Atmospheric Flight Mechanics Conference,** Tullahoma. Tenn. **Deadline info: (abst.) 10/15/69 to: Missiles,** Lester L. Cronvich, Applied Physics Lab., Johns Hopkins University, 8621 Georgia Ave., Silver Spring, Md. 20910; **Ordnance,** Warren H. Curry, Experimental Aerodynamics, Division 9322, Sandia Labs. Albuquerque. N. Mex. 87115; **V/Stol,** John Zvara, Kaman Corp., 2nd Avenue, Northwest Industrial Park, Burlington, Mass. 01803; **Entry Vehicles,** Victor Stevens. Mail Stop 229-3, NASA Ames Research Center, Moffett Field, Calif. 94035; **Aircraft,** Martin T. Moul, NASA Langley Research Center, Hampton, Va. 23490; **Other areas,** C. J. Schueler von Karman Gas Dynamics Facility, Arnold Engineering Development Center, Arnold Air Force Station, Tenn. 37389.

MAY 18-20, 1970: **AIAA 5th Aerodynamic Testing Conference,** University of Tennessee Space Institute, Tullahoma, Tenn. **Deadline info: (abst.) 9/8/69, (papers) 11/15/69 to:** Dr. Hans K. Doetsch, Arnold Engineering Development Center (AELR), Arnold Air Force Station, Tenn. 37389.

MAY 19-21, 1970: **Conference on Signal Processing Methods for Radio Telephony,** London, England. **Deadline info: (syn.) 8/25/69, (ms) 12/29/69 to:** IEEE Office, 345 East 47th Street, New York, N.Y. 10017.

Meetings

SEPT. 7-11, 1969: **Electrical Insulation Conference,** G-EI, NEMA, NAVSEC, Sheraton-Boston Hotel & War Mem. Aud., Boston, Mass. **Prog info:** H. P. Walker, NAVSEC, Code 6156D, Washington, D.C.

SEPT. 8-12, 1969: ***European Microwave Conference,** IEE, IRE, IERE, G-MTT, London, England. **Prog info:** IEE, Savoy Place, London, W. C. 2 England.

SEPT. 8-12, 1969: ***Int'l Man-Machine Systems Symposium,** G-MMS, Ergonomics. Res. Soc., St. John's College, Cambridge, Eng. **Prog info:** W. T. Singleton, Applied Psychology Dept., Univ. of Aston in Birmingham, Birmingham 4, England.

SEPT. 14-17, 1969: **Petroleum & Chemical Industry Technical Conference,** G-IGA. Statler Hilton Hotel, Los Angeles, Calif. **Prog. info:** R. L. Dhuy, Westinghouse Elec. Corp., 6252 E. Telegraph Rd., City of Commerce, Calif. 90022.

SEPT. 16-19, 1969: ***Solid State Devices Conference,** Inst. of Phys. & Phys. Soc., IEE, IERE, IEEE U. K. & Rep. of Ire. Sec., Univ. of Exeter, Exeter, Devon, England. **Prog info:** P. C. Newman, Allen Clark Res. Ctr., Caswell, Towcester, Northamptonshire, England.

SEPT. 21-25, 1969: **Joint Power Generation Conference,** G-P, ASME, White House Inn, Charlotte, North Carolina. **Prog info:** R. A. Budenholzer, Ill. Inst. of Tech. Ctr., Chicago, Illinois 60616.

SEPT. 21-26, 1969: **Intersociety Energy Conversion Engineering Conference,** AIChe, G-ED, AES, ASME, ANS, SAE, ACS, MTS' AIAA, Statler Hilton Hotel, Washington, D.C. **Prog info:** T. G. Kirkland, U.S. Army R & D Ctr., Fort Belvoir, Va.

SEPT. 24-26, 1969: **Ultrasonics Symposium,** G-SU, Chase Park Plaza Hotel, St. Louis, Missouri. **Prog info:** C. K. Jones, Westinghouse R&D, Churchill Boro, Pittsburgh, Penna. 15235.

SEPT. 29-Oct. 2, 1969: **International Orbiting Laboratory and Space Sciences Conference,** AIAA, Cloudcroft, New Mex. **Prog info:** Secretary, International Academy of Astronautics, 250 Rue Saint-Jacques, 75 — Paris 5, France.

SEPT. 28-Oct. 3, 1969: **106th Technical Conference of the SMPTE,** Century Plaza Hotel, Los Angeles, Calif. **Prog info:** Warren Strang, Hollywood Film Co., Hollywood, Calif.

OCT. 6-8, 1969: **Int'l Electronic Conf. & Exposition of Canadian Region of IEEE,** Automotive Bldg., Canacian Nat'l Exh. Grounds, Toronto, Canada. **Prog info:** R. DeBuda, Int'l Elec. Conf., 1819 Yonge St., Toronto 7, Ontario, Canada.

OCT. 8-10, 1969: **Allerton Conference on Circuit & System Theory,** Allerton House, Univ. of Ill., Monticello, Ill. **Prog info:** G. Metze, Univ. of Ill., Dept. of EE, Urbana, Ill. 61801.

OCT. 9-10, 1969: **Joint Engineering Management Conference,** Bonaventure Hotel, Montreal, Quebec, Canada. **Prog info:** James G. Ripley, General Conference Chairman, Management Engineering Division, c/o William A. McDill, Manager of Technical Services, Engineering Institute of Canada, 2050 Mansfield Street, Montreal, 110, or Walter A. Stanbury, Publicity Chairman, Chief Editor, Product Engineering, McGraw-Hill Publications, 330 W. 42nd Street, New York, N.Y. 10036.

OCT. 15-17, 1969: **1969 American Ceramic Society's Pacific Coast Regional Meeting,** Washington Plaza Hotel, Seattle, Washington. **Prog info:** Frank P. Reid, The American Ceramic Society, Inc., 4055 North High Street, Columbus, Ohio 43214.

OCT. 15-17, 1969: **Nuclear Division of the American Ceramic Society,** Washington Plaza Hotel, Seattle, Washington. **Prog info:** Frank P. Reid, The American Ceramic Society, Inc., 4055 North High Street, Columbus, Ohio 43214.

OCT. 15-17, 1969: **Switching & Automata Theory Symposium,** Univ. of Waterloo, Waterloo, Ontario, Canada. **Prog info:** John Hopcroft, Computer Sci. Dept., Upson Hall, Cornell Univ., Ithaca, N.Y. 14851.

OCT. 21-23, 1969: **Thermionic Energy Conversion Specialists Conference,** Holiday Inn of Carmel-by the sea, Carmel, Calif. **Prog info:** F. Rufeh, Thermo Electron Corp., 85 1st Av., Waltham, Mass. 02154.

OCT. 22-24, 1969: **Systems Science and Cybernetics Conference,** Univ. of Penna., & Warwick Hotel, Phila., Penna. **Prog info:** H. A. Raymond, 2446 UVF-STC. Gen'l Elec. Co., POB 8555, Phila., Penna. 19101.

OCT. 26-29, 1969: **Conference on Electrical Insulation & Dielectric Phenomena,** The Inn, Buck Hill Falls, Penna. **Prog info:** A. M. Sletten, High Voltage & Gas Physics, Westinghouse Elec. Corp., Pittsburgh, Penna. 15235.

OCT. 26-30, 1969: **Jt. Conference on Mathematical & Computer Aids to Design,** Disneyland Hotel, Anaheim Conv. Ctr., Anaheim, Calif. **Prog info:** J. F. Traub, Bell Telephone Labs., Mountain Av., Murray Hill, N.J. 07974.

Engineering News and Highlights

Professional activities

Central Engineering

D. R. Crosby has been elected as Secretary of the IEEE Group on Circuit Theory.

Magnetic Products, Indianapolis

A. L. Stancel has been elected to be Vice Chairman of the USASI Task Group X3.2.1 on Computer Tape and Transports. He was also appointed as a member of the SMPTE Video Tape and Reels Committee.

Missile Test Project

Dorsey Dean, Research Mathematician, has been re-elected Southeast Regional Director for the American Society for Quality Control.

Dr. L. E. Mertens and **William N. Beall** have been appointed to serve on the newly-formed Oceanography Advisory Committee for Brevard Junior College.

Dorsey Dean and **John Fahning** have been appointed members of the Brevard Junior College Quality Control and Reliability Advisory Committee.

Electromagnetic and Aviation Systems Division

George F. Fairhurst, Manager of Engineering Support and Logistics was recently elected to the Board of Directors of the American Institute for Design and Drafting.

Laboratories

J. E. Benbenek has been named national chairman of the American Scientific Glass Society. He will serve as Chairman of the Technical Papers Committee at the 14th ASGS Symposium this month in Albany, New York.

Aerospace Systems Division

O. T. Carver, Manager Systems Analysis & ATE was elected as Vice Chairman, Support Equipment Panel of the Maintenance Advisory Committee of the National Security Industrial Assoc.

Electronic Components, Somerville

Dr. Ronald B. Schilling, Engineering Ldr., Microwave Microelectronics has been elected Chairman, New Technical Scientific Activities Committee of the New York Section of the IEEE for 1969-1970. Dr. Schilling recently served as co-chairman of a seminar on Computer-Aided Device Analysis and Design, sponsored by NUTSAC.

Electronic Components, Harrison

Dr. Otto Schade, Sr., Staff Engineer in Special Products Engineering, has won the Technical Achievement Award from the American Society of Magazine Photographers. The award was given "for his contribution to photography by effecting a marriage of electronics and optics which revolutionized the design and evaluation of optical systems and made possible sophisticated designs of lenses".

Electronic Components, Lancaster

J. M. Forman, Administrator, Special Engineering Services has been elected to the position of Chairman of the Lancaster Engineering Education Committee. His fellow members are: 1st Vice Chairman, **J. A. Zollman, Ldr.,** Product Development, Conversion Tubes; 2nd Vice Chairman, **R. W. Hagmann,** Mgr., Color Application and Reliability Engineering.

Six members of the RCA Consumer Electronics Technical Service Activity were recognized for their contributions to the advancement of Engineering education by the Central Indiana IEEE. Left to right are: N. E. Egler, C. F. Moeller, L. M. Krugman (representing IEEE), C. W. Mitchell, H. C. Horton, G. F. Corne, and E. M. Milbourn.

Best paper award for W. F. Dietz

Wolfgang F. Dietz recently received an award for the best paper appearing in the *Transactions* of the Broadcast and Television Receivers Group of the Institute of Electrical and Electronic Engineers. The award-winning paper was entitled "An SCR Horizontal Sawtooth Current and High-Voltage Generator for Magnetically Deflected Picture Tubes. This paper also appeared in the RCA ENGINEER, Vol. 15, No. 1, June-July 1969.

W. F. Dietz

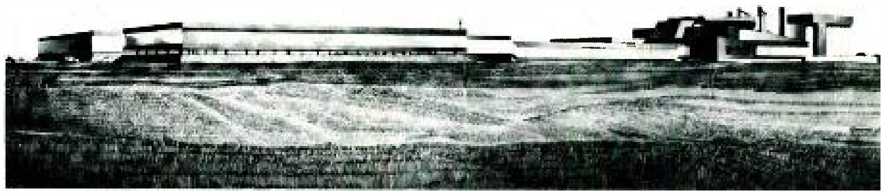
Mr. Dietz is presently an applications engineer with the thyristor products group of the Electronic Components in Somerville, N.J. He received the BSEE from Staatstechnicum Konstanz in Germany in 1948. After working for several other manufacturers of FM and TV receivers in Europe and the United States, he joined RCA in 1958. He was located at the David Sarnoff Research Laboratories until 1962, where he engaged in various advanced development projects. From 1962 to 1968, he was a design engineer in the RCA Consumer Electronics Division at Indianapolis, Ind., investigating various kinds of solid-state deflection circuits and other areas of color TV.

ASD holds Professional Recognition Reception

The Aerospace Systems Division recently cited those members of the ASD technical staff "who have, through significant contributions, increased their professional stature while adding to RCA's prestige in the Electronics Community." This group included engineers and scientists who had published technical articles, received Technical Excellence Awards, or served on National Committees. The engineers and their wives were invited to a Professional Recognition Reception held in their honor at the Boston 1800 restaurant.

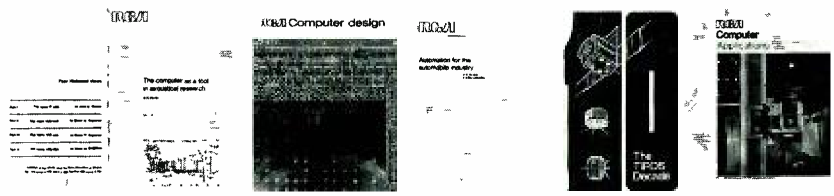
RCA to build glass manufacturing plant

RCA announced plans to build a $19 million plant at Circleville, Ohio to produce glass bulbs for color television tubes. The new glass plant will make RCA the industry's most fully-integrated color television manufacturer, from component parts to completed receivers. The glass components will be used only in RCA's own production of color television picture tubes. However, RCA plans to continue to buy the major portion of its glass bulb requirements for TV picture tubes from outside sources.



Architect's drawing of proposed manufacturing plant.

Reprints of RCA Engineer Articles



Any articles from past RCA ENGINEER issues are available for reprinting. Articles may be reprinted individually or several articles may be grouped together (and mixed from several issues) to form a reprint booklet. Covers for reprints may be tailored to your own use. The RCA ENGINEER editorial staff will provide assistance on such matters as cover layout and utilization of reprints.

The RCA ENGINEER editorial office administers all policy on reprint content, availability, and utilization since additional changes must be made to the articles before they can be distributed. Reprints can be obtained only through the RCA ENGINEER editorial office.

How reprints are used

The various divisions of RCA use over 100,000 copies of reprints of RCA ENGINEER articles each year. Such reprints range from simple, two-page leaflets to 88-page booklets with full-color covers. Reprints supplied by Technical Publications, Corporate Engineering Services, are inexpensive and may be used in numerous ways:

1) As information brochures or descriptive bulletins;
2) To display engineering and technical skills;
3) For marketing and sales mailings and handouts;
4) For mailings to prospects, customers, and opinion leaders;
5) For answering any inquiries that require technical explanations;
6) For use with commercial and government proposals; and
7) To give to personnel groups for orientation, training, and recruiting.

Various types of reprints recently produced are pictured at the top of this page.

Covers

On single-article reprints, a simple title-page imprint (article title, author, RCA logotype, and division) is included when a blank page is available. For economy, reprints are prepared in increments of four pages each; thus, a three-page article would be printed as a four-page reprint with the extra page used as a cover. In a four-page article, the cover information is placed on the title page of the article unless the separate title page is requested; the four-page article is then handled (and priced) as an eight-page reprint.

On the booklet reprints, covers are custom-designed to suit the "theme" of the articles, using typography and artwork to suit. These booklets also can utilize previous RCA ENGINEER covers in either full color or in black-and-white. Cover messages, marketing contacts, or other additional information appropriate to the purpose of the booklet may be placed on the inside front and back covers.

Delivery

Four- and eight-page reprints can be supplied within two weeks of the receipt of the order. Reprint booklets are available on a four- to eight-week time cycle, depending on the complexity of the additional cover material. Rush schedules may affect price and should be handled on an individual basis.

How to order

All reprints are ordered from the RCA ENGINEER Editorial Office, Radio Corporation of America, Bldg. 2-8, Front and Cooper Sts., Camden, N.J. For rush orders, phone WO 3-8000, Ext. PC 3396. The following information must be supplied with each order:

1) Article or articles desired;
2) Special instructions on cover requirements or special information to be added;
3) Quantity desired;
4) Delivery requirements (time and place); and
5) Account No. (*not* a purchase order).

RCA microscope business sold

RCA has sold its electron microscope business to the Forgflo Corporation, Sunbury, Pennsylvania, and a subsidiary of Waltham Industries, for more than $3 million in cash and notes. The agreement has been approved by the Boards of Directors of RCA, Waltham Industries and Forgflo and is effective June 30. It includes RCA's inventory of electron microscopes, subassemblies in process, microscope patents and all other data required for conduct of the business. No RCA plant facilities are involved in the transaction.

Staff Announcements

Electronic Components

J. B. Farese, Executive Vice President, Electronic Components, has appointed **L. Gillon,** General Manager, Television Picture Tube Division; and **H. R. Seelen,** Division Vice President, International Development and Glass Operations.

H. R. Seelen, Division Vice President, International Development and Glass Operations has appointed **C. T. Lattimer,** Manager, Operations Planning—Glass Operations and **J. G. VanDermark,** Manager, Personnel—Circleville Glass Operations.

H. R. Seelen, Division Vice President, International Development and Glass Operations has appointed **A. B. Dickinson** to the newly established position of Manager, New Project Development.

H. R. Seelen, Division Vice President, International Development and Glass Operations, announced the appointment of **D. E. Marquardt** as Manager, Financial Operations, Circleville—Glass Operations; and **R. K. Schneider** as Manager, Glass Technology, Glass Operations.

Aerospace Systems Division

J. R. McAllister, Division Vice President and General Manager, has appointed **F. J. Gardiner,** Manager, Systems Development and Application; **S. S. Kolodkin,** Manager, Tactical and Space Programs; and **E. F. Lockwood,** Manager, Command and Control Programs.

Defense Communications Systems Division

J. F. Burlingame, Division Vice President and General Manager, has appointed **S. Z. Daroff** as Manager, Resources Utilization.

Missile and Surface Radar Division

P. A. Piro, General Manager, has appointed **M. N. Cinelli,** Manager Special Manufacturing Programs; and **R. V. Donato,** Plant Manager, Moorestown Plant.

RCA Staff

Dr. G. H. Brown, Executive Vice President, Patents and Licensing, has announced the organization of Patents and Licensing as follows: **S. S. Barone,** Staff Vice President, International Licensing; **J. J. Benavie,** Staff Vice President. Domestic Licensing; **J. Epstein,** Administrator, Staff Services; **A. D. Gordon,** Manager, Planning and Coordination; **H. R. L. Lamont,** Director. European Technical Relations; **H. W. Leverenz,** Staff Vice President; **J. V. Regan,** Staff Vice President, Patent Operations.

G. A. Fadler, Vice President, Manufacturing Services and Materials has appointed **J. L. Kidwell** as Staff Vice President, Product Reliability and Quality.

J. L. Kidwell, Staff Vice President, Product Reliability and Quality has appointed **D. C. Crosby** as Manager, Quality Improvement.

Services

A. L. Conrad, Executive Vice President, Services has appointed **D. M. Knight** to the newly established position of Division Vice President, Educational Development.

Education Systems

D. M. Knight, Division Vice President, Educational Development, has appointed **L. F. Jones,** as Director, Education Systems Projects.

Awards

Electromagnetic and Aviation Systems Division

Robert B. Strohm of the Electronic Warfare Systems and Equipments activity was a recent recipient of the Professional Excellence Engineer Award. Mr. Strohm was cited for his continued outstanding performance in program direction of various technique contracts. **Robert J. Wayner,** also of EW Systems and Techniques, received a recent Professional Excellence Engineer Award. Mr. Wayne received his award because of his exceptional engineering effort on the Silicon Integrated Circuit Program.

Missile and Surface Radar Division

Three engineers were Technical Excellence Award winners for the first quarter of 1969: **R. E. Bender**—for his outstanding technical accomplishment in the design of a communications security system for the AN/FPS-95 radar site; **S. D. Gross**—for superior performance as technical director of the Camel radar design study program; and **R. W. Ottinger**—for significant contributions to the enhancement of TRADEX data gathering capability, involving conceptual analysis and basic design of a chafftracking subsystem for the TRADEX sensor.

Aerospace Systems Division

Leo C. Kaye, Engineering Scientist of Data Processing Engineering, has been selected as Engineer of the Month for April for his contributions to the logic design of advanced aerospace multiprocessors. He is recognized for his exceptional performance in the logic design of central processors.

The team of **R. W. Price, D. W. Smelser,** and **M. H. Zelnick** from Data Processing Engineering received a Technical Excellence Team Award for April for their outstanding performance in the electrical and mechanical design of the read-only memory for Advanced Aerospace Computer.

Astro-Electronics Division

The following have received Engineering Excellence Awards: **Jack Rebman** for April; **Frank Lang** for May; and **H. R. Mathwick** for June.

Degrees granted

J. R. Fendley, Jr., EC, Lanc. ....MS, Engineering, University of Pennsylvania, 6/69
D. H. Cooper, EC, Lanc. ....ME, Engineering Science, Penn State University, 6/69
J. A. Eshleman, EC, Lanc. ....MS, Physics, Franklin & Marshall College, 6/69
P. D. Birdwell, MTP, Cocoa Beach ....BSEE. Florida Institute of Technology, 6/69
I. B. Cottrell, MTP, Cocoa Beach ......BS, Math, Florida Institute of Technology, 6/69
L. L. Crabtree, MTP, Cocoa Beach ......MSEE, Florida Institute of Technology, 6/69
A. J. Edison, MTP, Cocoa Beach MS, Space Technology, Florida Institute of Tech., 6/69
D. B. Gennery, MTP, Cocoa Beach ......MS, Physics, Florida Institute of Tech., 6/69
C. E. Harris, MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
L. M. Hayes, Jr., MTP, Cocoa Beach ......MSEE, Florida Institute of Technology, 6/69
R. Lastra, MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
E. V. Lofgren, MTP, Cocoa Beach MS, Operations Research, Florida Inst. of Tech., 6/69
W. Lutz, MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
L. R. Minton, MTP, Cocoa Beach ......MS, Math, Florida Institute of Technology, 6/69
D. R. Partyka, MTP, Cocoa Beach ....BSEE, Florida Institute of Technology, 6/69
A. G. Roy, MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
H. A. Siemen, Sr., MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
R. C. Walter, MTP, Cocoa Beach ....MSEE, Florida Institute of Technology, 6/69
N. U. Huffmaster, AED ....MSEE, Drexel Institute of Technology, 6/14/69
J. J. Hawley, AED ....MSEE, Drexel Institute of Technology, 6/14/69
P. Curran, AED ....MS, Rutgers University, 6/69
C. Devieux, AED ....PhD, Polytechnic Institute of Brooklyn, 6/12/69
R. Marsala, AED ....MSEE, Princeton University, 6/69
F. G. Adams, M&SR ......MS, Mechanical Engineering, Drexel Institute of Tech., 6/69
R. S. Torrisi, M&SR ....MBA, Industrial Management, Temple University, 6/69
T. J. Horner, Mag. Prod., Indpls. ....BA, Chemistry, Manchester College, 6/69
A. G. Evans, Mag. Prod., Indpls. ....MS, Engineering, Purdue University, 6/69
M. J. Markulec, Jr., EC, Pr. ....BSEE, Newark College of Engineering, 6/69
J. P. Paczkowski, EC, Pr. ....BS, Physics, Brooklyn Polytechnic Institute, 6/69
D. L. Hill, MTP, Cocoa Beach MS Systems Management, Florida Institute of Tech., 6/69
Ted Hopson, MTP, Cocoa Beach ..MS Systems Management, Florida Inst. of Tech., 6/69
W. R. Mack, MTP, Cocoa Beach ..MS Systems Management, Florida Inst. of Tech., 6/69
L. Ulu, ISD, Camden ....PhD, University of Pennsylvania, 7/69

Promotions

Astro-Electronics Division

A. J. Aukstikalnis: from Adm. New Tech. to Mgr. Engrg. (W. Manger, Princeton)

G. A. Beck: from Adm. Systems Engrg. to Mgr. (Spec) Engrg. (M. Cohen, Princeton)

M. S. Feryszka: from Sr. Mem. Tech. Staff to Mgr. (Spec) Engrg. (W. Manger, Princeton)

L. A. Freedman: from Sr. Eng. to Mgr. Project (C. Hume, Princeton)

A. R. Garfinkel: from Adm. Syst. Engrg. to Mgr. (Spec) Engrg. (W. Manger, Princeton)

L. W. Jones: from Engr. to Mgr. (Spec) Engrg. (A. Schnapf, Princeton)

G. K. Martch: from Engr. to Mgr. (Spec) Engrg. (A. Schnapf, Princeton)

M. H. Mesner: from Sr. Mem. Tech. Staff to Mgr. (Spec) Engrg. (G. Barna, Princeton)

A. G. Holmes Siedle: from Ldr. Engrgs. to Mgr. (Spec) Engrg. (W. Manger, Princeton)

L. Weinreb: from Sr. Eng. to Mgr. Project (C. Hume, Princeton)

RCA Global Communications, Inc.

D. Epstein: from Design Engineer to Group Leader (J. R. McDonald, New York)

R. Jemison: from Design Engineer to Group Leader (J. R. McDonald, New York)

J. R. McDonald: from Mgr., New York Telex Engineering to Mgr., Telex Engineering (I. K. Given, New York)

RCA Service Company

W. R. Haldane: from Ldr., Engrs. to Mgr. Princeton Project Support (W. M. McGuffin-Cherry Hill)

W. J. Eddy: from I & M Engr. to Ldr., Systems Service Engrs. (H. Chadderton, Cherry Hill)

B. J. Ranjo: from I & M Engr. to Ldr., Systems Service Engrs. (W. J. Siddall-Cherry Hill)

Electromagnetic and Aviation Systems Division

E. B. Gamble: from Prn. Mbr., D&D Engrg. Staff to Staff Engrg. Scientist (J. MacFarlane, Van Nuys)

J. MacFarlane: from Sr. Mbr. D&D Engrg. Staff to Mgr. Design Supt. Engrg. (G. Fairhurst, Van Nuys)

Electronic Components

M. Ammenwerth: from Sr. Engr. Product Develop. to Eng. Ldr., Product Develop. (B. Halpern, Harrison)

G. D. Cartwright: from Engr, Mfg. to Engrg. Ldr., Mfg. (J. Kindbom, Lancaster)

G. R. Fadner: from Sr. Engr., Product Dev. to Engrg. Ldr., Product Dev. (R. Nolen, Lancaster)

T. Walsh: from Mbr. Tech. Staff (Princeton) to Mgr., Microwave Solid St. Tech. Ctr. (H. K. Jenny, Harrison)

GSD honors authors and speakers

The Graphic Systems Division recently held a reception and dinner for those engineers who had authored a technical paper or presentation. After dinner at the Forsgate Country Club in Jamesburg, N.J., each author received a handsome briefcase as a memento of the affair.

Automatic retrieval computer

The Computer Telegram Systems (CTS) was the first step in the modernization of RCA Globcom's message telegram service. The CTS provides automatic switching of telegrams which are properly formatted within seconds. However, approximately 15 to 20% of the telegrams entering the system are rejected and sent to the manual refile section for the following reasons:

The message contains a format error.
The message is a fully addressed telegram for delivery in New York.
The registered address contained in the telegram is not listed in the CTS drum. (The CTS drum can only accommodate 9,000 of the 26,000 registered addresses in New York City.)

To increase the speed of handling of these rejected telegrams and improve efficiency, it was determined that an Automatic Retrieval Computer (ARC) system be developed.

The ARC system is designed so that number lists and other statistical type programs can be run at the same time as messages are being received, corrected and retransmitted by the ARC system. This feature will make it possible for the CTS to run in a fully redundant mode and eliminate outages. It also provides for a wider range of statistical data to be generated which, in turn, will speed the operation of the Service Department.

It is expected that all messages which will be automatically corrected will spend less than 8 seconds in the ARC system. This is a tremendous improvement in service.

Future operations of the ARC system will consist of providing the ability to automatically dial directly into the CTE (Computer Telex Exchange) and permit automatic delivery of messages destined for Private Tieline subscribers.

Breakthrough allows holograms to be erased magnetically for the first time.

RCA recently announced the first method for producing holograms that can be erased magnetically. The holograms—called phase holograms—are produced on a special magnetic surface through the interaction of both the heat and light inherent in a laser beam.

The significance of the new technique is that it could make possible an optical computer memory able to store 100 million bits of data in a film one inch square, and this data could be read out, erased, and re-used repeatedly.

Present experimental techniques are based on the use of photographic film or similar photosensitive materials which cannot be erased because they undergo permanent chemical changes when exposed to light; therefore, these can only be changed or updated by removing them and inserting a fresh film—a very slow process.

By contrast, the new technique makes it possible to "write" information into a magnetic film in 10 billionths of a second, and to erase it in 20 millionths of a second.

Reuben S. Mezrich, who developed the novel technique under the direction of **Dr. Jan A. Rajchman**, Staff Vice President, Information Sciences, described it as follows:

An extremely thin film of manganese bismuth, a magnetic material, is deposited in a single-crystal layer two-millionths of an inch thick on a base of mica. The film is then subjected to a strong magnetic field that forces all its magnetic atoms to line up with their north poles in one direction, their south poles in the other.

Next, the light from a pulsed laser is split into two beams, one going directly to the film and the other going first to the information-bit pattern to be recorded and then to the film. At those points where the two beams interfere constructively (add their power together) the heat from the laser beams warms the magnetic material sufficiently to allow its magnetic atoms to realign themselves so that the north poles of those in the heated portions now point in the same direction as the south poles in the unheated portions. Where the two beams interfere destructively (tend to cancel each other) nothing happens. Thus, a magnetic pattern is created in the film that corresponds to the interference pattern created by the converging laser beams, and a magnetic hologram is born.

The magnetic hologram can be read out in two ways: either by transmitting a laser beam through it, or by reflecting the beam from it.

The hologram can be erased simply by pulsing a nearby wire coil that subjects the film to a strong magnetic field and forces the magnetic atoms to line up, as at first, with all north poles in one direction, all south poles in the other.

The speed and ease of making and erasing magnetic holograms coupled with the fact that their resolution (2000 line/millimeter) far surpasses that of ordinary photographic materials makes the process extremely attractive for achieving an optical computer memory.

Thus far, also, there is no indication that the process causes any thermal decay or other type of fatigue in the material. Apparently, the write-erase cycle can be repeated indefinitely, and, because of the inherent redundancy of holographic storage, dust or minor imperfections in the magnetic film do not seriously affect the hologram readout which can be detected, or read, by light sensitive devices, including the human eye.

W. Leis

A. Liguori

M. R. Sherman

A. G. Evans

New TPA's and Ed Reps

Mr. Walter S. Leis has been appointed Technical Publications Administrator (TPA) for RCA Global Communications, Inc., and **Mr. Anthony Liguori** has been appointed TPA for the Defense Communications Systems Division of Defense Electronic Products. As TPA's, Messrs Leis and Liguori are responsible for the review and approval of technical papers; for coordinating the technical reporting program; and for promoting the preparation of papers for the RCA ENGINEER and other journals, both internal and external.

Mr. Arthur G. Evans has been appointed Editorial Representative for the Magnetic Products Division of Information Systems, and **Mr. Milton R. Sherman** has been appointed Editorial Representative for Defense Microelectronics of Defense Electronic Products. The Editorial Representatives are responsible for planning and processing articles for the RCA ENGINEER, and for supporting the activities of the TPA's in their respective divisions.

A complete listing of Technical Publications Administrators and Editorial Representatives is given on the inside back cover of each issue of the RCA ENGINEER.

Mr. Leis is presently a Staff Engineer with RCA Global Communications, New York, New York, where he is engaged in digital communications activities. He received the BEE from the University of Detroit in January, 1952. From 1951 to 1961 he was with the RCA Laboratories at Riverhead, New York, a division of RCA Laboratories, Princeton, New Jersey. His work was centered around radio wave propagation analysis.

Mr. Liguori is presently Manager of R & D Planning and Coordination for the Defense Communications Systems Division. He has had over twenty four years of professional experience, starting with the RCA Laboratories in 1944. Mr. Liguori holds 21 patents in electronics and communications. He received RCA Laboratories Awards for outstanding work in research in 1950 and 1956. He is a Senior Member of the IEEE.

Mr. Sherman is presently Manager of Technical Programs for Defense Microelectronics. He received the BA in Mathematics from New York University in 1952 and studied Electrical Engineering and Applied Mathematics at Brooklyn Polytechnic Institute from 1952 to 1956. Mr. Sherman joined RCA after eighteen years of semiconductor research, development, and production experience with General Instruments, Texas Instruments, Semiconductor Products, Motorola, and Radio Receptor Co. He is a Member of the IEEE and the Electrochemical Society.

Mr. Evans has been Leader of the Magnetic Tape Engineering Group for the Magnetic Products Division since 1964. He is responsible for development of new test equipment and test methods for new tape products in the Electronics Engineering Group. He received the BSEE from the University of Illinois in 1947. After graduation, he joined RCA as a member of the Engineering Department of the Record Division. Mr. Evans is a member of IEEE, Eta Kappa Nu and a Fellow of the Audio Engineering Society.

Clip out and mail to Editor, *RCA Engineer*, #2-8, Camden

RCA Engineer

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City and State or Plant ______________________

*Please indicate the code letter(s) that appear next to your name on the envelope.

You and your engineering paper

Your technical paper is a valuable asset to RCA and to you as a professional engineer. To ensure that maximum value is gained for your paper, you should:

1. Contact your Technical Publications Administrator (TPA) or Editorial Representative (Ed Rep) and select the best journal in which to publish. These men are acquainted with the requirements of many journals and know how to contact the editors.
2. When your paper appears in print, be sure to report this fact at once to your TPA or Ed Rep. He will see that this is recorded in the *Pen & Podium* Index.
3. When your paper appears in an internal publication such as the RCA ENGINEER, contact your TPA or Ed Rep to explore the possibility of further publication in outside journals. They can assist you in slanting your paper toward the needs of another journal.
4. Determine whether your division can use your paper to advantage in other technical media, such as bulletins, catalog sheets, proposals and reprints. At least contact the responsible group to let them know you have information available for them.
5. Feel free to contact RCA Staff Technical Publication (Bldg. 2-8, Camden, PC-4018) for additional information on any of the above suggestions.

A listing of Ed Reps and TPAs is given on the inside back cover.

Professional engineers

G. R. Gaschnig, Information Systems Division, PE #16926; New Jersey

Charles E. Small, Aerospace Systems Division, PE #22737; Mass.

H. Ketler, Aerospace Systems Division, PE #22677; Mass.

Paul Wright, Advanced Technology Laboratories, PE #17027; New Jersey

RCA Engineer

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