rf design

1978 1988 10th ANNIVERSARY

engineering principles and practices

December 1988

RF Expo East 88 Wrap-Up






Featured Technology — Data Communications

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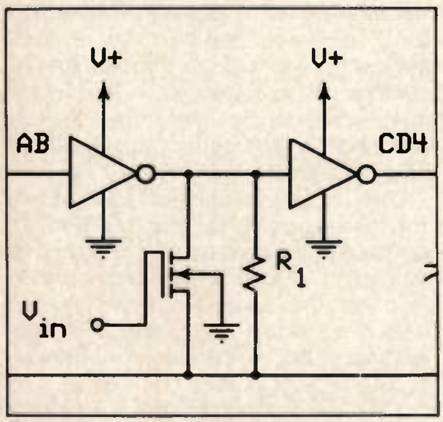
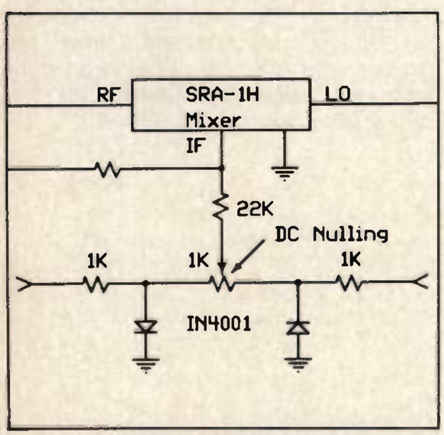
December 1988

Page 24 — RF Expo East 88



Page 57 — RF Probe Design



Page 62 — DSB Modulator Improvements

Cover Story

Featured Technology

Departments

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rf editorial

A 1989 Preview

By Gary A. Breed
Editor

Thanks to all of our readers and advertisers for making 1988 *RF Design*'s best year ever! In every measurable way — article contributions, reader feedback, RF Expo participation, and advertiser support — our tenth year has been tops.

We don't want to mess with success, so next year will bring just a few minor improvements to *RF Design*. One of these is greater involvement in engineering conferences and exhibitions related to the RF industry. The exchange of ideas at these gatherings is an essential part of an engineer's professional life, and by supporting them we can make a worthwhile contribution.

Another noticeable change is the addition of a news column called "Industry Insight." Each month will feature one segment of RF industry, looking at trends in technology, products, and companies. The first few areas getting our scrutiny are test equipment, GaAs technology, RF power transistors, device packaging, and frequency synthesis. With these general-purpose reviews of the state of the industry, we hope to give our readers a better perspective on topics lying outside their primary areas of expertise.

We will continue to feature one significant area of technology each month, starting in January with RF power amplifiers. Our RF Expo show issue in February will highlight small-signal amplifiers, and we will continue from there with filter design, EMC, oscillators and much more. April, May and June will go through the RF spectrum by frequency, covering low and medium frequencies, then HF techniques, and finishing the series with VHF/UHF design emphasis.

Our regular informational columns will continue, including the monthly RFI/EMC Corner. We will keep up our "nagging" on this essential topic for RF engineers. As long as the assault on the electromagnetic spectrum continues, *RF Design* will put EMC information in front of engineers every month.

Although we editors do our best to understand this industry, the best way to provide the material that you, our readers, want and need is for you to tell us. Critiques, suggestions, letters, and article contributions are all essential parts of this magazine. Make 1989 the year you let us know what's on your mind.

Gary A Breed

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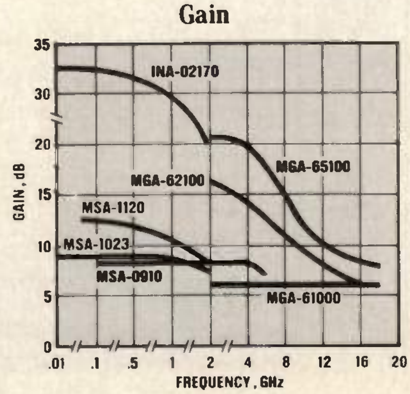
MSA-1023	1.0	9.0	—	27.0
MSA-0910	2.0	8.0	6.0	11.0
MGA-62100	4.0	14.0	2.5	12.0
MGA-65100	14.0	10.0	—	24.0
MGA-61000	18.0	6.0	6.5	14.0

Gain



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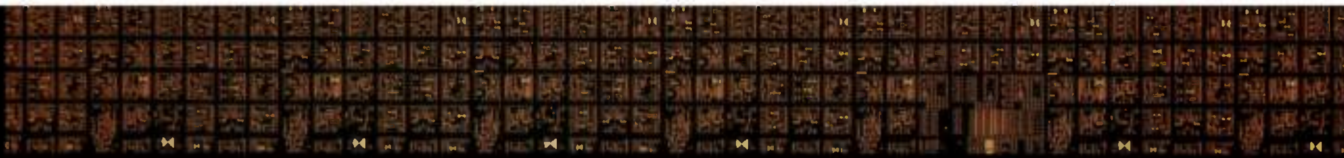

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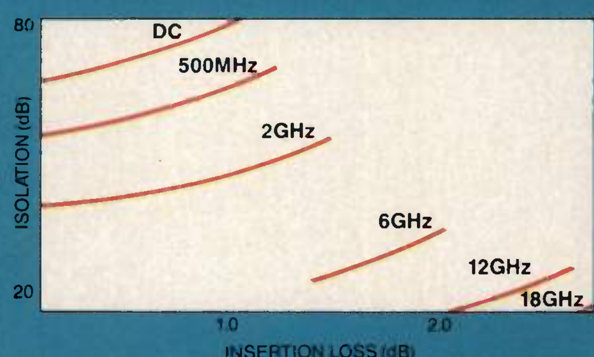

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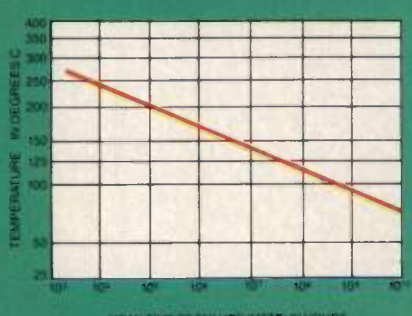

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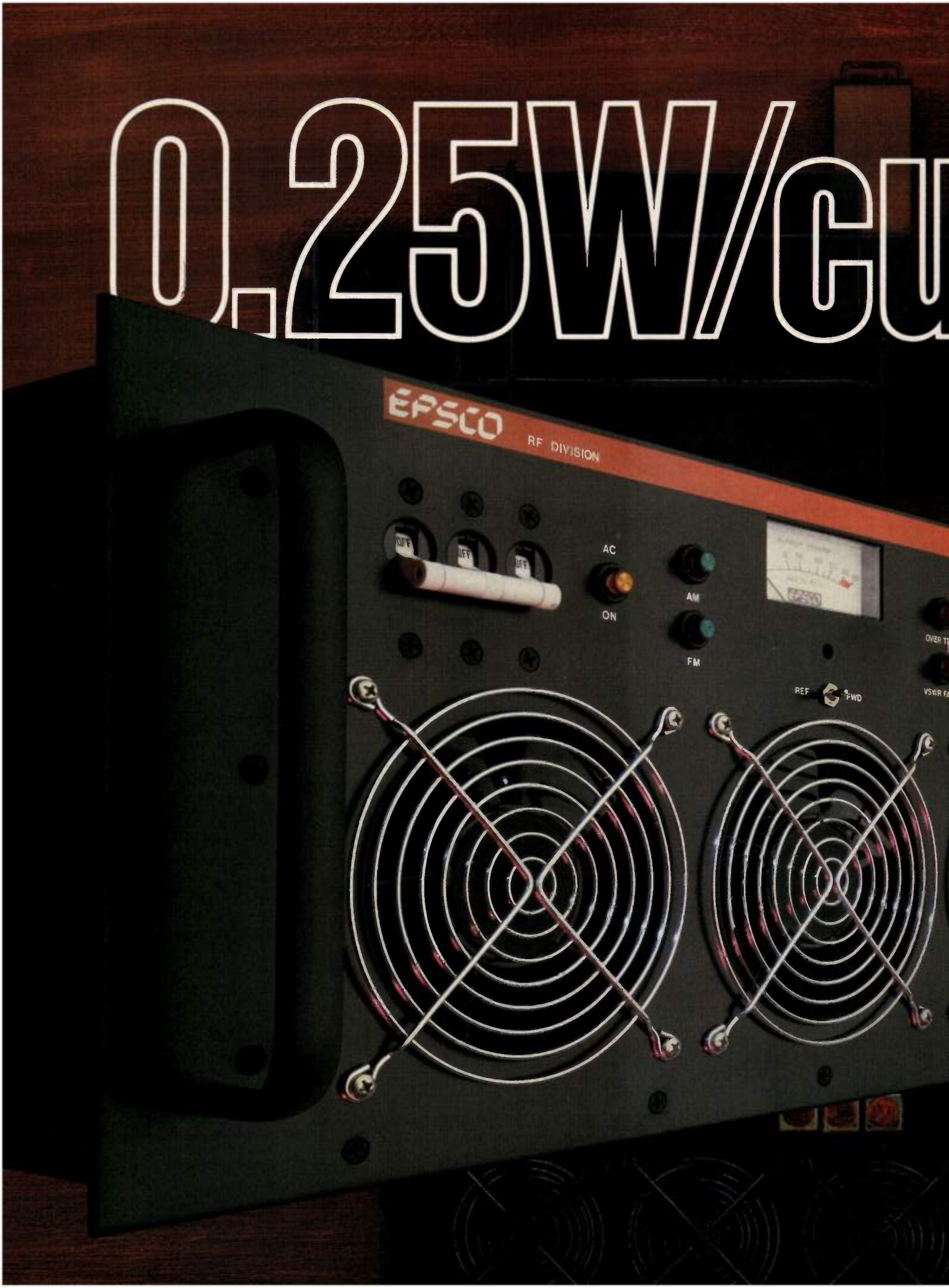
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INFO/CARD 9

rf letters

Letters should be addressed to: Editor, *RF Design*, 6300 S. Syracuse Way, Suite 650, Englewood, CO 80111.

Lest We Forget

Editor:

The abstract for Harvey Morgan's article ("An Emitter Follower Oscillator," October 1988 *RF Design*) says of an oscillating emitter follower, "Its mode of operation is strange, to say the least..." This is another example of a recurring problem in our industry — past knowledge is "lost" and previously available information is re-created.

It's not "strange" that an emitter follower would oscillate. The subject was discussed in at least the following publications:

1. N.O. Sokal and M. Chessman, "Prevent Emitter-Follower Oscillation by Understanding its Causes," *Electronic Design*, vol. 24, no. 13, June 21, 1976, pp. 110-113.

2. F. Ueno and M. Yoneyama, "Suppression of Oscillations in Emitter Followers with Inductive Drive and Capacitive Load (emitter LR method)," *J. Inst. Electrical Communication Engineers of Japan*, vol. 58, no. 11, November 1975. (Available from Scripta Publishing Co., 1511 K St., N.W., Washington, DC 20005.)

3. A. Barna, "On the Transient Response of Emitter Followers," *IEEE J. Solid-State Circuits*, vol. SC-8, no. 3, June 1973, pp. 233-255. (This paper does not consider the inductance in series with the base, an important factor in the oscillation; without the inductance, the circuit can ring, but will not oscillate.) The subject is discussed in more detail in Barna's book *High-Speed Pulse Circuits*, Wiley-Interscience, New York, 1970, pp. 119-128.

4. E. Tammaru, "Using an Analog Computer to Analyze Transistor Circuit Performance," *Solid State Design*, October 1964, pp. 28-36.

5. J.L. Kozikowski, "Analysis and Design of Emitter Followers at High Frequencies," *IEEE Trans. Circuit Theory*, vol. CT-11, March 1964, pp. 129-136.

Nathan O. Sokal
Design Automation, Inc.
Lexington, MA

Corrections

1. The September 1988 *RF Design* article "A Five-Decade System for Testing RF Susceptibility" contained an incorrectly labeled figure. For the graph shown in Figure 4 on page 21, line 1 should be labeled as 2, and 2 should be 1.

2. The deadline for submitted abstracts for the 2nd International Symposium on Recent Advances in Microwave Technology (November 1988 *RF Design*) has been changed. The new deadline is January 15, 1989. The conference has been rescheduled for September 4-8, 1989.

3. The author given in the November 1988 *RF Design* Table of Contents for "Electrostatic Discharge as an EMI Issue" should have been printed as Daryl Gerke of Kimmel Gerke and Associates, Inc.

rf calendar

January 9-12, 1989
SMART V
Hyatt Regency Hotel, New Orleans, LA
Information: Electronic Industries Association, 1722 Eye Street, N.W., Washington, DC 20006. Tel: (202) 457-4932

January 11-13, 1989
SC Global 89
Hyatt Regency, San Francisco, CA
Information: Superconductor Applications Association, 24781 Camino Villa Avenue, El Toro, CA 92630. Tel: (714) 586-8727

January 25-26, 1989
14th Annual San Diego Electronics Show
Del Mar Fairgrounds, Del Mar, CA
Information: Epic Enterprises, Show Management, 3838 Camino Del Rio North, Suite 164, San Diego, CA 92108. Tel: (619) 284-9268

January 30-31, 1989
Electronic Warfare
The Catamaran Hotel, San Diego, CA
Information: Susan Call, Frost & Sullivan, Inc., 106 Fulton Street, New York, NY 10038-2786. Tel: (212) 233-1080

February 12-17, 1989
IEEE 1989 Aerospace Applications Conference
Breckenridge, CO
Information: Harvey Endler, 15137 Gilmore Street, Van Nuys, CA 91411.

February 14-16, 1989
RF Technology Expo 89
Santa Clara Convention Center, Santa Clara, CA
Information: Linda Fortunato, Cardiff Publishing Company, 6300 S. Syracuse Way, Suite 650, Englewood, CO 80111. Tel: (303) 220-0600; (800) 525-9154

February 20-25, 1989
Asia Telecom 89
Westin Stamford and Plaza, Singapore
Information: Angelina Goh, Asia Telecom 89 Secretariat, Singapore Telecom, 31 Exeter Road #26-00, Comcentre, Singapore 0923. Tel: +65 730 3283

March 1-3, 1989
EMC Japan '89
Sunshine City Convention Center, Tokyo, Japan
Information: Secretariat of EMC Japan, Japan Management Association, 3-1-22, Shiba-koen, Minato-ku, Tokyo 105, Japan. Tel: (03) 434-1377; Fax: (03) 434-1836; Telex: J25870

March 21-23, 1989
3rd European Frequency and Time Forum
Le Kursaal, Place Granvelle, Besancon, France
Information: A. Remond, 41bis, avenue de l'Observatoire, 25044 Besancon Cedex, France. Tel: 81.80.22.66

April 5-12, 1989
Electronics and Electrical Engineering '89
Hannover Fairgrounds, Hannover, West Germany
Information: Hannover Fairs USA Inc., 103 Carnegie Center, Princeton, NJ 08540. Tel: (609) 987-1202

rf courses

The George Washington University

Microwave Systems Engineering
January 2-6, 1989, Washington, DC

Secure Communications Systems
January 2-6, 1989, Washington, DC

Global Positioning System
January 9-11, 1989, Washington, DC

Methods for Achieving Effective ECM Systems
January 9-13, 1989, Washington, DC

Modern Radar System Analysis
January 23-27, 1989, San Diego, CA

Intelligent Automated Target Recognition Systems
January 25-27, 1989, Washington, DC

Numerical Techniques in Electromagnetics
January 30-February 2, 1989, Washington, DC

Introduction to Electronic Warfare Receivers
February 1-3, 1989, Washington, DC

Radar Operation and Design
February 1-3, 1989, Washington, DC

Specifying, Testing and Evaluating Communication and Data Transmission System
February 6-8, 1989, Washington, DC

Broadband Communications Systems
February 13-17, 1989, Washington, DC

Electromagnetic Pulse and Its Effects on Systems
February 27-March 1, 1989, Washington, DC

Information: Misael Rodriguez, Continuing Engineering Education, George Washington University, Washington, DC 20052. Tel: (800) 424-9773; (202) 994-6106

UCLA Extension

Superconductive Electronics
February 7-9, 1989, Los Angeles, CA

Power Electronic Circuits
March 6-10, 1989, Los Angeles, CA

Information: UCLA Extension, P.O. Box 24901, Los Angeles, CA 90024-0901. Tel: (213) 825-1047

Compliance Engineering

EMI
February 14, 1989, San Diego, CA

Safety
February 15, 1989, San Diego, CA

ESD
February 16, 1989, San Diego, CA

Telecom
February 17, 1989, San Diego, CA

Information: Compliance Engineering, 271 Great Road, Acton, MA 01720. Tel: (508) 264-4208.

Integrated Computer Systems

C Advanced Programming Techniques and Data Structures
February 14-17, 1989, Los Angeles, CA
February 28-March 3, 1989, Washington, DC

CASE: Computer-Aided Software Engineering
January 24-27, 1989, Washington, DC
January 31-February 3, 1989, Los Angeles, CA

Digital Control Systems: Design Techniques and Tools
January 10-13, 1989, Washington, DC

Digital Signal Processing: Techniques and Applications
January 17-20, 1989, Los Angeles, CA
January 31-February 3, 1989, San Francisco, CA
February 7-10, 1989, Washington, DC

Fiber Optic Communication Systems
January 10-13, 1989, Washington, DC
January 31-February 3, 1989, Boston, MA
February 21-24, 1989, San Francisco, CA

Image Processing and Machine Vision
January 24-27, 1989, Toronto, Ontario, Canada
February 21-24, 1989, Los Angeles, CA

Information: John Valenti, Integrated Computer Systems, 5800 Hannum Avenue, P.O. Box 3614, Culver City, CA 90321-3614. Tel: (800) 421-8166; (213) 417-8888

Interference Control Technologies, Inc.

Grounding and Shielding
January 23-27, 1989, Orlando, FL

Practical EMI Fixes
January 16-20, 1989, San Diego, CA
January 30 - February 3, 1989, Orlando, FL

EMC Design and Measurement
February 6-10, 1989, Los Angeles, CA

TEMPEST Design and Measurement
February 7-10, 1989, Washington, DC

TEMPEST Facilities Design
January 16-20, 1989, Palo Alto, CA

Information: Penny Caran, Registrar, Interference Control Technologies, Inc., State Route 625, P.O. Box D, Gainsville, VA 22056. Tel:(703) 347-0030

Technology Dynamics Institute

Optical Fiber Communications Systems
January 23-25, 1989

Information: Technology Dynamics Institute, 140 North Vista Street, Los Angeles, CA 90036. Tel: (213) 935-4649

Predictions for Military TEMPEST Equipment Market

According to a new report by Frost and Sullivan Inc., a New York market research firm, the market for military TEMPEST equipment and services is estimated to have reached $1,008 million in 1987, a growth of 15.3 percent over the 1986 market of $874 million. This is a sharp reduction from the 44.8 percent growth rate estimated for the previous year. The 1987 slowdown is attributed mostly to the extreme downward pressure on defense spending in general. The market growth rate is estimated to be down further in 1988 to an annual rate of 9.5 percent, with $1,104 million sales expected for 1988. Higher growth rates are projected for the early 1990s, but not at the explosive levels experienced prior to 1987. The complete report is available at a cost of $2,150 from: Frost and Sullivan Inc., 106 Fulton Street, New York, NY 10038. Tel: (212) 233-1080.

NIST Facility to Aid PDES Standard Implementation

In a move to speed the development and use of computer-integrated design, manufacturing, and logistic processes, the National Institute of Standards and Technology (NIST) has announced that it will develop a facility for testing implementations of the Product Data Exchange Specification (PDES). The facility, known as the National PDES Testbed, will also provide a demonstration site for applications of PDES technology and will conduct an information and technology transfer program to speed the implementation of PDES standards. PDES is a cooperative industry/government project aimed at developing a standardized format for representing and exchanging information about almost any manufactured product.

HP Announces Opening of Modular Measurement System

Hewlett-Packard Co. announced the opening of its HP 70000 modular measurement system (MMS) architecture. Patent rights to the system's private modular system interface bus have been assigned to the general public at no cost and with no licensing requirements. The MMS architecture provides an environment for high-performance RF and microwave test instrumentation that complements the industry's VXI bus architecture. Together, the two architectures form the core of HP's modular test system architecture for automated test applications.

Commercial manufacturers are being asked to join in an industry body similar to the VXI bus consortium to develop the MMS specification. HP's only requirement is backward compatibility to existing HP 70000 system components. An HP 70000 system design overview, available free of charge, describes the MMS architecture in detail and discusses design considerations for building into the system. For information, contact: Hewlett-Packard Co., 19310 Pruneridge Avenue, Cupertino, CA 95014.

TRW Demonstrates SuperChip Technology

TRW Inc. has fabricated a microelectronic test chip incorporating functional CMOS devices with 0.5 micron gates and with other features as small as 0.25 microns. In a related step, the company has demonstrated a "mix-and-match" technique which combines both optical and electron beam methods of fabricating advanced chips. With this technique, only those layers of the chip's final design that demand the precision of electron beam lithography are fabricated using the exceedingiy accurate, but slower and more expensive, technique. The remaining layers are made using more conventional optical technology. The "mix-and-match" test wafers were fabricated using TRW's 1.25 micron radiation-hardened CMOS process, which has demonstrated radiation hardness in excess of a megarad, total dose. The "mix-and-match" and 0.5 micron lithography techniques will be used to fabricate the finished product of TRW's VHSIC Phase 2 effort, the Central Processing Unit — Arithmetic Extended (CPUAX) SuperChip. The CPUAX is designed to function as the central brain of advanced digital signal processing systems.

Report Analyzes GaAs/GaP Competition

Strategies Unlimited, a market research and consulting services firm in Mountain View, Calif., has released a new report entitled "GaAs/GaP Wafer Competition Report — 1988." The report reviews 33 manufacturers of GaAs and GaP wafers throughout the world. Profiles of suppliers provide a summary of the activities of each company including a brief background, description of current III-V wafer/materials activities, and commentary. This report is one of several feature reports which Strategies Unlimited publishes under the GaAs Industry Information Service, an open-ended subscription program for the GaAs device and materials community. For further information, contact Ron Lange or John Day at: Strategies Unlimited, 201 San Antonio Circle, Suite 205, Mountain View, CA 94040. Tel: (415) 941-3438.

EEsof Secures U.K. Universities Contract

An agreement between EEsof Inc. and the University of Manchester, England broadens the use of EEsof software as part of the United Kingdom's ECAD (Electronics Computer-Aided Design) Initiative. Universities in Great Britain have selected EEsof for their microwave/RF CAE needs and have agreed to purchase EEsof microwave design software products over the next twelve months for use in the ECAD program. The ECAD Initiative will provide hardware/software industrial standards in all U.K. higher educational institutions where electronics computer-aided design in teaching and research is required. The long-range goal is to increase the number and quality of graduates who are skilled in high-frequency circuit design to meet the demand from the growing microwave/RF industry sector rapidly developing in the United Kingdom.

Gould to Relocate Headquarters

Gould Inc. has announced that it is relocating its worldwide corporate headquarters from Rolling Meadows, Ill., to the Eastlake, Ohio, headquarters of its Foil Division near Cleveland. The relocation is expected to be completed by mid-1990. Following the move, Gould will employ about 550 people in the greater Cleveland area and about 750 others throughout Ohio.

Capacitor Market Growth Projected in New Study

The worldwide electronic capacitor market is projected to expand at an annual average growth rate of 4.6 percent from 1987 to reach a total value of $8.2 billion in 1991, according to a new study from Elsevier BEP. The study, "Profile of the Worldwide Capacitor Industry," looks at the market for electronic capacitors by technology in Europe, Japan, the United States and the rest of the world between

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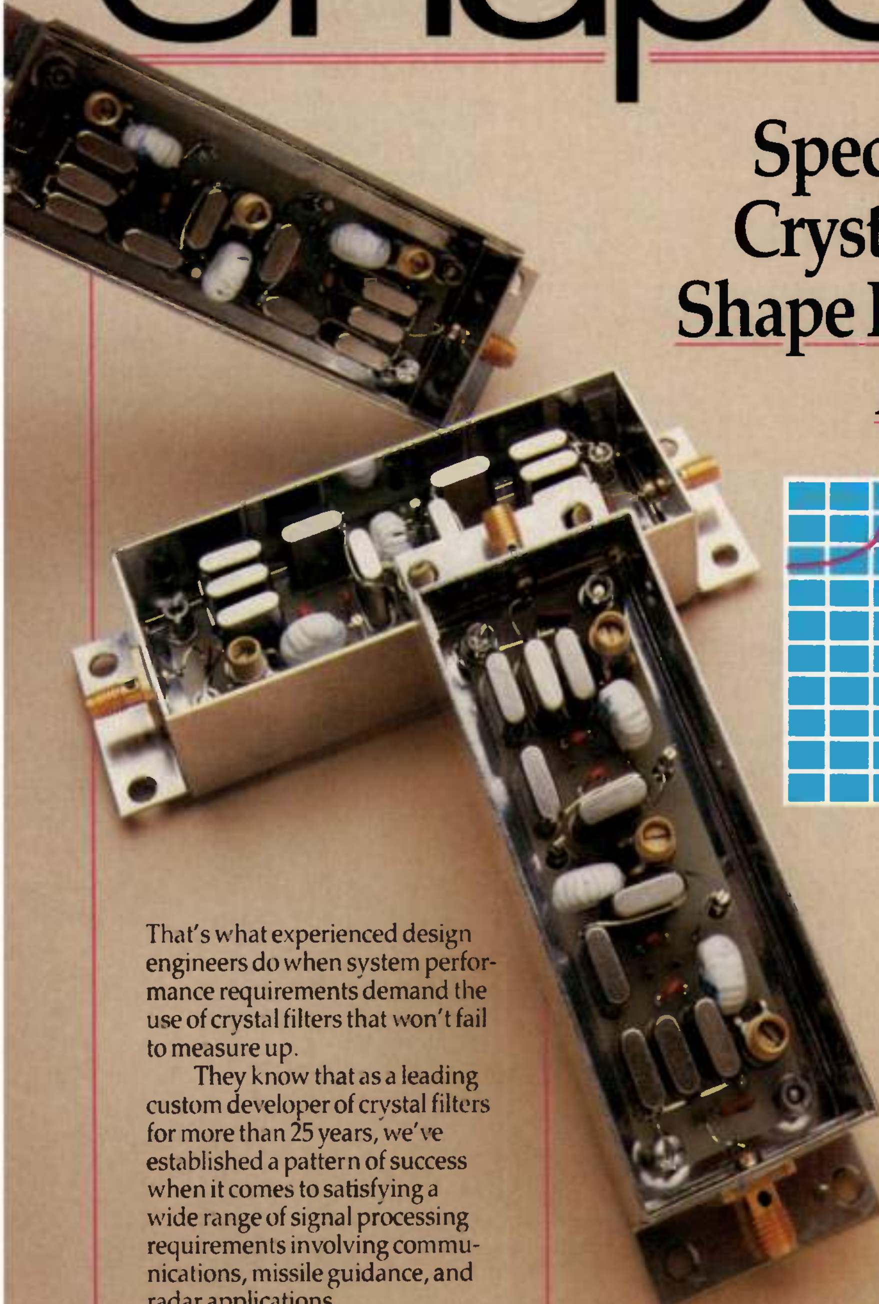

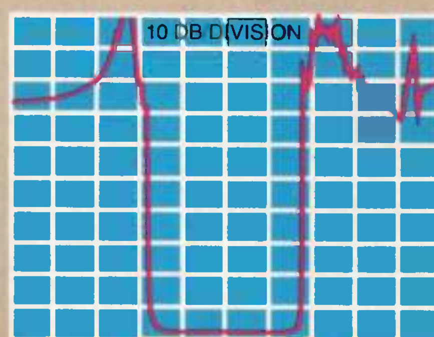

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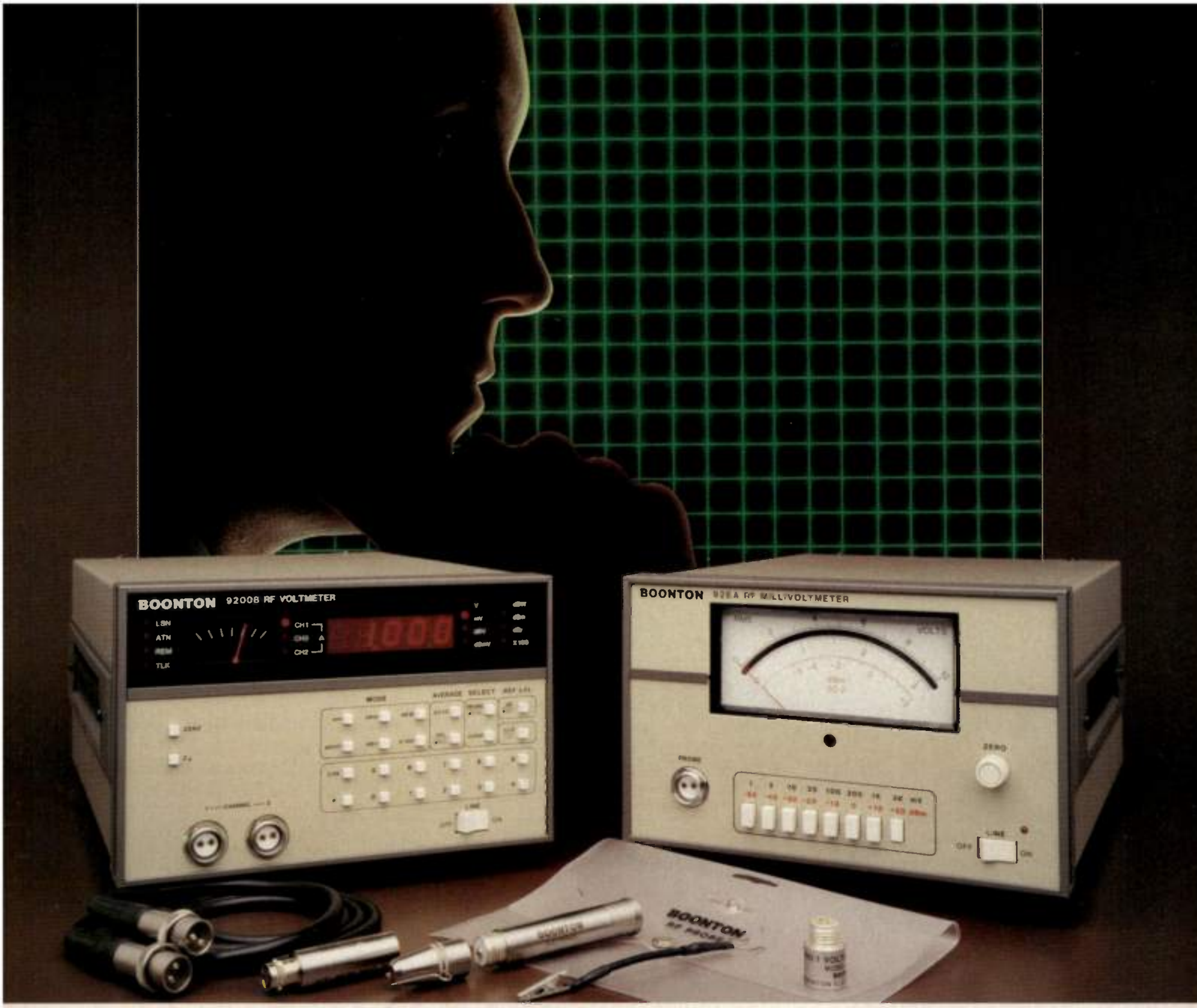
1985 and 1991. It includes a section on the world supply of capacitors and an analysis of manufacturing trends. "Profile of the Worldwide Capacitor Industry" is available at a price of $595 (overseas delivery only) from: Elsevier BEP Data Services, P.O. Box 28, Luton, Beds, LU2 OED, England.

Harris and Cambridge Instruments Sign Manufacturing Technology Agreement

Harris Microwave Semiconductor and Cambridge Instruments have signed a joint manufacturing technology development agreement. Under the terms of the partnership, Cambridge is installing its latest electron beam lithography system at Harris Microwave Semiconductor in Milpitas, Calif. The model 10.5 E-beam will be used in conjunction with Harris' new 10X ASET optical stepper, bringing a new technology to a commercial gallium arsenide (GaAs) volume manufacturing environment. The mixing and matching of E-beam and optical stepper lithography techniques allows the volume fabrication of quarter micron gate length GaAs FETs and MMICs. The advantage of direct-write



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electron beam lithography is its ability to pattern features directly onto a GaAs substrate. It will also be used to execute the process steps requiring tight control of critical device dimensions. The stepper will be used for other lithographic steps requiring a high throughput capability. Harris will apply this new technology on three- and four-inch diameter wafers.

Argonne National Lab and American Superconductor Announce Licensing Agreement

The U.S. Department of Energy's Argonne National Laboratory and American Superconductor Corp. of Cambridge, Mass., have announced an agreement that provides an exclusive license to American Superconductor for a technology to produce high-temperature superconductors. The agreement is the first to license superconducting technology from a national laboratory to private industry. Under the agreement, American Superconductor has exclusive rights to develop and market the technology developed by Argonne scientist Dieter Gruen, a process which yields a wire coated with yttrium-barium-copper oxide, a high-temperature superconductor. Under a separate agreement, American Superconductor will provide $100,000 to fund Argonne research on other superconducting technologies.

EMI/EMC Test Facility Opened by IBM

A new facility dedicated entirely to EMI/EMC specifications compliance has been built at the IBM Product Laboratory at Endicott, N.Y. The Ray Proof Shielding Systems Corp. handled all aspects of the construction from design to completion of the building and its built-in test facilities. The special facility includes a 68-foot-long semi-anechoic chamber for testing of computers and associated equipment to FCC-mandated specifications and for susceptibility testing. Additionally, it contains seven shielded rooms for instrumentation and radiated and conducted testing to other specifications as well as areas for electrostatic discharge testing.

ARX Subsidiary Receives $4 Million Navy Award

ARX Inc. announced that its subsidiary, T-Cas Corp. of McLean, Va., has been awarded a $4 million contract by the Department of the Navy for a turnkey communications system for the Mid-Atlantic Electronic Warfare Range in the vicinity of the Marine Corps Air Station (MCAS), Cherry Point, N.C. The communications system consists of digital microwave radio datalinks, fiber optic cable land-line communications networks, multiplexing and switching equipment, supervisory and monitoring facilities, antenna towers, equipment enclosures and support structures, and ancillary items.

Electrospace Receives $42.7 Million Air Force Contract

Electrospace Systems Inc. of Richardson, Texas, a Chrysler company, has been awarded a three-year, $42.7 million Air Force contract for converting two 707-320 aircraft into Cruise Missile Mission Control Aircraft (CMMCA). The award comes from the Aeronautical Systems Division (ASD) at Wright-Patterson Air Force Base and will be completed in mid-1991 with the delivery of two EC-18D aircraft. The two CMMCA aircraft will provide the military with the capability to monitor and control the test flight of cruise missiles. The on-board radar and telemetry antennas will receive information from the cruise missile and process the data to give ongoing analysis during the tests.

Steinbrecher Awarded MIT Lincoln Laboratory Contract

Steinbrecher Corp. of Woburn, Mass., has been awarded a $250,000 contract from the Massachusetts Institute of Technology, Lincoln Laboratory. The award calls for Steinbrecher to build low-level radar equipment, including a Ku-band transmitter/receiver, a wideband ramp multiplier and a remote receiver.

Racal-Dana Receives Contract From U.S. Army

The U.S. Army has awarded Racal-Dana Instruments Inc., a multi-year contract for 5002A Wideband Level Meters. The contract comes from the Test Measurement Diagnostic Equipment (TMDE) Procurement Branch, USA Communications and Electronics (USACECOM) of Fort Monmouth, N.J. The five-year, indeterminate-quantity contract has an estimated first-year worth of $3.6 million. The 5002A will be used for general-purpose AC RMS measurement at various Army depots and repair stations throughout the world. Applications include the maintenance and calibration of ground-based radios. The 5002A will be used to measure the signal-to-noise ratio and gain on the radio receivers, as well as receiver audio out-put power and system noise.

EIP Receives $13 Million Air Force Contract

EIP Microwave Inc. of San Jose, CA, announced receipt of a $12.97 million contract from the U.S. Air Force's Kelly Field Command. The contract, for EIP Models 548B WB-70 and 548B WB-36 Microwave Counters, requires the Air Force to purchase all of its needs for this kind of product from EIP for the next 30 months. This is the largest single contract ever received by EIP Microwave.

Wiltron Awarded Test Equipment Contract

Wiltron Co. of Morgan Hill, Calif., has been awarded a British Navy contract worth close to $1 million. The contract calls for Wiltron to supply 22 units of the model 6747A-20 Synthesizer along with accessories. The award was made by the Admiralty Research Establishment and will be part of the Common Range Test Equipment (CRETE).

RF Expo East 88 Wrap-up

By Gary A. Breed
Editor

October 24-27, Philadelphia: Over 1000 RF engineers from the eastern United States, Canada, and several other countries were treated to an excellent technical program, top-notch courses, and a collection of the most important suppliers of components, equipment and software in the RF industry.

As has been the case in both previous Expo East gatherings, the educational opportunities were extremely well received by the engineers in attendance. 172 people took part in Les Besser's now-famous RF Circuit Design Fundamentals course, and most of them continued their participation on the following day, where a class of 150 attended the first presentation of the new RF Circuit Design: Part II, a continuation of the original Fundamentals course. Both of these courses received high marks from the attending engineers. Nearly all agreed that the new RF Circuit Design: Part II is extremely valuable, although some refinement is still needed.

Another new course was Computer-Aided Filter Design, taught by Randy Rhea. Despite being scheduled at the same time as the popular Fundamentals course, 30 engineers chose to take part in this tutorial on the basics of filter design and the use of computers to assist in design of practical circuits. Reviews of this course were emphatically positive; many of those in attendance commented on Randy's clear explanations and complete answers to questions from the class.

The Exhibition Hall

The eighty companies exhibiting at RF Expo East were visited by engineers working on a wide range of applications in RF manufacturing, research, and services. Attendees were treated to several first-time public showings of new products. Ramsey Electronics introduced their RSG10 synthesized signal generator, covering 0.1 to 999.99 MHz, with -30 dB harmonics and a $2495 price tag. A real-time SAW spectrum analyzer was shown by Phonon, utilizing dispersive delay lines on unheated quartz substrates.

A new six watt Class A power amplifier module for 100 to 500 MHz (PAA0105-29-6L) was on display at the Motorola booth, along with another module for 800 to 1000 MHz with 40 dB gain, the PAA0810-40-50L. Hewlett-Packard's HP 8644A (252 kHz - 2060 MHz) and HP 8665A (100 kHz - 4.2 GHz) synthesized signal generators were shown for the first time, along with a 6 GHz spectrum analyzer, the HP 8561A. These and most other companies noted that new products are being prepared, with likely introduction in February at RF Technology Expo 89.

Exhibiting companies brought nearly 500 members of their staff to RF Expo East. Most, of course, were sales and marketing people to deal with the prospective customers who came to examine their products. However, many of them were engineering personnel, on hand to take part in the technical program.

Technical Papers

Special thanks needs to be given to Program Chairman Carl Erikson, and to the speakers who took the time and effort to prepare and present technical papers in Philadelphia. A review of the evaluation forms filled out by attending

Williams Pond's presentation on crystal filters was part of the popular quartz crystal session.

Assistant Editor Katie McCormick learns about AEL's RF product line.

engineers shows that this years' program was the best of any previous RF Expo! Three 3-hour tutorial sessions were included in the program, and all were exceptionally well-received. Donald Steinbrecher's Mixer Tutorial filled the same room used for the Fundamentals course. Drawing nearly as many were Antenna Fundamentals by Benjamin Rulf, and Radiowave Propagation by Daniel R. Dorsey.

Sessions on SAW Devices, Receiver Design, Synthesizers and Quartz Crystals were extremely popular. From Canadian participants, Noel Boutin's paper on complex signals, and an L-band amplifier design paper by Gilles Brassard were among the highly regarded presentations.

Other Highlights

Attracting a lot of attention were prize drawings at several of the exhibitors' booths. Complete Hybrid Parts Supply (C.H.P.S.) found a winner for their VCR when Sal Losapio of General Electric had his name drawn. Leslie Debelius of AAI Corp. won an RF wattmeter, carrying case and sampling element from Coaxial Dynamics.

Another winner, receiving the =Super star= circuit analysis program from Circuit Busters, is Philip East of Emhiser Research, Ltd. Also joining the group was Donald Hoerr of Krautkramer Branson, the pleased winner of a laptop computer awarded by American Technical Ceramics. Rounding out the winners, with a compact disc (CD) player from Amperex/Philips, is Joseph Chiaravallo from G.E. Aerospace.

In summary, RF Expo East was good business for exhibitors, and a good education in both engineering and prodduct availability for RF engineers. The next RF Expo East will be held October 24-26, 1989 at the Tropicana Hotel, Atlantic City, New Jersey.

From top to bottom, the staffs of Harris Microwave Semiconductor, Signetics, and Instruments for Industry enjoy RF Expo East.

Multipath Interference in FM Data Transmission

Problems and Possible Solutions to High Data Error in VHF/UHF Radio Systems

By Steven E. Turner
Universal Data Systems

As the business community becomes more dependent on numerical data, and with much of today's business conducted away from the office, there is increasing interest in the use of FM radio as a means of data transfer between portable or mobile receivers and a central office. Multipath interference is a major problem that must be overcome before VHF and UHF FM data transmission can become widespread. This article seeks to provide an explanation of what multipath is, what problems it creates for VHF and UHF FM communication, and what can be done to counteract its effects so that reliable data communication can take place over mobile FM radio links.

For many years, the use of frequency modulation (FM) on the VHF and UHF radio bands was confined almost exclusively to commercial broadcast stations and to users of limited-distance communications such as public services or transportation and utility companies. These applications were exclusively audio in nature — music and voice communication. In today's business world there is a growing need to access numerical data from the home, automobile and other business locations as quickly and conveniently as in the office. Historically, FM has been one of the least expensive and most reliable means of wireless short-range communication; thus it is logical that it be used as a means of communicating data between the office and a mobile station in a vehicle miles away. Furthermore, as electronics costs continue to come down, it is becoming feasible to build and market portable data terminals that can be taken virtually anywhere. It becomes a simple matter to tie into the office data bank via the FM radio and retrieve the address of a client, a customer's account balance, or any other piece of data that might be valuable while away from the office.

The potential user base is almost endless. So why hasn't this form of communication become widespread already? There are two principal reasons. First, until recently, the cost of building devices that would perform this task was prohibitive. After all, the user might want to have a large network of these portable terminals, like the mobile voice radios that are so common today. For this reason, the cost of the product must be reasonably low. The second major problem is "multipath interference" — the condition encountered when multiple transmission paths occur between the transmitter and the receiver, resulting in strong interference at the receiver and correspondingly high data error rates.

A Typical VHF/UHF FM Data Radio

Before getting into the details of multipath interference rejection, it is helpful to consider how a typical FM radio can be used for effective digital data transfer. This setup is illustrated in Figure 1. The unique feature of the transmitter is the data source. Instead of an analog voice or music signal driving the frequency modulator, this radio employs a digital data signal, appropriately scrambled and filtered, as the input to the transmitter. The modulator, therefore, is simply a frequency-shift-keyed (FSK) modulator, transmitting one frequency to represent an input data symbol of ZERO and another frequency to represent a data symbol of ONE. This input signal could represent virtually any information imaginable, as long as it can be expressed as a string of data symbols.

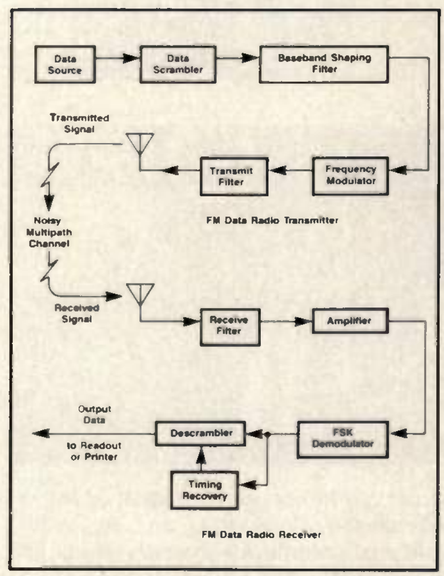

Figure 1. Basic structure of a UHF/VHF FM data radio.

The data scrambler is used to turn the input data into a random-looking stream

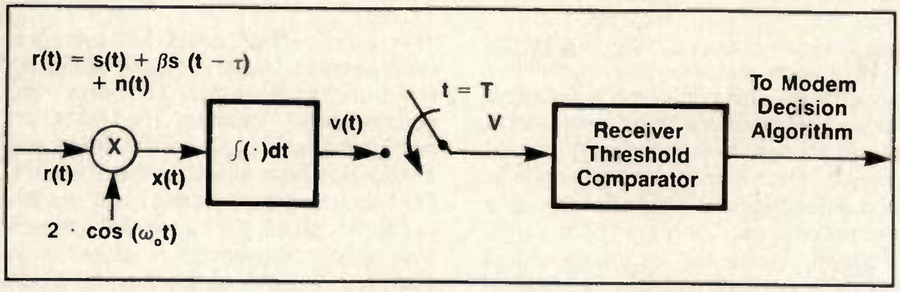

Figure 2. Correlation detector for a binary FSK signal demodulator.

of ZEROs and ONEs. This serves two distinct purposes. First, the pseudo-random output signal has a much whiter power spectrum than the deterministic input signal; that is, it has a more uniform power spectral density across the transmit bandwidth. This makes for more successful detection by a traditional correlation or matched-filter receiver and is an almost universal procedure in data communication. The second function of the scrambler is to provide message security for the user. It is a simple matter to use a different scrambler/descrambler set for each network of users. As a result, only those radios having the appropriate descrambler will be able to successfully descramble and demodulate the transmitted signal. To those with a nonmatching descrambler, the received signal will appear as random noise, and the signal will be unintelligible.

With transmitter center frequencies in the tens of megahertz and signal bandwidths several megahertz wide, it is not unreasonable to send data at rates of up to 5,000 to 10,000 bits per second (bps) — speeds comparable to those obtained over telephone lines using high-speed modems. The frequency modulator and transmit filter used in an FM data radio are the same standard components used in any FM radio transmitter, and the output signal is a standard FM signal — it is simply a data signal rather than an audio signal.

The front-end of the radio receiver in Figure 1 is a typical FM receiver, much like the commercial units found in home and automobile radios. The difference is that the demodulator used is a frequency-shift-keyed (FSK) demodulator. These come in several varieties, many of which involve implementations of a standard matched-filter detector. One version, a typical FSK correlation demodulator, is illustrated in Figure 2. Here the received signal is summed over some sampling period no more than half the baseband digital data rate (i.e., it is sampled at or above the Nyquist frequency). The input signal r(t) is made up of the direct signal s(t), the fading coefficient β, the multipath signal $s(t-\tau)$ delayed τ seconds in time, and noise. The sampled output is then sent to a threshold comparison device, which determines what signal was most likely sent, based upon the value of the sampler output. For simplicity, Figure 2 assumes a binary data signal and a single threshold; therefore, there are only two possible answers — ZERO or ONE. If the sampler output is above the threshold, a ONE is detected; if the output is below the threshold, a ZERO is detected. To accommodate higher data rates, multi-level rather than binary modulation schemes could easily be employed, accompanied by multi-level threshold comparators. After the received signal passes through the threshold device, the recovered data signal is sent to the descrambler and to the timing recovery loop (as shown in Fig. 1), and the descrambled output data stream is sent to a display to memory.

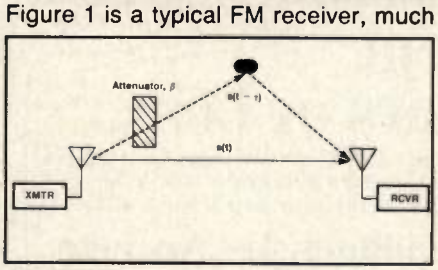

Figure 3. Channel model for multipath transmission in a VHF/UHF FM data radio.

The Multipath Problem

Now that the operation of the FM digital radio has been considered, it should be easier to understand how multipath interference wreaks such havoc on this type of radio transmission. First, it is important to consider the physical phenomenon of multipath interference. Multipath occurs any time a transmitted free-space signal bounces off an object in the environment and finds its way to the receiver. The receiver sees both the direct-path signal over the shortest route between the transmitter and receiver, plus one or more multipath signals that bounced their way around the landscape before arriving at the receiver. Such a multipath condition is depicted in Figure 3 where, for the sake of simplicity, only one multipath signal is shown. Since the multipath signal takes a longer path as it travels between the transmitter and receiver, it suffers some time delay represented by τ in Figure 3. It will also experience attenuation (β) as it passes through the atmosphere and bounces off one or more objects. As a result, the FM radio receiver sees the direct signal plus an attenuated, delayed multipath signal, as well as noise picked up by both signals as they make their way to the receiver. Out of this conglomeration of signals, the receiver is required to detect accurately the transmitted direct-path signal and reject all others.

What causes multipath? Obviously, any object that is in sight of both the transmitter and receiver can serve as a reflector. If the entire network is indoors, then walls, ceilings, floors, furniture, and even people serve as effective reflectors for a multipath signal. Moreover, the people move, causing the reflection sent to the receiver to vary in delay and attenuation from one instant to the next. Outside, the problems get much worse. In the first place, the increased distance over which the network is expected to work requires the receiver to be much more sensitive — and thus more susceptible to the damaging effects of multipath. Furthermore, there are many different objects to serve as reflectors in an outside environment. The causes of outdoor multipath interference also vary with the terrain. In an urban environment, for example, it is common to see reflections of the transmitted signal from a multitude of buildings, as well as towers, vehicles and roadways. Each of these reflections bombard the receiver, interfering with one another until the radio sees a garbled jumble of signals instead of a single, clear signal.

In a rural environment tall buildings and towers are not normally encountered, so one might think that the problem there would be lessened. This is not always the case, however. Multipath in a rural setting can be caused by reflections from the various layers of the atmosphere, especially at night. During the day, wind and rising convective currents usually mix the atmosphere thoroughly, but on a calm, clear, summer night this normal mixing ceases, and the troposphere tends to form layers characterized by the temperature and moisture content of the air. This results in the well-known "anomalous propagation" effect which often masquerades as rainfall on weather radar screens on muggy summer evenings. These layers are ideal multipath reflectors, and since there are often many separate atmospheric layers, there are many multipath signals present at the radio receiver, all associated with different delay and attenuation factors.

If a portable FM receiver is mobile, as in a moving vehicle, the multipath problem is even worse, since the location of the radio relative to the various objects serving as reflectors is constantly changing; as it moves out of the way of some reflecting surfaces, it moves into the range of others. Thus, whatever technique is used to keep the multipath signals from degrading radio detection and demodulation must also be versatile enough to deal with rapidly changing conditions in the interfering signals at the radio receiver input.

Two Types of Multipath Interference

Before addressing solutions to the multipath problem, it is necessary to examine what the radio receiver experiences when multipath is present. There are two distinct types of multipath, which cause two very different problems for the FM receiver. For example, if the interfering reflector is relatively close to the line-of-sight path between the transmitter and receiver, the time delay and amplitude attenuation imposed on the multipath signal will often be quite small. This is referred to as "rapid" multipath. In general, the receiver's tracking loop cannot successfully track this quickly changing multipath signal present at its input. The multipath signal therefore

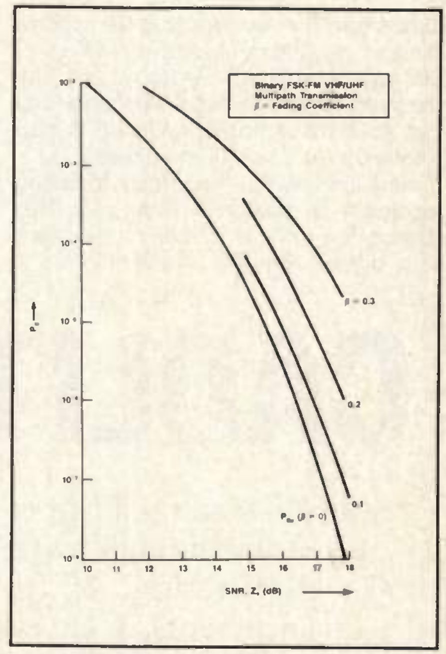

Figure 4. Probability of error versus SNR, Z, for conditions of fading multipath.

appears to the receiver to be a uniform random noise signal, and the effect of the rapid multipath is to cause the received signal to fade slowly in and out. As a result, rapid multipath is also referred to as "fading" multipath.

An illustration of the effects of fading multipath is shown in Figure 4. This depicts the error probability associated with binary FSK-FM modulation as a function of the signal-to-noise ratio (SNR) and the fading coefficient, β. The P_{E0} curve in Figure 4 symbolizes typical performance when no multipath is present. As β increases (i.e., as the amplitude of the multipath signal gets stronger), the performance of an unassisted FSK receiver degrades drastically due to interference between the desired and unwanted signals. As β approaches 0.3, so that the strength of the multipath signal present at the receiver is 30 percent of the direct-path signal strength, the ability of the receiver to discriminate between the desired signal and the interfering signal is severely impaired. Clearly, the radio receiver must have some assistance if it is to operate effectively in the presence of multipath interference.

The problem becomes even more complex when the second type of multipath comes into play. If the interfering object(s) is some distance away from the line-of-sight path between the transmitter and receiver, the time delay becomes much longer, and the received signal is affected as adjacent bits of the direct signal and the multipath signal overlap. That is, the multipath signal is delayed long enough so that it arrives at the receiver after the corresponding bit of the direct-path signal has already passed on and the next bit is arriving. For obvious reasons, this is referred to as "slow" multipath. The result of this overlapping condition is intersymbol interference, which may manifest itself either as a very deep fade or as an apparent improvement in the received signal SNR on a bit-by-bit basis. Strong fluctuations in signal strength are perceived by the receiver, depending on whether a given delayed, overlapping multipath bit is adding constructively or destructively with the direct-path signal bit present at the receiver input. The detection circuits in the receiver cannot tolerate such rapid signal strength variations, and momentary failure of the receiver often results. This phenomenon is familiar to anyone who has listened to an FM commercial broadcast station while driving through an urban, reflector-filled area. When the effects of slow multipath are heard, the station will at times sound quite clear, and at other times the signal will fade slowly in and out. At other times, it will fade rapidly in and out, sounding somewhat like the radio personality is blowing into the microphone rather than broadcasting music.

The best way to understand the phenomenon of slow multipath is to examine what takes place on a bit-by-bit basis at the input to the receiver when this type of multipath is present. This situation is outlined in Figure 5, which depicts the four possible cases of adjacent-bit overlap between the desired and the interfering multipath signal. These cases are a transmitted ONE bit followed by another ONE bit, a ZERO

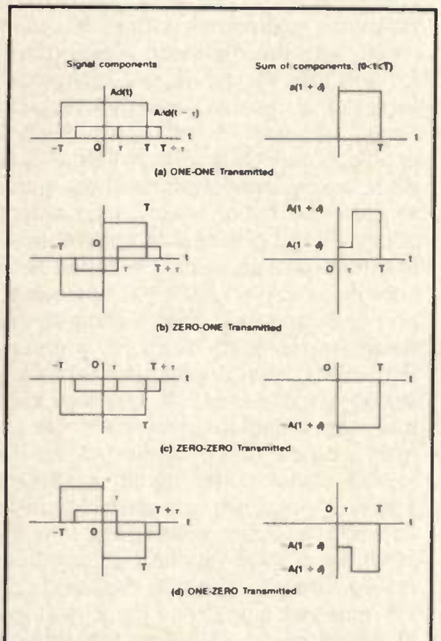

Figure 5. Various cases of intersymbol interference in multipath transmission.

followed by a ONE, a ZERO followed by a ZERO, and a ONE followed by a ZERO. In place of the fading coefficient, β, that was used in the case of rapid multipath, a new parameter, δ, has been substituted to account for the combined effects of fading and time delay, since both are significant factors in the ultimate characteristics of the slow multipath signal. Specifically, δ is defined as

$$\delta = \beta \cos(\omega \tau)$$

where ω is the multipath signal fluctuation frequency, and τ is the delay associated with the multipath signal. Figure 5(a) shows that if a ONE bit is transmitted and the following bit is also a ONE, then as the first transmitted ONE arrives at the receiver via a delayed multipath signal at about the same time the second ONE arrives via the direct-path signal, in-phase interference takes place, and a uniform signal is presented to the receiver over the bit interval $0<t<T$. The same situation occurs when a ZERO bit is transmitted and is followed by an adjacent ZERO bit.

This case is depicted in Figure 5(c). In the cases of Figures 5(b) and (d), however, where the adjacent transmitted bits are not alike, interference due to the overlapping of received bits alters the shape of the received signal as well as the power in the signal over the bit interval of interest, $0<t<T$. The effects of these conditions on receiver performance are made clear in Figure 6, which shows the severe damage that results when the received signal is contaminated by the combined effects of fading and intersymbol interference (i.e., when both rapid and slow multipath are present). Specifically, Figure 6 shows the receiver detection error probability resulting from these effects plotted versus the received signal SNR. The curve labeled P_{E0} identifies the ideal situation, when no multipath is present. It is apparent from Figure 6 that when the fading coefficient δ is greater than zero, the degradation shows a strong dependence on τ/T, the time delay normalized to the bit interval T. When τ/T is greater than zero, some overlapping of adjacent

received bits must occur, indicating that intersymbol interference is a primary source of corruption of the received signal. The general case scenario occurs when both rapid and slow multipath are present. Unfortunately, this is the most common condition encountered, especially in urban environments.

Several significant conclusions can be drawn from Figure 6. First, it is noted that when the multipath factor, τ, is less than zero, the degradation of the received signal is actually negative. That is, the performance is actually better when intersymbol interference is present than when it is not. This condition occurs when the multipath signal fades out-of-phase with respect to the direct-path signal. This is not a surprising result, since it is clear from Figure 5 that when the direct-path signal is out-of-phase with the multipath signal (cases (b) and (d)), the result is a momentary increase in received energy over what would result if $\tau/T=0$. That such a condition can happen is not surprising, since surely everyone has encountered an FM radio station which, in an instant, boomed in at a very high volume level, and then just as quickly returned to its normal volume. Also, as previously noted, it appears from Figure 6 that when the multipath factor, δ, is greater than zero, the degradation shows a strong dependence on τ/T, indicating that intersymbol interference is the primary source of corruption of the received signal under these conditions. This is of critical importance when unlike adjacent bits are transmitted. On the other hand, when identical adjacent bits are transmitted (Figures 5(a) and (c)), the received signal energy is relatively independent of τ/T, and the primary performance degradation is a deep amplitude fade caused by the destructive interference of the two signals.

Finally, Figure 6 illustrates that when both τ/T and δ are large, resulting in both a significant time delay and notable amplitude attenuation, the effects on system performance are often catastrophic. For example, if τ is 0.9 and τ/T is 1 (the multipath signal strength is 90 percent of the direct-path signal strength, and there is a complete overlapping of adjacent bits at the receiver), then on the average about 20 dB of additional SNR are required in the direct-path signal to achieve the same level of performance that is obtained when no multipath is present. Of course, one cannot solve the problem simply by "building in" the additional transmitter signal strength needed to obtain a 0 dB fade margin. It would probably not be economically feasible, nor would it likely be allowed by the appropriate regulatory agency. In addition, the increased transmitter power would result in a corresponding increase in multipath signal strength. Therefore, a more ingenious solution is required.

Solutions To The Multipath Problem

Clearly, the effects of multipath interference can be crippling to FM data radio transmission, especially if the desire is to establish a network of mobile radios in a sprawling urban environment. Communication with such a radio while it is moving down the road could logically be expected to endure the

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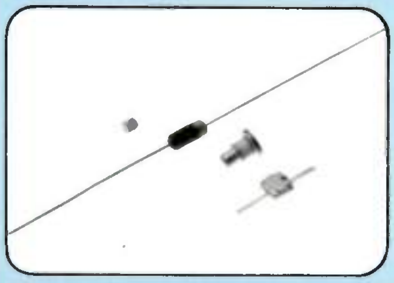

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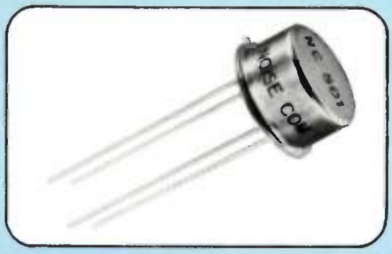

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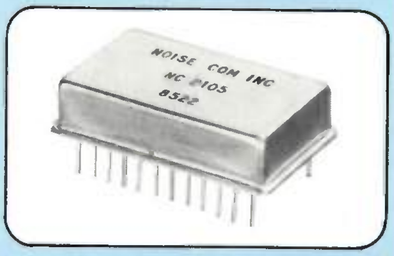

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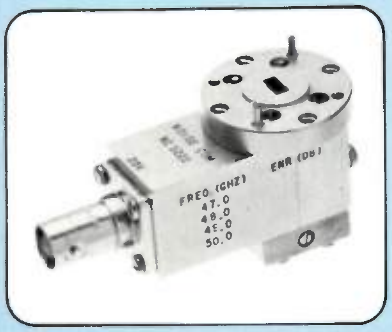

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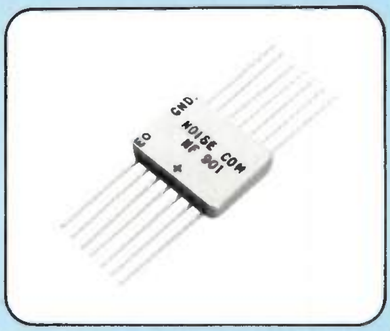

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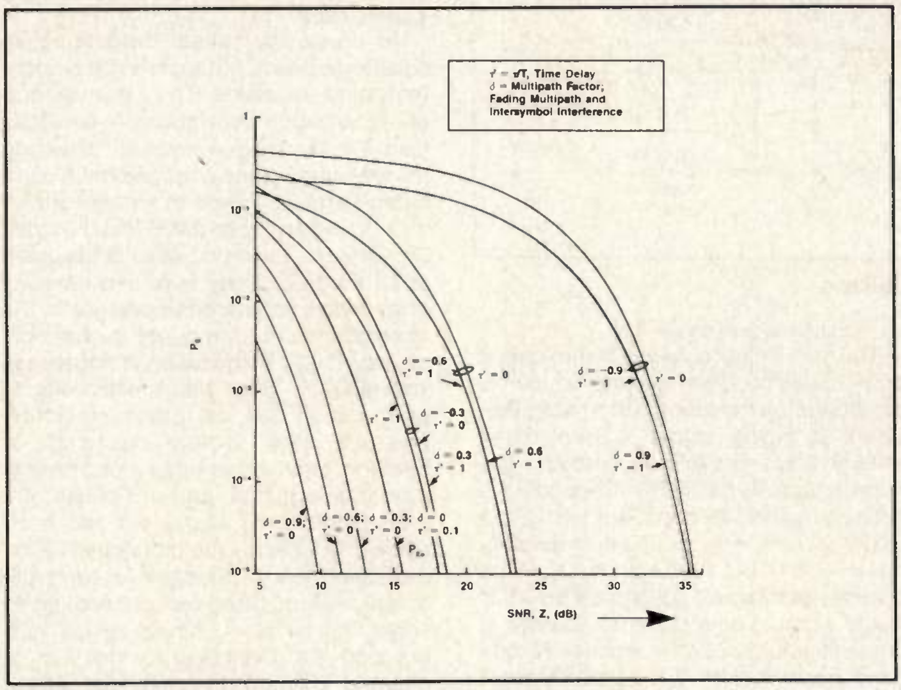

Figure 6. Probability of error vs. SNR, Z, for various conditions of fading and intersymbol interference.

worst-case effects of multipath on a regular basis. So what can be done to FM data radios to make them perform better? Put another way, what can be done to reduce the effects of the multipath signal, so that the radio receiver will better detect the desired direct-path signal? Numerous solutions have been proposed. The most promising techniques that have appeared to date include diversity transmission and several forms of received signal equalization. Because both of these techniques are important and since the success of each depends on equipment and environmental conditions, they will be discussed separately.

Diversity Transmission

Diversity transmission has been used to combat the effects of multipath interference in the microwave radio business for several years. It has also gained some measure of application in commercial broadcast FM receivers in automobiles. Quite simply, the diversity technique provides an alternate modulator when multipath interference is present to degrade the received signal. Typically, the transmitted signal power is divided between two or more subchannels which (hopefully) fade independently. The outputs of the subchannels are combined at the receiver, and since degradation will not likely be as severe in some subchannels as in others, the combined signal produces better performance than would result from a single transmission channel. Three types of diversity are common —frequency, space and time.

Predictably, frequency diversity is accomplished by transmitting the signal at two (or more) different frequencies. The receiver, likewise, has two (or more) independent receive sections tuned to the same set of frequencies. Since multipath interference is normally frequency selective, there is a good chance that if the message transmitted via one frequency is corrupted by the multipath, the signal at the alternate frequency will be received relatively unscathed. If the frequencies are chosen far enough apart and not at integral multiples of each other, the sum of the received signals should always be strong enough to provide acceptable performance. Unfortunately, frequency diversity requires dual transmitters and receivers on all units plus equipment on both ends to switch between the two frequencies at the proper time. This would more than double the cost of portable data radios, putting them out of reach of many potential users.

Space diversity is another alternative which has recently become widely used in the high-capacity digital radio field. Instead of multiple frequencies, space

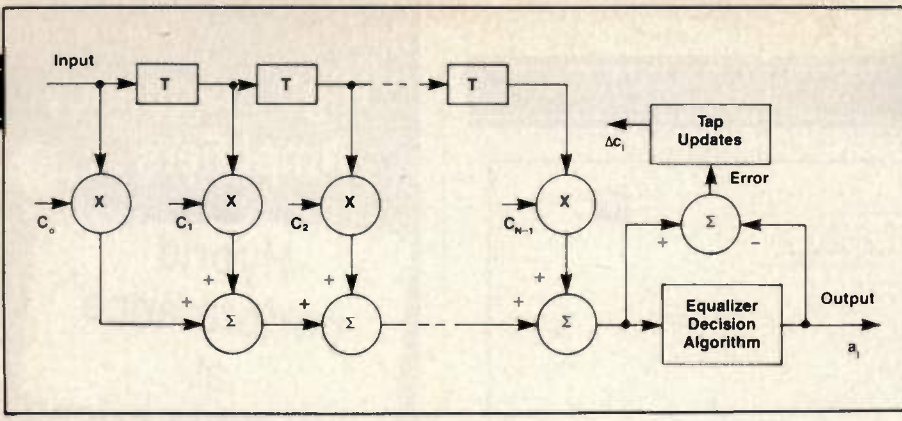

Figure 7. Linear adaptive channel equalizer.

diversity employs physically different locations for its transmitters, usually placing one some vertical distance above the other. The basis for this technique is that differing vertical angles between the transmitters and the receiver should result in a multipath signal bouncing off different objects (or at least at different angles) on its way to the receiver. Hopefully, any degradation that occurs will not affect both paths in the same way, and the sum of the two received signals will usually result in a good, detectable signal at the radio receiver. Space diversity techniques have been shown to reduce multipath outages by a factor of 6 to 12 in many instances (1). Unfortunately, as observed in Figure 6, as much as 20 dB of degradation can routinely occur from multipath interference, so space diversity alone is often not sufficient to cure the problem. Besides, since two transmitters at vertically differing locations are required to make this technique work, space diversity is not an acceptable solution for portable FM radio applications, especially if two-way data transmission is desired.

The remaining diversity technique is time diversity. This is just a simple time-division multiplexing scheme, where a single signal is transmitted several times in rapid succession. The hope is that if the multipath conditions change rapidly, then at least one of the transmissions will escape the deleterious effects of the interference. Of all the diversity techniques, only time diversity would seem to be a potential solution to the multipath problem in mobile FM data radio transmission. It is relatively inexpensive and easy to perform. Unfortunately, even a mobile FM radio located in a car traveling down a city street does not always move quickly enough relative to the multipath reflectors for any one of the time-multiplexed subchannels to be received clearly with great consistency. And, the relative location of a multipath reflector to a stationary receiver rarely changes quickly enough to make this technique work effectively. Therefore, the time diversity technique must also be ruled out as a solution to the problem due to unreliable performance.

Equalization

As previously stated, the alternative solution to diversity transmission is some form of equalization. The simplest form of equalization is amplitude equalization. This technique involves distorting the amplitude of the corrupted multipath-laden received signal in expectation of making it resemble the desired signal. This is done based on what is assumed to be the most likely form and intensity of multipath interference present in the atmosphere. As one might guess, simple amplitude equalization is not always very helpful, since the specific effects of multipath are not easily predicted, and are often rapidly changing. In addition, multipath propagation corrupts both the amplitude and the phase of a transmitted radio signal. As has been seen, it is typically the phase corruption that does the most damage, and the amplitude equalizer can do nothing to solve that problem. Amplitude equalizers can be designed to equalize a channel properly for minimum phase fading, but such equalization of a nonminimum phase fade has been shown to as much as double the distortion imposed by the multipath delay (2); in this case, therefore, amplitude-only equalization actually does much more harm than good.

A remedy for the deficiencies left by amplitude equalization is to equalize the channel for both delay distortion and amplitude attenuation. This can be done with a linear adaptive channel equalizer, similar to the ones used on high-speed telephone line modems such as the

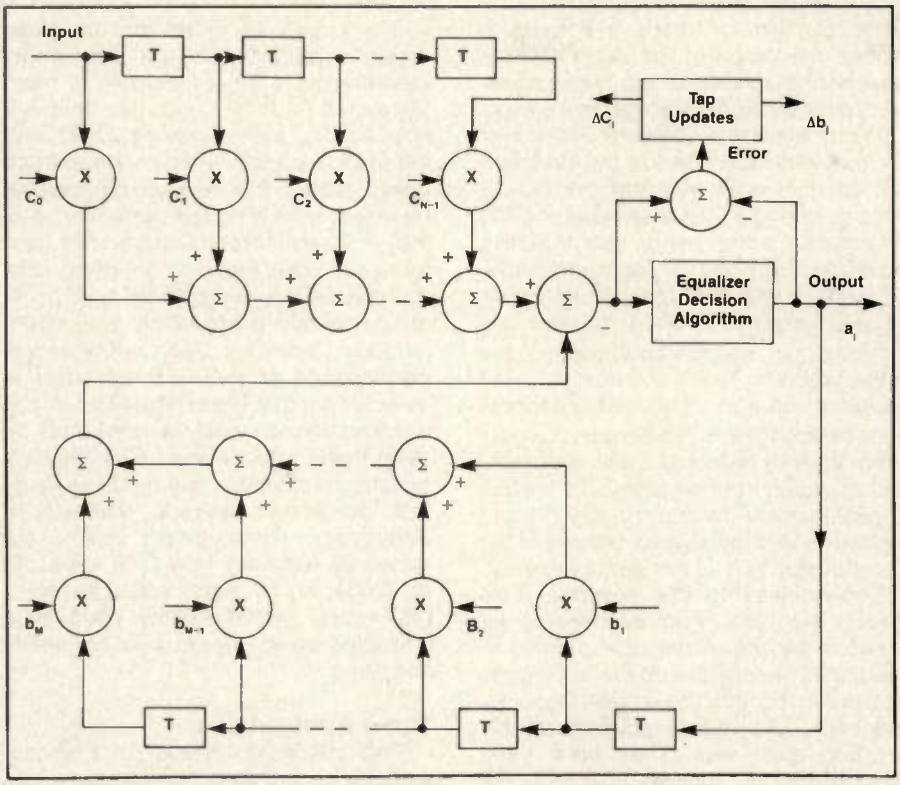

Figure 8. Decision-feedback adaptive channel equalizer.

V.29, V.32, and V.33 modems. An excellent tutorial on adaptive equalization can be found in Reference 3. The idea behind the adaptive channel equalizer is to characterize the corrupted channel, including the effects of the multipath interference. If one knows what the channel looks like, one can correct for it and remove its damaging effects. For example, if the Fourier transform of a corrupted received signal is divided by the Fourier transform of a clean, undistorted transmitted signal, the result is a frequency-domain description (transfer function) of the channel. Ideally then, dividing the frequency-domain representation of the received signal by the known channel transfer function would remove the degradations imposed by the channel every time. Since the delay and fade of the multipath signal are constantly changing (i.e., the channel transfer function is unknown and variable), the equalizer must be able to adapt to these changes in order to correct properly for them.

The question that remains is how one designs an adaptive channel equalizer so that a mobile FM data radio will work properly even under multipath conditions. To answer this question, one should first understand the structure of the adaptive equalizer. It is essentially an implementation of an ordinary tapped-delay-line set up in the form of an adaptive finite-impulse-response (FIR) filter. The taps may be spaced a symbol period apart, or they may be separated by only a fraction of a symbol period (a fractionally-spaced equalizer). The symbol-spaced equalizer covers a greater signal duration with a given number of taps than does a fractionally-spaced equalizer, but fractional spacing relieves the equalizer of some of the timing problems that are associated with the symbol-spaced equalizer. An FM data radio equalizer is normally implemented at baseband frequencies because it is fairly simple to span a few milliseconds of 5,000 or 10,000 bps data when that data is at baseband. On the other hand, it would be impractical to perform the equalization at passband, where one would have to span a few milliseconds of data at VHF or UHF frequencies.

A diagram of a linear, symbol-spaced adaptive channel equalizer is depicted in Figure 7. The corrupted received signal is passed into the equalizer filter and delayed accordingly. The output of each stage of the equalizer is multiplied by a tap coefficient which is varied according to the equalizer output. The products of each stage of the equalizer are summed together to yield an equalized estimate of the desired direct-path signal. This estimate is then passed on to the receiver's equalizer decision algorithm (illustrated in Figure 7). The equalizer output is also used to update the tap coefficients within the equalizer, so they can better characterize the channel they are attempting to model. The specific algorithm used to update the equalizer tap coefficients is typically a least-mean-square (LMS) technique (4). This method generally provides excellent results because it enables the equalizer to converge rapidly, it is normally very robust, and most importantly, the LMS adaptive equalizer is capable of simultaneously minimizing both intersymbol interference (slow multipath interference) and additive noise at its output.

As an example, a ten-tap, symbol-spaced LMS adaptive equalizer was inserted into a UHF data radio receiver subjected to simulated multipath interference consistent with the conditions shown in Figure 6. A companion radio transmitter was used to convey 4800 bps binary data modulated via FM-FSK at a carrier frequency of 900 MHz. The results indicate that this adaptive equalizer was able to reduce the effects of the multipath to a level within 1 dB of the ideal (no multipath) curves shown in Figures 4 and 6. In effect, this small adaptive channel equalizer was able to eliminate virtually all of the negative effects of the multipath interference. This radio, which could not have operated with any degree of reliability in a multipath environment before the equalizer was added, should, with the aid of the equalizer, be able to perform quite nicely under fairly severe urban multipath conditions. Because adaptive channel equalization independently equalizes amplitude and phase, and because it performs effectively in the presence of both minimum and nonminimum phase fading, it is generally believed to be the most powerful technique presently available to economically reduce the effects of multipath interference in the world of FM digital data radio.

So far, only linear feedforward adaptive channel equalization has been considered as a viable solution to the multipath problem. From the simulation example just considered, it appears that such an equalizer works quite well. But there are some conditions which might strain the abilities of even the best linear equalizer. As long as one does not stretch the operating range of the FM radio, linear equalizers are usually sufficient. But what if there is a need to extend the range of the radio network beyond the abilities of the linear equalizer as the desired coverage area grows? One can usually eradicate the effects of the multipath interference, but the inherent channel noise will limit the radio's operating range. This is an issue of great importance when using an adaptive equalizer because a linear equalizer, although it produces a minimum-mean-square error estimate of the received signal, actually contributes to the noise problem. This is so because linear adaptive equalizers condition a channel by inverting the distorted received spectrum, thereby reducing linear distortion. Unfortunately, the penalty paid for this improvement in distortion is a significant increase in the noise level present in the "post-cursor tail" of the symbol interval.

The solution to this dilemma is to cancel the intersymbol interference instead of just equalizing the channel to reduce its effects, thereby removing the post-cursor contribution as well. Decision-feedback (DFB) equalizers perform this function quite well. They have been used with great success in analog FM radios transmitting over fading channels and in high-speed (9600 bps and above) telephone line modems for several years. They are now starting to invade the domain of digital FM radio as well. A description of the details of DFB equalization techniques can be found in Reference 5. A typical decision-feedback equalizer is depicted in Figure 8. It consists of both feedforward and feedback sections, with the feedforward section being identical to the linear adaptive equalizer previously considered. The feedback section uses decisions based upon previously estimated symbols, a_i, to cancel that portion of the intersymbol interference in the present estimate that is contributed by all previous symbols. It is this part of the intersymbol interference that is referred to as the post-cursor. Generally, only the most recently received symbol provides a significant contribution to the post-cursor. The feedback portion of the equalizer is converged after the linear feedforward portion has converged, since it must have reasonable estimates of the receiver decision algorithm's output symbols to operate effectively. The tap coefficients of the decision-feedback portion are typically adapted using the LMS approach, just as was done for the feedforward portion of the equalizer.

It is largely accepted that the post-cursor contribution to the intersymbol interference in slow multipath is more significant than the pre-cursor contribution, as long as the channel fades with minimum phase. For nonminimum phase fades, this relationship can be reversed, modifying the performance of the DFB equalizer. Comparative performance data between linear equalizers and DFB equalizers on fading FM radio channels is not widely available. It is known, however, that the theoretical performance of the DFB equalizer is superior to the linear equalizer if the transmission channel is corrupted by deep fade phenomena. Experimental results on telephone line modems verify this conclusion; several decibels of performance improvement can be obtained by substituting a DFB equalizer in place of a linear equalizer in a high-speed modem if the channel is corrupted by deep nulls in its frequency spectrum.

Other Applications

This article has presented a discussion of techniques for reducing the effects of multipath interference in digital FM data radios operating in the VHF and UHF bands. It has been shown that diversity transmission is one technique used in some radio applications, but that it does not produce consistently good results in radios that are in a mobile environment. Instead, adaptive channel equalization seems to be an answer to the mobile FM-FSK multipath problem. Linear adaptive channel equalization appears to improve significantly the performance of FM data radios in both urban and rural environments; decision-feedback adaptive equalization provides still more protection from the post-cursor of the intersymbol interference found in slow multipath interference. The techniques used in adaptive equalization can also be applied to the solution of many other data communication problems.

Adaptive equalization is simply a special case of adaptive filtering; specifically, it is an example of inverse modeling, since it seeks to emulate the inverse of the channel characteristics. A similar application of these techniques in data communications is in adaptive echo cancellation. In echo cancellation, however, the problem is one of direct channel modeling, since the echo canceller is used to model the echo path inside the telephone network. Another example is adaptive noise cancellation.

Applications of adaptive filtering outside the communications area include the adaptive control of precision machinery, adaptive geophysical modeling in mineral exploration, and adaptive beamforming and sidelobe cancellation in the fields of antenna and radar engineering. Regardless of the application, adaptive filtering as it has been discussed in connection with the equalization of multipath channels in VHF and UHF FM data radios is useful in almost any field of engineering. Whether in the field of FM radio, modem engineering, radar, or even geophysics, one should have no trouble finding a multitude of applications for adaptive filtering techniques.

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About the Author

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Looking Ahead: The Next Ten Years

To complete our tenth anniversary celebration, we present three views on the future of RF technology. The first is from Jerry Arden, President of California Eastern Laboratories. As a supplier of RF transistors and ICs, CEL provides the unique vantage point of an international company with a strong financial interest in both engineering and marketplace trends.

Another view is expressed by Tom Mills of National Semiconductor, one of the authors contributing to the first issue of RF Design. *Involved in IC product development and applications engineering, mainly for consumer and commercial use, Tom has another important perspective on the next ten years of* RF *technology.*

Finally, our Consulting Editor Andy Przedpelski takes a look at things to come. Andy's firm, A.R.F. Products, is primarily involved in military and space applications, areas with a major influence on technology. All three contributors offer a combination of honest guesses and plenty of wishful thinking. We predict that you will enjoy their "crystal ball gazing."

The Future of RF and Microwave

By J. A. Arden
President,
California Eastern Laboratories, Inc.

Anyone trying to forecast the future is only setting himself up for future ridicule. However, being unaccustomed to ridicule, I will share my thoughts on the subject. We have already seen tremendous advances both in the technology and applications of RF and microwaves, and the ever-increasing variety of technologies, products, and systems under development spawn even more ideas. These new products will be directed to all facets of the world marketplace.

Military Electronics

The cost of military systems is growing out of proportion to today's need. Peace may be breaking out. In many troubled areas of the world, it is just too expensive to wage a protracted campaign with today's weapons systems. Do you think Iran and Iraq agreed to a cease-fire because they solved their differences, or because they were running out of money and blood?

As the common man in developing nations becomes aware of what is available with a better standard of living, one can easily believe that governments will be hard pressed to sacrifice commercial and industrial development for increased military spending. We are even seeing this in our own country and that of our traditional adversary, the USSR. The consequences, of course, will be reduced spending in the military sector.

Strategic nuclear weapons have long been a "cheap" way to inflict a lot of damage, but the political problems and collateral cost of production and maintenance of them and their carriers is growing. The most recent example of this is the estimated $10 billion required to bring our country's nuclear material processing plants up to current OSHA codes. It may be cheaper to purchase tritium and plutonium from the French!

The cost of maintaining large and expensive forces around the world will eventually be addressed in the next administration. The US will have to reduce its traditional role as world policeman. Assume, if you will, that the US does reduce its presence. Our allies, the Japanese and Europeans, will have to fill the void with increased spending of their own, if they want to maintain the current level of military activity.

High-tech nations will always have a requirement for some strategic nuclear deterrence, but today's technology allows them to start relying more on smart non-nuclear weapons. These systems are also politically acceptable. You never see demonstrators protesting outside a Stinger factory, but they are always outside the Lawrence Livermore Labs.

History shows us that every time a major weapons treaty is signed with the Soviet Union, military spending increases on both sides. Every time there are cutbacks in new military systems, there is increased spending in the area of increasing the current systems' lifetimes and capabilities. While the big systems will be cut or reduced in scope, the world's military electronics market should see continued growth, but at a lower rate. If the current exchange rates keep the US dollar down, then I see a good export market for high-tech weapons systems and components.

"History shows us that every time a major weapons treaty is signed . . . military spending increases."

This opinion appears to be shared by others, since most of the major systems manufacturers have acquired, expanded, or are planning to acquire in-house electronic manufacturing capabilities. They are doing this not only for vertical integration, but also for market diversity. When the big Pentagon contracts become fewer

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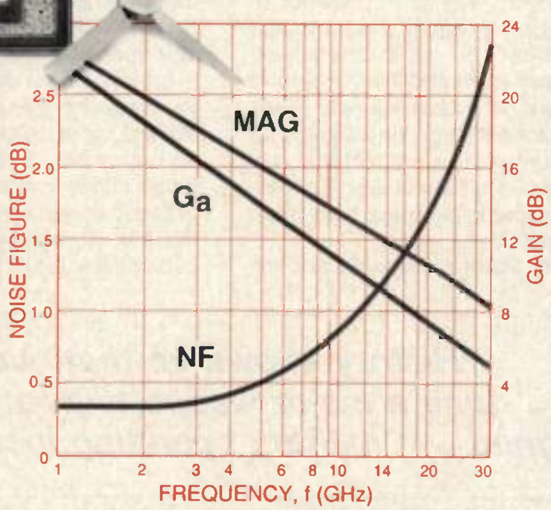

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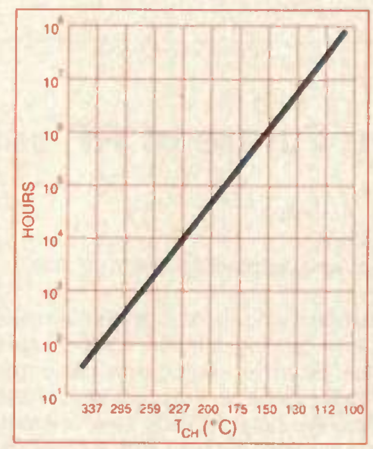

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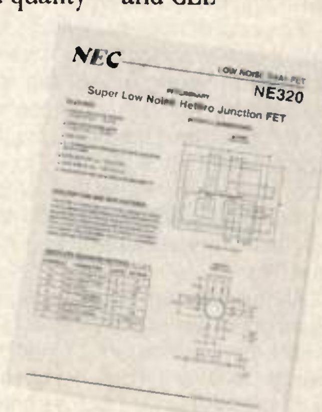

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and more competitive, for their own survival, the large systems manufacturers must diversify.

Commercial Applications

In the past several years we have seen increased demands on the world's communications systems. The amount of information that is being generated and disseminated today will be dwarfed in the next decade. All of the developing countries and geopolitical regions recognize the need for better communications, encompassing the entire radio spectrum.

Microwave links still remain a viable option for widely dispersed areas. Satellite communication is useful for larger areas. Private radio usage has and will continue to grow. As cities develop and expand, the use of fiber optics appears to be the best option for growth. Future housing and industrial developments from Dallas to Nipple will start relying more and more on electro-optic (E-O) links. As the access to information increases, more systems are required to support the generation of more data and information. The human mind and its desire for information is unlike the bucket of sand; the more you put in, the more it is capable of holding. NEC's byline "Computers and Communications" is really what the future of electronics is about.

Consumer Products

As more and more of the world's peoples' standard of living improves, and as world communications permits awareness of what is available, there will be an increased demand for consumer electronics. Imagine the year 2005: In the past three years 30% of what was being expended on the world's military budgets has been transferred into improving the various nations' standards of living. How many PCs, high-resolution TVs, vehicle GPS systems, cellular telephones, and all other "things" that rely on RF, high-speed, or microwave electronics will be manufactured, distributed and sold?

How much money could be saved if the automobile insurance companies required digital RF bar-codes embedded in each car? Stolen automobiles could be detected and recovered at border points, expressway toll booths, and by roaming police units.

I believe that the variety, application, and demand in the next 20 years will be even more phenomenal than what we have recently seen in consumer electronics. The electronic content in the building industry is still in its infancy. Besides security systems, imagine all the neat electronics that will be available for "smart" homes and offices in the future. A good number of professionals will be working at home rather than commuting. The business equipment market should do very nicely. I hope that it is not all from Korea or Taiwan.

High resolution TV and DBS ground stations will be commonplace. Cellular RF data links for portable computers are coming on the market now. What will be offered in ten years? With new power sources, the use and proliferation of portable, cordless devices will be major attractions. Non-lethal personal security systems could be available and widely accepted. Outpatient care could be monitored at central stations at hospitals or clinics, thus relieving the burden on hospitals. Constant monitoring by cellular radio/GPS systems could make house arrests for minor criminals and parole violators the wave of the future. This is being tried now in a few cases.

In all the examples I've described, the electronics industry will provide the basic ingredients. There will be a heavy use of computer chips, but RF and microwaves will provide the links, the conduits for information. If the world economies continue to improve, our industry will truly benefit. The most difficult obstacle will be competing in a world market. The US RF and microwave industry must maintain its technological leadership. We can not do this if we continue to be a nation of consumers, and not producers.

The future for our industry is very promising. The next several years could provide the environment for a second Renaissance.

"The business equipment market should do very nicely. I hope that it is not all from Korea or Taiwan."

Predictions for the Next 10 Years in RF

By Thomas B. Mills
Member, Technical Staff
National Semiconductor

The next ten years will see tremendous growth for the semiconductor industry, a portion of which will be in the RF area. On top of that, the percentage of semiconductor usage in the RF area will also increase. In consideration of the costs associated with a particular RF function, a shift will occur away from passive components to semiconductor (active) components.

An obvious immediate change will be a shift from discrete transistor amplifiers to monolithic building blocks that offer matched source and load impedance, wide bandwidth, and stable gain. Advances in semiconductor processing have made these components the "op-amp" of the RF world.

In all fields, existing technology reaches a saturation point such that further improvements are difficult to achieve, whether it be in performance, size, or cost. A new technology, usually more complex, is necessary to provide further increases in performance. The field of transportation illustrates this very well with the progression from horse and buggy to railroad to motor trucks to airplanes. With the exception of the horse and buggy, all of these areas are still experiencing consistent improvements. In the field of sound reproduction, the compact disc (CD), utilizing digital techniques, has taken us beyond the performance of even the best studio equipment of just a few years ago.

" . . . little has been done in the area of digital techniques in the signal path."

Conventional uses of RF are communications. Whether it be broadcast radio and television, commercial land mobile and cellular telephone, satellite voice and data, or military, these systems have used conventional analog processing techniques at least until the demodulator stages. The RF signal path has been dominated by conventional LC, crystal, mechanical and ceramic filters for many years. While we have seen an infusion of digital techniques in the non-signal path related functions, particularly in frequency synthesizers and their controllers (re: my article in the first issue of *RF Design*), little has been done in the area of digital techniques in the signal path. For example, the first consumer application of

digital signal processing (DSP) for video (5 MHz) only recently took place with the introduction of the ITT DSP TV chip set. High definition TV (HDTV) will require a much greater sophistication of DSP techniques.

In the commercial area, some radios have already been designed with DSP filtering/demodulation. However, they have been implemented with conventional A/D converters, DSP processors, and peripheral logic/memory that require large amounts of power and generate high levels of interference from the needed clocks. Shielding and layout problems have plagued these designs. As semiconductor technology continues to reduce feature size and increase speed (Figure 1), power consumption and interference levels will be reduced, especially as more functions are placed "on chip" and it is not necessary to drive high capacitance I/O ports. Advanced semiconductor processes that combine small feature size bipolar and CMOS technologies on the same chip will be the key for the development of high speed DSP chips.

The most significant change in RF in the next ten years will be the introduction, then widespread usage, of digital signal processing for the filtering, equalizing, and demodulation of RF signals. This will be accomplished not with the power hungry, general purpose DSP chips available now, but with dedicated, easy-to-use processors designed to interface with existing controller technology. At first, these RF-DSP processors will operate on IF signals below 10 MHz, but as technology improves, operation on RF signals to the 100 MHz range and beyond will take place.

Who will be the first to offer a center frequency and bandwidth programmable IF filter in an 8-pin mini-DIP? Will the same supplier also offer a **DSP AM-FM-SSB-CW** demodulator chip?

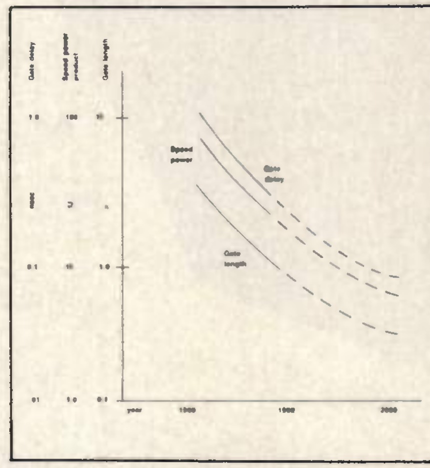

Figure 1. IC performance trends.

"Who will be the first to offer a center frequency and bandwidth programmable IF filter in an 8-pin mini-DIP?"

Thoughts and Wishes for the Next 10 Years

By Andrzej B. Przedpelski
Vice President, R & D
A.R.F. Products, Inc.

My predictions in the past were not necessarily very accurate (usually too ambitious), and I do not expect these to be any better:

1. Multilayer PC Boards: Now that multilayer PC boards are more reasonably priced and available from reliable sources, I feel that their usage will increase. This increased popularity will not be based on increased circuit density and decreased board area (usually the main reason for taking this approach), but by exploring other unique features of this design.

Now that digital people are realizing that high-speed logic is really RF and has to be treated as such, the multilayer approach will allow real transmission line designs using microstrip construction with a solid ground plane, without the penalty of increased size.

RF people can use stripline (vs. microstrip) construction, also without size penalty. Stripline, being shielded on both sides, provides better containment of RF fields. EMI problems can also be reduced because of the different shielding properties. There is no reason why some of the inner layers could not be magnetic instead of copper, thus providing magnetic shielding possibilities for even better EMI performance.

Could some of the dielectric layers be ferrites? This would allow the integration of magnetic components into the overall PC board design. How about light conducting layers? Fiber optics?

2. Semiconductor Materials: We have had germanium, silicon and GaAs. With the just announced new techniques for producing diamonds from methane (very cheap material), the diamond may be a good solution for high temperature semiconductors.

3. Transistors: Along with our bipolars, FETs, MOSFETs, etc., some of the experimental types (maybe the SIT?) will become common and new types will be introduced. The trend towards tube-like characteristics will continue. We will have to dust off some of our old vacuum tube books to look for design examples.

High frequency transistors will have better built-in matching networks, optimized for particular frequency ranges. The matching may not necessarily be to 50 ohms, but some other standard. Matching close to the source of the problem (inside the transistor) is much more satisfactory than matching further down the line.

4. Frequency Sources: The direct digital frequency synthesis trend will continue in several directions. The upper frequency limit will be extended, the circuits will become simpler and more functions will be combined into specialized ICs, more versatility will be built-in (multiple simultaneous frequencies, different types of modulation, etc.)

PLLs have reached maturity, but some new developments will occur. For instance, PLL ICs will be available allowing wideband FM (down to DC). Frequency dividers (a necessary component in high frequency PLLs) will have specified phase noise. Phase comparators will be improved to provide lower phase noise, possibly going back to analog types to eliminate the "dead zone" of the digital types, and to allow high comparison frequencies. In may cases MHz, not kHz, are needed.

5. RF Amplifier Modules: RF amplifier modules will be optimized for particular frequency ranges. For instance, what good is a DC-2000 MHz low level amplifier if its noise figure is 7 dB? The trend toward optimized devices was started by some manufacturers using the lossless feedback technique. However, most of the hybrid/monolithic modules still do not approach discrete designs.

Higher power modules will be more widely available. The devices will be scaled to permit easy cascading to any desired power levels. At present, this is difficult and devices from different manufacturers (not very compatible) must sometimes be used.

"The trend towards tube-like [power transistor] characteristics will continue."

6. Digital Components: More and more digital components will be used in RF designs, not only for interfacing with logic circuits, but for strictly RF applications. A current example is the use of digital phase comparators and frequency dividers in PLL applications. The direct frequency synthesizers will be big digital IC users, but there will be other applications as the distinction between RF and digital becomes more muddy.

7. Antennas: There is a need for small, efficient antennas in all frequency ranges. This is especially true in the VLF and LF ranges. The present types are very difficult to match efficiently to the rest of the circuit. The active antenna will be revived to solve some of the problems, but new types will also be developed.

At the higher frequencies, especially in the portable transceiver applications, the antenna will be built-in, possibly using the multilayer PC board design.

8. Packaging: A new package will be developed for monolithic RF components. It will be a modified chip construction with overall dimensions of 0.1 x 0.08 to 0.15 x 0.1 inches, for most applications. The devices will be mounted directly on the PC board to provide some heat sinking. The main problem will be connections to the PC board. Since most applications only require four connections, this may not be a big problem. Two or three standard configurations should cover most of the low to medium power applications (the TI TGA series, for example). rf

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SAS-200/512	200 - 1800 MHz	Log Periodic
SAS-200/518	1000 - 18000 MHz	Log Periodic
SAS-200/530	150 - 550 MHz	Broadband Dipole
SAS-200/540	20 - 300 MHz	Biconical
SAS-200/541	20 - 300 MHz	Bicon'l Collapsible

MODEL #	FREQ. RESP.	DESCRIPTION
SAS-200/542	20 - 300 MHz	Biconical, Folding
SAS-200/550	.001 - 60 MHz	Active Monopole
SAS-200/560	per MIL-STD-461	Loop - Emission
SAS-200/561	per MIL-STD-461	Loop - Radiating
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A Micropower RF Probe

This device can be configured as a field, voltage or current sensor for VHF/UHF applications.

By Dr. P. S. Neelakanta,
Florida Atlantic University, and
A. S. Al-Hinai, Oman

RF probes for controlled-environment EMI/RFI measurements require specific design considerations. Wide dynamic range, broad frequency range, high sensitivity and excellent noise immunity are desirable performance characteristics of such probes. In addition, simple circuitry immune from undesirable extraneous interference, especially when weak signals are measured, is often required. Further, the probe and the circuitry should operate with minimum power consumption if remote-sensing strategies are adopted. Another nice feature would be to telemeter the measured data or implement a fiber optics communication link between the probe and receiver so as to avoid any direct RF energy being coupled into the probe-to-receiver path.

Conventionally, three types of RF probes are used in EMI measurements. The first type measures radiated EMI field measurements and uses an electrically small dipole or monopole for E-field measurements or a loop for measuring H-field parameters. The second type is a voltage probe used in conducted interference measurements with low shunt-capacitance and very high input resistance. The third version is a current probe that measures the conducted current component of interference through a cable or conducting surface.

Description of the Proposed Probe

The design discussed is an RF probe for VHF/UHF applications which can be arranged as a field, voltage or current sensor. It uses an RF silicon rectifier diode coupled to the gate of a CMOS device (CD4007AB). Depending on the gate potential variations as decided by the rec-

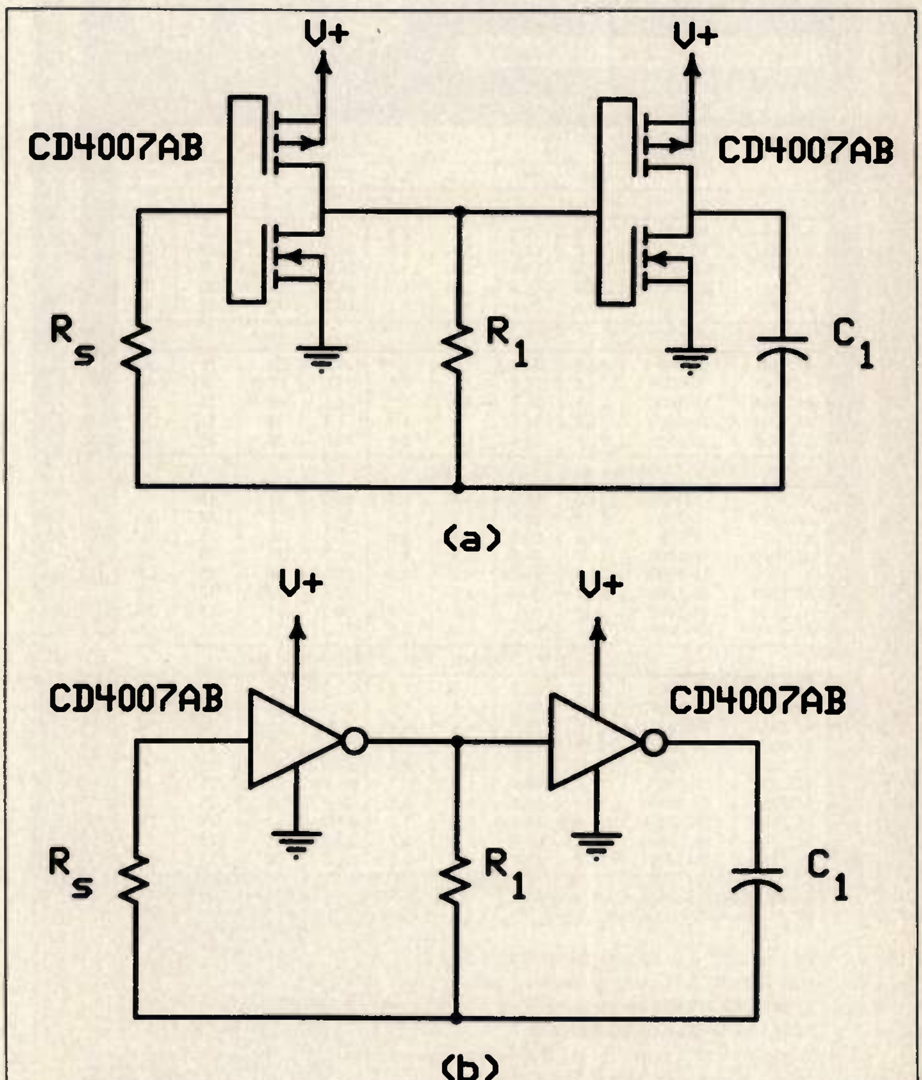

Figure 1. Basic astable multivibrator circuit.

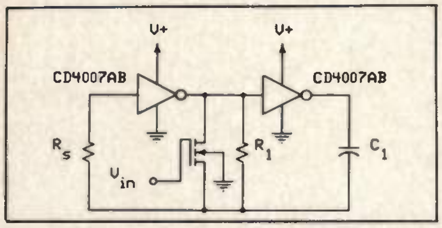

Figure 2. N-channel MOSFET VCO.

tified diode voltage, a nonlinear resistance is presented to a voltage-controlled oscillator (VCO) formed by two CMOS inverters. Thus, the sensed voltage at the rectifier alters the VCO frequency. The entire circuitry is based on CMOS technology; hence, the operational power requirement is very small (microwatts). Another advantage of CMOS devices is their high noise immunity (1). The sensitivity of the circuit can be enhanced further by employing a preamplifier between the diode and VCO.

This preamplifier can utilize a special purpose operational amplifier (CA3078)

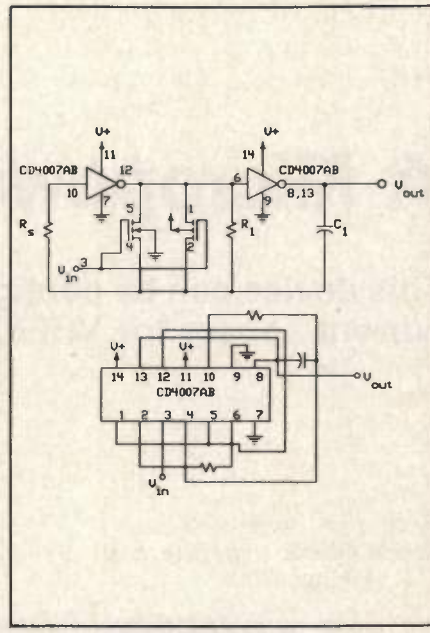

Figure 3. CMOS VCO.

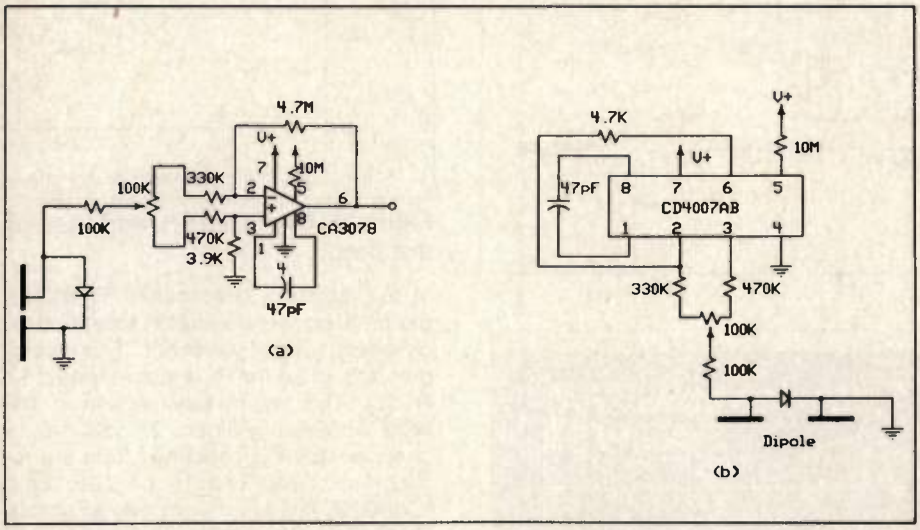

Figure 4. The preamplifier.

that consumes micropower. The whole arrangement can be set in a miniaturized assembly for easy mechanical manipulation of the probe direction or polarization. It can also operate with a single polarity power supply of two button-type Ni-Cd batteries (3 V each). The VCO output can be transmitted for data collection either via telemetry or coupled to a fiber optic circuit.

Circuit Description and Design Considerations

In Figure 1, the oscillation frequency is governed by R_1 and C_1. The inverters of the multivibrator circuit use CMOS pairs

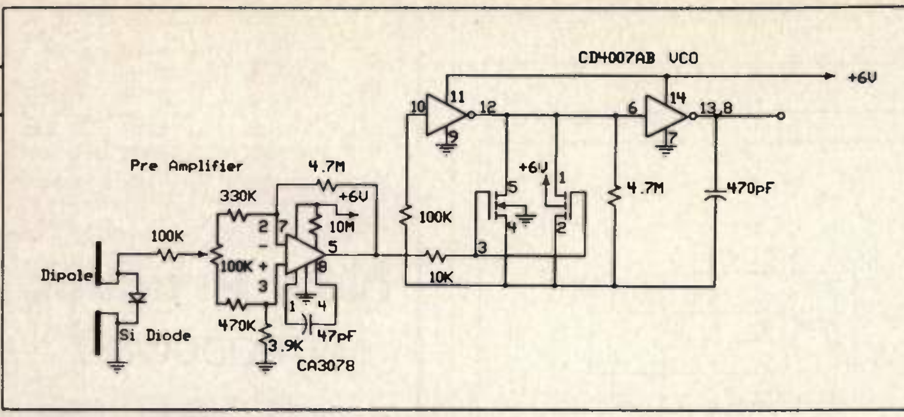

Figure 5. Test probe circuit diagram.

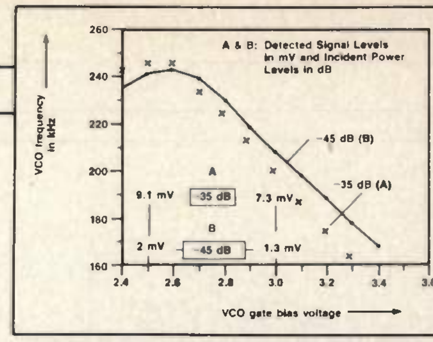

Figure 6. Dynamic/RF response of the probe.

of a CD4007AB. Resistance R_s makes the frequency of oscillation independent of supply voltage variations. The recommended value for R_s is about ten times R_1 (2). The preliminary version of the VCO is shown in Figure 2. Here, the n-channel MOSFET obtained from the remaining CMOS pair of the chip (CD4007AB) is simply connected across R_1 of Figure 1.

The frequency of oscillation is governed by C_1, together with the parallel combination of the input resistance of this FET and R_1. Hence, it can be varied by the voltage applied at the FET input. The VCO of Figure 2, however, yields a sensitivity of approximately 20 Hz/mV, and an improvement to the circuit is required. This is done by paralleling an additional p-channel MOSFET (Figure 3). The p-FET is obtained from the third CMOS pair of CD4007AB. The following equation then decides the effective value of the resistance which, in association with C_1, determines the frequency of oscillation:

$$R_{eff} = \frac{1}{1 + 4K\,(V_{GS} - V_T)} \quad (1)$$

where K is a constant determined by the oxide capacitance and the channel dimensions of the MOS structure. V_{GS} is the gate-to-source voltage and V_T is the threshold voltage of the device. The frequency of oscillation of the VCO is then given by:

$$f_{VCO} = \frac{1}{R_{eff}}\,C_1\,\ln\left(\frac{V_{TR}\,(V_{DD} - V_{TR})}{V_{DD}^2}\right) \quad (2)$$

where V_{DD} is the supply voltage and V_{TR} is the transfer point of the inverter.

For the circuit in Figure 3 it can observed that R_1 has no significant influence on the oscillation frequency when its value is large. It enables a small charge bleed-off across the CMOS during cutoff.

The sensitivity of the circuit depends on the quiescent bias at the input, yielding a good sensitivity response when the input bias is between 2.5 and 3.5 volts (which renders the MOSFET able to operate well above V_T). This quiescent bias at the input is enabled by having a preamplifier preceding the VCO which

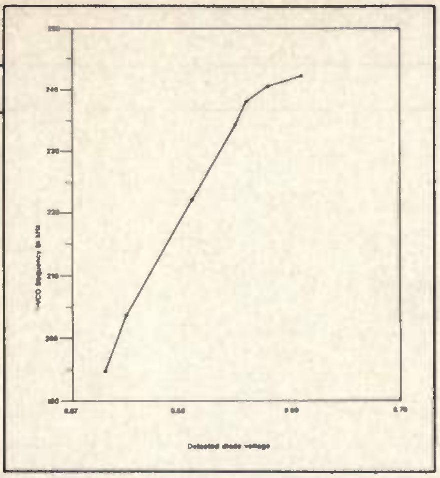

Figure 7. Static response of the VCO.

provides the required bias under zero-signal conditions. Figure 4 shows the circuit diagram of the preamplifier connected in the inverting mode with a gain of approximately 10. This preamplifier uses a special purpose micropower op amp (CA3078), which can be energized by a single polarity power supply. The potentiometer (100K) in the preamplifier circuit in conjunction with R_5 is used to adjust the required DC bias at the VCO input. The complete circuit diagram of the probe is shown in Figure 5.

The VCO output, which carries the measured data, should be linked to the remote receiver without being corrupted by the ambient EMI/RFI. This can be accomplished two ways: The nominal (zero-signal) VCO frequency can be set for direct telemetry transmission, or a fiber optic link can be established between the probe and receiver.

Absence of cable-link between the probe and receiver-end would reduce the systematic errors caused by pick-ups from the ground-loops or from other conductive noise sources as well as from unbalanced transfer impedance characteristics of the cable (asymmetry factor).

Measurements and Test Results

Performance characteristics of the test probe were evaluated by the following measurements:

A. Dynamic/RF Response of the Probe

A prototype probe was tested on a VHF/UHF slotted line. The RF diode mounted at the coaxial open end of the test transmission line was excited by a standard signal source over the VHF/UHF band (30 MHz and 300 MHz). The signal level was varied using a calibrated attenuator. The VCO output frequency was measured as a function of the detected signal voltage and the incident power at the diode. The performance characteristics of the test probe are illustrated in Figure 6.

B. Static Characteristics of the VCO

The diode was forward-biased by means of an external DC voltage and the VCO output frequency was measured as a function of the diode voltage at the probe input, with an initial setting of the gate-bias potential being 2.9 volts adjusted via the 100K potentiometer of the preamplifier circuit. The measured response is shown in Figure 7.

Acknowledgement

The authors gratefully acknowledge the USARC Grant (1988) extended by the University of South Alabama (Mobile, Ala.) under which this project was performed.

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2. Astable and Monostable Oscillators using RCA cos/MOS Integrated Circuits, RCA Solid-State Application Note (ICAN-6466).

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An Improved Double Sideband Modulator

By George J. Misic
Medrad, Inc.

Most single sideband systems use one or two double balanced mixers to produce a double sideband suppressed carrier signal. Also, applications such as NMR imaging systems require a double sideband suppressed carrier output. A common method of performing this function utilizes a double balanced diode ring mixer with the local oscillator port as the RF input, the signal port as the output, and the IF port as the input for the modulating waveform.

The LO-RF isolation specification for this genre of device (such as the Mini-Circuits SRA-1H) is typically around 45 dB. The addition of a DC nulling circuit as in Figure 1 generally allows the adjustment of isolation to about 55 dB. Since the insertion loss of the mixer as a modulator is about 5 dB, the dynamic range of the device is 50 dB. While this is generally an acceptable value for many non-critical applications, greater dynamic range and, therefore greater isolation, is often required.

For this application, two requirements were specified: the carrier suppression had to be in excess of 70 dB (requiring a null of about 75 dB to allow for the modulator insertion loss), and the system had to have a frequency response of at least DC to 100 kHz. Generally, the author found that the dynamic range for double balanced mixers falls in the 45 to 60 dB range between 20 and 90 MHz. In the interest of minimal complexity and cost, a more sophisticated balanced modulator system or double balanced diode ring mixer constructed from discrete components was not used.

Analysis with a wideband oscilloscope revealed some interesting data. When the DC nulling control of Figure 1 is adjusted near the optimum null point, the phase of the output waveform ceases to be at zero or 180 degrees with a visible 90 or 270 degree component. It is not possible to null the in-phase component and the quadrature phase component of the residual carrier at the same point of the adjustment control. However, it is possible to null the 90/270 degree residual carrier by allowing a small level of the 180 degree component to remain. It is then possible to cancel the 180 degree component with a small feed-forward signal from the modulator input using a simple adjustable resistive divider.

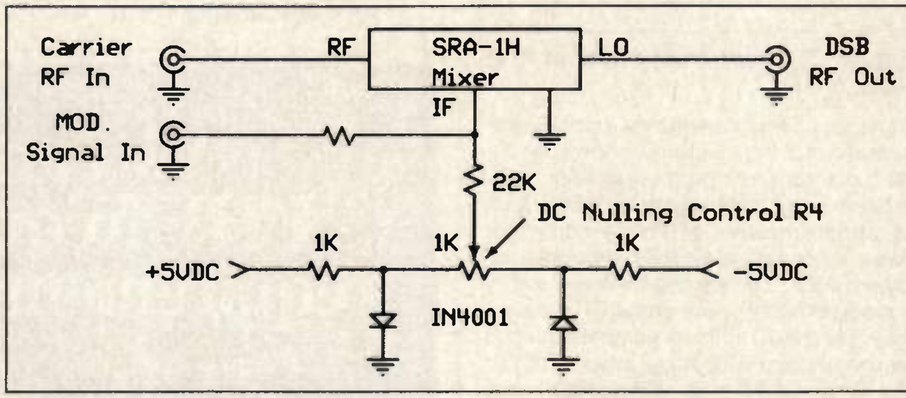


Figure 1. Double balanced mixer used as a double sideband suppressed carrier modulator with a DC nulling control.

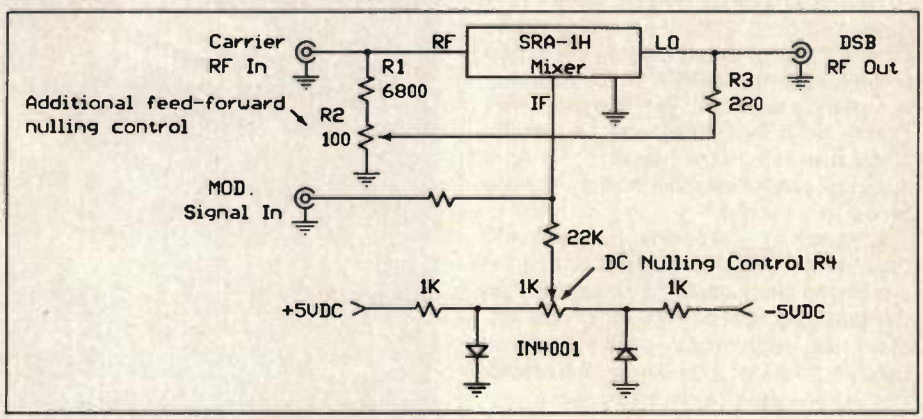


Figure 2. Addition of feed-forward nulling control.

The circuit used to accomplish this is shown in Figure 2. Component values were selected for use with the Mini-Circuits SRA-1H mixer used as the modulator. The input resistor of the voltage divider, R1, was chosen to accomplish two goals: to provide an appropriate level signal for the nulling circuit, and to present a high impedance load to the source driving the modulator so as not to attenuate the driving signal level or cause a noticeable increase in the input VSWR. Since the carrier suppression without the added network is on the order of 55 dB, a level of around that value for the feed-forward signal seemed reasonable. A 6800 ohm resistor was selected initially for R1. The adjustment potentiometer value used was 100 ohms, so that near the center of its range, the division network would provide a signal level about 43 dB down from the input. In order not to upset the output impedance or signal level, R3 was chosen to be 220 ohms. This resistor in combination with the impedance seen at the modulator output port forms about a 9 dB attenuator. Hence, the overall feed-forward signal is approximately 55 dB below the applied signal input at the midway setting of the adjustment control. The sensitivity and range of the control were found to be quite satisfactory; none of the tests run on the design showed any difficulty with the control being out of range. The potentiometer used for the feed-forward control must be a non-inductive type; a Bourns style 3299 Cermet control was used. Wirewound controls are not suitable. All resistors are 1/4 watt, 5 percent carbon. Lead dress and printed circuit layout were done to provide short, direct connections without overlap of signal conductors. A double-sided circuit board was used, with the component side being the ground plane.

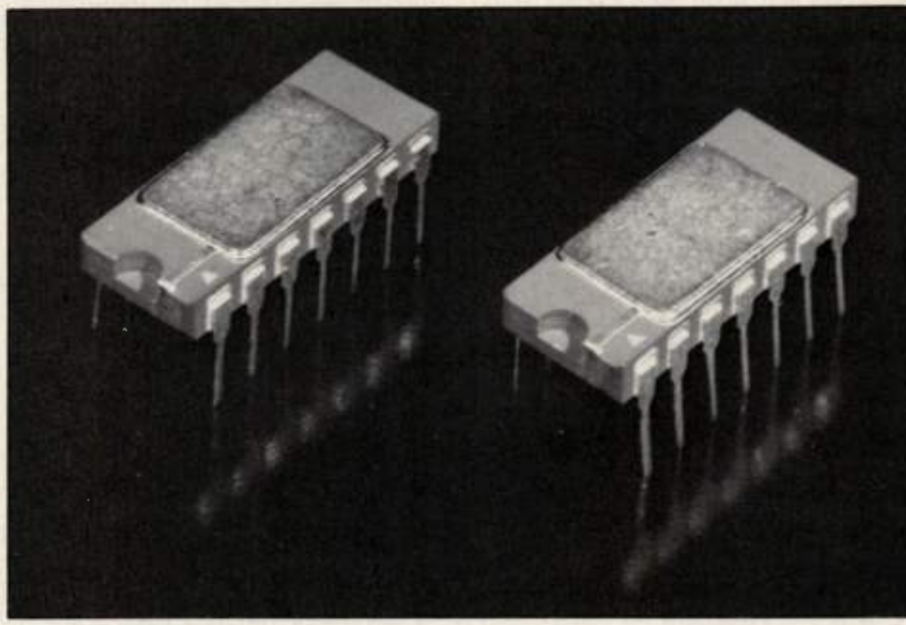
The method for adjusting the modulator for best carrier suppression is quite simple. It is accomplished by first setting the feed-forward control, R2, to zero ohms toward the ground end, for a minimum feed-forward level. The DC nulling control, R4, is adjusted for best carrier suppression. Next, the feed-forward control is tuned to further null the carrier. The two controls will interact significantly, so the fine adjustment is an iterative procedure. When fine tuning the carrier null, it may be necessary to deliberately deviate the feed-forward control from its best null, then readjust the DC offset nulling control, as the greatest carrier suppression cannot always be found by adjusting one control to the best null and then the other to the best null because of control interaction. What is actually occurring is that the DC offset control is being set to minimize the 90/270 degree component of the carrier leakage, and the feed-forward control is cancelling the residual 180 degree leakage, the level of which is raised by the process of using the DC offset control to null the quadrature phased leakage.

This approach has been used successfully at frequencies from 10 to 100 MHz with the SRA-1H mixer. The depth of the null was greater than 80 dB in each case. However, the null does not hold over wide frequency ranges. Typically, the null will hold to greater than 75 dB over an octave of operating frequency. Since most applications will require single frequency or limited coverage operation, the frequency dependence of the best null should not be a severe handicap. rf

About the Author

George J. Misic is RF engineering projects manager at Medrad, Inc., 271 Kappa Dr., Pittsburgh, PA 15238. Tel: (412) 767-5336.

New High-Speed Op Amp Family from Harris



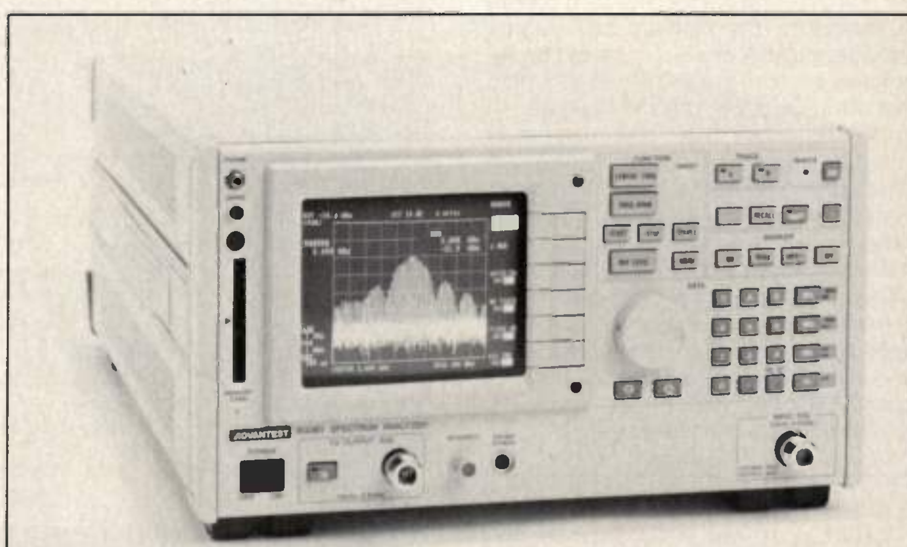
The HFA-0001 is a bipolar op amp featuring 100 V/us slew rate, unity gain bandwidth of 300 MHz, and full power bandwidth of 43 MHz. These features together with a 25 ns settling time make this product useful for high-speed data acquisition systems, RF, video and pulse amplifier designs. Other characteristics include a bias current of 75 uA, offset current of 40 uA and offset voltage of 30 mV. A 50 ohm resistor, which can be used for driving 50 ohm stripline, microstrip or coax cable, is connected from the output to a separate pin. The HFA-0001 is available in 8 pin and mini plastic DIP, TO-8, and 20 pin plastic LCC packaging.

The HFA-0002 features a gain bandwidth product of 1 GHz, slew rate of 150 V/us, open loop gain of 100 dB and offset voltage of 1 mV. Power consumption is 150 mW while common-mode rejection ratio is typically 78 dB. Available packaging includes 8 pin sidebraze, plastic mini DIP, TO-9 and 20 pin plastic LCC.

Harris is also introducing the HFA-0005 operational amplifier with 250 MHz bandwidth, 25.8 MHz full-power bandwidth and 600 V/us slew rate. Other characteristics include a bias current of 75 uA, offset current of 40 uA and offset voltage of 30 mV. The device is available in 8 pin sidebraze, epoxy mini DIP, TO-99 and 20 pin plastic LCC.

In 100-piece quantity, the price on the HFA-0001 ranges from $8.05 to $39.85 depending on packaging and temperature versions. For the same quantity, the HFA-0002 ranges from $7.05 to $38.15. The HFA-0005 ranges from $6.39 to $29.70 in 100-piece quantity. **Harris Corp., Semiconductor Sector, Melbourne, FL. INFO/CARD #220.**

Advantest Unveils Synthesized Spectrum Analyzers



The R3261/3361 synthesized spectrum analyzers cover the 9 kHz to 2.4 GHz (R3261A/3361A) and 9 kHz to 3.6 GHz (R3261B/3361B) frequency range. The instruments feature stop, start and center frequency resolution of 1 Hz together with a built-in frequency counter and overall resolution of 1 Hz.

Quasi-peak value measurements can be made with a dynamic range of 70 dB, enabling EMC measurements to be made with large and small signals displayed simultaneously without having to switch the attenuator. The analyzers can achieve a displayed dynamic range of 120 dB.

For testing purposes, the 3.6 GHz version (B-type) enables measurements up to the third harmonic. The 3361A/B with a built-in tracking generator is ideal for passband measurements where a wide dynamic range is required. In addition, occupied bandwidth, adjacent-channel leakage power and intermittent signal measurement functions are available as options. For use in measurement systems, together with an internal controller, these analyzers have a GPIB interface and memory card function provided as standard. **Advantest America, Inc., Lincolnshire, IL. INFO/CARD #219.**

Transimpedance Amplifier

The ATA03010 is a transimpedance amplifier GaAs IC with an input noise spectral density of less than 2pa/Hz and third-order intercept of +18 dBm. Dynamic range is 60 dB and 3 dB bandwidth is 250 MHz in a TO-77 package and 325 MHz in an 8-pin flatpack. In 100-piece quantity, price is $44.

Also from Anadigics is the ATA30011 transimpedance amplifier with 3 dB bandwidth of 2 GHz and output impedance of 25 ohms. Power output at 1 dB compression is 8 dBm and third-order intercept is +20 dBm. Applications include use in CATV analog receivers, wideband gain blocks and low-noise RF amplifiers. **Anadigics, Inc., Warren, NJ. Please circle INFO/CARD #217.**

3.2 GHz Spectrum Analyzer

The SNA-5 spectrum analyzer from Wandel & Goltermann has a frequency range of 50 Hz to 3.2 GHz with resolution of 0.1 Hz. Intrinsic noise is below -140 dB and intermodulation noise is -95 dB. Third-order intermodulation noise ratio is less than or equal to 100 dB. Memory storage for up to 10 setups and results curves is provided. **Wandel & Goltermann, Inc., Research Triangle Park, NC. INFO/CARD #216.**

Thermal Converter Set

Precision Measurements is offering a thermal converter set (secondary standard) for calibrating RF equipment. The standard line set offers a flat frequency response up to 10 MHz while 100 MHz is available. A choice of input voltages and balanced or unbalanced thermal converters is provided. **Precision Measurements, Sun Valley, CA. Please circle INFO/CARD #215.**

DDS Evaluation Kit

The Q2334 direct digital synthesizer evaluation kit facilitates the evaluation of the performance and functionality of the Q2334 DDS device. It simplifies testing by providing a sine waveform synthesis system on a circuit card. The circuit includes a pre-programmed microcontroller interfaced to the DDS, a 12-bit digital-to-analog converter, lowpass filter, frequency reference and output buffer. Analog

rf products *Continued*

outputs are jumper-selectable to be either direct from the D/A converter (without the lowpass filter), through the on-board reconstruction lowpass filter, or converted to TTL square-wave format to demonstrate the ability of the DDS to generate high accuracy digital clock signals. Only one of the two DDS circuits on the Q2334 device is connected to on-board D/A conversion circuitry. The second is connected to a 40-pin auxiliary port connector to allow the user to interface with external circuits. **Qualcomm, Inc., San Diego, CA. INFO/CARD #218.**

Silicon MMIC Amplifier

The MODAMP™ cascadable silicon bipolar MMIC amplifier is a general purpose 50 ohm gain block with a 0.1 to 4 GHz frequency range. It features 8 dB of gain with ±0.2 dB gain flatness. The 3 dB bandwdith extends from 0.1 to 6 GHz. MSA-0910 is packaged in a 100 mil, hermetically sealed, metal ceramic package. **Avantek, Inc., Santa Clara, CA. INFO/CARD #214.**

200 MHz Transimpedance Amplifier

Analog Devices' AD9615 settles to 1.0

and 0.1 percent in 8 and 13 ns respectively while exhibiting typical rise and fall times of 2.6 ns. With a 20 MHz input tone, the second harmonic is typically -62 dBc. When the bandwidth is limited, the decrease in noise floor and distortion spurs the amplifier to be used in 14-bit systems that sample at 2 MHz. **Analog Devices, Inc., Norwood, MA. Please circle INFO/CARD #213.**

Fiber Optic Cable Assembly

Suchard Enterprises introduces an SMA (Type 905) to SMA (Type 906) fiber optic cable. The assembly is available in simplex (single cable), duplex (two cables) and quad (four cables) types. It is also obtainable in 50/125 um, 62.5/125 um and 100/140 um graded fiber indexes. Standard sizes are 1, 3, 5 and 10 m. **Pasternack Enterprises, Irvine, CA. Please circle INFO/CARD #212.**

Digitizing Oscilloscope Test Set

The HP 54114A test set, an accessory for the HP 54111D digitizing oscilloscope, increases the maximum sampling rate of the oscilloscope from one to two gigasamples per second. This additional speed increases the maximum single-shot bandwidth of the 54111D from 250 MHz to 500 MHz. Bandwidth limit filters provide 6, 7 and 8-bit vertical resolution. **Hewlett-Packard Company, Palo Alto, CA. INFO/CARD #210.**

Return Loss Bridge

This bridge has a frequency range of 5 to 600 MHz, impedance of 75 ohms, directivity of 40 dB, bridge loss of 12.5 dB and short-open error of 1 dB max. Price is $100 each. **Viewsonics, Inc., Syosset, NY. INFO/CARD #209.**

Class AB Linear Amplifier

This Class AB linear amplifier has a frequency range of 1400 to 1800 MHz with power output of 200 watts. It accepts CW, FM, AM and pulse modulation with input VSWR of 2:1. Harmonics are measured at −30 dBc and spurious signals are -60 dBc. Model BHC 148188-200 has a pulse rise and fall time of 150 ns. **Power Systems Technology, Inc., Hauppague, NY. INFO/CARD #207.**

RF Relay

Model RF2X1-F is an RF relay with isolation up to 90 dB at 50 MHz and over 80 dB at 250 MHz. It operates on 200 mW at various voltages from 5 to 28 volts. **Alaun Engineering, Montrose, CA. INFO/CARD #206.**

Chip Resistor/Capacitor Prototype Kits

KCK's chip resistor kit, CR-1, contains two standard sizes, 0805 (1/10W) and 1206 (1/8W), with 145 values from 10 ohms to 10 M ohms and a 0 ohm jumper. Each resistor has 5 percent tolerance and is marked with a three-digit value. The chip capacitor prototype kit, CC-1, features the same standard sizes with 61 values from 1 pF to 0.33 uF. Temperature range characteristics range from NPO to Y5V. **KCK America Inc., Schaumburg, IL. INFO/CARD #208.**

2 GHz Generator

The Model SMH signal generator from Rohde and Schwarz has a frequency range of 100 kHz to 2.08 GHz with resolution of 1 Hz. Spectral purity is better than −130 dBc for a 1 Hz bandwidth and 20 kHz offset. Pulse modulation is provided with typical rise times of 20 ns and a

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Your idea may win this Grand Prize, provided by Webb Laboratories:

CommView
Receiver simulation software. Calculates pre- and post-detection SNRs, bit error probability and AGC voltage for user-entered system cascades. Graphics support Pagemaker and Ventura desktop publishing software.

FilSolv
Webb Labs' filter synthesis package. Creates practical, buildable lowpass, highpass and bandpass filters in Butterworth, Chebyshev, Bessel and Elliptic realizations. Incorporates losses found in "real" components. Files can be saved in formats compatible with major circuit analysis packages.

SYSCAD
RF/Microwave system engineering software. Performs link, terminal and RADAR characterization, receiver architecture analysis, transmit and receive spurious analysis through an order of 2000, plus phase noise calculations.

TRANSCAD
Powerful single and coupled transmission line and waveguide synthesis package. Analyzes and synthesizes over 40 structures, including nearly every microwave geometry of interest. Applies numerical methods to the best known algorithms to eliminate common synthesis errors.

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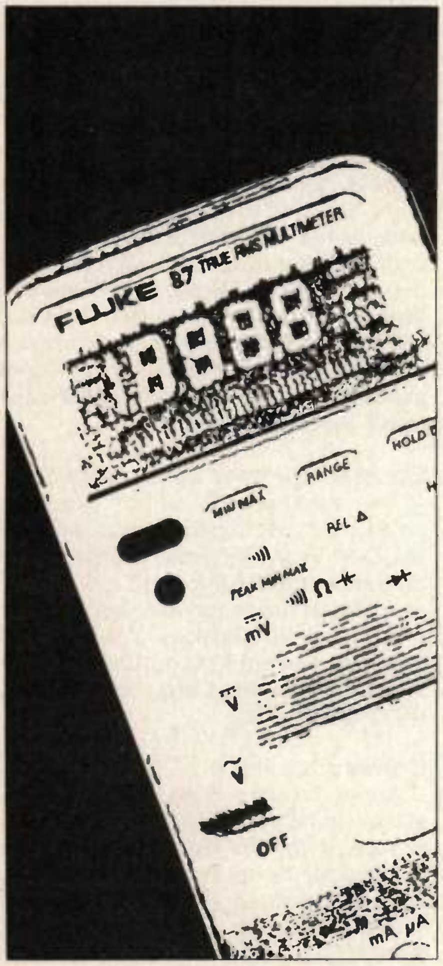
★ RF Design Awards Contest ★ ★

or one of five runner-up prizes from Fluke.



The model 87 True RMS Digital Multimeter, with high resolution analog pointer, MIN MAX averaging, 10pF - 5μF capacitance measurement, plus, duty cycle from 0.1 to 99.9% overload protection, 4¾ digit display and ragged, sealed construction are additional features.

Provided by John Fluke Mfg. Co., Inc.

Great ideas deserve great prizes!

Just follow these simple entry rules:

1. Entries shall be RF circuits containing no more than 6 single active devices or 4 integrated circuits, or be passive circuits of comparable complexity.

2. The circuit must have an obvious RF function and operate in the below-3 GHz frequency range.

3. Circuits must be the original work of the entrant. If developed as part of the entrant's employment, entries must have the employer's approval for submission.

4. Components used must be generally available, not obsolete or proprietary.

5. Submission of an entry implies permission for *RF Design* to publish the material. All prize winning designs will be published, plus additional entries of merit.

6. Winners shall assume responsibility for any taxes, duties or other assessments which result from the receipt of their prizes.

7. Deadline for entries: March 31, 1989

JUDGING CRITERIA

1. **Originality:** The purpose of the contest is to reward engineers for their unique design contributions. Each design will be evaluated according to its similarity to work by others, unusual application of a device or technique, and other judgments of its contribution to the advancement of the engineering craft.

2. **Engineering:** Engineering is the application of technology to solve a problem or meet a design goal. Entrants should clearly identify how their circuit was created in response to such a need. Judges will evaluate performance, practicality, reproducibility and economy.

3. **Documentation:** Communicating ideas to others is the business of *RF Design* and a necessary part of good engineering. Each entry will be judged on its description, analysis and graphical material. Each circuit should have a complete list of components, explanation of functions, and a summary of performance and test data.

MAIL YOUR ENTRY BY MARCH 31, 1989 TO GARY BREED, EDITOR. . .

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minimum on/off ratio of 60 dB. Output levels are settable from −137 to +13 dBm with 0.1 dB resolution. Maximum level error is less than 1.5 dB with resettability of 0.05 dB. An optional low-distortion synthesizer adds a continuously variable modulation or voltage source from 10 Hz to 100 kHz. The instrument is priced at $14,900. **Rohde & Schwarz, Lanham, MD. INFO/CARD #211.**

100 MHz Crystal Oscillator

Brightline's Model 1071 100 MHz quartz oscillator has phase noise floor below -175 dBc/Hz. Stability at 1 ms is 10^{-12}. **Brightline Corp., Cedar Park, TX. INFO/CARD #205.**

100 W Amplifier

Model 100HB is a 100 W Class A amplifier with a 400 to 1000 MHz bandwidth. An integral leveling preamplifier, front-panel metering of forward and reflected power, and provision for scope display are featured. The instrument is priced at $35,000. **Amplifier Research, Souderton, PA. INFO/CARD #204.**

GaAs FET Amplifier

Janel Laboratories introduces the PF884A quadrature coupled low power GaAs FET with BNC connectors. Typical performance includes 0.8 dB noise figure, and +22 dBm third-order intercept point over 20 MHz bandwidths from 406 to 512 MHz with 16 dB gain. Options include a built-in attenuator and/or fault alarm. Price is $216 in single quantities. **Janel Laboratories, Inc., Corvallis, OR. Please circle INFO/CARD #203.**

Ceramic Trimmer Capacitors

The Johanson Seal-Trim® series of ceramic trimmer capacitors is qualified to MIL-C-81. Twelve incremental capacitance ranges of 0.6 to 2.5 through 8 to 50 pF are available in nominal diameters of 5 mm and 7 mm. In quantities of 100 to 299 price ranges from $2.00 to $2.25. **Johanson Manufacturing Corp., Boonton, NJ. INFO/CARD #202.**

Conductive Paint

Aremco-Shield™ 615 is a silver-elastomer compound used as a conductive paint for EMI/RFI shielding. The material can be applied by brush or spray and can be cured at room temperature. **Aremco Products, Inc., Ossining, NY. INFO/CARD #201.**

Downconverter Subsystem with Preselector Filter

Pacific Monolithics' PM-CI0201 is a subsystem with a low noise RF amplifier, double-balanced mixer, LO buffer and an IF amplifier. For a specified RF input frequency (300 MHz bandwidth), an internal inductor is used to match the RF input port to the first stage of the MMIC to achieve low noise. The preselector filter can be included in the package after the first amplifier stage to provide 12 dB rejection of undesired image frequencies. The subsystem provides 25 dB of RF to IF gain and 4 dB overall SSB noise figure over any specified bandwidth. Frequency range is 0.5 to 2 GHz, LO frequency is 0.5 to 2 GHz and IF frequency ranges from 50 to 500 MHz. Output power at 1 dB compression is typically 5 dBm and third-order intercept point is typically 12 dBm. **Pacific Monolithics, Inc., Santa Clara, CA. INFO/CARD #198.**

rf software

GaAs FET Parameter Extractor

Xtract™ performs linear/nonlinear modeling characterization of microwave and RF GaAs FETs. Xtract works with Anacat™ and provides custom models for foundry services. Anacat acquires the measurement data that Xtract uses to perform FET modeling characterization. It (Anacat) collects S-parameter data from vector network analyzers, data acquisition systems and semiconductor parameter analyzers. From the Anacat acquired data, Xtract generates transistor characterization files. It lets the user graphically compare modeled results with original measurements so as to immediately judge the quality of the model.

The price of the program is $34,500 and varies according to configuration and options. **EESof, Inc., Westlake Village, CA. Please Circle INFO/CARD #180.**

Analog Test Automation System

Analog Design Tools and Teradyne announce the availability of an integrated system for the design and test of analog integrated circuits. The Test Development Tool Kit links Teradyne's Image™ test simulator with the Analog Workbench™ circuit simulation software, providing a total simulation solution for designing and testing functionality of ICs in a simulated work environment. Teradyne's IMAGE (Interactive Menu-Assisted Graphics Environment) software is a high-level, graphics-based environment that provides the ability to write code for test program development.

The Test Development Tool Kit is compatible to Sun-3™ workstations and includes a tester interface, statistical analysis tools, paramentic plotter, translator, basic device library and test instrument models. It is priced at $21,500. **Analog Design Tools, Sunnyvale, CA. INFO/CARD #179.**

EMI Test Software

The EMI Test Software EZM-K1 from Rohde & Schwarz is designed for EMI measurements when used in conjunction with the Test Receivers ESH 3 and/or ESVP and the spectrum monitor EZM. With the package it is possible to measure RFI voltages, currents, powers and field strengths to VDE, CISPR and FCC regulations, and conducted and radiated interference to MIL and VG standards. The software splits measurements up into two stages — a preliminary measurement on the interference spectrum and a final measurement at critical frequencies. It is tailored for frequencies between 20 Hz and 1300 MHz. **Rohde & Schwarz, Munich, West Germany. Please circle INFO/CARD #200.**

rf literature

Brochure Describes Generators for EMC/EMI/EMS Testing

Cober Electronics' line of high-power microwave energy generators is described in this brochure. With peak pulse power levels of 5 MW, or 10 kW CW, these units are used for testing EMC, EMI and EMS. Frequency range is from 1 to 40 GHz depending upon microwave tube selected. **Cober Electronics, Inc., Stamford, CT. INFO/CARD #193.**

RF and Microwave Component Catalog

Highlighted in this catalog are Phoenix Microwave's capabilities in the RF and microwave modular component area. Specifications for a wide range of monolithic and integrated amplifiers in TO-8, flatpack and connectorized packages are presented. In addition, a line of hermetic switches covering the DC to 8 GHz range is described. A test fixture with broadband characteristics is featured. **Phoenix Microwave Corp., Telford, PA. INFO/CARD #192.**

Electronic CAD Buyer's Guide

Design Solutions introduces its Electronic CAD Buyer's Guide for personal computers. It is intended to educate the first-time buyer on electronic CAD for the PC. Also, experienced workstation CAD users will benefit from the guide by learning where PC-based products may have problems relative to workstation systems. The guide costs $25. **Design Solutions, Soquel, CA. INFO/CARD #191.**

Attenuator and Switch Catalog

This catalog celebrates JFW's 10 years of product, service and innovation in attenuators, switches and special RF products. Items in this catalog include hybrid thick film switches and attenuators, high-power products up to 300 watts, thick film microstrip attenuators and terminations, impedance matching transformers and GPIB interface capability. **JFW Industries, Inc., Indianapolis, IN. Please circle INFO/CARD #190.**

News Brochure

"News from Rohde & Schwarz" (number 122) introduces a process controller, RF step attenuator RSP for 0 to 139.9 dB, test generator SFSP for digital sound broadcasting, audio decoder DDA for digital sound transmission, and traffic-control direction finders. Other instruments and topics highlighted include the universal radiocommunication tester CMT for cellular radio networks, selftest and diagnostics for signal generators, new functions for the logic analyzer LAS for software-performance analysis and data-network monitoring. **Rohde & Schwarz, Munich, West Germany. Please circle INFO/CARD #189.**

Multimeter Brochure

This brochure highlights three members of the Fluke 80 Series: the 83, 85 and 87. The series offers a combination of measurement functions and safety features, including frequency, duty cycle, capacitance, and simultaneous minimum-maximum average recording. **John Fluke Mfg. Co., Inc., Everett, WA. INFO/CARD #187.**

Op Amp Application Guide

"Current-Feedback Op Amp Application Circuit Guide" from Comlinear features various circuit configurations using op amps. Circuits shown include summing amplifier, coaxial cable driver, output current booster, offset adjustment, FET input circuit, non-inverting composite amplifier, reducing frequency response peaking, lowpass filter (10 MHz), bandpass filter (40 MHz), D/A converter buffer amplifier, 4 MHz bandstop filter and a peak detector. **Comlinear Corp., Fort Collins, CO. INFO/CARD #186.**

Capabilities Brochure

Listed in this Plessey brochure are locations and facilities, key processes, packaging, quality screening options, future developments, CMOS, ECL and bipolar gate arrays, bipolar analog/digital arrays, CMOS analog/digital arrays, bipolar analog arrays, Plessey megacell and Plessey compiled ASIC. Also included is a section on computer-aided design, RF digital, data conversion, RF analog and discrete components. **Plessey Semiconductors, Scotts Valley, CA. Please circle INFO/CARD #185.**

Bipolar Transistor Reliability Report

Motorola has announced the publication of the Bipolar Transistor Reliability Report which serves as a library of detailed up-to-date reliability performance information for the particular devices. It includes a description and purpose of all tests performed in a reliability audit as well as the actual audit results. The results are displayed in graphs and tables showing the failure rate in time (FIT) and trends for each major device package. Process capability, statistical process control, process-improved package and ruggedness are included. **Motorola Semiconductor, Phoenix, AZ. INFO/CARD #184.**

Coaxial Products Division Catalog

Catalog #1989 features a line of amplifiers, breakouts, coaxial cable, cutting tools, power dividers, crimping tools, stripping tools, coaxial adapters, coaxial detectors, coaxial connectors, coaxial attenuators, coaxial terminations and coaxial cable assemblies. In addition, twinax adapters, connectors and cable assemblies are featured together with connectors and adapters including MHV, BNC Twin-ax, C, HN, SC, GR874, radius right angle and type LC. **Pasternack Enterprises, Irvine, CA. INFO/CARD #183.**

Brochure Describes Power Meters

Marconi has released a brochure on their 6900A line of power meters. It describes features, specifications and accessories for the 6950 and 6960A power meters. A section describes Marconi's line of precision sensors. **Marconi Instruments, Inc., Allendale, NJ. Please circle INFO/CARD #182.**

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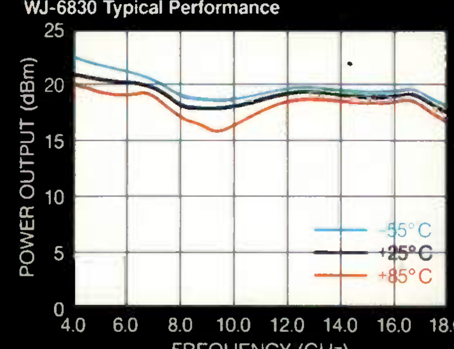

For complete information on the WJ-6830 series of YIG oscillators, contact the Watkins-Johnson Field Sales Office in your area, or telephone Ferrimagnetic Devices Applications Engineering in Palo Alto, California, at (415) 493-4141, ext. 2252.

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