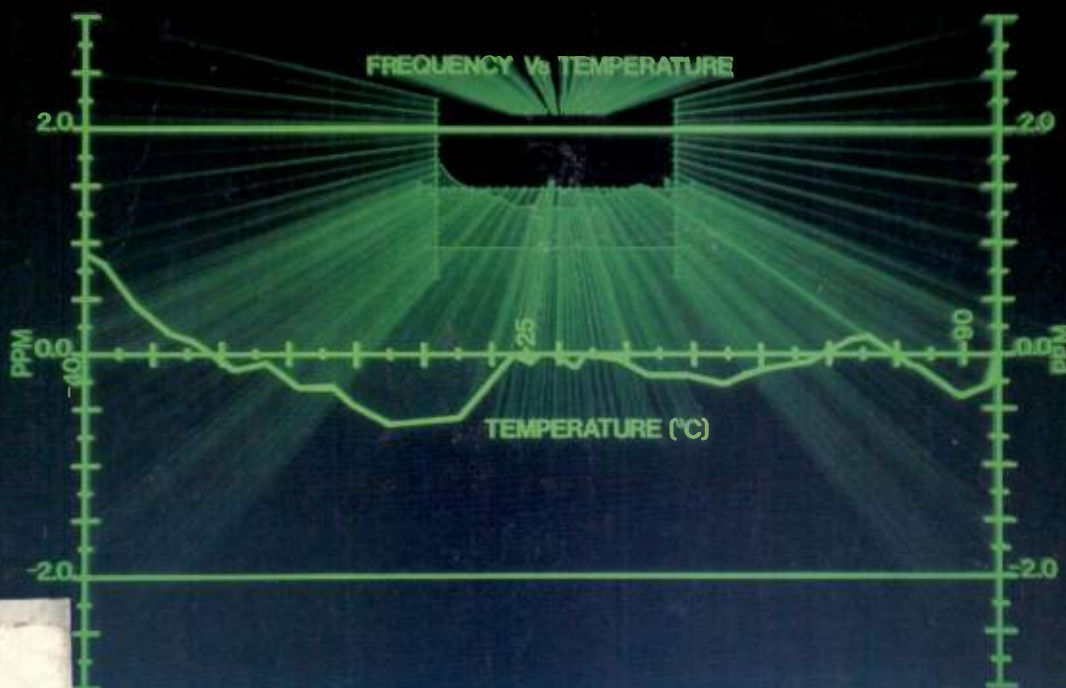


rfdesign

ideas for engineers

March 1985



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Special Report:
New Waves in Oscillator Design

A collection of various electronic components, including integrated circuits, transistors, diodes, and connectors, arranged on a light-colored surface. Some components are labeled with text like "SMALL SIGNAL RF SEMI'S", "CUSTOM RF HYBRIDS", "LINEAR WIDEBAND AMPS", and "CATV AMPS".

INFO/CARD 1

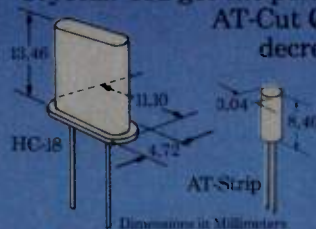
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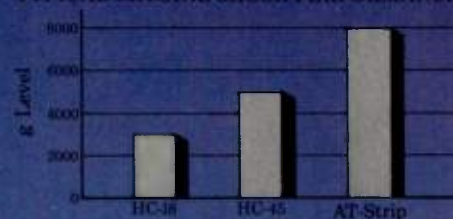
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Cover

This month's cover features Motorola's MDO-2 (left) and the new MDO-3 (right) temperature-compensated crystal oscillators. Motorola considers these MDO products to be the best in TCXO performance in their cost range. The MDO-3 is described in this month's Special Report, along with other recently announced oscillator products. Many of the considerations mentioned in Dennis Marvin's article on frequency-temperature performance determination in crystal oscillators were incorporated in the MDO-2 series. (Photo courtesy of Motorola, Inc.)



Features

20 Special Report: New Waves in Oscillator Design

This month's Special Report covers common oscillators designed to operate primarily at frequencies below 2 GHz. Examples of the kinds of improvements being made in crystal and SAW resonator oscillators are described, along with indications of probable trends in oscillator design — James N. MacDonald.

26 The SAW Resonator: How It Works — Part 2

The author continues his explanation of the surface acoustic wave resonator and his program to model device responses. He describes how to use the program to examine the properties of reflective arrays and single and multiple cavities. A BASIC version of the program is given for microcomputer users. — Jeffrey S. Schoenwald, Ph.D.

53 Frequency-Temperature Performance Determination in High Stability TCXOs

High stability temperature-compensated crystal oscillators are subject to many instabilities not normally considered in the design of lower stability products. The design engineer must carefully consider the system requirements in dynamic environments and as a function of time. The author reviews several second order effects and attempts to quantify the amount of performance debasement that can result. — Dennis Marvin.

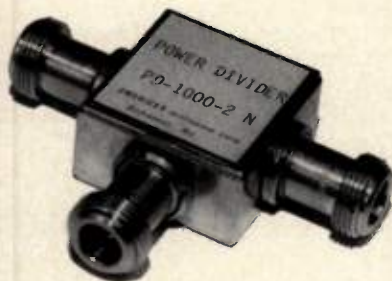


Scenes from RF Technology Expo 85 — Anaheim, Calif.

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R.F. DESIGN (ISSN: 0163-321X USPS: 453-490) is published monthly plus one extra issue in June, March 1985, Volume 8, No. 3. Copyright 1985 by Cardiff Publishing Company, a subsidiary of Argus Press Holdings, Inc., 6530 S. Yosemite Street, Englewood, CO 80111 (303) 694-1522. Contents may not be reproduced in any form without written permission. Second-Class Postage paid at Englewood, CO and at additional mailing offices. Subscription office: 1 East First Street, Duluth, MN 55802, (1-800-346-0085). Subscriptions are sent free to qualified individuals responsible for the design and development of communications equipment. Other subscriptions are: \$15 per year in the United States; \$25 per year in Canada and Mexico; \$25 per year for foreign countries. Additional cost for first class mailing. Payment must be made in U.S. funds and accompany request. If available, single copies and back issues are \$5.00 each (in the U.S.). This publication is available on microfilm/fiche from University Microfilms International, 300 N. Zeeb Road, Ann Arbor, MI 48106 USA (313) 761-4700. POSTMASTER & SUBSCRIBERS: Please send address changes to: R.F. Design, P.O. Box 6317, Duluth, MN 55806.

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INFO/CARD 4

Where Do You Learn About RF Circuits?



James MacDonald
Editor

The biggest surprise at the RF TECHNOLOGY EXPO was the response to the Fundamentals of RF Design course. Based on pre-registrations, the room was set up for a maximum of 350. By starting time the first day the room was filled and more than 100 conference attendees were in the hall hoping to register. We were able to add some chairs, but many who had not pre-registered had to be turned away.

The situation was similar when the course was repeated the next day. By then the room had been expanded to seat 500, anticipating the overflow from the first day. All seats were filled and remained filled throughout the day.

On one hand, this overwhelming response reflected the response to the EXPO as a whole. Attendance exceeded our expectations, if not our hopes. On the other hand, it provided dramatic proof of a serious lack of educational opportunities for RF engineers. The audience composition ranged from young recent graduates to university professors with well-established reputations in electrical engineering.

As I talked with attendees the same fact was mentioned over and over; electrical engineering students have little opportunity or incentive to study RF circuit principles. In many universities the courses simply are not available. Where they are available advisors do not encourage such courses.

Current employment opportunities apparently are greater and salaries higher in the digital and power fields, but this not-very-widely promoted course in RF design fundamentals attracted more than 800 engineers and others involved in designing RF equipment, some from foreign countries. Clearly there is a significant lack of educational opportunities in RF circuit theory and design. We think engineering colleges should take a look at this educational need.

Proceedings of the sessions, including the Fundamentals of RF Design course, will be published soon. RF designers who could not attend the EXPO may want to order a copy. Each session was tape recorded, as well. Tapes may be ordered from Meyer Communications Corp., 13791 E. Rice Place, Aurora, CO 80015.

During World War II many amateur radio operators were hired by defense contractors to build communications gear. Even fewer engineers were trained in RF principles at that time. Amateurs knew how to build equipment, even if they did not thoroughly understand how it worked. Many of them eventually became engineers.

This is one reason so many RF designers are amateur radio enthusiasts. Most of those who worked during WWII are retired, but they passed their enthusiasm on to the younger generation. During EXPO 85 quite a few hams were seen with handheld 2-meter gear and others were heard on the band with mobile and base station rigs.

Carl Lodstrom, SM6MOM/W6, has suggested that we select a frequency for simplex operation during the next EXPO and publicize it. Carl said such a frequency seemed to be chosen by chance at EXPO 85, perhaps because people heard others talking on it and joined the net. He said it was a great way for hams to get together for dinner or meetings.

What do *RF Design* readers think of this idea?

James H. MacDonald



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That Old Black Magic — Losing Its Old Spell



Keith Aldrich
Publisher

Something happened at the RF TECHNOLOGY EXPO 85 in January: something which spells the end for that old myth about RF technology being a "black art" which practitioners exercise by instinct, or by "the seat of the pants."

Call it a new generation. Call it the light of rational analysis breaking like a dawn to dispel the blackness. Whatever you call it, it became obvious at the EXPO that "weakling" and "tuning" approaches to RF design are giving way to analytic approaches, in which the vagaries of RF propagation are not regarded as unexplainable mysteries, but phenomena which can be characterized, predicted, and harnessed with precision. The end result is designs which take days instead of weeks and which are proved in the lab instead of the field.

The new generation factor was evident in viewing the 800-plus attendees who listened with such close attention to Les Besser and other instructors at the "RF Fundamentals" course. While there was a liberal sprinkling of gray heads... more, perhaps, than the title of the course would lead you to expect... the studiously attentive faces were mainly young, young, young. Not college young. The badges read "Hughes" and "Rockwell" and "General Dynamics," and the exhibitors who encountered them later in their booths exclaimed over their knowledgeable questions and their purchasing power (one instrument manufacturer an-

nounced sales of \$250,000 worth of equipment the first day). No, these were real engineers... just young — and *eager to learn*. Les Besser was up there talking about constant gain circles, and S-parameters, and computer-aided design, and they were eating it up.

Just a couple of years ago, RF engineers were characterized as being hostile to such innovations, on the average, preferring to "do it their way." And, on the average, they have successfully resisted the innovations. Instructor Besser asked for a show of hands, toward the end of his lecture, to see how many attendees commonly applied tolerance analysis to check out their designs. Only a small fraction raised their hands. "About three percent," Les computed; "about the national average." He went on to preach the gospel: how his listeners could cut down their failures in the field by applying some of the methods he was espousing.

It had the ring of one of those futile lectures about littering or something. Except for one thing. These young people were listening carefully, not yawning and fidgeting. And you realized, if you thought about it, that these people were not *inherently* antagonistic to computers, and modeling and simulation. They grew up with computers. They are already competent EEs, for the most part. It is only RF that is new to them. They are listening so carefully to Les because they are going to *practice* what he is preaching.

That is good news for their employers, and for the RF boom that was so apparent in the mood of RF TECHNOLOGY EXPO 85. While much of the electronics industry is faltering, and while digital engineers in many parts of the country are being thrown out of work, manufacturers of RF equipment can hardly keep up with the demand. To keep up with what is needed from them RF engineers must be as productive as modern technology can make them. We are pleased to have been of service in helping bring them up to speed.

Keith Aldrich

Publisher
Keith Aldrich

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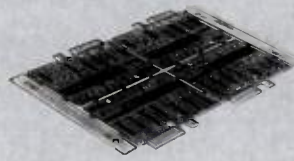
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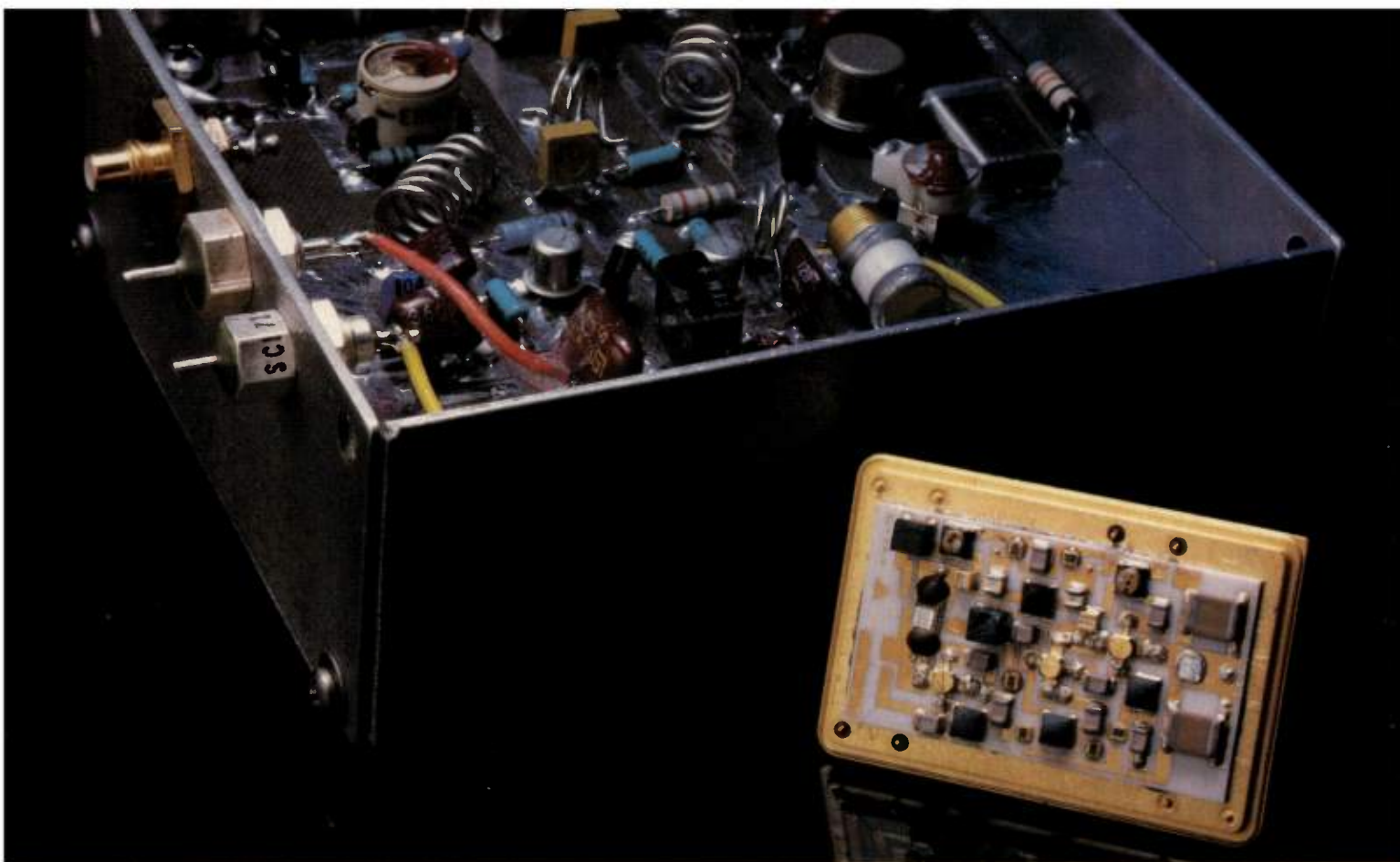
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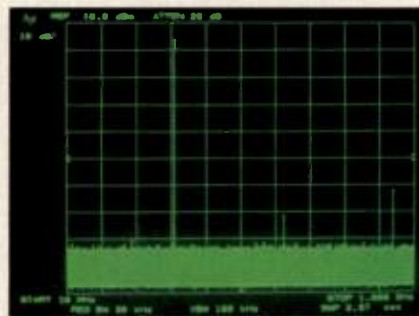
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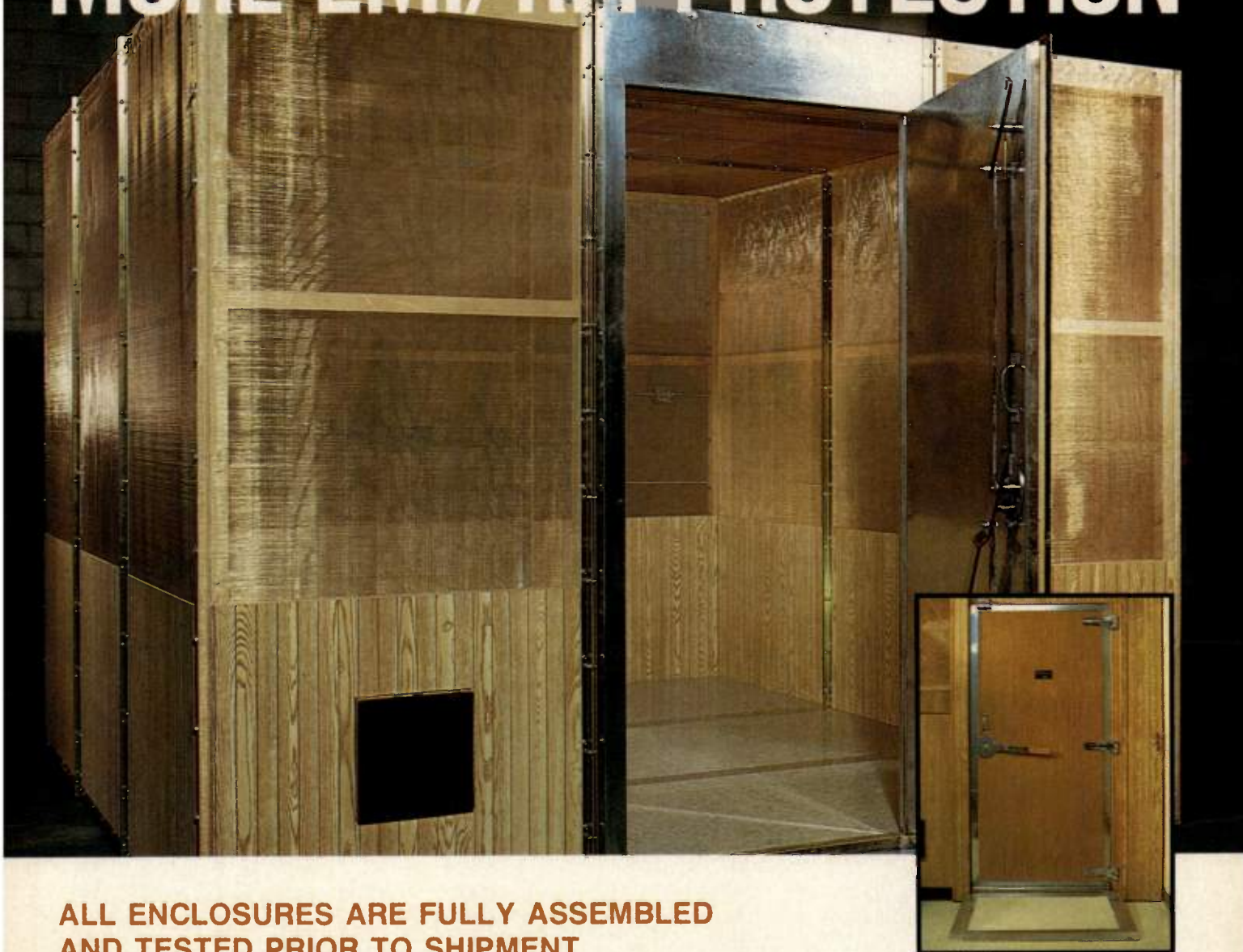


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Editor:

I enjoyed the "Frequency Synthesized Signal Generators" article in the November/December 1984 issue of *RF Design*.

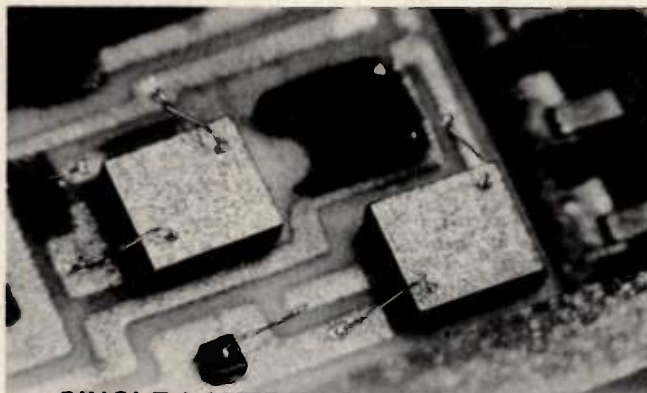
I was dismayed, however, to find that Eaton Electronic Instrumentation Division's signal generator products were not included in the story, or the product briefs which followed, although I responded to your request for information.

I am sure the oversight was unintentional but, in the event you are planning future coverage of this product line, I have included data sheets descriptive of both the Model 460 AM/FM Φ M Signal Generator and the 360, 380 Series of Direct Synthesized Signal Generators for your future reference. The 380 Series is particularly exciting offering 20 microsecond switching to 4 GHz.

If I can ever provide additional information on Eaton's broad line of test and measurement instrumentation, please call me without hesitation.

Sincerely,
Patricia W. Ullrich
Marketing Communications Manager

Because of the large response from manufacturers to our call for new product information we must set limiting guidelines for our special reports. We attempt to keep our readers informed of the most recent product developments. A number of products were not included in the special report on "Frequency Synthesized Signal Generators" because they had been on the market long enough for most RF engineers to know of them. We welcome comments from manufacturers and readers on this subject. Readers wanting information about the products mentioned in Patricia Ullrich's letter may circle info/card #177. — editor



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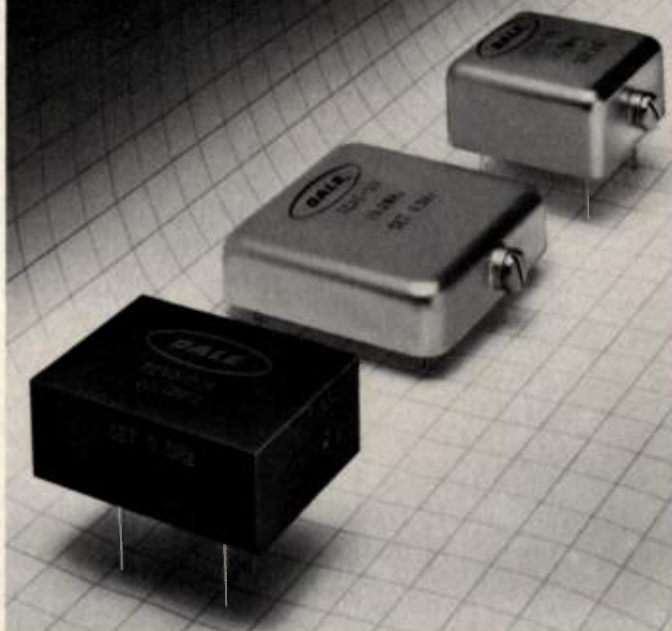
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INFO/CARD 18

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INFOCARD 12

Sweet Smell of Success at RF Technology Expo 85



Even the night before it opened, at a crowded VIP reception in one of the Disneyland Hotel's posh ballrooms, exhibitors and speakers were congratulating executives of sponsoring Cardiff Publishing Company, *RF Design* magazine staff members and each other. Cardiff president Robert A. Searle, veteran of many such shows, said late that night, "They're declaring it a success before it happens. When they do that it's a good sign."

The stage was set. In the exhibit hall 60 exhibits were poised in 75 booth spaces. Elsewhere in the complex five large rooms were set up for the concurrent technical sessions accommodating the 71 papers to be given at the first RF TECHNOLOGY EXPO.

Shortly after dawn the next day, long before registration desks opened, the line of attendees began to form. The hundreds who already had registered by mail were there just to pick up their badge and program, but they were joined by hundreds starting from scratch.

The final attendance figure was 1,300, plus 400 exhibit personnel and speakers, and as Convention Manager Kathy Kriner said, "Nobody expected them show up all at once!"

The opening day jam-up was alleviated by dispatching those who were there for the Fundamentals of RF Design course directly to the classroom sans admission, to return for registration at the noon break.

In the hotel's huge Embassy Room, classroom for the fundamentals course, instructor Les Besser was staggered as an overflow crowd topping 400 poured into a space set up for 350. Adapting admirably, the president of Microwave Educational Programs held the jammed-in crowd spellbound through a four-hour lecture on Small Signal Amplifier Design.

In mute testimony to the value of the material they were receiving, the crowded participants sat silently and seemingly motionless as instructor Besser revealed the mysteries of what others have called the "Black Art." The art became a science.

In other rooms, some almost as crowded, three papers were being given concurrently, truly offering something for everyone. Attendees could go from room to room, from topic to topic, picking up the particular knowledge needed for the job back home. Four papers were delivered in each room.

Registration continued through the morning, as exhibitors prepared for the noon opening. Many of them later said they were not prepared for the number and caliber of people who crowded their booth constantly until the exhibits closed at 6:00 p.m.

"Every person I talked to was a qualified customer," was a common remark from exhibitors.

Many discovered they had brought too few people to talk to the visitors and too little printed material to hand out. Frantic calls went out for help and literature. Business cards became unexpectedly scarce items.

While attendees enjoyed lunch at the variety of famous restaurants in the hotel complex, hotel employees expanded the Embassy Room to provide comfortable seating for the extra 100 in the Fundamentals class. University of Colorado Professor K.C. Gupta started the afternoon session with a detailed explanation of striplines and microstriplines. He was followed by Joe Johnson, president of Microwave Modules and Devices, explaining high power amplifier design: John Morton, engineering manager for Microsonics, Inc., who gave an overview of oscillators; and Carl Erickson Jr., with a complete description of surface acoustic wave devices.

From the silence that prevailed all day the intensely concentrating crowd of 400 could have been a group of six. Very few had left by the end of the session, and those who left may have gone to catch a particularly interesting presentation in one of the other sessions.

When all papers had been presented most attendees gathered at the exhibit hall for free refreshments and relaxed conversation. Even now the exhibit booths were crowded, although the pace was slower. Some exhibitors had made thousands of dollars worth of unexpected sales that afternoon. They were pleasantly tired, not just from the constant flow of visitors to their booths but also from the depth of the questions they had to answer.

"You were smart to only open the exhibits from noon to 6:00," one exhibitor told *RF Design* publisher Keith Aldrich. "I don't think we could have taken this all day."

Attendance at the RF Fundamentals course was even larger the second day. Once again the room was expanded as

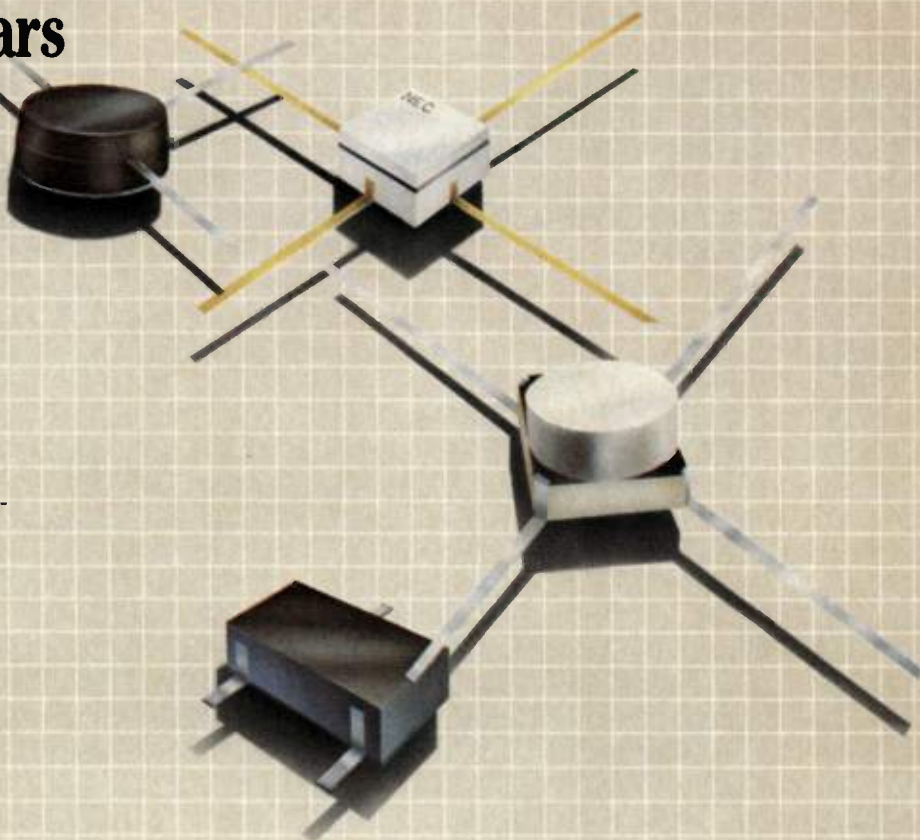
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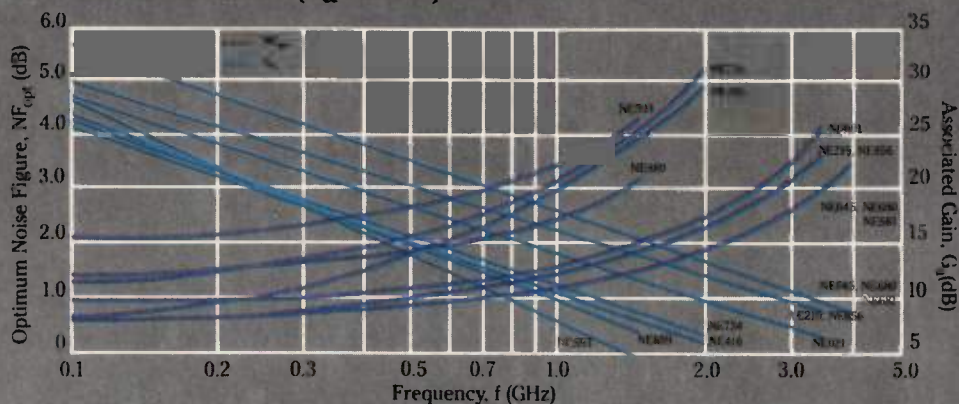
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hotel employees removed walls and brought in chairs. When they had finished, nearly 500 chairs were occupied.

It was remarkable that in spite of the last minute rearrangement of the room, leaving about 100 without tables to write on, there were no complaints. Those who were there considered themselves lucky to receive the information, regardless of the circumstances.

As many as 200 attended some of the

other sessions, covering the general topics of circuits, transmitters, computer-aided design, antennas, techniques and components. Sessions were arranged both days so conference attendees could go from room to room and hear papers on each topic. RF TECHNOLOGY EXPO registration badges could be seen everywhere in the hotel complex as attendees went from session to session or to the exhibit hall.

His work was over, but program chairman Andy Przedpelski could be seen many places during the EXPO, going to sessions or touring the exhibits or just joining one of the many spontaneous discussion groups that seemed to develop wherever attendees came together. He had put together a valuable program, and now he could enjoy and benefit from it along with those he had done it for — the RF designers who came from as far away as China and Israel to attend.

It was no surprise to the staff that 360 copies of the proceedings had been ordered by those in attendance, or that 67 percent of the exhibitors said they definitely would be back for EXPO 86. Another 30 percent said they probably would be back. One who said he probably would not return said his products were "too microwave" for the attending engineers. He said most of those he talked to worked in frequencies "from 2 GHz down."


Of course, that was the idea of the RF TECHNOLOGY EXPO. It was the first show held specifically for engineers working from 2 GHz down. But Cardiff officials say it won't be the last one.

Keith Aldrich said, as the show was closing Friday morning, "This phenomenon confirms the premise of the show — that there is a desperate need for RF engineering information that is not being met, among engineers who have been pressed into service without adequate training in RF."

Dates and site of the RF TECHNOLOGY EXPO 86 will be announced in next month's issue of *RF Design*.

Dow-Key Becomes Subsidiary of Kilovac

Dow-Key Microwave Corp. was incorporated Jan. 2, as a wholly owned subsidiary of Kilovac Corp., Carpinteria, Calif. Sales manager Jack Dysart announced the company's new status at a news conference at RF TECHNOLOGY EXPO 85. The company previously had been a division of Kilovac involved in the design and manufacture of coaxial relays and switches for the RF and microwave communications, radar, electronic warfare and test equipment markets. The company recently moved into a large facility in Carpinteria with class 100,000 clean room facilities and MIC capability.

Dysart said the company is introducing the concept of intelligent relays which integrate higher levels of digital, analog and microwave integrated circuits into their existing line of electromechanical switches designed to meet Mil-S-3928. 

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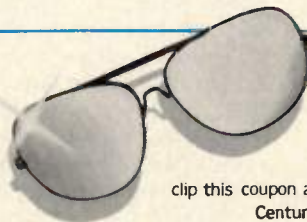
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INFO/CARD 15

New Waves In Oscillator Design

By James N. MacDonald

It starts with an amplifying device, usually a semiconductor. Part of the current is tapped from the amplifier output and fed back into the input. This feedback current is passed through a circuit designed to be resonant at a specific frequency. The resonant frequency within the band of frequencies in that current is again boosted by the amplifier and the process is repeated. If the amplifier provides sufficient gain and the current remains in phase, the circuit oscillates continuously at that frequency. This is the common oscillator circuit.

There are three types of oscillator circuits in general use by RF engineers, and nearly all receiving and transmitting systems as well as many other devices use one or more of each type. The types are based on inductor-capacitor (LC) circuits, crystals and surface acoustic wave resonators (SAWs). All types are widely used and new designs are being developed regularly from each type.

When first developed each type of circuit represented a new wave in oscillator design. The next new wave, described later in this report, will probably combine microprocessors with analog oscillator circuits. Between these major developments improvements have tended to involve better manufacturing methods, resulting in smaller and more stable devices to meet increasingly rigorous military and commercial requirements. Engineering design improvements have made the better manufacturing methods possible.

This report will discuss some of the latest developments in oscillators designed to operate primarily in the lower RF frequencies (through UHF). The distinction is difficult to make since design and manufacturing improvements are steadily extending the operating ranges of crystal and SAW oscillators. In general, we will not discuss atomic standards and oscillators designed to operate primarily above 2 GHz.

LC Circuits

The LC circuit is the first oscillator circuit learned by an RF designer. A coil and a capacitor connected in an AC circuit will resonate at a certain frequency determined by the reactance of each component. The resonant frequency is reinforced by the coil and capacitor, while other frequencies meet impedance. It is a simple circuit and relatively easy to

design. The many improvements that have been made in this type of oscillator have depended mostly on the creativity of circuit designers. The LC circuit, sometimes called the tank circuit, can be used at any frequency, but in and above the UHF frequency range the electrical characteristics of inductors and capacitors begin to change and circuit design becomes more complex. At higher frequencies discrete components are replaced by thin-film deposited on small circuit boards or by cavity resonators.

The LC circuit with discrete coils and capacitors often is the only practical oscillator for low-priced, low frequency equipment where size is not a major consideration. A problem with this circuit is frequency instability in environments of wide temperature variation and physical shock. However, the LC circuit is still the choice of many RF designers in applications where these disadvantages are not significant or can be compensated for.

Quartz Crystals

For many years the quartz crystal oscillator has been the workhorse of the industry. A piece of quartz crystal will vibrate when AC voltage is applied across it. The frequency of vibration depends on the dimensions of the crystal piece, a slice from a naturally formed crystal. Current alternating at the natural vibrating frequency of the crystal will be in resonance with the crystal. The crystal functions like an LC circuit in a single element.

Held between metal electrodes the quartz crystal acts like a capacitor. It has very high Q and, consequently, good frequency selectivity.

Quartz crystal oscillators are also highly stable, holding on frequency under physical shock that might change the resonating frequency of an LC circuit. However, the resonant frequency of a crystal changes as its temperature changes. Since electronic equipment often is subjected to wide temperature variations, this tendency must be compensated for.

Frequency-temperature changes can be reduced by controlling the oscillator temperature, varying oscillator tuning voltage or using a phase lock loop. The PLL has been discussed in several previous articles, so it will not be discussed here. Oscillator temperature can be controlled by containing the oscillator in an "oven," a metal chamber kept at a con-

stant temperature. Tuning voltage can be varied by a thermistor network reacting to oscillator temperature changes.

This issue's cover features Motorola's new line of temperature-controlled crystal oscillators. As the latest addition to their line of hermetically sealed oscillators, the MDO-3 offers ± 5 ppm frequency stability over a -30 to $+70^\circ$ temperature range, company officials say. This stability is said to be inclusive of variations in temperature, voltage, load and humidity. Measuring 0.82 in. x 0.52 in. x 0.32 in. with DIP compatible pin out, this oscillator is said to be ideal for those applications in which low cost and small size are required. Motorola claims aging rates for this oscillator of ± 1 pp.m

The MDO-3 operates from a 5 volt power supply over a frequency range of 10 to 20 MHz. It uses the AT-Strip crystal to achieve reductions in size and improvements in mechanical shock survivability over previously offered designs. The all-metal welded package provides a full hermetic seal which minimizes RF radiation while keeping the oscillator on frequency in environmental extremes of temperature and humidity.

The MDO-3 can be adjusted through the use of an external potentiometer, or it can be electronically tuned, providing AFC capability. Motorola says the automated manufacturing, proprietary thick film hybrid design and use of the AT-Strip quartz crystals have resulted in reduced parts count for cost savings with improved field reliability.

These are the kinds of improvements crystal oscillator manufacturers are making.

Often the designer wants the oscillator circuit frequency to be variable. This can be done by changing the capacitance of the circuit, either mechanically, with a variable capacitor, or electronically, with a varactor.

At the higher frequencies the crystal is so small and thin it is subject to breakage from its own vibrations. To avoid this problem crystal manufacturers obtain higher frequencies from a harmonic overtone of a crystal that resonates at a lower frequency. A frequency multiplier is used to select and amplify this harmonic overtone.

An analysis of new products recently announced shows that crystal oscillator manufacturers generally are striving for high stability, low power consumption,

small size and fast warm-up.

Greenray Industries' new digitally compensated crystal oscillator is said to offer frequency-temperature stabilities approaching those of ovenized oscillators while consuming only a small fraction of the input power required to operate an oven. The advantage, Greenray says, is that the oscillator is on frequency instantly, eliminating the wait for an oven to stabilize.

The angle at which a slice is cut from a crystal is one of the factors determining its frequency-temperature stability, and many different cuts are used. CTS Corp., Knights Division, says their relatively new doubly-rotated S-C cut crystal resonator provides fast warm-up and excellent temperature and long-term stability in an ovenized oscillator. They say their TCXO design can consistently be produced to less than $\pm 4 \times 10^{-7}$ over a -55 to $+85^\circ$ temperature range for the life of the oscillator, even after the center frequency has been adjusted to account for aging.

As a custom manufacturer, CTS/Knights reports receiving more than a few inquiries for such devices as:

A small, low power, fast warm-up ovenized oscillator that can withstand the severe environments encountered in tactical jet fighters;

An oscillator packaged and mounted to permit mechanical shock operation of 3000 Gs;

A synthesized multiple-output device using monolithic VCOs to lock to a stable ovenized reference;

A leadless chip-carrier crystal oscillator — a complete quartz crystal oscillator in a ceramic chip carrier package.

CTS/Knights considers the requirements described above to be among the factors determining the future of the quartz crystal oscillator market.

Seiko Instruments has developed a series of oscillators using a GT-cut crystal, which company officials say provides good frequency-temperature characteristics. Seiko says it has developed a photolithographic fabrication process that permits the high-accuracy dimensioning required to mass produce the GT-cut.

Wenzel Associates has developed a small, low power ovenized oscillator they call the Small Fry. Officials say the Small Fry uses a 3rd overtone crystal which provides aging of 5×10^{-10} per day, with close in phase noise that can be specified to -135 dB at 10 Hz for 10 MHz oscillators. They attribute the performance to a tiny vacuum flask that insulates the oven and provides a five-fold improvement in thermal conductance over conventional foam and to a low flicker crystal exciter design.

The Vari-L Company has just announced a new line of voltage controlled oscillators covering frequencies as low as 25-50 MHz. The company says the low power dissipation, less than 200 mW, helps them meet rigid military specifications of -55 to $+100^\circ$.

These are a few of the new developments announced recently. They are examples of the kinds of improvements many quartz crystal oscillator manufacturers are making in their products. Designers are urged to contact all manufacturers for information before specifying a product.

Designers specifying crystal oscillators should be familiar with a recent study by V. Rosati, S. Schodowski and R. Filler of the Electronics Technology & Devices Laboratory, Fort Monmouth, New Jersey. Oscillator vendors were asked to identify two temperature-compensated crystal oscillators for testing, one to meet certain specifications and the other to be their best available TCXO. A total of 105 oscillators were tested for frequency-voltage, frequency-load, frequency-temperature and aging. The researchers asked for moderate (5.0 ppm) or high (0.5 ppm) stability oscillators.

Oscillators in the 1-5 ppm stability range were found to conform to manufacturers' specifications, but long-term aging characteristics were widely variable. A significant percentage of those between 0.5 ppm and 1 ppm were found to be out of specification. No correlation between price and performance was found. The researchers concluded that system designers should carefully specify and test TCXOs before designing them into systems and supporting data should be requested for each oscillator being considered in the 0.5 ppm class.

Reporting the study results, the laboratory's Frequency Control branch chief, J.R. Vig, said "historically the accuracy of quartz oscillators has improved by an order of magnitude approximately every seven to 10 years." He said he expects the rate of improvement to continue.¹

Vig said he expects revolutionary improvements in TCXOs from the use of microcomputers and "dual-mode" techniques. He said a dual-mode device measures crystal temperature without using an external sensor. The temperature-frequency profile of a crystal is stored in a dedicated microcomputer chip that controls compensation as a function of crystal temperature. Vig predicted frequency-temperature stability of 5×10^{-9} by 1990, with designs that are one-third smaller and use one-third as much power as current TCXOs.

SAW Devices

At frequencies above 100 MHz Surface Acoustic Wave (SAW) devices have a cost and a size advantage over quartz crystal oscillators, which need frequency multipliers, and a frequency stability advantage over LC circuit oscillators.

A typical SAW resonator consists of thin metal strips laid or deposited on a thin substrate, usually of quartz or lithium niobate. High frequency AC voltage across the strips creates surface waves along the face of the crystal. Because of the piezoelectric effect of the crystal the surface waves are detected by other strips on its surface. The principal feature of the SAW resonator is that the surface waves travel many times slower than the electromagnetic waves causing them. This frequency reduction feature allows SAW resonators to handle frequencies up to 1 GHz. Because they can work directly in higher frequencies, SAW oscillators avoid non-harmonic spurious outputs that are a problem with crystals and frequency multipliers.

SAW devices can be designed with taps at any point for multiple use of the oscillating signal. They are often used in hybrid modules and components because they are so small.

The major problems with SAW devices are frequency drift as the crystal substrate ages and contaminants introduced in the manufacturing process. Aging can be compensated for as quartz crystal resonator aging is compensated for. The amount of contamination depends on the care taken when the SAW device is made. SAW devices must be hermetically encased. Water vapor condensing on the surface of the substrate could slow the surface wave and might mix with contaminants to form acids that could etch the surface, changing its wave propagation characteristics.

Trends in SAW oscillator design are toward higher frequencies and better temperature stability. The higher frequencies (mass production above 400 MHz) are aimed at the cellular radio and microwave link markets. Better temperature stability will probably be achieved by using different materials.

Andersen Laboratories uses a SAW delay line as the frequency controlling element in their standard hybrid oscillator. They say their oscillators are capable of operating at fundamental frequencies in the VHF and UHF ranges and beyond, reducing the need for frequency multipliers and post multiplier filtering. The oscillator signal is coupled out of the loop by a power divider and further isolated from the load by the output amplifier, which minimizes load pulling.

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Avantek, Inc., is working on development of integrated subassemblies at the substrate level, combining thin-film oscillators, switches and monolithic amplifiers into an oscillating unit that can be tuned over several octaves. They expect to be in production by the end of the year.

Only a few of the many reputable oscillator manufacturers have been mentioned in this report. It was not our intention to present a complete report on all available manufacturers or devices. Such a report would be incomplete the day it was published because new designs or improved devices are being announced almost weekly. Only by reading new product announcements and literature from manufacturers can the designer keep well informed.

Designers may obtain specific information about currently manufactured oscillators by circling the following Info/Card numbers.

Crystal Oscillators

- Austron — Info/Card #130
- Aydin Vector — Info/Card #129
- Bliley Electric — Info/Card #128
- Cinox — Info/Card #127
- CTS/Knights Div. — Info/Card #126
- Dale Electronics — Info/Card #125
- Frequency Control Products — Info/Card #124
- Frequency Sources — Info/Card #123
- Greenray Industries — Info/Card #122
- Hewlett-Packard — Info/Card #121
- K&L Quartztek — Info/Card #120
- McCoy Electronics — Info/Card #119
- Merrimac Industries — Info/Card #118
- Microsonics — Info/Card #117
- Motorola, Inc. — Info/Card #116
- Piezo Crystal — Info/Card #115
- Piezo Technology — Info/Card #114
- Seiko — Info/Card #113
- Signetics — Info/Card #112
- Sokol — Info/Card #111
- Vectron Laboratories — Info/Card #110
- Wenzel — Info/Card #109

SAW and Other Types

- Alpha Industries — Info/Card #108
- Andersen Laboratories — Info/Card #107
- Avantek — Info/Card #106
- Crystal Technology — Info/Card #105
- Phonon — Info/Card #104
- RF Monolithics — Info/Card #103
- Sawtek — Info/Card #102
- Teledyne — Info/Card #101

Footnotes

1. Phillip J. Klass, "Advances Forecast in Crystal Oscillators," Aviation Week and Space Technology, Nov. 28, 1983, pp 148-149.



March 1985



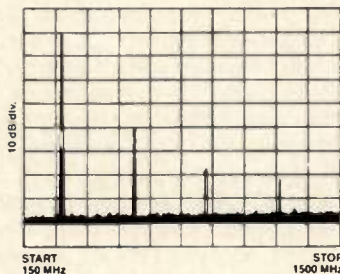
SAW Oscillators

Sawtek's Surface Acoustic Wave oscillators for military and commercial applications simplify design and improve noise performance. High-Q SAW resonators offer quartz stability at fundamental frequencies from 100 MHz to 1250 MHz. Hybrid oscillators in hermetic packages are available for reduced size and increased reliability. FM or pulse code modulation capability is optional.

Sawtek maintains a large selection of frequencies from an inventory of pre-tooled resonator crystals and new designs can be tooled rapidly. Our engineers also offer assistance in oscillator design for specific applications and are prepared to help evaluate the

suitability of SAW oscillators for your requirements.

In addition to oscillators and resonator products, Sawtek produces other high performance SAW components including bandpass filters, delay lines, and pulse compressors for cable television, satellite communications, modems, radar, EW, and many other signal processing applications. And, if what you need is not among our hundreds of standard products, we can provide technical assistance and rapid response to new design and production requirements. Quality and performance have made Sawtek the industry leader in SAW technology; you can rely on us for the total engineering support you need.



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INFO/CARD 17

Controlling Radiated EMI From Digital Systems

By W. Scott Bennett
Hewlett-Packard Company
Ft. Collins, Colo.

Radiated electromagnetic interference (EMI) from digital systems results from the poor design — or lack of design — of current-path geometries in digital systems. In digital circuits, if the path followed by each return current is not effectively the same as the path followed by its associated forward current and the current has RF Fourier components, unacceptable levels of radiated EMI will almost certainly result. This can be predicted from the expressions for the electric and magnetic fields of a small loop antenna⁽¹⁾, both of which are directly proportional to the area bounded by the loop. Current loops in a digital system are not all necessarily "small;" however, the fields of any large current loop can be equivalently represented as the superposition of the fields from a number of smaller current loops having the same perimeter as the large loop. Thus, to effectively control radiated EMI from digital systems one must effectively reduce the areas bounded by the current loops in such systems.

A coaxial cable, for example, can make the effective area enclosed by its current loop equal to zero. At every point external to the cable there are two components which make up the electric field and two components which make up the magnetic field. In each case, one component is due to the (forward) current in the inner conductor and one component is due to the (return) current in the outer conductor. However, because the conductors are coaxial the field components result from currents which are coaxial as well. The forward and return currents appear to be following the same path but they are oppositely directed. If, at each point on the path the currents are equal and oppositely directed, at each point outside the cable the net fields due to the currents are zero.

A simple method for reducing current loop areas on a printed circuit (PC) board is to make one full layer of the board a

ground plane. Return currents will then tend to follow the same paths in the ground plane as their associated forward currents follow in adjacent layers. The distance between each forward current path and its return current path will then be the distance between the layer of the forward current trace and the layer of the ground plane. Thus, all current loop areas on the board will tend toward zero and radiated EMI due to those loop areas will tend toward zero as well. This same technique can be applied to flat multi-conductor cables which connect one PC board to another.

To obtain a quantitative understanding of the importance of minimizing current loop areas, consider the following equation:

$$A = 58.9 \frac{E_d}{f^2}$$

in which A represents current loop area in square inches, E represents electric field strength in microvolts/meter, d represents distance from the loop in meters, f represents the frequency of a current component in Megahertz and I represents the amplitude of a current component in milliamperes. This equation was derived from the expression for the maximum electric field of a small current loop, assuming the loop is positioned over a large conductive ground plane. It provides a good worst-case approximation of the electric field that would be observed from such a loop when measured according to FCC specifications⁽²⁾.

Now, suppose one wishes to know the loop areas which are associated with the FCC Class A and Class B radiated EMI limits for digital devices at 200 MHz. At that frequency the Class A limit is an electric field strength of 50 $\mu\text{V/m}$ measured over a ground plane at a distance of 30 meters and the Class B limit is an electric field strength of 150 $\mu\text{V/m}$ measured over a ground plane at a distance of 3

meters⁽²⁾, (3). From the above equation, the loop area associated with the Class A limit for a 1 mA current component at 200 MHz is 2.2 in² and the loop area associated with the Class B limit for the same current and frequency is 0.66 in². It should be clear from the small sizes of these areas that current loop areas *must* be minimized by digital designers if the FCC regulations are to be met.

Finally, since the current loop areas associated with the FCC radiated EMI limits for digital systems are so small, it should be clear that long cables between major components of digital systems must be designed very carefully. For example, any common mode currents measured on a multiconductor cable of more than a few inches in length will more than likely be a problem because the associated return current paths must lie elsewhere. Although current components in I/O cables, for example, are generally lower in frequency than current components on PC boards, current loop areas established by I/O cables are generally much larger than those of PC boards because the cables are generally long and the PC boards are relatively small. Thus, from long intrasystem cables one generally has radiated EMI problems at frequencies lower than those of PC board radiation.

In summary, the importance of RF current-path geometries cannot be overlooked if one is to design marketable digital systems.

1. J.D. Kraus, *Antennas*. New York: McGraw-Hill, 1950, p.157.
2. U.S. Federal Communications Commission, "Methods of measurement of radio noise emissions from computing devices," in *Rules and Regulations*, pt. 5, subpt. J. Appendix A, pp. 163-171, July, 1981.
3. R.K. Keenan, *Digital Design for Interference Specifications*. Vienna, VA.: The Keenan Corp., 1983, p. A1-5.

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SAS-200-510	300 - 1800 MHz	Log Periodic	SAS-200-542	20 - 300 MHz	Biconical, Folding
SAS-200-511	1000 - 12000 MHz	Log Periodic	SAS-200-550	.001 - 60 MHz	Active Monopole
SAS-200-512	200 - 1800 MHz	Log Periodic	SAS-200-560	per MIL-STD-461	Loop - Emission
SAS-200-518	1000 - 18000 MHz	Log Periodic	SAS-200-561	per MIL-STD-461	Loop - Radiating
SAS-200-530	150 - 550 MHz	Broadband Dipole	BCP-200-510	20 Hz - 1 MHz	LF Current Probe
SAS-200-540	20 - 300 MHz	Biconical	BCP-200-511	100 KHz-100 MHz	HF VHF Crnt. Probe
SAS-200-541	20 - 300 MHz	Bicon I Collapsible			

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The SAW Resonator Filter: How It Works. Part II

By Jeff Schoenwald
Contributing Editor

Last month, SAW resonator theory and a program for the TI-59 calculator and printer were described. This month, we use the program to learn about SAW resonators. Of special value is the definition and order of parameter entry.

Unless otherwise indicated, certain initial parameters that must be entered will always be the same:

$$\begin{aligned} l_1 &= l_2 = 0.25 \\ n_2 &= 1 \\ f_0 &= 100 \end{aligned}$$

As a first example, consider the characteristics of a single reflector array as a function of changing strip/gap impedance ratio Z at a fixed number of segments $N = 200$. Figures 1a and 1b show the reflection loss and transmission power loss respectively for $Z = 1.005$, 1.01 and 1.015. At frequencies above or below f_c the reflectors are transparent to traveling waves, so the transmission loss is small and the reflected wave loss is quite large. Closer to center frequency, the reflection efficiency of the gratings improves and the transmission loss increases relative to the impedance mismatch Z or number of segments in the array.

In the next example, shown in Figure 2, two reflectors are cascaded. $Z = 1.01$, $N = 100$ in each reflector, and the cavity is 5 wavelengths long (i.e., $l_g = 4.75$). Away from the center frequency, the results are similar to that of the previous examples. Near center frequency, the Fabry Perot cavity becomes resonant and the structure is "transparent," and at f_c the reflected energy is negligible.

While we have assumed no losses due to absorption in the transmission line, we

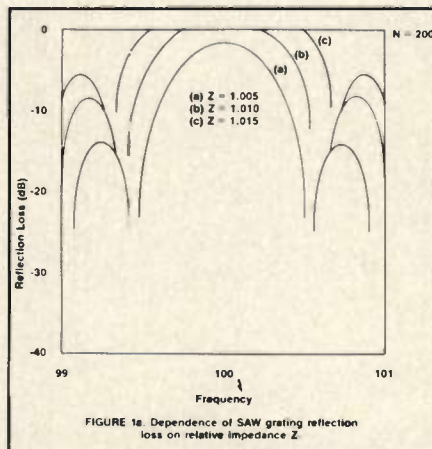


FIGURE 1a. Dependence of SAW grating reflection loss on relative impedance Z .

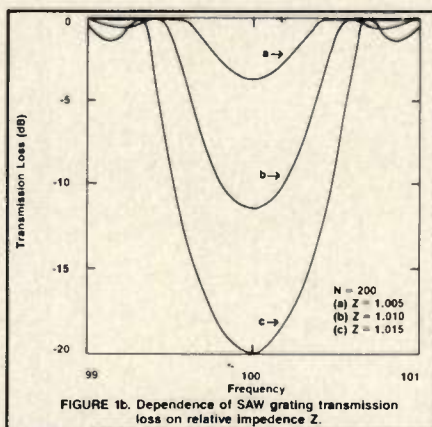


FIGURE 1b. Dependence of SAW grating transmission loss on relative impedance Z .

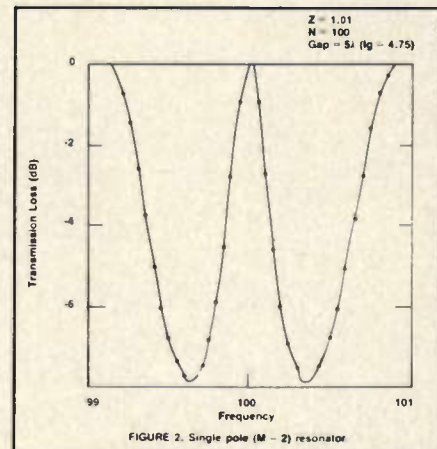


FIGURE 2. Single pole ($M = 2$) resonator

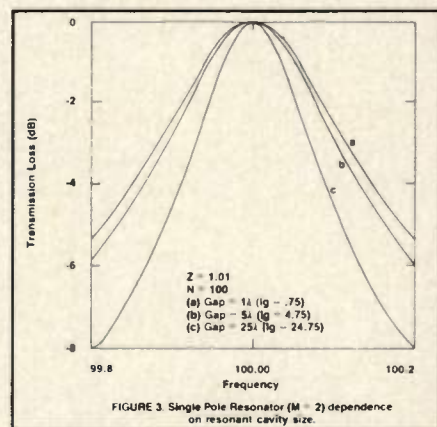


FIGURE 3. Single Pole Resonator ($M = 2$) dependence on resonant cavity size.

will still never obtain an infinite Q factor in a lossless device because a reflective array can never be 100% efficient unless Z or N go to infinity. What we do observe is a resonant peak at the center frequency with the 3 dB fractional bandwidth that determines the unloaded Q ($= f_c \Delta f_{3\text{ dB}}$) of the resonator. Figure 3 shows the

power transmission characteristics near $f_0 = f_c$ for a single cavity resonator ($M = 2$), with 100 sections/reflector, $Z = 1.01$, with the cavity size as the variable. It is apparent that the 3 dB bandwidth of the resonance decreases and Q increases as the cavity length increases. Figure 4 shows how the Q varies with

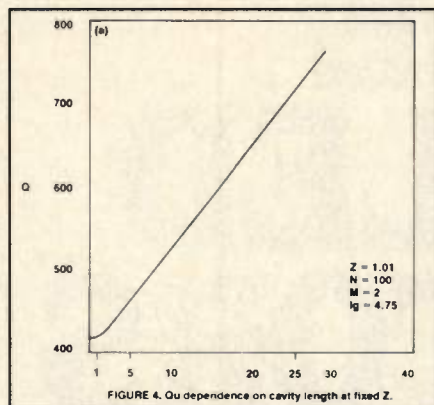


FIGURE 4. Q_u dependence on cavity length at fixed Z.

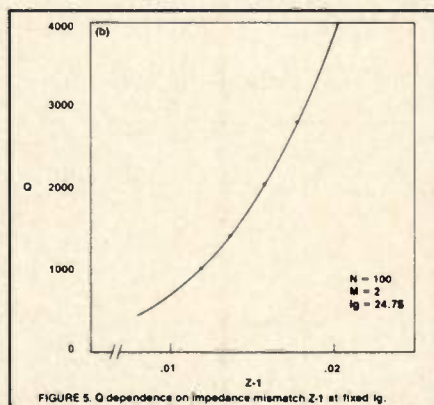


FIGURE 5. Q dependence on impedance mismatch Z-1 at fixed lg.

cavity length while N and Z are held constant. Similar sets of curves can be obtained to determine the dependence of Q or N or Z, which I encourage you to do. Figure 5 shows how Q varies with Z at fixed cavity size.

Cavity Dimension Is Critical

The resonant Fabry-Perot cavity formed by the two reflective arrays will act as an interference filter that efficiently transmits energy at wavelengths which satisfy the cavity relationship:

$$L = \frac{n\lambda_c}{2} \quad (1)$$

where $L = (l_1 + l_g) \cdot \lambda_c$. λ_c is the normalized wavelength at the peak of reflectivity of the grating. If the wavelength is different from λ_c , narrow band transmission through the structure will not occur at the center of the reflection stop-band of the grating. Another way of saying this is, if we let $L = l_1 + l_g$ be equal to some non-integer multiple of $\lambda_c/2$, the transmission spectrum appears non-symmetric. Figure 6 illustrates the effect of advancing the cavity dimension successively by $\lambda_c/8$. If resonance is not precisely

centered at the stop band center of the reflectors the Q, selectivity and efficiency of the resonator suffer.

Another interesting case is worth mentioning before we move on to more complicated structures. If we obey the Fabry-Perot condition of Eq. (1), but make n very large, we encounter a regime in which several longitudinal modes of the cavity can exist, all at slightly different wavelengths (frequencies). This is precisely the case for lasers. A simple laser with two mirrors will have many possible longitudinal cavity modes because the cavity is orders of magnitude larger than wavelength. Special techniques are used to lock the laser into a single mode for added spectral purity. Figure 7 shows some examples of multiple resonances due to oversized cavities.

Designing Multi-Pole Filters

The program is capable of synthesizing device designs that exhibit the essential features of multi-pole SAW resonator filtering behavior. There is no limit to the number of poles one may wish to model, nor does this affect the speed at which the frequency response is synthesized. A design consisting of M grating reflectors will result in an M-1 cavity structure with an M-1 pole response. This assumes, of course that the cavities are kept small enough to avoid more than a single longitudinal mode in each one. The resonances in each cavity will begin to couple and we shall begin to see how this coupling through the grating reflectors that separate each cavity give rise to the very narrow bandpass filtering which has made the SAW resonator popular in the RF and signal processing community.

With this program, all cavities will be the same size and all reflectors will have the same number of strip/gap segments for any one example run. How much can you expect from the TI-59? *C'est la vie*. We will, however, squeeze a bit more out of it.

Figures 8a, b, c and d show the transmission characteristics of 1-, 2-, 3-, and 4-pole resonators. All reflectors have 200 sections, with $Z = 1.01$, and all cavities are $5\lambda_c$ long (i.e., $l_g = 4.75$). The valleys between resonant peaks are very characteristic of the SAW resonator multi-pole filter. Typically, interdigital transducers (idts) are placed within the two outermost cavities of such a structure. This has the property of enhancing the resonance behavior over the broadband response of the idts, since by themselves they have an insertion loss that is often 20 or 30 dB,

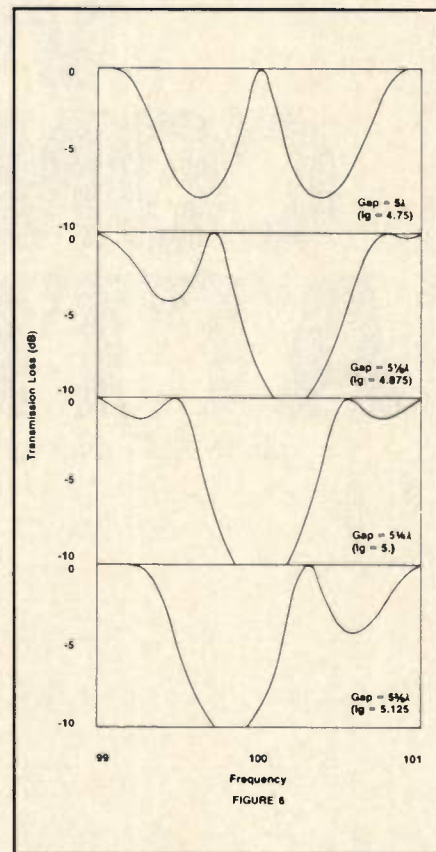


FIGURE 6

whereas the resonances are much stronger because the device impedance drops markedly at those frequencies. Before the idt is properly matched electrically, the resonator response is essentially that of the "unloaded" device and is quite well reproduced by the TI-59 program model. Impedance matching the electrical equivalent circuit of the idt to the cavity impedance will flatten the transmission response over the multipole pass-band.

The Phase of the Reflected and Transmitted Waves

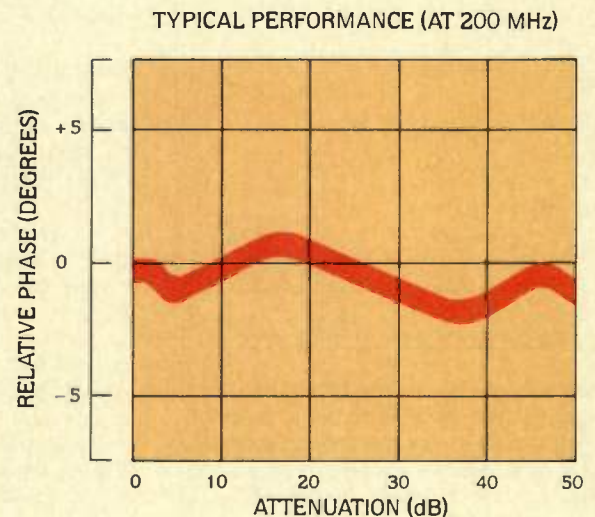
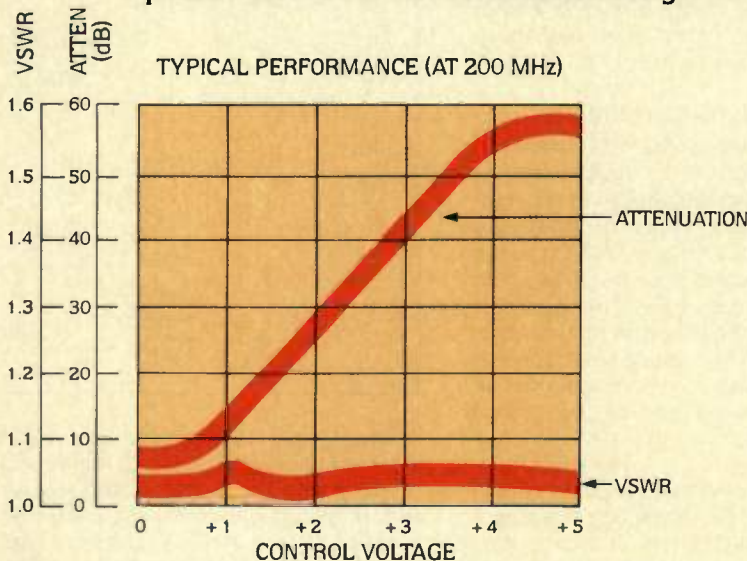
Once the transmission matrix for the entire structure has been calculated, we may easily determine the phase of the reflected and transmitted wave from the transmission factor and reflection factor, T_F and R_F , using equations 2a and 2b.

$$\Phi(\text{refl}) = \arctan \frac{\text{Imag}(R_F)}{\text{Real}(R_F)} \quad (2a)$$

$$\Phi(\text{trans}) = \arctan \frac{\text{Imag}(T_F)}{\text{Real}(T_F)} \quad (2b)$$

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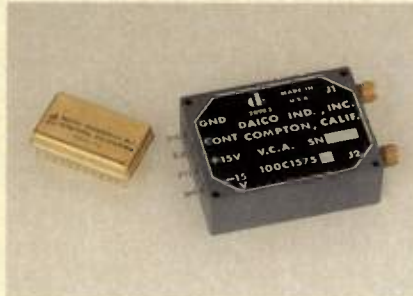
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insertion loss	4 dB max
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control	0 to +5 volts
RF power	+ 15 dBm max
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impedance	50 ohms
size	1.5 x 2.0 x .6 in
connectors	SMA
part number	100C1575



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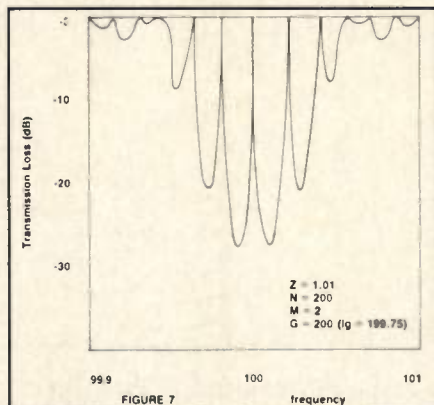


FIGURE 7

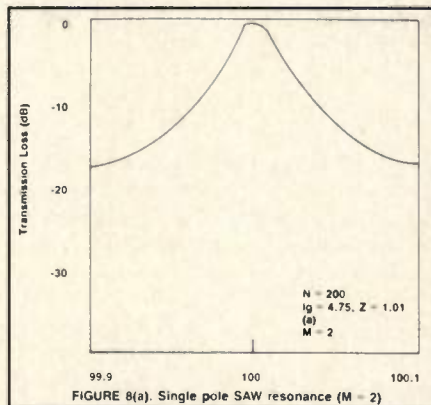


FIGURE 8(a). Single pole SAW resonance (M = 2)

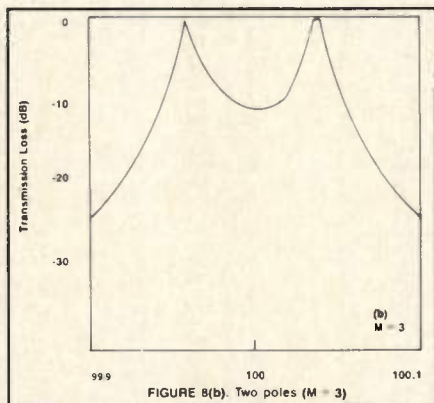


FIGURE 8(b). Two poles (M = 3)

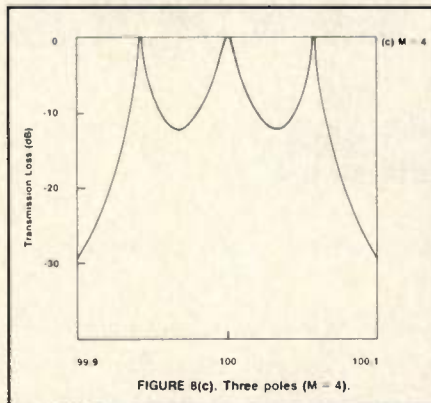


FIGURE 8(c). Three poles (M = 4).

In order to implement this calculation, the listing shown in Table I may be substituted for the last portion of the program, starting at step 638. This may be stored in a simple way. Since the calculator is partitioned for 720 steps, the entire program can be stored in three data banks. The modification occurs only in bank 3. The modified version can be stored on the second edge of the second card (normally used for bank 4). Be sure the calculator is in floating point mode (exit the learn mode and press INV 2nd FIX). Press 3 2nd WRITE but feed in the second magnetic card upside down. Later, when loading the program for phase analysis, the calculator will recognize this as a bank 3 read.

Using this method, power magnitude calculations can be done first, then the third bank replaced with phase calculation, the input parameters re-entered and the calculation repeated, yielding the phase response. Not all registers containing the input parameters are re-used. Look at Table II to determine at which label you must re-enter data. Practically speaking, however, it is easier and safer to re-enter all the data from scratch.

Figures 9 and 10 are examples of the phase response for a single pole resonator. They have identical structures but different values of Z . Rather than short-change the phase computational ability of this program, I will spend a few moments to explain some of the things you can learn from it about SAW resonators. For a plane wave incident on a reflecting surface, the general form of the reflected wave, relative to an incident wave of unit amplitude and zero phase at the front of the reflector, is

$$R_r = re^{2ik \cdot D} \quad (3)$$

where r is the coefficient of reflection magnitude and D is the distance from the point at which the observation is made to the plane of the reflecting surface. If we imagine that the observation point is the front edge of the distributed grating reflector and D is the distance to a fictitious point at which we may assume a single reflecting mirror is placed, then we are constructing a simple model that represents the distance to the "effective center of reflection."

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The phase of the reflected wave is given by the argument of the exponential. If we take the first derivative of this phase with respect to the frequency and convert from radians to degrees, we obtain

$$\Phi_{\text{rad}} = 2 \frac{2\pi}{\lambda} D = \frac{4\pi D f}{v}$$

$$\frac{d\Phi_{\text{rad}}}{df} = 4\pi \frac{D}{v} = \frac{4\pi D}{f\lambda} \quad (4)$$

Therefore,

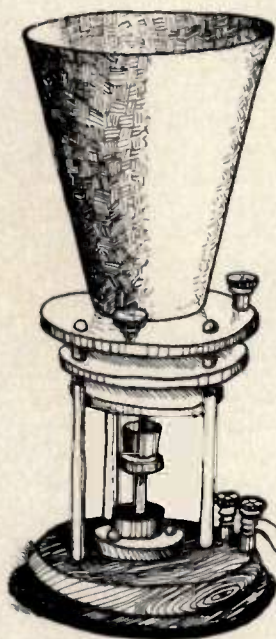
$$D = \frac{\lambda f}{4\pi} \cdot \frac{d\Phi}{df} = \frac{\lambda f}{4\pi} \frac{\pi}{180} \frac{d\Phi_{\text{deg}}}{df}$$

$$\frac{D}{\lambda} = \frac{f}{720} \frac{\Delta\Phi}{\Delta} \quad (5)$$

Thus, by measuring the slope of phase data we obtain for the reflected wave we are able to compute the distance to the

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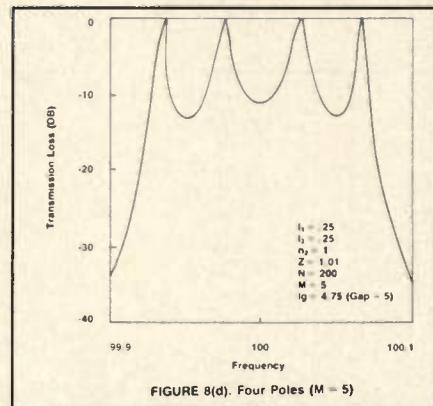


FIGURE 8(d). Four Poles (M = 5)

TABLE I Phase Calculation

638	60	DEG	678	53	(
639	53		679	43	RCL
640	02	2	680	06	06
641	65	x	681	85	+
642	53		682	43	RCL
643	43	RCL	683	07	07
644	08	08	684	54)
645	65	x	685	55	+
646	43	RCL	686	53	(
647	06	06	687	43	RCL
648	75	-	688	05	05
649	43	RCL	689	85	+
650	05	05	690	43	RCL
651	65	x	691	08	08
652	43	RCL	692	54)
653	07	07	693	94	+/-
654	54)	694	22	INV
655	55	+	695	30	TAN
656	53		696	95	=
657	43	RCL	697	99	PRT
658	05	05	698	98	ADV
659	33	x²	699	43	RCL
660	85	+	700	13	13
661	43	RCL	701	32	X-T
662	06	06	702	43	RCL
663	33	x²	703	26	26
664	75	-	704	67	EQ
665	43	RCL	705	19	D'
666	07	07	706	43	RCL
667	33	x²	707	29	29
668	75	-	708	42	STO
669	43	RCL	709	11	11
670	08	08	710	61	GTO
671	33	x²	711	14	D
672	54)	712	76	LBL
673	54		713	19	D'
674	22	INV	714	43	RCL
675	30	TAN	715	26	26
676	95	=	716	91	R/S
677	99	PRT			

"effective center of reflection." At the peak in reflectivity the center of reflection appears to move toward the front of the reflective array, as evidenced by a decrease in the magnitude of the phase slope. Away from resonance, where the array ultimately looks transparent, the center of reflection moves to the geometric center of the array.

For the cases shown in Figures 10a and 10b, the reflection centers are located, at resonance, a distance of 22 and 17 wavelengths, respectively, inside the array, as viewed from the direction of incidence. Now consider two identical reflectors separated by a distance necessary to produce a single pole resonance. The total length of the cavity is then given by

$$L = (l_g + 1/4) \cdot c + 2D \quad (6)$$

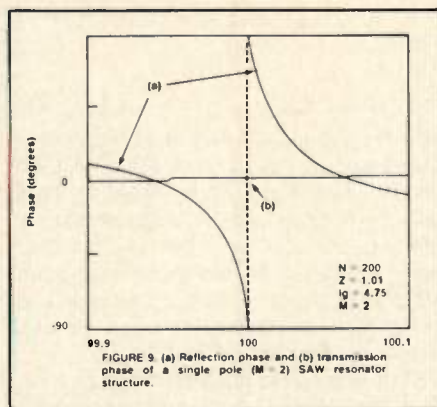


FIGURE 9 (a) Reflection phase and (b) transmission phase of a single pole ($M=2$) SAW resonator structure.

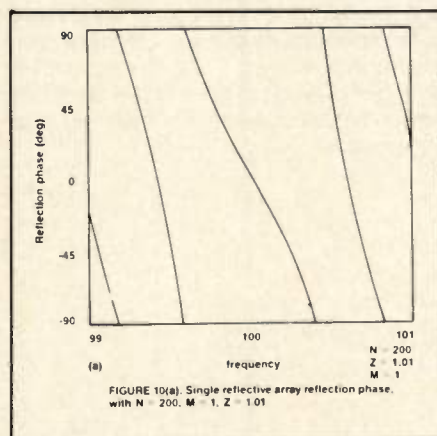


FIGURE 10(a). Single reflective array reflection phase, with $N=200$, $M=1$, $Z=1.01$.

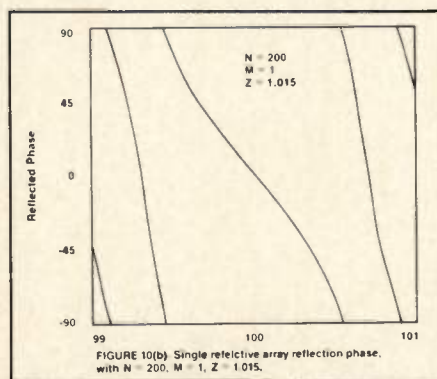


FIGURE 10(b). Single reflective array reflection phase, with $N=200$, $M=1$, $Z=1.015$.

Knowing the value of D is important for determining the frequency spacing between longitudinal modes in the resonant cavity formed by the two arrays. Now we can see that mode spacing is a function of both cavity size and reflective properties of the array, as represented by the distance D . It is possible to derive frequency spacing dependence on effective length of the cavity L , and such derivations abound in books on lasers. The reader is encouraged to do this for the specific case shown in Figure 7. You will indeed find that the mode spacing observed in large SAW resonator cavities,

or in SAW resonators with Z so close to unity that D is sizable, is properly described by taking this reflection distance into account properly. More than once, ignorance of this fact has bitten SAW resonator designers when they least expected it.

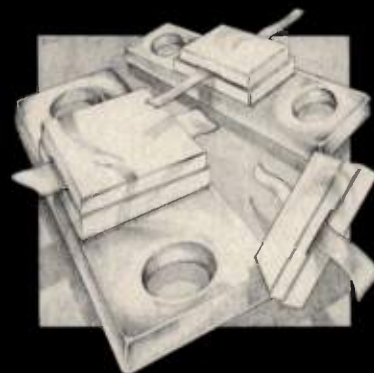
Conclusion

I have tried to give the reader a tool for modeling and exploring the behavior of the SAW resonator, a very interesting tool in RF technology. Even if you have no plans for designing such devices you may very likely wish to specify one from a number of vendors that supply them. In that case, you will be better off for having become familiar with the properties of these devices and being an educated customer.

TABLE II

Register	Variable
0	$N, N-1, M, M-1$
1	λ_1, λ_2
2	M
3	lg
4	$\Theta, \lambda_1 \uparrow N, \lambda_3 \uparrow N$
5	$I_1, A(N), A(N+9)$
6	$I_2, B(N), B(N+9)$
7	$n_2, C(N), C(N+9)$
8	$f_0, D(N), D(N+9)$
9	fc
10	Z
11	N
12	$t, \cos \Theta = (A + D)/2$
13	f_1
14	df
15	$\alpha = \pi \cdot f_1/f_c$
16	$Z + 1$
17	$Z - 1$
18	$1 - 2t$
19	$A(1), A(N)$
20	$B(1), B(N)$
21	$C(1), C(N)$
22	$D(1), D(N)$
23	$[(A + D)/2]^{1/2} - 1$
24	λ_1
25	λ_2
26	$f_2 + df$
27	$\sin N\Theta$ or $(\lambda_1 \uparrow N - \lambda_2 \uparrow N)/(\lambda_1 - \lambda_2)$
28	$\sin (N-1)\Theta$ or $(\lambda_1 \uparrow (n-1) - \lambda_2 \uparrow (n-1))/(\lambda_1 - \lambda_2)$
29	N

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BONUS!:
A *BASIC* Version

For readers who own or work with a computer, here is a BASIC version of the TI-59 calculator program to model the transmission and reflection power and phase of a SAW resonator type of structure. This program was written on a Commodore 64, which uses a version of BASIC and an ASCII character set that is slightly different from standard ones. I have taken pains to write the program to be as transportable as possible, indicating, when necessary, what lines are not transportable and require change or deletion. The POKes only pertain to screen or letter color. There are no PEEKs. The printer commands are usable "as is" only on Commodore printers and serve as an example which must be tailored for other brands.

Because memory is not as tight for most micros, power and phase are computed and provisions are made for screen display and hard copy. Disk or tape storage of data files and high resolution plotting are routines that the devoted hacker should add, but these have been left out because of differences between computers in storage procedures and screen addressing.

Data entry is simple and screen prompted. If the velocity in a strip segment is different from the gap velocity the center frequency will be different from the designated reference frequency. I suggest you start with a ratio of 1 and then try small changes to observe the trend. The same advice holds for the impedance ratio and cavity size.

```

10 REM *****
20 REM * CERTAIN LINES ARE *
30 REM * SPECIFIC TO THE *
40 REM * COMMODORE 64. *
50 REM * DELETE OR ALTER AS DESIRED. *
60 REM *****
70 PI = 3.14159265 REM * C-64 RECOGNIZES SYMBOL FOR PI. USE IT IF YOU CAN. *
80 POKE 53281,0:POKE 53280,0:REM *SET BACKGROUND TO BLACK FOR C-64*
90 PRINT CHR$(145);REM *SET SCREEN LETTERS TO YELLOW ON C-64*
100 PRINT CHR$(147)
110 PRINT"SAW RESONATOR TRANSMISSION"
120 PRINT" LINE SIMULATION"
130 PRINT"
140 PRINT" *OF RIGHT JEFF SCHENWALD*
150 PRINT" 1984"
160 FOR I = 1 TO 2000
170 NEXT I
180 PRINT CHR$(147)
190 INPUT" *GAP SEGMENT LENGTH, L1*L2"
200 INPUT" *LINE SEGMENT LENGTH, L3*L4"
210 INPUT" *RELATIVE VELOCITY INDEX OF L3 AND L4"
220 INPUT" *REFERENCE FREQUENCY F0*F0
230 INPUT" *STRIP GAP IMPEDANCE RATIO, Z0/Z
240 INPUT" *OF SEGMENT PAIRS PER REFLECTOR, N*N
250 REM
260 INPUT" *START FREQUENCY, F1*F1
270 INPUT" *FREQUENCY INCREMENT, DF*DF
280 INPUT" *STOP FREQUENCY, F2*F2
290 INPUT" *OF REFLECTOR ARRAY SECTIONS, M*M
300 INPUT" *CAPACITY SIZE, LG*LG
310 F0=F0/2*(L1+L2+L3+L4)
320 PRINT CHR$(147)
330 PRINT" *CENTER FREQUENCY = *F0
340 T=LN(LG)/LN(2)
350 K1=INT (F2-F1)/DF
360 DIM AN*(K1+BN+KN),CN*(K1+DN+KN),TP*(K1+PN+KN),TF*(K1+RN+KN)
370 FOR K = 0 TO K1
380 F = F1 + DF*K
390 LET GAMMA = F1-F0
400 A1 = (Z-1)/(Z+1)*COS(GAMMA) - (Z-1)/(Z+1)*COS(GAMMA*(1-D+T))
410 B1 = (Z-1)/(Z+1)*SIN(GAMMA) - (Z-1)/(Z+1)*SIN(GAMMA*(1-D+T))
420 C1 = (Z-1)/(Z+1)*SIN(GAMMA) - (Z-1)/(Z+1)*SIN(GAMMA*(1-D+T))
430 D1 = (Z-1)/(Z+1)*COS(GAMMA) - (Z-1)/(Z+1)*COS(GAMMA*(1-D+T))
440 NB=N
450 GOSUB 600 REM *COMPUTE EIGENVALUES FOR ONE ARRAY AND COMPUTE T MATRIX*
460 GOSUB 700 REM *COMPUTE CAPACITANCE MATRIX*
470 GOSUB 1000 REM *MULTIPLY MATRICES*
480 GOSUB 1090 REM *REDEFINE NEW T MATRIX*
490 NB=M
500 GOSUB 640
510 REM
520 REM *COMPUTE EIGENVALUES AND MATRIX FOR *
530 REM *M CASCADED REFLECTORS AND CAPACITIES*
540 AN(K1)=AN
550 BN(K1)=BN
560 CN(K1)=CN
570 DN(K1)=DN
580 PRINT CHR$(147)
590 PRINT" *FREQUENCY PT. M*(K1) = *F
590 GOSUB 1160 REM *COMPUTE POWER & PHASE*
600 NEXT K:REM *NEXT FREQUENCY POINT*
610 REM *GOTO OUTPUT MENU*
620 GOTO 470
630 REM
640 REM**REAL OR COMPLEX EIGENVALUES**
650 TRIG = A1/D1/2
660 IF TRIG(2-1)=0 THEN 690
670 IF TRIG(2-1) THEN 870

```



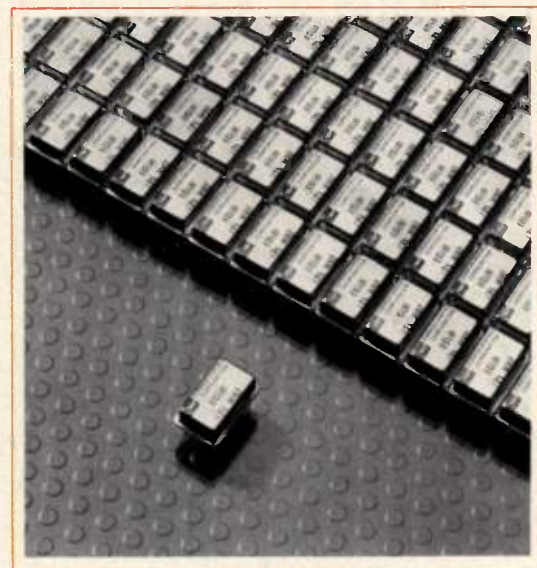
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600 RETURN
610 REM * MATRIX FOR COMPLEX EIGENVALUE READY.
620 AGL = -2*TRIG/SQR(-TRIG*TRIG+1)+PI/2
630 IF AGL=0 THEN 780
640 N1=N0-1
650 AN=A1/SIN(N0*AGL)/SIN(AGL)-SIN(N1*AGL)/SIN(AGL)
660 BN=B1/SIN(N0*AGL)/SIN(AGL)
670 CN=C1/SIN(N0*AGL)/SIN(AGL)
680 DN=D1/SIN(N0*AGL)/SIN(AGL)-SIN(N1*AGL)/SIN(AGL)
690 GOTO 720
700 GOSUB 1010
710 RETURN
800 REM * WHEN EIGENVALUES ARE *
810 REM * DEGENERATE *
820 AN=A1-1
830 BN=B1
840 CN=C1
850 DN=D1-1
860 RETURN
870 REM * MATRIX FOR REAL EIGENVALUES *
880 K1=TRIG+SQR(1-TRIG*2-1)
890 K2=1-K1
900 N1=N0-1
910 AN=A1*(K1*N0-K2*N0)/(K1-K2)-(K1*N1-K2*N1)/(K1-K2)
920 BN=B1*(K1*N0-K2*N0)/(K1-K2)
930 CN=C1*(K1*N0-K2*N0)/(K1-K2)
940 DN=D1*(K1*N0-K2*N0)/(K1-K2)-(K1*N1-K2*N1)/(K1-K2)
950 RETURN
960 REM ***GENERATE CAVITY MATRIX***
970 REM
980 A=COS(2+GAMMA*LG)
990 B=SIN(2+GAMMA*LG)
1000 C=SIN(2+GAMMA*LG)
1010 D=COS(2+GAMMA*LG)
1020 RETURN
1030 REM ***MATRIX MULTIPLICATION***
1040 AP=AN*A-BN*B
1050 BP=AN*B+BN*B
1060 CP=CN*A+DN*B
1070 DP=DN*A-CN*B
1080 RETURN
1090 REM
1100 A1=AP
1110 B1=BP
1120 C1=CP
1130 D1=DP
1140 RETURN
1150 REM ***COMPUTE REFLECTED AND***
1160 REM ***TRANSMITTED POWER AND***
1170 REM ***PHASE***
1180 Q = (AN(K)-DN(K))*2*(BN(K)+CN(K))*2
1190 TP=4*Q
1200 TPX = 10*LOG(TP)/LOG(10)
1210 RP=1-TP
1220 IF RP = 0 THEN 1280
1230 RPK = 10*LOG(RP)/LOG(10)
1240 TPK = -10*LOG(1-TP)/LOG(10)
1250 RF=2*(BN(K)+DN(K)+AN(K)-CN(K))*2-DN(K)*2-CN(K)*2
1260 RFX = 10*LOG(RF)/LOG(10)
1270 RETURN
1280 RPK = -99.0
1290 GOTO 1010
1300 W=20:REM *STOP SCREEN PRINT EVERY 20 LINES*
1310 PRINT CHR$(147)
1320 PRINT "FREQ. R-PWR T-PWR(DB) R-PHA T-PHA"
1330 PRINT " (DB) (DB) (DEG) (DEG)"
1340 FOR K=0 TO K1
1350 F = F1+DF*K + .000001
1360 B1=STR$(F):GOSUB 1690:F1=B1
1370 R1=STR$(RPK)
1380 B1=R1:GOSUB 1590:R1=B1
1390 T1=STR$(TPK)
1400 B1=T1:GOSUB 1590:GOSUB 1670:T1=B1
1410 R2=STR$(RFX)
1420 B1=R2:GOSUB 1590:R2=B1
1430 T2=STR$(TFK)
1440 B1=T2:GOSUB 1590:T2=B1
1450 IF W*W<2 THEN 2000
1460 PRINT F;TAB(14-LEN(R1));R1;TAB(20-LEN(T1));T1;TAB(30-LEN(R2));R2;TAB(40-LEN(T2));T2
1470 PRINT R1;TAB(39-LEN(T1));T1
1480 IF K=0 THEN 1510
1490 IF K<K2 THEN 1520
1500 IF K/W=INT(K/W) THEN 1920
1510 NEXT K
1520 IF W<K2 THEN 2000
1530 PRINT "END OF LISTING. PRESS C FOR MENU"
1540 GET #1
1550 IF A#="" THEN 1540
1560 IF A#="C" THEN 1700
1570 IF A#="Q" THEN 1540
1580 RETURN
1590 REM *MANIPULATE STRINGS TO LINE UP COLUMNS*
1600 FOR U = 1 TO LEN(B1)
1610 IF MID$(B1,U,1)="" THEN 1640
1620 NEXT U
1630 RETURN
1640 B1=LEFT$(B1,U-1)
1650 IF LEN(RIGHT$(B1,U-1))<2 THEN B1=B1+" "
1660 RETURN
1670 IF ABS(TPK)/100 THEN B1=""-0.00"
1680 RETURN
1690 FOR U = 1 TO LEN(B1)

```

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ECL DIP High Frequency

Models: ECLA, ECLB
Frequency: 8MHz—200MHz, $\pm .01\%$
Supply: $-5.2\text{Vdc} \pm 5\%$ or $-4.5\text{Vdc} \pm 5\%$
Output: 10K ECL or 100K ECL
Package: All metal, hermetically sealed

DIP SINEWAVE Low Frequency

Models:	DPS1	DPS2
Frequency:	1KHz—75KHz	100Hz—100KHz
Tolerance:	$\pm .01\%$, THD $\leq 5\%$	$\pm .01\%$, THD $\leq 5\%$
Supply:	5Vdc $\pm 10\%$	8Vdc—15Vdc
Package:	All metal, hermetically sealed	

TTL CLOCKS Tight Tolerance

Models:	S10C	S10D	S10E
Frequency:	31KHz—25MHz		
Tolerance:	$\pm .001\%$	$\pm .0025\%$	$\pm .005\%$
Temp. Range:	0°—50°C	0°—70°C	-25°—75°C
Package:	All metal, hermetically sealed 14 pin DIP		

TTL CLOCKS Stock Frequencies/ Low Cost

Models:	S14R8	S15R8
Tolerance:	$\pm .005\%$	$\pm .01\%$
Supply:	+5Vdc $\pm 10\%$, 60mA max	
Frequencies:	1,2,4,5,6,8,10,12,16,20,24,40,70MHz	
Package:	All metal, hermetically sealed 14 pin DIP	



CONNOR-WINFIELD CORPORATION
West Chicago, IL 60185 USA
Phone: 1-312-231-5270
TWX No. 910-230-3231
Cable: CONWINWCGO


```

1700 IF MID$(B$,0,1)="" THEN 1730
1710 NEXT U
1720 RETURN
1730 B$=LEFT$(B$,U-3)
1740 IF LEN(RIGHT$(B$,U-3))=3 THEN B$=B$+"00"
1750 RETURN
1760 PRINT CHR$(147)
1770 PRINT "CHOOSE AN OPTION. PLEASE"
1780 PRINT""
1790 PRINT "1 - REPEAT CALCULATION" CHR$(13)
1800 PRINT "2 - PRINT DATA TO PRINTER" CHR$(13)
1810 PRINT "3 - PRINT DATA TO SCREEN" CHR$(13)
1820 PRINT "4 - QUIT PROGRAM" CHR$(13)
1830 GET A$
1840 IF A$="1" THEN 1850
1850 IF A$="2" THEN 2000
1860 IF A$="3" THEN 1300
1870 IF A$="4" THEN END
1880 IF A$="" THEN 1830

```

```

1890 CLR
1900 GOTO 190
1910 PRINT CHR$(147)
1920 PRINT "PRESS CTR TO CONTINUE"
1930 GET A$
1940 IF A$="C" THEN 1950
1950 IF A$="" THEN 1930
1960 PRINT "FREQ. R-PWR T-PWR E-PHA T-PHA"
1970 PRINT "DB DB DEG DEG"
1980 GOTO 1300
1990 PRINT CHR$(147)
2000 W=1/2
2010 OPEN "4.4 CMD" REM * C-44 COMMAND TO OPEN CHANNEL TO COMMODORE PRINTER *
2020 REM * TO SUIT YOUR PRINTER PLEASE ALTER THE FOLLOWING *
2030 REM * LINES 2010, 2030, 2100 AND 2110
2040 GOTO 1310
2050 PRINT "CLOSE"

```

```

2060 PRINT CHR$(147)
2070 PRINT "END OF HARD COPY LISTING"
2080 GOTO 1770
2090 REM
2100 PRINT "1" CHR$(13) CHR$(13) CHR$(13) CHR$(13) CHR$(13)
2110 PRINT "2" CHR$(13) CHR$(13) CHR$(13) CHR$(13) CHR$(13)
2120 GOTO 1450

```



Why do it yourself when we've done it for you?



The Schaffner FN 380.

We've put it all together for you.

Schaffner's FN 380 universal power entry module is a complete package. . . in fact, it's fast becoming the standard of the industry.

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And of course, it's all agency approved.

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Erratum:

There was an error in equation (13) as printed in Part I. It should have read:

$$[Tg] = \begin{vmatrix} \cos y & jZ_1 \sin y \\ j\sin y & \cos y \end{vmatrix} \begin{vmatrix} \\ Z_1 \end{vmatrix}$$

rf calendar

March 11-15

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Information: Shirley Forlenzo, George Washington University; Tel: (202) 676-8530 or toll-free (800) 424-9773.

March 18-20

Dielectric Resonators

A Three-day Short Course

University of Mississippi, Oxford Campus
Oxford, MS

Information: Dr. Darko Kajfez, Department of Electrical Engineering, University, MS 38677; Tel: (601) 232-7231.

March 19-22

Componentes Electronicos '85

Guadalajara, Mexico

Information: Ms. Raquel Polo, Deputy Project Manager, United States Trade Center, P.O. Box 3087, Laredo, TX 78044; Tel: (905) 591-0155.

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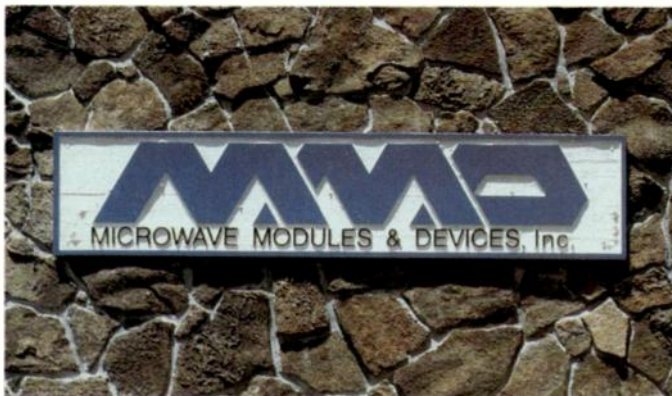
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The Company

Microwave Modules & Devices is uniquely dedicated to integrating device and circuit technology to break through current technological barriers to achieve a new level of pricing and performance in the RF/Microwave field.

The professionals who head the company have been engaged in the design, development and production of high power, solid-state microwave modules and devices for over 15 years. Today, MMD's expanding line of products includes amplifiers employing both hybrid micro-circuitry and modular printed circuit technology. The company's high performance amplifiers are targeted for use in military and industrial applications worldwide. In addition, MMD is deeply involved in the design, development and manufacture of a wide variety of RF and microwave functions for high technology applications both for military and industrial markets. MMD's markets include communications, counter-measures, radar, space, broadcast, avionics, industrial, scientific and medical. Reduction in size is one of MMD's on-going goals while constantly striving to improve both performance and product reliability. This brochure highlights MMD's current capabilities and its technological direction in the future.



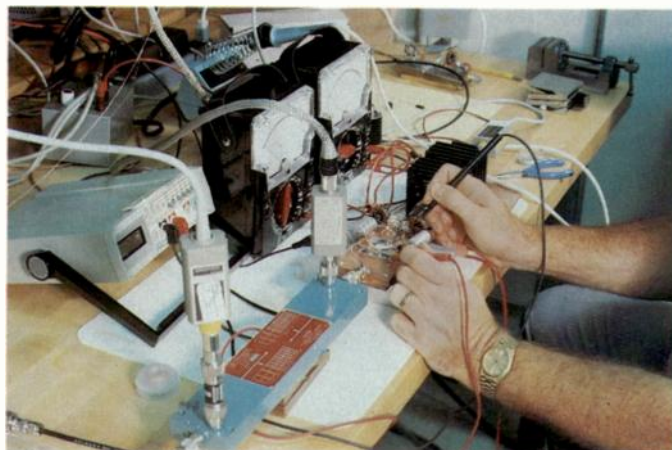
Fast Response Time

Fast response to customer amplifier needs is assured by a complete in-house design, prototyping and manufacturing capability. This is due totally or in part to:

- Complete engineering model shop.
- Computer-aided design.
- Automated die attach.
- Automated test capabilities.
- Engineering staff with more than 125 years combined experience.
- Computerized manufacturing/accounting systems.

Soft Board Amplifiers

State-of-the-art performance, high reliability, small size and fast development time are among the challenges that MMD is accepting every day. If these sound like your particular problems, MMD can provide the solutions you have been looking for. For example, complete solid-state amplifiers with power outputs to more than 1 KW can be designed and manufactured to your specifications. If you have a new design requirement for TV, radar, communications, avionics, EW, or need a solid state replacement for a vacuum tube, MMD is in business to solve your problems **fast!!** If improvements in efficiency or linearity are important in your application, MMD can help. In fact, MMD is providing an order of performance previously unachievable in RF power amplifier modules. MMD can **demonstrate** how to reach such goals as wide bandwidth, high efficiency, power outputs to



Custom Modules

MMD specializes in developing and manufacturing modules to your specifications. What do you need to maintain your competitive edge?

- Higher power?
- Wider bandwidth?
- Better efficiency?
- Smaller size?
- Improved reliability?

MMD can solve these design problems to meet your performance requirements.

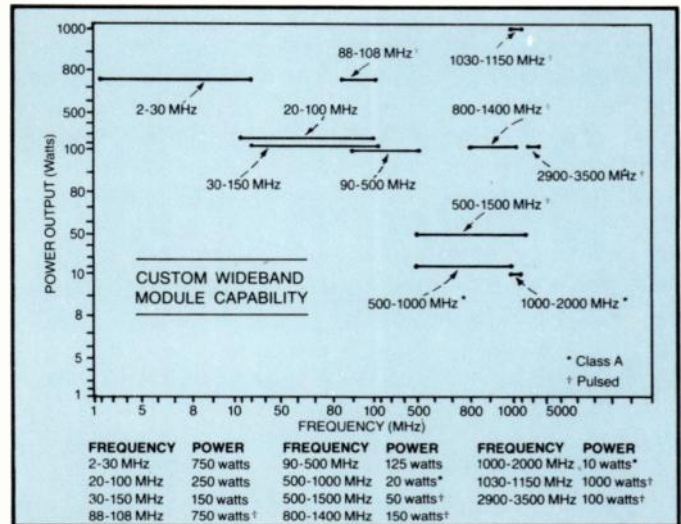
The Plant

Microwave Modules & Devices (MMD) is located in Mountain View, California, in the heart of the high technology area known internationally as "Silicon Valley." The modern 10,000 square foot plant is fully equipped with the most advanced test, process and assembly equipment. It has clean room and assembly capabilities for delivering softboard and hybrid modules to the demanding requirements of military programs and sophisticated industrial applications. MMD's quality assurance procedures are designed to incorporate the latest military standards.



Hybrid Power Amplifiers

MMD hybrid power amplifier modules using chip transistors and either thick or thin film construction offer improved performance and ease of use compared to discrete designs. Hybrid power amplifier modules can provide guaranteed performance with no additional tuning or impedance matching headaches and the "Drop-in" configuration simplifies the user's mechanical design. In addition, smaller size offers a real advantage in systems where space is at a premium. MMD specializes in custom designs requiring BeO substrates or chip carriers to achieve performance not possible with discrete designs.



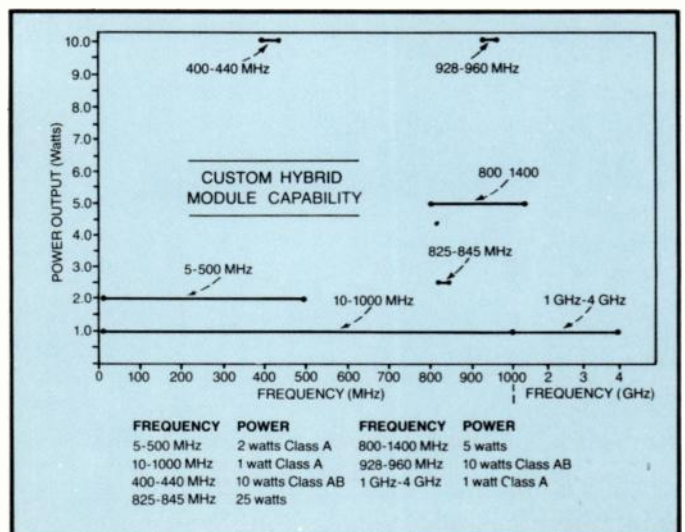
more than 1 KW Class C or Linear, Pulse or CW. All of this can be achieved by several unique MMD capabilities including:

- Custom die designs for optimized performance.
- Custom BeO ceramic chip carriers for best die/circuit interfaces.
- In-house custom ceramic/metal device packaging for lower thermal resistance; lower parasitics; hermetic seal.
- Device assembly.

For example, these unique capabilities come together to create MMD's "POWER QUAD" concept which combines with new wideband matching components to offer power/bandwidth capability far superior to that of conventional designs. So, if **performance** is an important consideration, call and find out how Microwave Modules & Devices can provide you with a **cost effective** alternative to in-house design, development and manufacturing of your critical power amplifier modules.

RF Functions

MMD can provide all the RF functions you need for your particular system requirements. Active mixers, AGC amplifiers, high speed modulators, wideband amplifiers and IF amplifiers are just some of the products under development. MMD functions use transistors with F_t up to 8GHz and power capability up to 1 watt, making them ideal for low distortion, wide dynamic range EW applications. A variety of packages are available for your custom requirements such as welded hermetic enclosures or small microstrip styles.





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TO DEVICES AND
PACKAGING
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MICROWAVE MODULES & DEVICES, Inc.



AC-0003-500W

500 WATT SOLID STATE AMPLIFIER MODULE

The AC-0003-500W is a modular wideband HF Class AB Linear Power Amplifier that provides 500 watts of output power at an intermodulation distortion level of better than -35dB (IMD₃). The module incorporates wideband 90° quadrature combiners resulting in predictable 50 ohm system interfaces and superior performance into imperfect loads. The unit also contains internal voltage regulation and reverse voltage protection.

A single AC-0003-500W can be used as the final stage in a 500 watt system or modules can be combined to construct multi-kilowatt transmitters.

The MMD AC-0003-500W module is a reliably rugged building block designed for a wide variety of uses in Military and Industrial HF applications.

MODULE SPECIFICATIONS

PARAMETER	LIMITS		UNITS	CONDITIONS
	MIN.	MAX.		
GAIN	13.0		dB	P _{OUT} = 500 WATTS PEP FREQ. = 2 TO 30 MHz V ₁ = 5.0 VOLTS V ₂ = 45 VOLTS
GAIN FLATNESS		±1.5	dB	
EFFICIENCY	30		%	
INPUT VSWR		1.5:1		
OPERATING LOAD VSWR		2.0:1		
NON-DESTRUCTIVE LOAD VSWR		5.0:1		
IMD ₃		-35	dB	FREQ. = 2 TO 30 MHz V ₁ = 5.0 VOLTS V ₂ = 45 VOLTS
P _{SAT}	700		W	
OUTPUT SOURCE VSWR		1.5:1		
WEIGHT		7	LBS.	

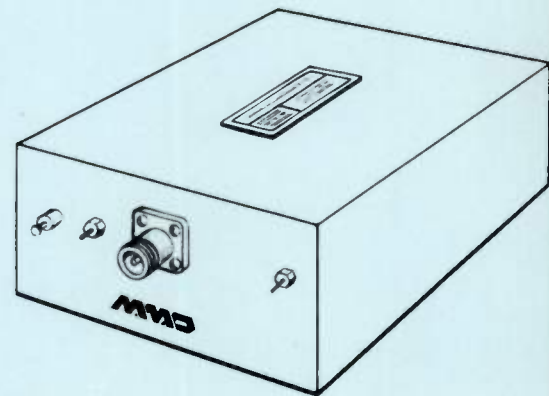
All specifications are at a 30° C baseplate unless otherwise stated.

PRIME POWER REQUIRED: V₁ = 5.0 ±0.1 VOLTS @ 2.5 AMPS.
 V₂ = 45.0 ±1.0 VOLTS @ 40 AMPS.

OPERATING BASEPLATE TEMPERATURE: -25°C TO +85°C.

CONNECTORS: TYPE "N" FEMALE (RF). SOLDER PIN (DC).

2 to 30MHz
HF MODULE



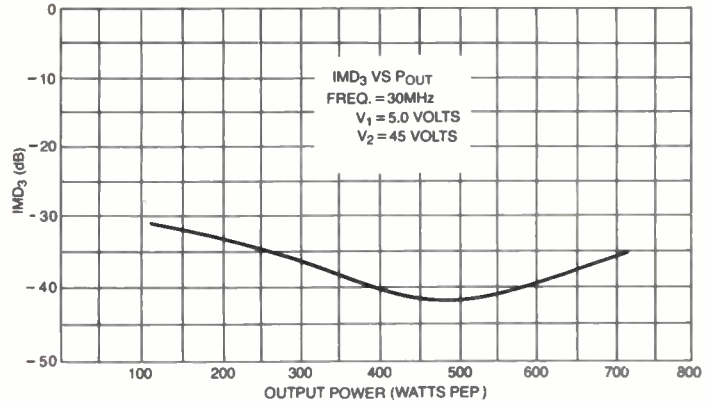
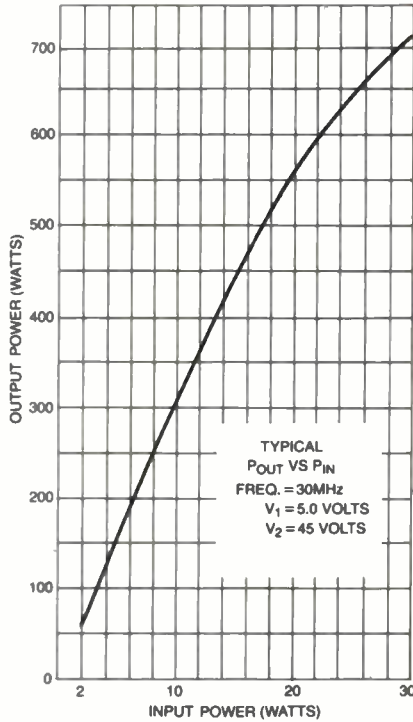
FEATURES:

- HIGH POWER HF BUILDING BLOCK MODULE
- 500 WATT LINEAR OUTPUT
- 50 OHMS IN AND OUT
- WIDEBAND 2 to 30MHz
- 14dB GAIN
- FLAT GAIN VS FREQUENCY
- INTERNAL VOLTAGE REGULATION AND REVERSE VOLTAGE PROTECTION

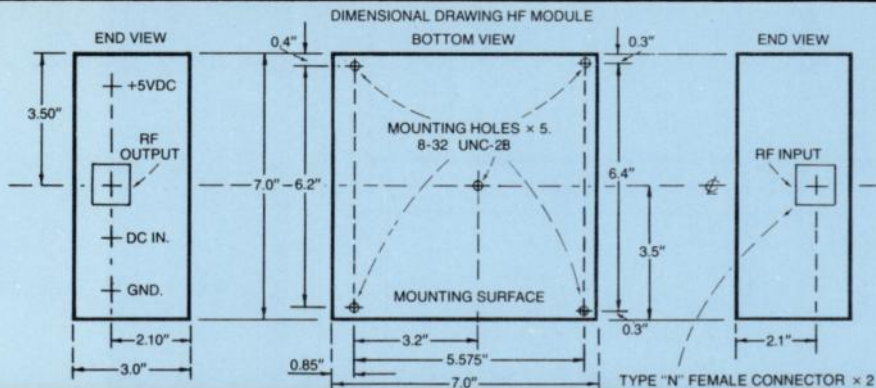
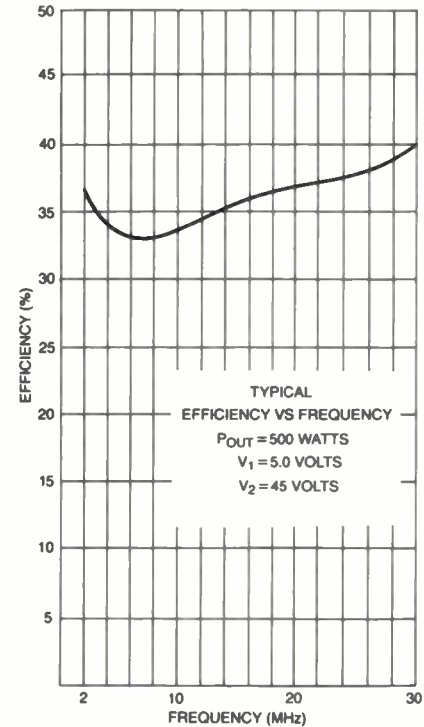
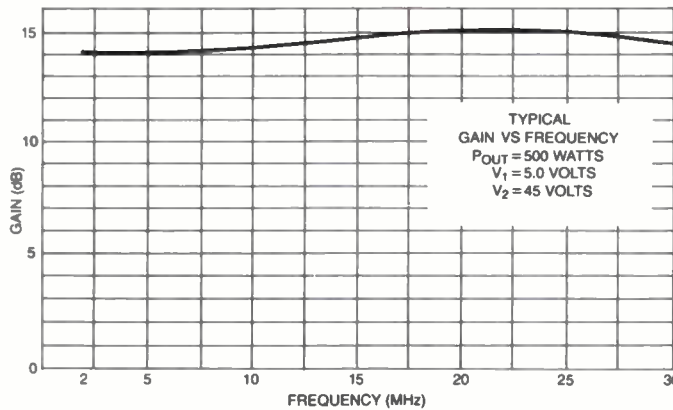


AC-0003-500W

500 WATT SOLID STATE AMPLIFIER MODULE



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MICROWAVE MODULES & DEVICES, Inc.

FA-501

WIDEBAND RF FUNCTION AMPLIFIER

FREQUENCY RANGE: 5-500 MHz.

The FA-501 is an RF function amplifier that offers the circuit designer the versatility of an operational amplifier in both transmitter and receiver applications. With more than 20dB of reverse isolation and unconditional stability, a wide variety of systems problems can be solved. Features include 5.5dB noise figure, 10dB gain, 25dB AGC and a bandwidth that exceeds 500 MHz. In some applications the FA-501 is useful to 750 MHz. The compact unit is housed in a hermetically sealed package.

AMPLIFIER SPECIFICATIONS @ 25°C, $V_{CC} = +5V$.

Frequency Range:	5-500MHz.
Gain ($I_0 = 110$ ma)	10dB min.
Gain Flatness:	(G = 0 to 10dB) ± 1 dB (G = -15 to 10dB) ± 3 dB
Power Output @ 1dB Gain	
Compression ($I_0 = 110$ ma)	+10dBm min.
Noise Figure ($I_0 = 110$ ma)	5.5dB max.
VSWR (50 ohms)	Input: 2.5:1 max. Output: 2.5:1 max.
3rd Order Intercept Point ($I_0 = 110$ ma)	+20dBm typ.
2nd Harmonic	-25 dBc @ P_{1dB}
Suppression:	-40 dBc @ $P_{1dB} - 10$ dB.
Reverse Isolation:	20dB min.

AGC RELATED:

Control Range:	5-500 MHz: 25dB min. 5-100MHz: 30dB min.
Control Input Range:	+1 to +4 V 2 to 18 ma.
Response Time for 25dB Δ :	1 μ sec max.
Gain Stability: -30 to +50°C	4dB p-p max. (For Any Setting Within Specified Control Range)

ENVIRONMENTAL:

Operating Case Temp.	-55° to +85°C.
Storage Temp.	-62° to +125°C.

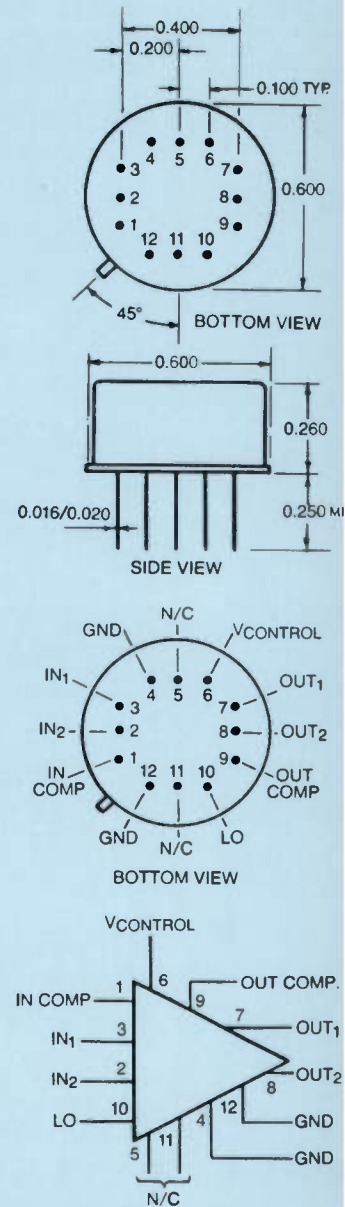
ABSOLUTE MAXIMUM RATINGS:

V_{CC}	+8 volts.
$V_{CONTROL}$ (Without External Resistor)	+5 volts.
Current (I_0):	150 ma.
RF Input Power At Any Port:	+13dBm.

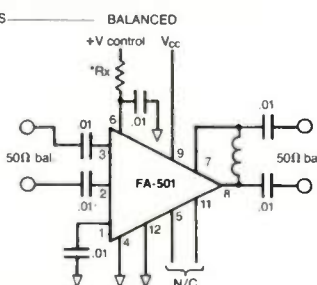
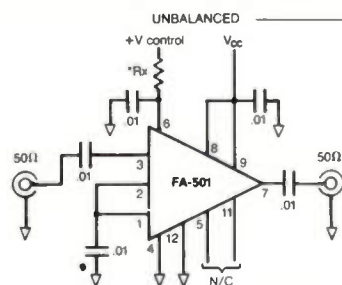
MIXER CHARACTERISTICS:

Frequency Range:	LO: 5-500MHz. RF: 5-500MHz. IF: 5-500MHz.	Isolation:	LO-RF: 25dB min. LO-IF: 10dB min. RF-IF: 0dB min.*	Two Tone IM_3 : 35dBc at -10 dBm RF Port Power
Conversion Loss/Gain:	Minimum: -4dB. Typical: 0dB. Maximum: +2dB.	Noise Figure:	10MHz: 17dB 200MHz: 17dB 500MHz: 17dB	VSWR at R Port: 2.0:1 max. VSWR at L Port: 1.8:1 max. VSWR at I Port: 2.0:1 max. (5-500 MHz)

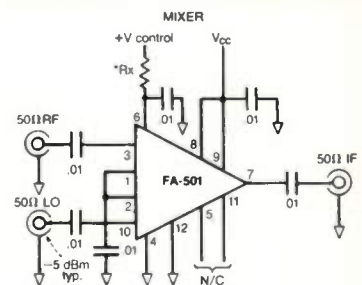
NOTES: 1. V_{cont} Set for $I_0 = 40$ ma.
2. LO Level: -5 dBm typical.
* Measured At 10MHz



TYPICAL APPLICATIONS



* R_x required for control voltages higher than +5 volts:
 $R_x = 560\Omega$ for $V_{CONTROL} = +15V$.



* Set $V_{CONTROL}/R_x$ for $I_0 (V_{CC}) = 40$ ma.



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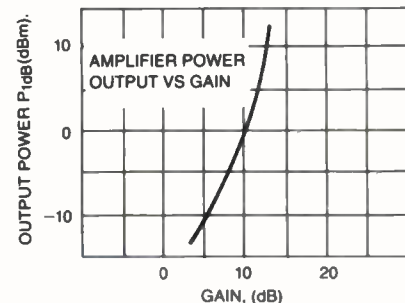
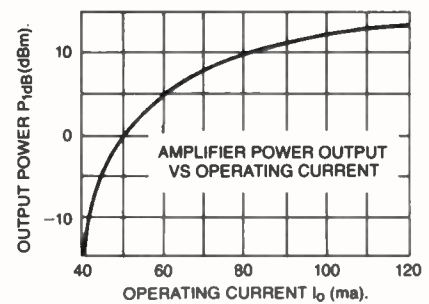
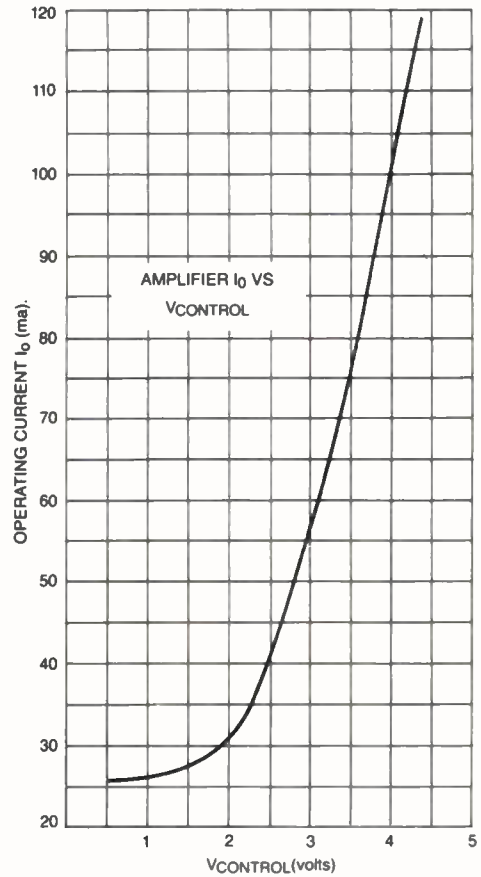
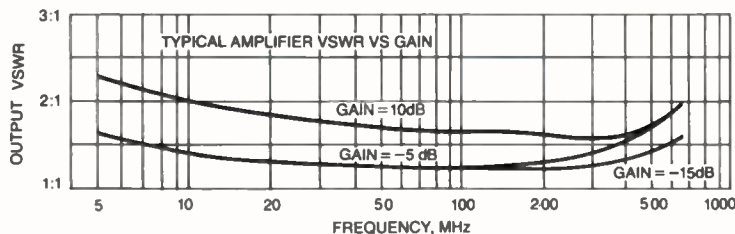
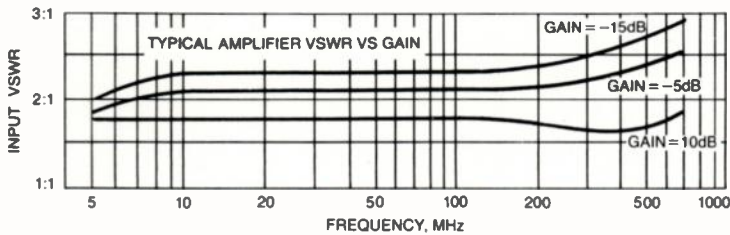
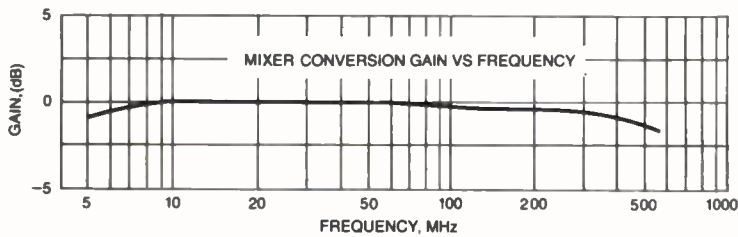
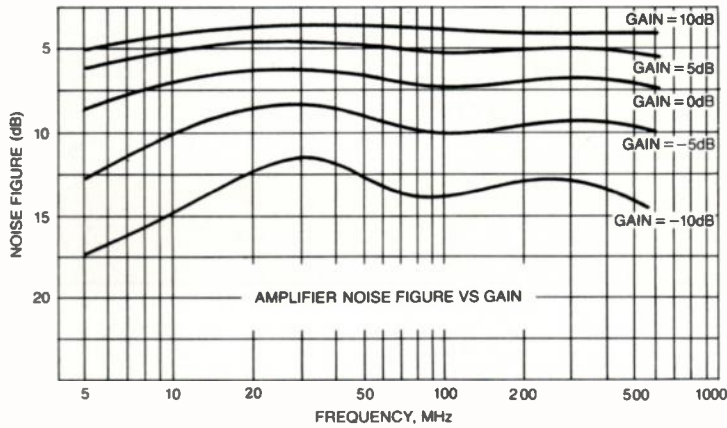
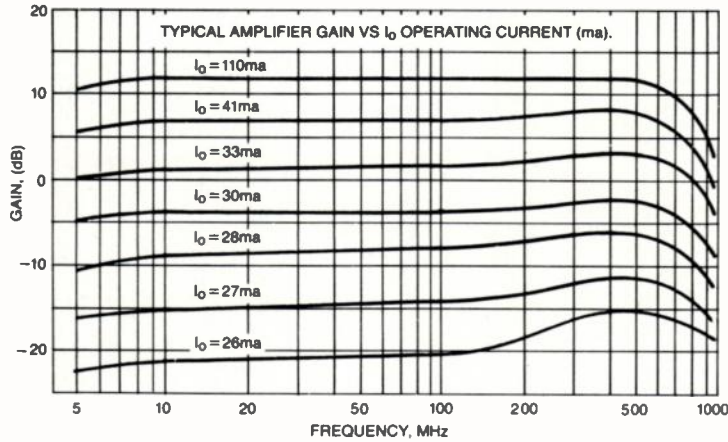
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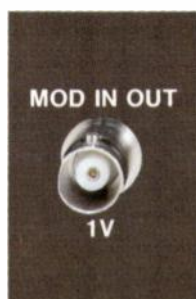


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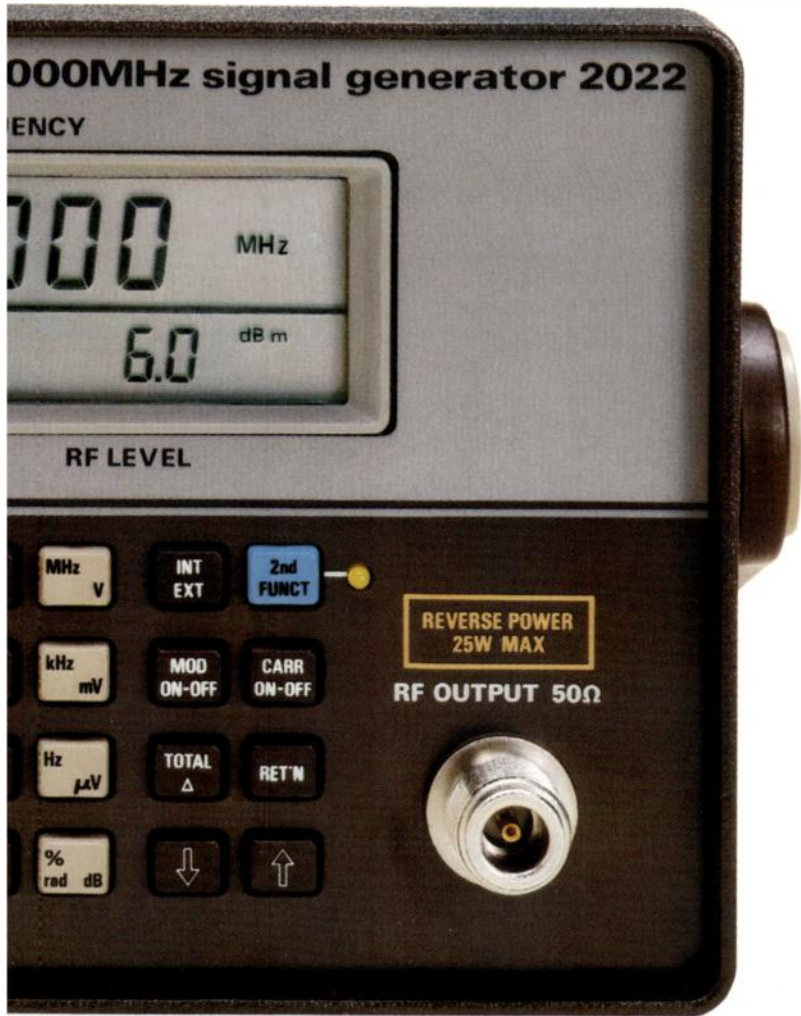
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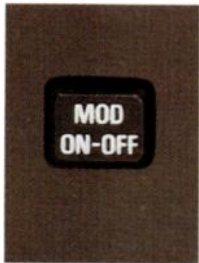
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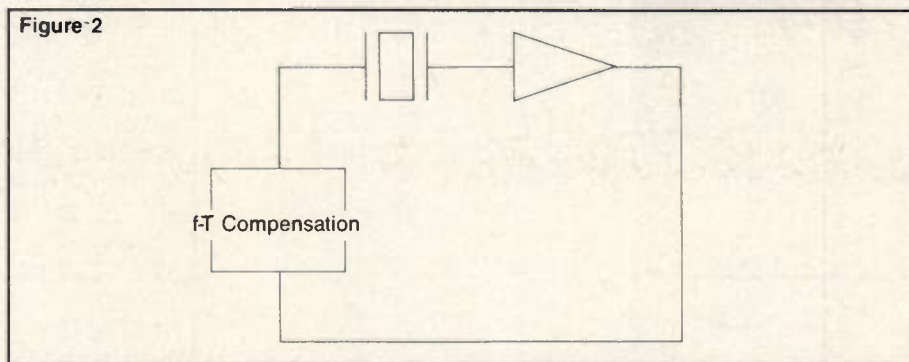
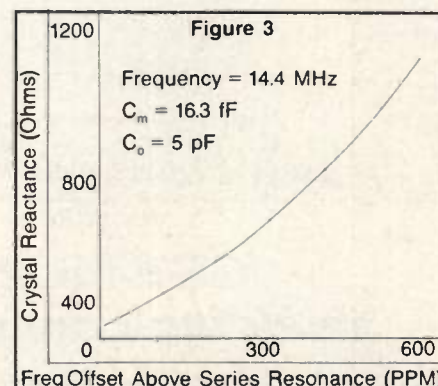
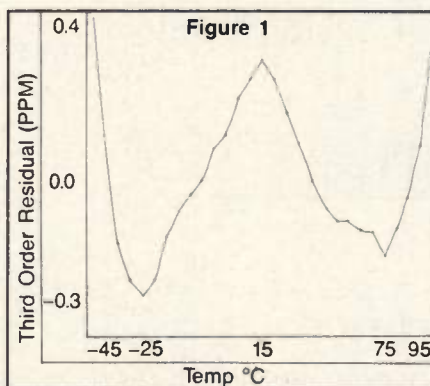
Frequency-Temperature Performance Determination In High Stability TCXOs

By Dennis Marvin
Motorola, Inc.
Communications Systems Division

The temperature compensated crystal oscillator (TCXO) has been with us for over thirty years and is quite often taken for granted. However, as frequency vs. temperature (f-T) stability requirements continue to tighten, many of the previously ignored second order effects will have a significant impact. TCXO stability requirements of 0.5PPM or 2PPM over temperature ranges as wide as -55 to $+95^{\circ}\text{C}$ are becoming commonplace. This article will review several of these second order effects and attempt to quantify the amount of performance debasement that can result.

AT-cut crystals are commonly assumed to have an f-T characteristic that can be represented by a third order polynomial. While this fit is quite adequate for most current applications, it can be inadequate for tight f-T requirements over wide temperature ranges. Figure 1 shows the difference between actual data and the least squares third order curve fit for a typical fundamental crystal. There is a decided, consistent fourth order component. Oscillators with f-T stabilities approaching 1PPM must incorporate a compensation scheme capable of correcting for the fourth order term and crystal evaluation algorithms must do a fourth order fit to insure that good crystals are not discarded.

Tight tolerance TCXO designs are further complicated by component TC and non-linear transfer characteristics. Even though the frequency stability of an AT-cut crystal is almost always less than 1PPM/ $^{\circ}\text{C}$, work at Motorola and by Holbeche and Morley(1) has determined that the motional capacitance, C_m , of a



fundamental crystal varies approximately 230PPM/ $^{\circ}\text{C}$. This variability must be addressed during the oscillator design. The varactor and its operating voltage must be carefully selected. If a varactor with a non-linear V-X characteristic is used, the compensation network will have to generate a more complex V-T function to compensate for the distorted varactor transfer function. Similarly, if a nonlinear varactor is used for both temperature compensation and aging adjust, the amount of compensation will change as the aging is corrected.

Background

A fundamental AT-cut (3-20 MHz) TCXO can be simply represented by the block diagram of Figure 2, where the feedback scheme is incorporated into the amplifier block. This block can represent any of the common configurations: Colpitts, Pierce or Clapp. The oscillator operates by meeting Barkhausen's criterion; the sum of the reactances around the loop must equal zero, with the crystal operating at whatever frequency meets this requirement. Figure 3 shows that the crystal reactance is a function of fre-

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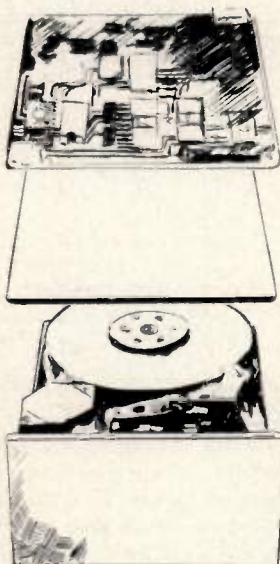
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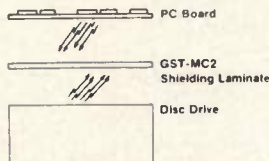
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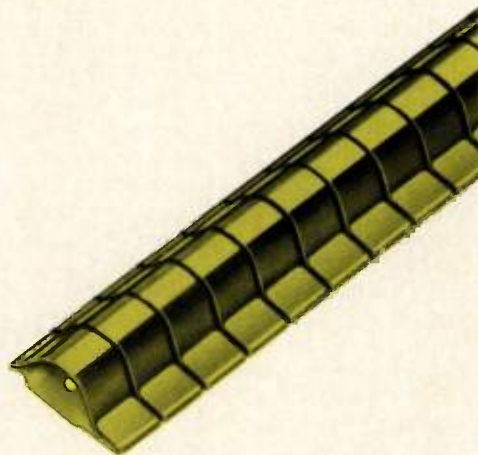


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quency by following the nonlinear relationship:

$$X = 1 / ((C_m / 2 \Delta f / f - C_o) w)$$

Where: C_m is the motional capacitance of the crystal model;
 C_o is the capacitance of the crystal plate, the holder and any associated stray circuit capacitance;
 $\Delta f / f$ is the fractional frequency change of the crystal from series resonance.

Such a circuit can be temperature compensated by having a compensation block that generates a reactance characteristic as a function of temperature such that it causes the crystal to change the operating point on its reactance curve. By carefully designing this block the crystal can be operated so as to cause a net "zero" frequency change over temperature.

There are several networks that are used for the compensation block, both direct and indirect. The preferred circuits are indirect, i.e., a DC voltage is generated external to the oscillator loop and is used to vary the loop reactance via a varactor. Direct compensation, where the compensation is inserted directly in the oscillator loop, has fallen on disfavor, as its use lowers circuit Q. Of the several methods of indirect compensation used, including custom integrated circuits and digital compensa-

tion, the most common and the most easily understood is thermistor-resistor compensation. One embodiment of this is shown in Figure 4(2). Other designs can be similarly analyzed.

If we assume that the varactor has a $\partial = 1$ (not bad for hyperabrupt varactors over a limited voltage range) and that all other parts in the oscillator are constant over temperature ms. characteristic of the crystal. This is a good approximation for initial analysis purposes, with corrections necessary for an exact compensation.

In any case, this thermistor-resistor network has the following transfer function:

$$V_{out} = V_{in} \frac{RT_3(R_1 + RT_1)(R_2 + RT_2)}{(R_1 + RT_1)(R_2 + RT_2)(R_3 + RT_3) + R_2 RT_2(R_1 + RT_1 + R_3 + RT_3)}$$

where RT_1 , RT_2 and RT_3 are the resistances of the three thermistors at a particular temperature.

R_1 and RT_1 affect performance over the entire temperature range, while R_2 and RT_2 primarily affect the cold end and R_3 and RT_3 primarily affect the hot end. Care must be taken to obtain suitable parts values so the appropriate transfer function can be obtained while still maintaining a high degree of independence among the temperature ranges. The use of a personal computer to gather f-T data and process it reduces the need for in-

dependence among the compensation sections.

Parts Aging

When oscillators are being temperature compensated one is normally concerned with passing the specification at a half-dozen or so temperatures with a little margin for measurement error. This is quite adequate for oscillator stabilities of 5PPM or looser, but if a tighter system stability is required parts aging can become very important.

Parts aging can have two effects on the oscillator stability. The first is a positive or negative frequency shift over the entire temperature range, i.e., the oscillator will have the same f-T characteristic after aging has occurred as it did before, but the whole response has a new room tem-

TYPE	AGING
Resistors	
Carbon Comp	>10%
Carbon Film	3 to 5%
Thick Film	1 to 5%
Metal Film	1.5 to 2%
High Precision Metal	
Film Thermistors	0.1 to 0.5%
Non-hermetically sealed	1 to 5%

TABLE 1

perature reference frequency. A more insidious result of parts aging is the distortion done to the f-T response.

Over the life of a product, the resistors and thermistors can age as shown in Table 1.

The effects of parts aging on frequency drift and the f-T characteristic can be determined by inserting a small resistor or thermistor change (e.g., 1%) into the transfer function and analyzing the results. Parts changes of + and - 1% for all of the resistors and thermistors in Figure 4 were inserted and the resulting errors maximized by proper selection of sign. The maximum offset was 36mV or 0.61PPM given a sensitivity of 17PPM/V. Figure 5 is a plot of the maximum f-T distortion. Changes in f-T performance as poor as 0.80PPM/% change are possible. Allowing the 1% aging to occur in a random direction among the resistors and thermistors, there is on average a 0.27PPM/% offset and a 0.41PPM/% f-T distortion to the T.C. curve.

Of these figures the f-T distortion is by far the more serious problem, since a means of frequency adjust can usually be provided to compensate for the frequency drift. With these results now available, the

appropriate resistors and thermistors can be specified and the initial f-T specification appropriately tightened so that system stability can be maintained to allow for compensation aging.

Frequency Adjust Aging

Compensation aging isn't the whole story, unfortunately. The major source of frequency drift is almost always the crystal. This drift is normally corrected by adjusting a capacitor or inductor in the oscillator loop to shift the operating point in the crystal curve and thus return the oscillator to nominal frequency. This shift in operating point also distorts the f-T characteristic and is known as trim effect. Galla and McVey(3) have developed equations to quantify this distortion for both series and parallel adjust circuits (see Figure 6). The values shown are typical for a fundamental frequency equivalent circuit. These equations are:

f-T distortion (PPM)

$$\frac{\text{SERIES}}{4\pi C_o(C_o+C_1)X_{10}-3} \frac{C_1 C_m}{C_1 C_m}$$

$$\frac{\text{PARALLEL}}{4\pi(C_o+C_1)X_{10}-3} \frac{C_m}{C_m}$$

where a is the amount of aging to be corrected (PPM)

p is the amount of temperature compensation (PPM)

C_o is the crystal and holder capacitance (pF)

C₁ is the load capacitance seen by the crystal (pF)

C_m is the motional capacitance of the crystal (fF).

As the distortion in the series adjust configuration is equal to that of the parallel adjust multiplied by C_o/C₁, and this term is significantly less than 1, the series performance far surpasses that of the parallel. The parallel adjust should never be used in a high stability design if the use of a series is possible. Even if a series adjust is used, an additional 0.17PPM distortion will be generated. Figure 7 shows the f-T characteristic for a series adjust oscillator and its trim effect.

There are several ways that this problem could be alleviated. If C_m were increased, the distortion would decrease. However, all things being equal, C_o would increase in proportion to C_m. Additionally, the larger C_m becomes, the more the variations in the oscillator components affect performance.

The easiest way to reduce this distortion is to reduce p, the amount of temperature compensation, by carefully selecting the crystal angle. It can be further reduced by not overspecifying the temperature range. The smaller the temperature range, the smaller p will be.

Reducing a, the amount of aging to be corrected, is also possible. This can be done by using a better aging design, preaging the crystals or by sorting them for aging. Remember that a reasonably well made crystal will age approximately as much in the first year as it will age in the next ten years combined.

Voltage Regulator Contributing

In addition to the compensation circuitry and the crystal aging, one must also consider the voltage regulator circuit driving the compensation. The regulator is very important, as any voltage variations in it are directly coupled to the varactor and will create drift and distortion problems.

Using the compensation network of Figure 4 and allowing the regulator to vary +1mV/° (a fairly typical value for a fixed commercial regulator) results in an f-T distortion of about 0.4PPM, as shown in

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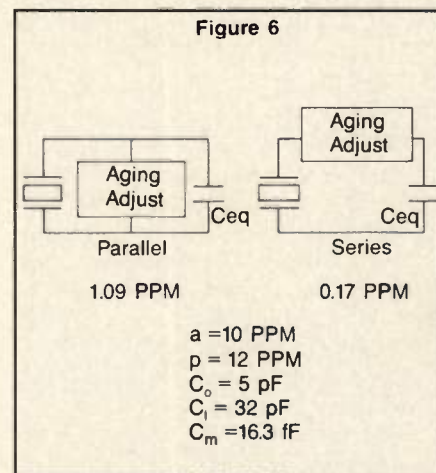
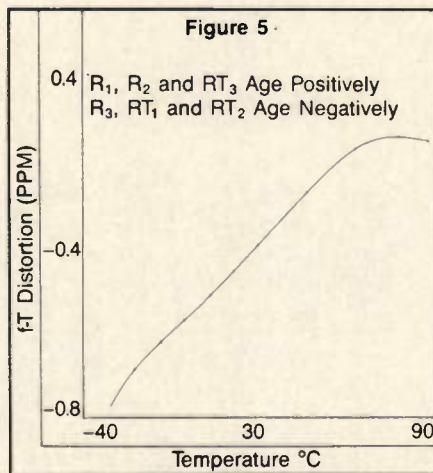
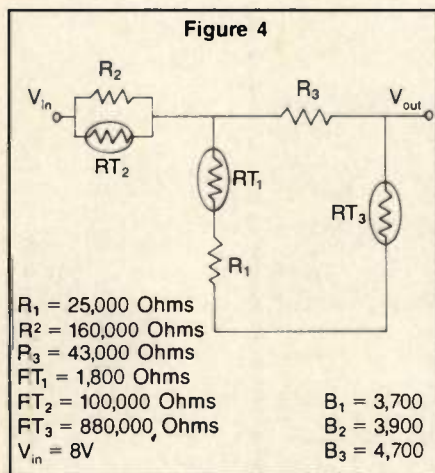
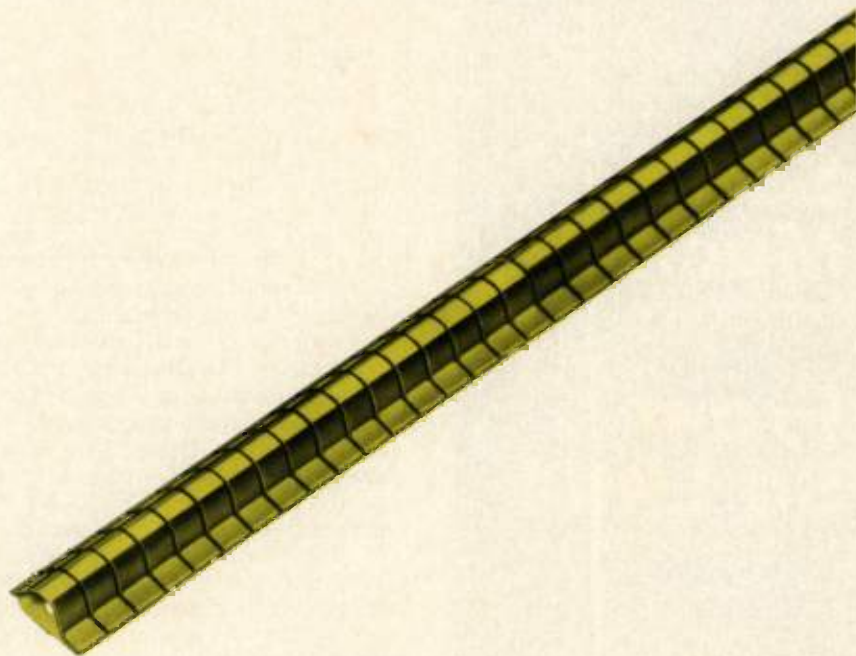


Figure 8. The only way to alleviate the problem of regulator voltage variation with temperature is to temperature compensate the oscillator with an internal regulator so that the temperature variations are compensated out.

Even with a built-in regulator, there is still the potential for aging. Figure 9 shows the distortion for a +1% change in regulator voltage.

Hysteresis

Crystal oscillator frequency performance can be very dependent on environmental dynamics. The designer must consider what dynamic frequency

stability is required and what maximum rate of change of temperature the oscillator will see. The temperature of the oscillator does not normally change nearly as fast as the ambient, as it is generally well isolated inside the system.

There are two major contributors to the hysteresis problem. The most easily visualized is the imbalance in thermal time constants among the several thermistors and the crystal. Time constants for thermistors in still air range from less than 0.1 sec. for small chips to over 10 sec. for 0.1 inch diameter beads, while typical HC-18 crystals have time constants of from 1 to 2 minutes. There is a

lot of variability in the crystal time constant. Important parameters causing this variability include package, lead and mount material and size, crystal blank size, crystal mounting technique and the type and density of gas sealed in the package.

There are so many variables present that the best way to determine the magnitude of the frequency shift is to measure it for the particular application. Tests performed on a hand-held 2-way radio subjected to a -30 to $+90^\circ$ temperature shock have given shifts as large as 0.3PPM.

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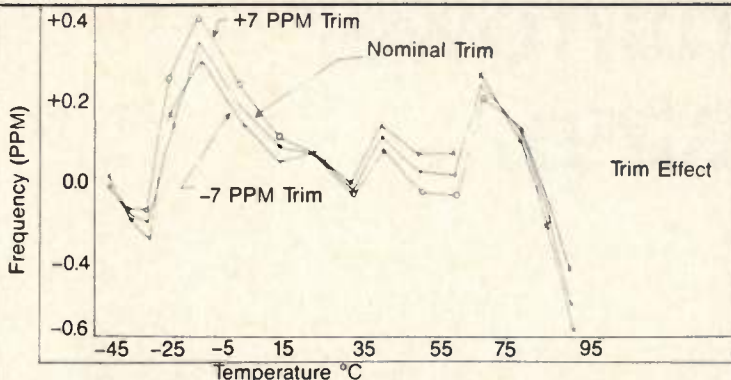
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Figure 7



swings, this effect can be reduced by better matching time constants through thermally coupling the compensation temperature sensors to the crystal or by increasing the shorter time constant.

The second hysteresis problem lies within the crystal. If an AT-cut crystal undergoes a temperature change, stresses will be set up within it. As the temperature of the crystal is swept back and forth an f-T characteristic is generated that traces a loop about the familiar static characteristic. The direction and magnitude of this offset is dependent upon the particular crystal design, the

temperature range and the speed with which the temperature is changed.

Ballato(4) has modified this effect by changing the familiar crystal model from

$$f/f = a_0 \Delta T + b_0 \Delta T^2 + c_0 \Delta T^3$$

to

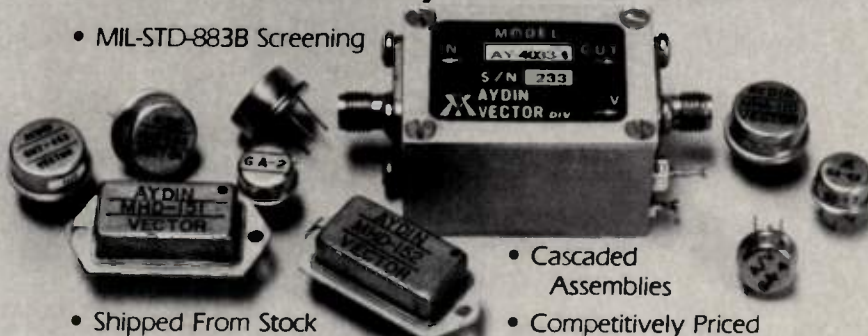
$$f(t)/f = a(t) \Delta T(t) + b_0 \Delta T^2(t) + c_0 \Delta T^3(t)$$

where $a(t) = a_0 + \hat{a}T(t)$ with \hat{a} being evaluated separately for each crystal design.

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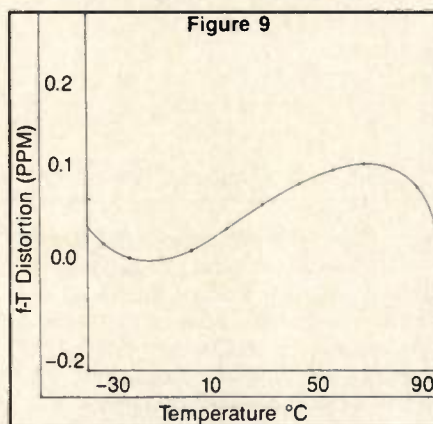
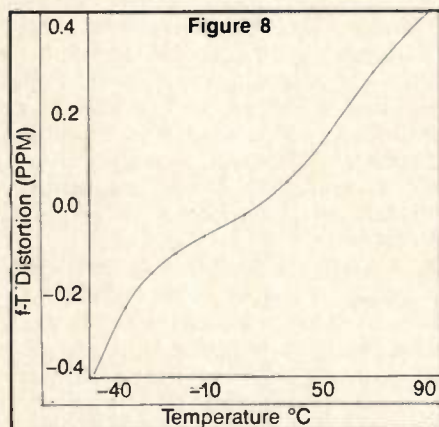
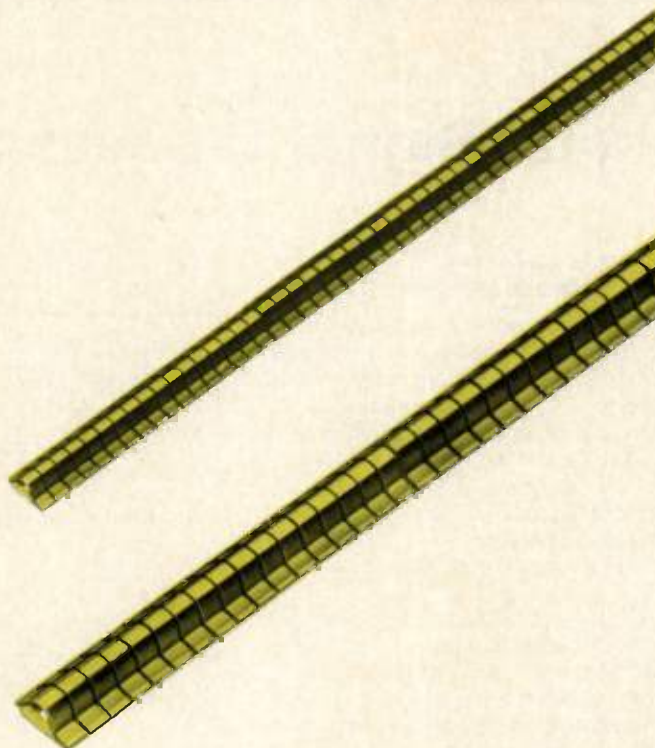
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MHD Multi-Stage	1-500	21	2.5-6.5	5-20	1.6 (typ.)	1.6 (typ.)	+15 typ.	50-115 (range)	4-pin DIP

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


temperature is varied in a sinusoidal manner + and - 60° about 30° at a frequency of 0.01Hz (an orbital time of 628 sec.) the peak deviation from the static curve was 7.2PPM. As the deviation is linearly related to the frequency of the temperature change for this model, the maximum orbital time to keep the peak deviation below 0.1PPM for this crystal is 12.6 hours. Hence, fast temperature changed can and do affect the desired stability. It should be stressed that the magnitude and direction of this deviation is quite crystal dependent, with this example tending to be worst case, and that this is the peak error over the entire temperature loop.

Conclusion

High stability TCXOs are subject to many instabilities not normally considered in the design of lower stability products. Several of these have been reviewed. The design engineer must carefully consider the system requirements in dynamic environments and as a function of time.

For example, the design Motorola has chosen to use is shown in Figure 10. The as shipped f-T stability requirement is as tight as 1PPM from -40 to +95° with a total system stability of better than 2PPM. In order to accomplish these specification and still maintain a small package size (< 0.3 cu.in.) while minimizing costs, a

custom integrated circuit in a hermetic chip carrier was used (5). The chip consists of a three segment non-linear compensation ms, but has improved isolation between the stages for ease of production. Compensation is achieved with four trimmable resistors. Hermetic sealing of the IC minimizes regulator drift. Parts drift is minimized by utilizing the matched TC characteristics in the IC design while good crystal aging is maintained by pre-aging and then sorting crystals with a curve fit routine using data obtained by actively aging the crystals. Hysteresis is also minimized through crystal sorting and with attention to thermal design. Overall hysteresis and aging are further controlled by hermetically sealing the entire oscillator. 

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Digital Signal Processing

By Thomas Callaghan
Watkins-Johnson Company

Digital signal processing is not an easy topic to comprehend. It combines theories of both the analog and the digital disciplines. To ease this understanding, one should remember that all aspects of DSP can be divided into three areas:

- 1) Input Signal
- 2) Digital Processor
- 3) Information Extraction

The input signal must be sampled and quantized before it can be fed to the digital processor. The digital processor can only perform the operations of addition, multiplication and delay (storage) on the signal data. The end result of the digital processor is to extract information from the signal or modify it in some way. This article will explain the input signal.

The input signal, which is analog in nature, can be classified as a continuous time, continuous amplitude signal. To be of a form useful to a digital processor the signal must be converted to a discrete time, discrete amplitude signal.

Sampling

Sampling is the process by which the continuous time, continuous amplitude signal is converted to a discrete time, continuous amplitude signal. This is done by periodically taking minute time chunks out of the analog signal. The output of a sampler is a series of pulses whose envelope approximates the original signal. The process can be represented by multiplying the input signal by a pulse train of uniform amplitude and equal spacing, (Figure 1).

The pulse spacing, T , that is the sampling frequency, $1/T$, cannot be arbitrarily chosen. According to the Sampling Theorem, "If a continuous time function contains only frequency components below F cycles per second, $2F$ samples per second suffice to represent it perfectly and permit perfect recovery." The reason for this is more readily seen in the frequency domain. Referring to Figure 2, one can see that one of the byproducts of sampling is the duplication of the signal every F_s , the sample frequency. If the sample frequency is kept above or equal to $2F$, (Figure 2b), the sampled frequen-

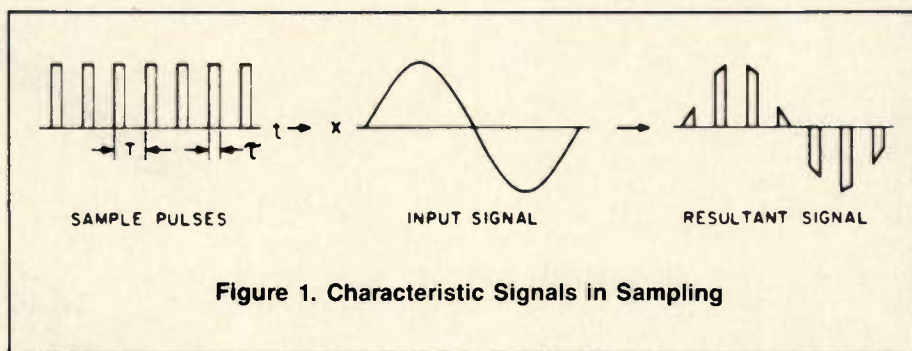


Figure 1. Characteristic Signals in Sampling

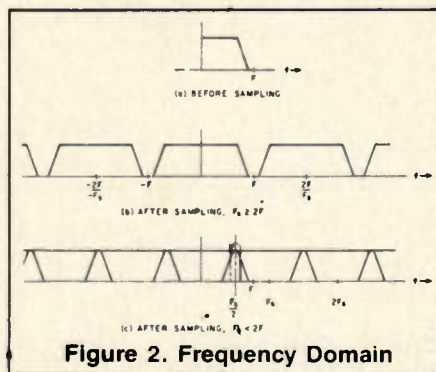


Figure 2. Frequency Domain

cy spectrum produces no overlap and the original signal can be retrieved. If the sample frequency drops below $2F$, the sample frequency spectrum starts to overlap. Any of the frequencies whose spectra are contained in this overlap tend to fold over about $F_s/2$ and into the actual frequency band, as indicated in Figure 2C. This foldover of frequency is called aliasing.

Examples of frequency aliasing are witnessed daily by many unknowing observers. For example, in the old "Westerns," the stage coach rides out of town and its wheels appear to speed up, stop and then go backwards. The backwards revolution is caused by the movie camera not taking sufficient frames per second to dependably capture the wheel's revolution. Another example is when a television or computer terminal is shown in a movie with black bars across the screen. Again, the movie camera is not updating the screen fast enough. In this case, the camera moves at 24 frames per second while the television scans a new frame at

60 times per second.

The sampling theory is all well and good on paper, but in reality it is difficult to remove all unwanted frequencies above the frequency of interest. The most common solution is to place a filter ahead of the sampler to remove unwanted frequencies. The filter, however, has two disadvantages; it alters the signal of interest and unless it has very steep skirts certain unwanted frequencies are passed. A second solution is to sample at a faster rate than $2F$. How much faster is open to debate. Sample too fast and one puts an undue burden on the digital processor.

Another consideration in determining sampling frequency is interpolation errors. Since one is dealing in discrete time, what has happened to the input signal between samples is not known. Naturally, the faster the sample rate the more information known about the signal. When processing is finished, it may be desired to convert back to an analog signal. The conversion is usually done with a D/A converter and some type of low-pass filter to smooth, or interpolate, the discrete points.

So how does one select the sample rate? Gardenhire in [1] presents a good approach to the problem. In his work, the sampling rate is based upon the amount of interpolation error tolerable from the output filter given a specified input filter roll-off characteristic. The input filter roll-off determines the order of the system. Given a certain roll-off, m , the sample rate can be determined from the acceptable interpolation error. The rate is given for a 5% error in Table 1.

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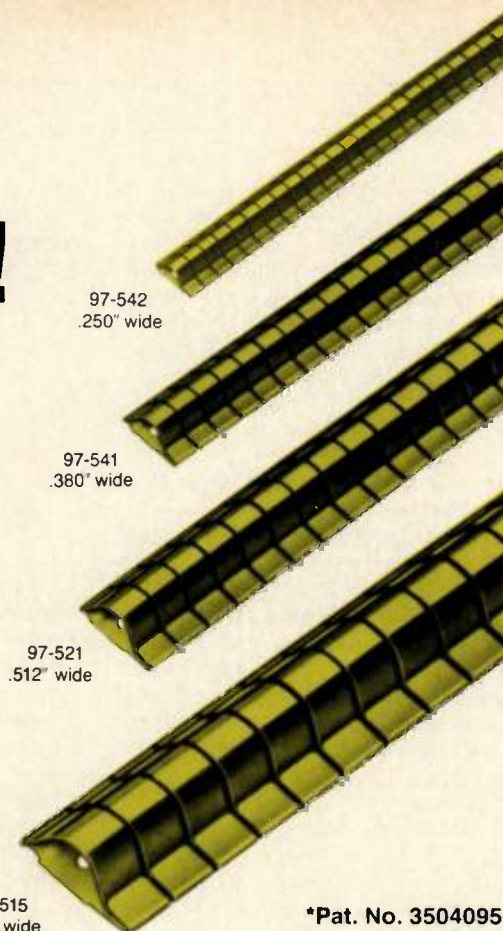
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The filter method employs analog interpolation after D/A conversion. The 2, 3, or 4 point linear interpolation method is done via a computer and the output is still in a digital format. It is interesting to note how the sample rate approaches the theoretical rate of $2F$ as the order of the filter increases. It is also worth noting how the sample rate increases drastically as one tries to follow the input signal more closely with a minimum of error.

For communications applications, however, one is dealing primarily with input filters whose order does approach infinity. The output filters are also optimized, or of Butterworth types. For these reasons a sample rate in the range of 2 to 5 times F should prove satisfactory.

Another error that appears during sampling is known as aperture error. This error is caused by the sample pulses taking a small amount of time to capture the analog signal. During this time, the input voltage can change drastically as the signal goes through zero. This is indicated in Figure 1 by the triangular shapes of some of the sampled data pulses. The aperture error can be expressed mathematically [2] for a sinusoidal input by:

$$\epsilon = \frac{\Delta V}{V_{FS}} = 2\pi\tau$$

Table 1. Systems Resulting in a 5% Interpolation Error [1]

Normalized sample frequency (F_s/f_1)

Interpolation Method	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6
Wiener Optimum Filter	640	11	5.1	3.8	2.6	2.0
Butterworth n = 4	—	16	8.3	5.5	5.5	5.5
n = 3	—	18	9.2	6.7	6.7	6.7
n = 2	1.2×10^3	29	17.0	11	11	11
RC Filter n = 1	1.2×10^4	220	130	91	91	91
2 Point and Linear Interpolation	640	13	8.3	5.9	5.9	5.9
3 Point Linear Interp.	640	12	6.2	5.2	—	4.0
4 Point Linear Interp.	640	12	5.7	4.3	—	3.3

where V_{FS} is the full scale voltage and τ is the duration of the pulse.

Expressed another way, the acceptable pulse duration can be calculated as

$$\tau = (2\pi \times F \times 2^n)^{-1}$$

where n is the number of bits of resolution of the A/D converter for an A/D converter with a 1LSB error. For instance, if the input frequency is 10 kHz and eight bits or resolution are used, the allowable pulse duration = 63.5 ns.

To alleviate aperture error, a track and hold amplifier can be inserted before the

A/D converter. This device's output will follow the input signal while its track digital level is active. When the track input switches, the output is held at its current level and will not vary over the duration of the pulse.

Quantization

After the discrete time, continuous amplitude signal is obtained, it must then be converted to a discrete time, discrete amplitude signal for the digital processor. This process is formally called quantization, but it is more commonly known as analog to digital (A/D) conversion. A quantizer takes a specific amplitude

range and divides it into a series of discrete steps, Q . A digital number is then assigned to each Q .

The number of bits in the digital word determines the number of steps that can be achieved. For n bits, the number of steps would be 2^n . Each step Q , or each change of 1LSB, would be

$$Q = V_{FS}/2^n$$

where V_{FS} is the full scale magnitude of the allowable input voltage.

If the input signal falls between steps then the digital number assigned to it depends on whether the quantizer rounds the samples or truncates them.

As its name implies, the quantizer rounds off the analog input to the nearest quantizer level, Q . In truncation, (Figure 3), the signal is represented by the highest Q level that is not greater than the signal. Thus, for each LSB (least significant bit) step of the digital output word, the error from the original signal would be $\pm 1/2$ LSB for rounding and a 0 or +1LSB for truncation. An error of $\pm 1/2$ LSB yields a mean error of zero, whereas a 1LSB error yields a mean error of $+1/2$ LSB. For

this reason, rounding is preferred in most practical considerations.

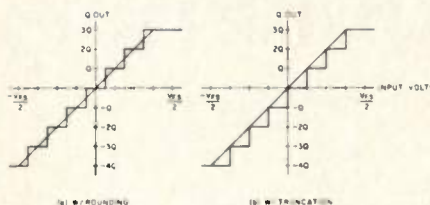



Figure 3. Quantizer Characteristics

How the digital word is represented is another area of consideration. Binary representation varies widely for positive and negative numbers. Again, for most practical considerations, two's complement representation is chosen because most processors use this type of representation. Also, for other applications only positive numbers are expected. Many A/D converters allow either; that is, a range of 0 to V_{FS} or $-V_{FS}/2$ to $+V_{FS}/2$, as well as other representations.

Finally, once the quantizer or A/D converter is chosen the number of bits of

resolution must be decided. While a large number of bits will represent an analog signal more accurately, they will not represent a cleaner analog signal. In every analog signal, there exists some inherent noise that is some small portion of that signal. The more bits of resolution, the smaller the step size in the quantizer. The smaller the step, the more the digital word is affected by noise, so that the lower significant bits only serve to give a good representation of this noise. 

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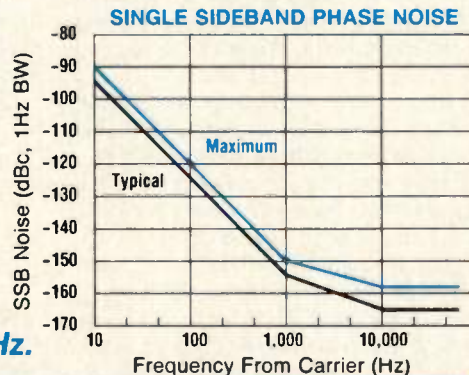
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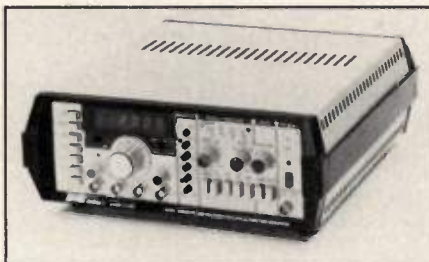
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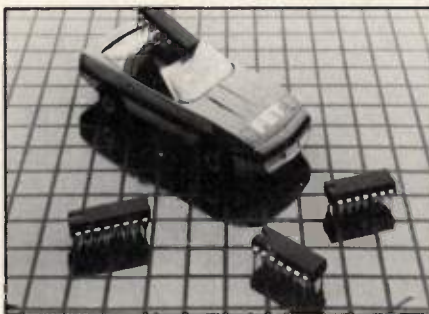
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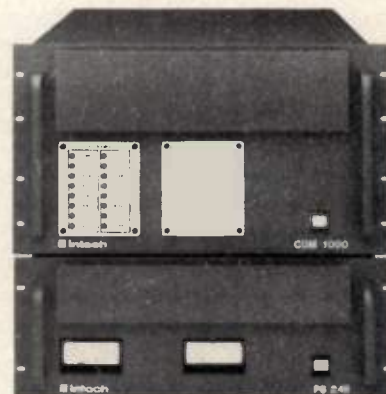
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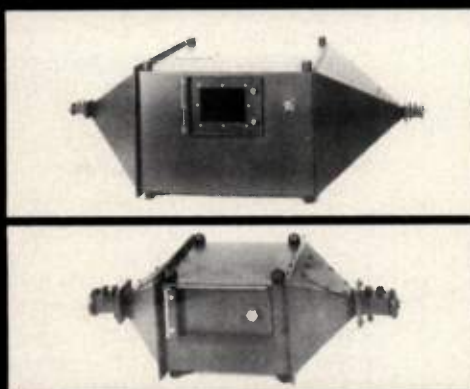
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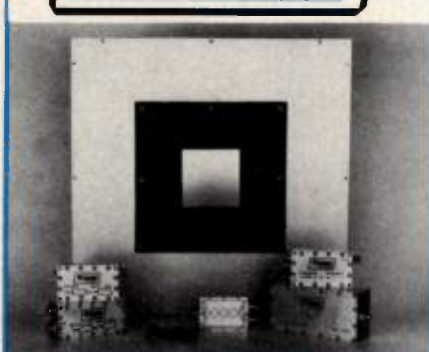
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INFO/CARD 39

rf products Continued

Tech Inc., Fair Lawn, New Jersey,
INFO/CARD #168.

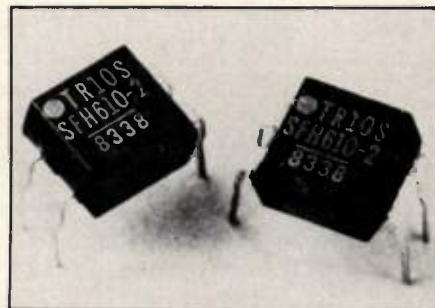
PIN Diode Drivers

Model 254's small 1/4 wide x 3/8 long size makes it easy to fit into any circuit. This inverting driver with typical output current of 20 mA is fully TTL compatible, including low power Schottky logics. It operates from ± 5 VDC and dissipates less than 1/2 watt under switching conditions of 35 ns max. In house screenings per MIL-STD-883C, Method of 5008.2, Class B, Table VIII is available for a minimal charge of \$10 each. New England Microwave Corporation, Hudson, New Hampshire, INFO/CARD #167.

Miniature Optocouplers

The SFH 610/611 series of miniature optocouplers in a 4-lead dual in-line package is being offered in four high current transfer ratio groups: SFH 610/611-1: 40-80%; SFH 610/611-2: 63-125%; SFH 610/611-3: 100-200%; and SFH 610/611-4: 160-320%. The difference in the SFH 610 and SFH 611 is only in the pin connections. Package dimensions for

this handy 4-pin single-channel coupler are significantly scaled down in length to only .2" — compared to a standard 6-pin DIP length of .34" — and make it especially suitable for applications where board space is at a premium. It is designed for use in electronic test equipment, medical instrumentation, computer



peripherals and communications equipment. The devices are optically coupled isolators employing a gallium arsenide (GaAs) infrared emitter and a silicon phototransistor detector. They feature a 2800 volt isolation and are awaiting VDE approval. Siemens Components, Inc., Cupertino, Calif., INFO/CARD #165.

LOWEST PRICED, HIGHEST QUALITY ATTENUATORS - BNC \$11.00 1-9EA, SMA \$8.90 10EA, AND TERMINATIONS - BNC \$5.60 10EA, SMA \$5.60 10EA, MIL. HI-REL. NETWORKS

Model Number (2)	Impedance Ohms (Power W)	Frequency Range	BNC	UNIT PRICE (4) EFFECTIVE 1-18-85	SMA	PC
Fixed Attenuators, 1 to 20 dB						
AT-50(3)	50 (1 SW)	DC-1.5GHz	14.00	20.00	18.00	—
AT-51	50 (1 SW)	DC-1.5GHz	11.00	18.00	15.00	12.00
AT-52	50 (1 SW)	DC-1.5GHz	14.50	20.50	18.50	—
AT-53	50 (2 SW)	DC-3.0GHz	14.00	17.00	15.00	—
AT-54	50 (2 SW)	DC-4.2GHz	—	—	18.00	—
AT-55	50 (2 SW)	DC-4.2GHz	—	—	8.90 (10EA)	—
AT-75 or AT-90	75 or 93 (1 SW)	DC-1.5GHz (750MHz)	14.00	20.00	18.00	—
Detector, Mixer, Zero Bias Schottky						
CD-51	50	01-4.2GHz	84.00	—	54.00	—
DM-51	50	01-4.2GHz	—	—	64.00	—
Resistive Impedance Transformers, Minimum Loss Pads						
RT-50/75	50 to 75	DC-1.5GHz	10.50	19.50	17.50	—
RT-50/93	50 to 93	DC-1.5GHz	13.00	19.50	17.50	—
Terminations						
CT-50 (3)	50 (1 SW)	DC-4.2GHz	11.80	15.00	17.50	—
CT-51	50 (1 SW)	DC-4.2GHz	9.50	12.00	9.50	—
CT-52	50 (1 SW)	DC-2.5GHz	10.50	15.00	13.00	15.50
CT-53M	50 (1 SW)	DC-4.2GHz	5.60 (10EA)	—	5.60 (10EA)	—
CT-54	50 (2 SW)	DC-2.0GHz	14.00	15.00	17.50	—
CT-75	75 (2 SW)	DC-2.5GHz	10.50	15.00	13.00	15.50
CT-93	93 (2 SW)	DC-2.5GHz	13.00	15.00	—	15.50
Mismatched Terminations, 1:05:1 to 3:1, Open Circuit, Short Circuit						
MT-51	50	DC-3.0GHz	45.50	45.50	45.50	—
MT-75	75	DC-1.0GHz	—	45.50	—	—
Feed thru Terminations, shunt resistor						
FT-50	50	DC-1.0GHz	10.50	19.50	18.00	17.50
FT-75	75	DC-500MHz	10.50	19.50	19.50	17.50
FT-90	93	DC-150MHz	13.00	19.50	19.50	17.50
Directional Coupler, 30 dB						
DC-500	50	250-500MHz	90.00	—	—	—
Resistive Decoupler, series resistor or Capacitive Coupler, series capacitor						
RD or CC-1000	1000 (1000PF)	DC-1.5GHz	12.00	18.00	18.00	17.00
Adapters						
CA-50 (N to SMA)	50	DC-4.2GHz	—	—	13.00	13.00
Inductive Decouplers, series inductor						
LD-R15	0.15uH	DC-500MHz	12.00	18.00	18.00	17.00
LD-R6	6.5uH	DC-55MHz	12.00	18.00	18.00	17.00
Fixed Attenuator Sets, 3, 6, 10, and 20 dB, in plastic case						
AT-50-SET (3)	50	DC-1.5GHz	60.00	84.00	84.00	78.00
AT-51-SET	50	DC-1.5GHz	48.00	64.00	64.00	60.00
Reciprocal Multipliers, 2 and 4 output ports						
TC-125-2	50	1.5-125MHz	64.00	—	67.00	67.00
TC-125-4	50	1.5-125MHz	67.00	—	81.50	81.50
Resistive Power Dividers, 3, 4 and 8 ports						
RC-3-30	30	DC-2.0GHz	84.00	—	—	84.00
RC-3-30	30	DC-500MHz	64.00	—	—	84.00
RC-8-30	30	DC-500MHz	—	—	—	84.50
RC-3-75, 4-75	75	DC-500MHz	64.00	—	—	84.00
Double Balanced Mixers						
DBM-1000	50	5-1000MHz	81.00	—	71.00	81.00
DBM-500PC	50	2-500MHz	—	—	—	34.00
RF Fuse, 1/8 Amp and 1/16 Amp						
FL-50	50	DC-1.5GHz	12.00	18.00	—	17.00
FL-75	75	DC-1.5GHz	12.00	18.00	—	17.00

NOTE: 1) Critical parameters fully tested and guaranteed. Fabricated from Mil. Spec. High-Rel. materials. Schottky diodes. Mil. Spec. plated parts and connectors (in nickel, silver, and gold). 2) See catalog for complete Model Number, Specify connector series. Specials available. 3) Calibration marked on label of unit. 4) Price subject to change 1985-A without notice. Shipping \$5.00 Domestic or \$15.00 Foreign on Prepaid Orders. Delivery by stock to 30 days ARO.

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INFO/CARD 40

TWT Power Supply

A MODULAR INTEGRATED TWT POWER SUPPLY, Model No. 10755 coupled to a 50-125w (C-Band) or 50-125w (Ku-Band) TWT tube will reduce waveguide losses for Ku-Band and C-Band antenna pedestal installation. Highly efficient with state of the art current driven VFET circuitry, the power supply is easily adaptable to particular customer specifications and unique requirements. Fully encapsulated high voltage components are included in this easy to operate unit with capacity up to 125 watt TWTs. The power supply has a modular concept, extreme wide operating temperature range and is conduction cooled. **MCL, Inc., LaGrange, Ill., INFO/CARD #163.**

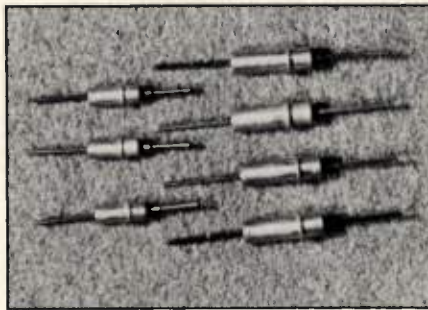
Circuit Simulator

The SIMON circuit simulator is a full circuit simulation software package created specifically for MOS and CMOS circuits. Using an entirely new algorithm (not a SPICE derivative) SIMON offers unmatched speed (10 to 50 times faster than SPICE), guaranteed convergence, simulation of circuits far larger than

previously possible and state of the art user friendly features. SIMON is available for a variety of host computers with price depending on the individual installation and CPU unit. Ongoing support, maintenance and updates are available via a maintenance agreement. **Simon Software, Inc., San Jose, Calif., INFO/CARD #162.**

Ruggedized EMI Filter Pins

EMI Filter Pins are improved and updated versions of the traditional tubular ceramic-bodied filter pin. Features include: metal shell construction providing a rugged housing to withstand assembly and environmental rigors; round or



square cross section pins for solder or wire-wrap applications; expanded capacitance range. 100 pf to .07 μ f available; voltage ratings of 50-300 VDC and 115 VAC; current rating 10 AMPS; available in C, L, π and T circuit configurations; typical insertion loss values of 4 dB at 100 kHz, 20 dB at 1 MHz, 50 dB at 10 MHz and 70 dB at 100 MHz and up for the 50 volt rated π section filter. **Ceramic Devices, San Diego, Calif., INFO/CARD #161.**

Digital Potentiometer

The HEDS-7500 digital potentiometer produces digital output directly from manual rotary input. The new device



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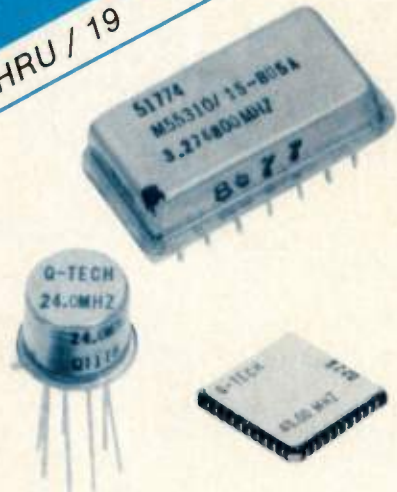
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rf products *Continued*

enables bi-directional counting by decoding two digital-pulse trains, which are out of phase by 90 electrical degrees. Available with a standard 256 pulses per revolution, the device commonly is used as a knob on the front panel of equipment where a digital display may be used to indicate the position of the knob. Hewlett-Packard, Palo Alto, Calif., please circle INFO/CARD #160.

Snap Lock Connectors

An environmentally sealed series of quick connect/disconnect connectors that provides a labor-saving alternative to traditional environmental PC board connectors, called Snap Lock Environmental (SLE), is specifically designed for computer/controlled applications that must



withstand severe environments. The SLE design does away with expensive slide latches, spring latches or even center jack screws by integrally molding snap locks to the receptacle body on the mating side. This side also offers a heavy duty interfacial gasket and multiple labyrinth seals in the rear to protect against severe conditions. ITT Cannon, Fountain Valley, Calif., INFO/CARD #159.

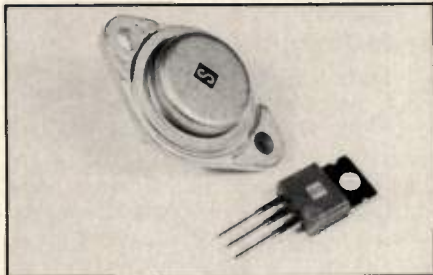
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March 1985

800 Volt Hi-Rel Power MOSFETs

A new series of high reliability, fast switching power MOSFETs meet high temperature requirements and feature hexagonal geometry, voltage (drain to source) to 800 volts and drain currents to 456 amps. Identified as SWITCHMOS,



these units offer eutectic mounted packaging for military and industrial applications in TO-220 and TO-3 cases. Solitron Devices, Inc., Riviera Beach, Fla., INFO/CARD #157.

Miniature Pin Switch

This miniature pin switch has a frequency range of 10-1000 MHz at a 50 ohm impedance with an environmental temperature range of -55°C to +85°C. It

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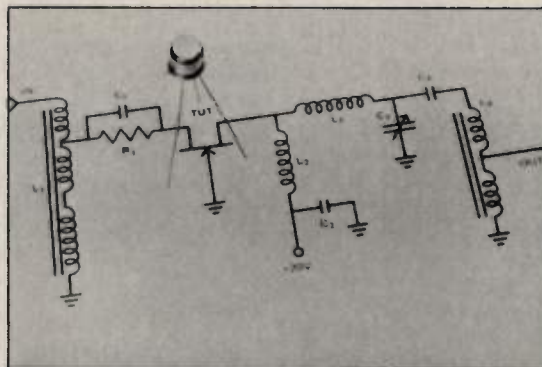
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rf products *Continued*

is available in the TO-5 housing. Power requirement is ± 15 volts at 10 mA, and a maximum RF input at 20 dBm. This SPST configuration has an insertion loss of less than 1.75 dB at 1000 MHz and isolation greater than 30 dB at 1000 MHz. Wavetek Indiana, Inc., Beech Grove, Ind., INFO/CARD #156.

Modular Probe Family

A unique high voltage RF detector probe, Model 10851A, features an optional "Tee" connector for direct 50-ohm measurements and a 100:1 divider to handle very high RF input voltages; the first multimeter probe capable of this performance. The new probes are designed to mate with virtually any brand of laboratory-grade oscilloscope. An adjustable wideband probe cable terminator network is provided so that correct high frequency compensation can be obtained for any scope. There is no compromise in risetime or bandwidth relative to comparable original equipment probes. Switch-selectable X1/X10 attenuation is also available on several models.

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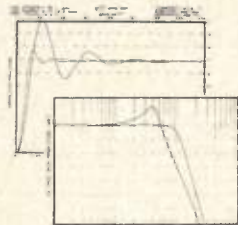
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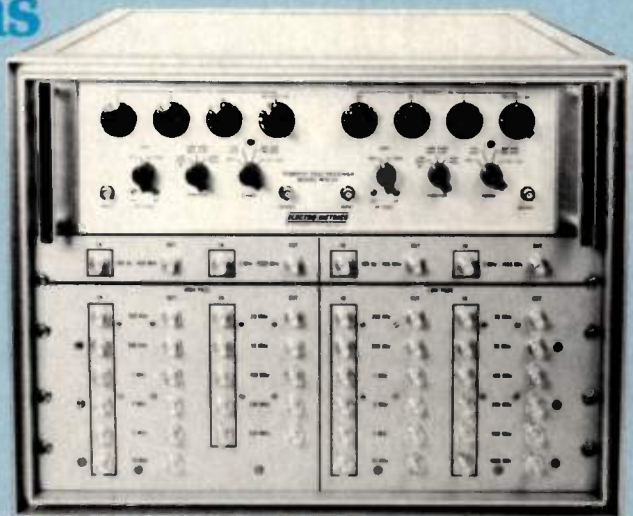
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A quartz resonator for UHF oscillators has surfaced...



Introducing the surface acoustic wave (SAW) resonator. This fundamental-mode UHF resonator is manufactured with semiconductor processing techniques using quartz as a substrate. The high-Q resonance of the SAW resonator arises from phased reflections across the surface of the device — similar mathematically to the resonance of a laser. The quartz SAW resonator makes an excellent frequency control device for UHF oscillators from 300 to over 1000 MHz. SAW resonators are used in RF applications from precision instrumentation to high-volume consumer electronics.

For more information on the characteristics and applications of the quartz SAW resonator please contact:



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rf literature

Electrolytic Capacitor Catalog

Included in a new 33-page Electrolytic Capacitor Catalog are complete electronic and mechanical specifications for high voltage and extended temperature range versions; miniature, subminiature, and super subminiature sizes; low leakage, low noise and bi-polar versions; low ESR and low impedance types. **Paccorn Electronics, Redmond, Wash., INFO/CARD #142.**

Semiconductor Catalog

The comprehensive 400-page catalog from Alpha Industries contains technical data sheets and application notes for mixer and detection diodes, including Schottky barrier and point contact diodes; control diodes, including PIN switching, attenuator, and limiter diodes, and Silicon/GaAs tuning diodes; power generation devices, including Gunn diodes/modules, and Silicon GaAs parametric amplifier diodes; Silicon/GaAs multiplier and step recovery diodes. **Alpha Industries, Inc., Woburn, Mass., INFO/CARD #138.**

Triple Output Power Supply Comparison Chart

A free triple output power supply comparison chart covers Electronic Measurements, Lambda, Kepco, Hewlett Packard, Dynascan and Systron Donner models. Parameters needed to select the proper triple output supply for your specific needs are detailed, including outputs for 1, 2, 3, max. output power outputs isolated, series operation, parallel operation, output modes, voltage current set, panel meter, simulation read volts and amps, regulation, ripple, isolation, output/case, frequency at output, size, bench area sq. ft., warranty and price. **Electronic Measuring, Inc., Neptune, New Jersey, INFO/CARD #137.**

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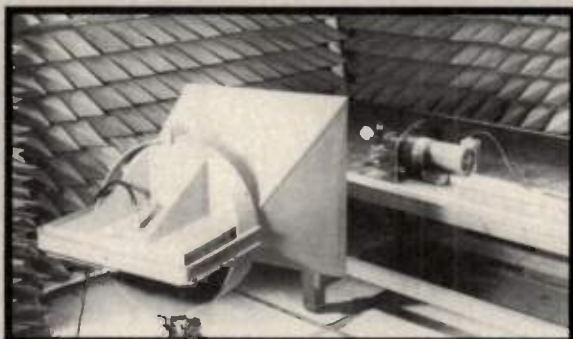
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- Radiated susceptibility testing: 10kHz-18 GHz
- Enclosure treated with RF anechoic material
- Emissions testing: 20 Hz to 40 GHz
- Modern semi-automatic swept EMI receivers
- Automated analysis; x-y plots to 40 GHz
- Mobile EMI vans for remote-site testing
- EMC consulting and custom EMI filter designs

Current Capabilities Include:

Frequency	Field Intensity	Modulation	Antennas
10 kHz - 30 MHz	200 V/m	CW, AM, FM or β M	IFI EFG-3, AR AT3000, parallel plate
30 MHz - 150 MHz	200 V/m	CW, AM, FM, β M or pulse mod	IFI EFG-3
150 MHz - 375 MHz	200 V/m	CW, AM, FM, β M or pulse mod	IFI EFG-3, AR AT1000
375 MHz - 1 GHz	200 V/m	CW, AM, FM, β M or pulse mod	AR AT1000, Stoddart 92270-1 Horn
1 GHz - 18 GHz	200 V/m	CW, AM or pulse mod	Standard gain horns, and ridged-guide horns
18 GHz - 40 GHz	200 V/m	CW, AM or pulse mod	(Available by August 1985)

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INFO/CARD 53

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50 ohms nominal

Use two or more in tandem for odd values, or use with Bird High Power Attenuators (to 4000 watts) for additional attenuation.

Input Power Watts	dB Attenuation	Frequency GHz	Connectors	VSWR Max.
2	1, 2, 3, 6, 8, 10, 14, 20	DC-2	BNC-M/F	1.2
5	3, 6, 10, 20, 30	DC-4	N-M/F	1.25
10	3, 6, 10, 20, 30	DC-4	N-M/F	1.25
15	3, 6, 10, 20, 30	DC-4	N-M/F	1.25
25	3, 6, 10, 20, 30	DC-4	N-M/F	1.25
75	3, 6, 10, 20, 30	DC-2	N-M/F	1.25

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216-248-1200 TLX: 706898 Bird Elec UD

WEST: Ojai, CA 805-646-7255

For Low Power Bulletin
circle INFO/CARD 54

For High Power Bulletin
circle INFO/CARD 55

HIGH DYNAMIC RANGE

RF AMPLIFIERS



Janel offers a wide variety of high dynamic range RF Amplifiers. The chart below shows a sampling of what's available. All feature high *guaranteed* performance and yet are competitively priced. Many models are available from stock.

Model	Frequency	Gain	N.F.	3rd I.P.
PF811A	1-32 MHz	16.5dB	4.5dB	+42dBm
PF841	2-32	16.5	5.0	+46
PF804	215-320	27.0	4.0	+32
PF829	406-512	16.5	4.5	+38
PF833	800-920	26.5	2.8	+34
PF845	800-915	18.0	2.0	+35

In addition to RF Amplifiers, Janel manufactures a wide range of standard Power Dividers and other rf components. Custom designs can be provided for unusual applications. For detailed information, call or write Janel Laboratories, Inc., 33890 Eastgate Circle, Corvallis, OR 97333. Telephone (503) 757-1134.



JANEL LABORATORIES

INFO/CARD 56



How to get fast delivery on step attenuators

Select from the wide range of precision step attenuators in our catalog and get fast delivery. Of course, if you require a custom design we will build it for you but this increases lead time and your cost. Consider modifying your requirements to our catalog specifications. This will get you fast delivery and save you money. It is to your advantage to compare your needs with our specs below.

Alan Step Attenuator Condensed Catalog List

All products manufactured per MIL-Q-9858A and MIL-STD-45662

Series Description	Attenuation Range/Steps	Frequency Max.	Connectors
SV, Subminiature	0-10dB/1dB 0-100dB/10dB	DC-1.5GHz	SMA, SMB, SMC
V, Low Attenuation	0-1dB/0.1dB 0-70dB/10dB	DC-2GHz	TNC, BNC, N, SMA, F
V, Medium Attenuation	0-80dB/10dB 0-100dB/10dB	DC-1GHz	TNC, BNC, N, SMA, F
V, High Power	0-10dB/1dB	DC-500MHz	BNC, TNC, SMA, N
B, Low Cost	0-10dB/1dB 0-50dB/10dB	DC-300MHz	BNC, TNC, SMA, F
SDV, Miniature Dual Concentric	0-29dB/1dB 0-109dB/1dB	DC-1GHz	BNC, TNC, N, SMA
DV, Standard Dual Concentric	0-10.9dB/0.1dB 0-109dB/1dB	DC-1.5GHz	BNC, TNC, N, SMA, F

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INFO/CARD 57

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Standard frequencies are available from 1

DIP M80	T05	T08	BAUD RATE GENERATOR	FLAT PACK
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NOTE 1: Very low current CMOS analog logic requires an input frequency of up to 20 MHz and 5V is available

NOTE 2: Non standard custom designing with multiple outputs, 20MHz outputs, ECL, 8 pin package available

NOTE 3: Low or high impedance outputs available with custom designing

TCXO's	VCXO's	XO's
<p>STABILITY:</p> <p>1 $\pm 1 \times 10^{-4}$ (0°C to 50°C)</p> <p>2 $\pm 2 \times 10^{-4}$ (-20°C to 70°C)</p> <p>3 $\pm 5 \times 10^{-4}$ (-40°C to 85°C)</p> <p>4 $\pm 1 \times 10^{-3}$ (-55°C to 105°C)</p>	<p>STABILITY: $\pm 0.001\%$ to $\pm 0.01\%$</p> <p>LINEARITY: $\pm 1\%$ to $\pm 10\%$</p> <p>DEVIATION: $\pm 0.001\%$ to $\pm 1\%$</p>	<p>STABILITY:</p> <p>1 $\pm 5 \times 10^{-4}$ (0°C to 50°C)</p> <p>2 $\pm 10 \times 10^{-4}$ (-20°C to 70°C)</p> <p>3 $\pm 20 \times 10^{-4}$ (-40°C to 85°C)</p> <p>4 $\pm 45 \times 10^{-4}$ (-55°C to 125°C)</p>

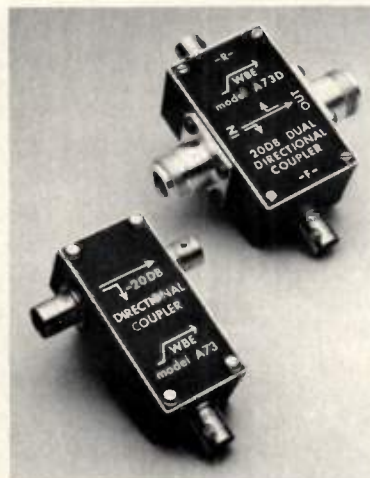
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				1-500 MHz	5-300 MHz			
A73-20	1-500	single	5W cw (10W cw 5-300 MHz)	20	30	.4 max .2 typical	±.1 5-300 MHz ±.25 1-500 MHz	1.5:1
A73-20GA				30	40			
A73-20GB				40	45			
A73-20P	1-100	single	50W cw (75 ohm limited to 10W cw)	35 dB min		.15	±.1	1.1:1 max
A73D-20P		dual		40 dB min typical		.3		
A73-20PX		single		45 dB min		.15		
A73D-20PX		dual		35 dB min		.15		
A73D-20PA		dual		40 dB min typical		.3		
A73-20PAX	10-200	single		45 dB min		.15		1.04:1 typical
A73D-20PAX		dual				.3		

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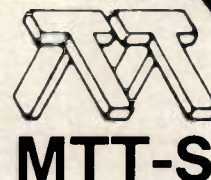
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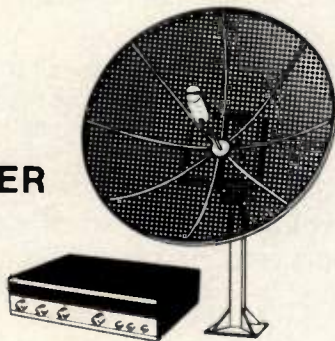
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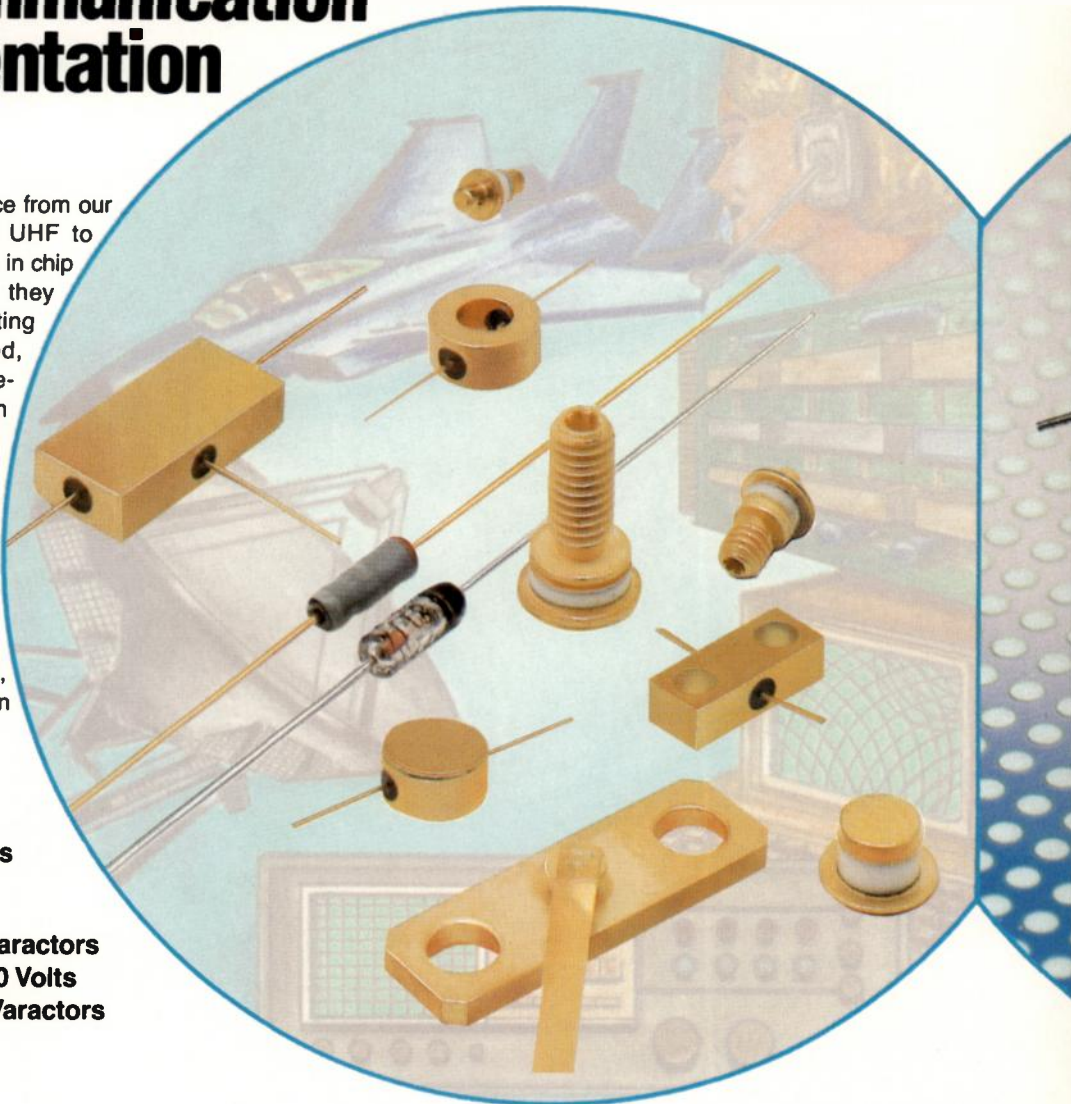
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