rf design

engineering principles and practices

1978-1988 10th ANNIVERSARY

June 1988

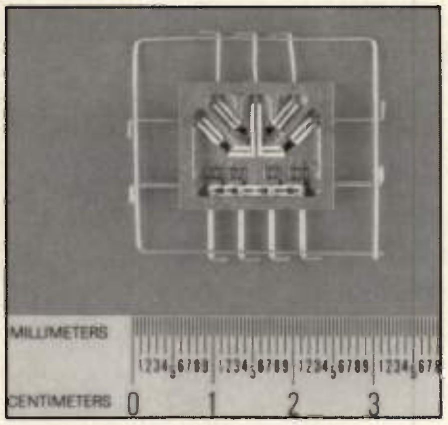
GaAs MESFET Switches Reach Higher Power

Featured Technology — Microstrip Design Basics

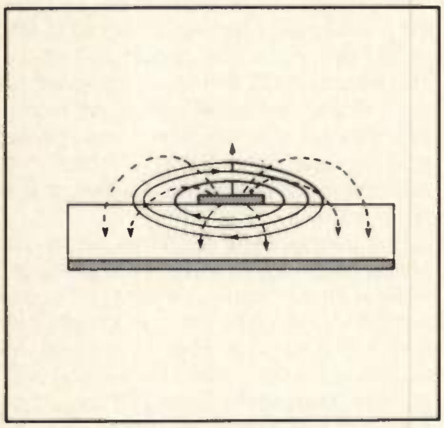
Plus: Product Introductions at MTT-S Show

rf design

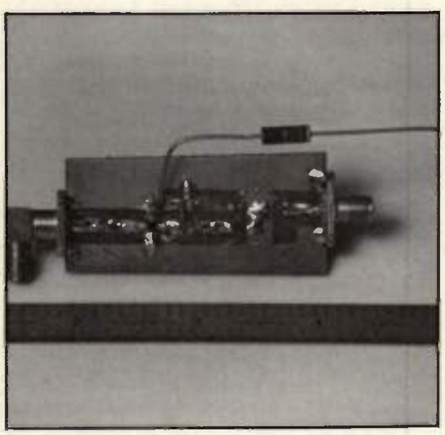
June 1988



Page 19 — GaAs MMIC Switches



Page 29 — Microstrip Basics



Page 64 — MMIC Multipliers

Cover Story

Featured Technology Section

Departments

R.F. DESIGN (ISSN: 0163-321X USPS: 453-490) is published monthly plus one extra issue in September. June 1988, Vol. 11, No. 6. Copyright 1988 by Cardiff Publishing Company, a subsidiary of Argus Press Holdings, Inc., 6300 S. Syracuse Way, Suite 650, Englewood, CO 80111 (303) 220-0600. 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, (218-723-9355). Domestic subscriptions are sent free to qualified individuals responsible for the design and development of communications equipment. Other subscriptions are: $33 per year in the United States; $41 per year in Canada and Mexico; $45 (surface mail) 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 $5.50 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.
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rf editorial

In Search of Human Engineering

By Gary A. Breed
Editor

A while back, my parents flew to Colorado from Illinois to pay a visit. Upon arrival, they got into their rental car, turned the key, and were greeted by a blaring radio, fans going full blast, and no idea how to shut them off! You see, this was one of those new models with a master computer system and a touch-screen video display — the highest of high tech. Yet, it wasn't even possible to start the car and drive away without a lesson from the attendant.

This scenario isn't limited to a few fancy cars, either. Think about it: How many pieces of test equipment in your lab required a thorough analysis of the instruction manual (or a call to the factory) before you could make a routine measurement? How many hours did it take to become friendly with your favorite "user-friendly" computer program?

It is extremely unproductive when the complexity of an engineer's tools makes it difficult to perform his or her design tasks. It is even more disconcerting that a manager, who doesn't use the equipment on a daily basis, might not be able to independently evaluate an engineer's design procedures and test results! What is needed is attention to the operators' needs, with the same priority that is given to features and performance.

We need to get through this bottleneck of complexity. The power of computers and intelligent instruments has to be accessible to the users.

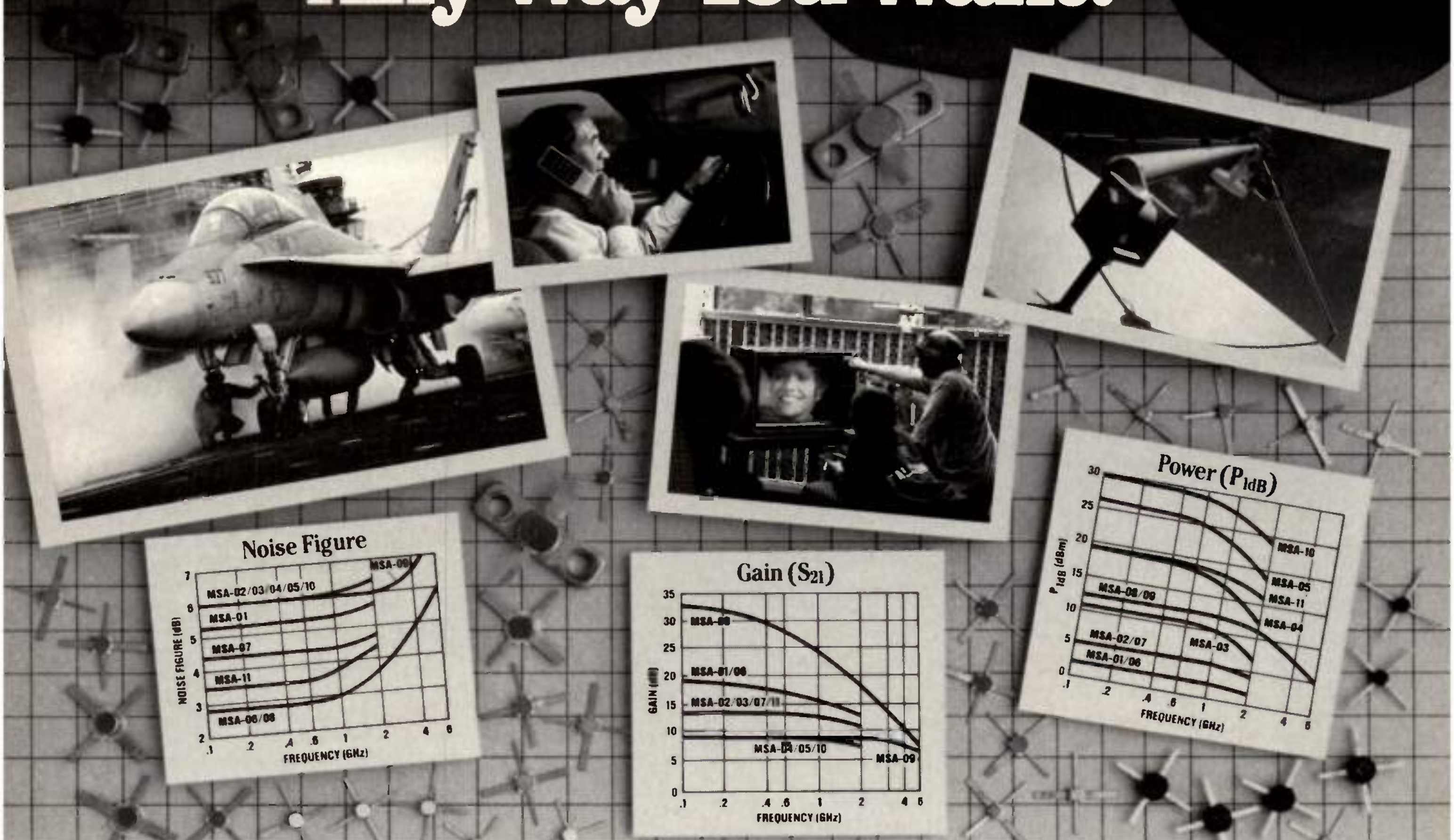
OK, so I've overstated the problem. There are plenty of straightforward instruments and programs that are uncomplicated in the way they operate. However, the clear trend is toward greater capability as microprocessors and memory become truly universal, and as personal computers become more powerful. This increased capability cannot be accessed by the normal front panel, where each control has a specific function. It also means that the user cannot simply "read" the front panel to determine the machine's operation.

Fortunately, there are some beginning efforts under way to improve the situation. Software may incorporate mice, windows, and HELP keys, and can prompt the user for the data it needs. Some of these ideas are being incorporated into test and production equipment, via CRT or other means of text and graphic display. It is obvious that these are early efforts, with many different arrangements of "soft keys," windows, pre-programmed setups, keypads and rotary dials.

Despite my concern, I am certain that this bottleneck will be overcome. Over and over through history, new technology has taken some time to become accessible to everyone who can benefit from it. For RF engineers to benefit from the computing power in software and test equipment, it has to become more accessible, and soon.

Gary A. Breed

Silicon MMICs Any Way You Want!



Avantek Offers the Widest Selection of Wideband Silicon MMIC Amplifiers

Now the trade off between performance, package and price is easier. Avantek has a package/die combination that offers the ideal solution to your overall system performance and cost goals. Our MODAMP™ series, DC to 6 GHz silicon MMIC wideband amplifiers, includes eleven different amplifier die types and nine package options. A total of more than 70 different models. These MMIC amplifiers are available with a wide spectrum of performance options to satisfy nearly every design need.... Minimum noise figures as low as 2.8 dB, gains as high as 33 dB, and P_{1dB} as high as 29 dBm.

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- SOT-143 Plastic
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- 85-Mil Plastic
- 85-Mil Plastic Surface Mount
- micro-X Stripline
- 70 Mil Hermetic
- 100 Mil Hermetic
- 200 Mil BeO
- 230 Mil Flange

Available in Quantity for Volume Applications

Avantek presently produces more than 1,000,000 MMICs per month. So you can be assured the MMICs you need will be available to support your volume production programs. And, all MODAMP MMICs are in stock at your local Avantek distributor. For additional information, or the name and address of your local distributor, contact the regional sales office nearest you.

Regional Sales Offices

North America

Eastern:	(301) 381-2600
Central:	(214) 437-5694
Western:	(805) 373-3870
European:	(44) 276-685753

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Santa Clara, California 95054-3292

INFO/CARD 7

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a Cardiff publication — Established 1978
Main Office:
6300 S. Syracuse Way, Suite 650
Englewood, CO 80111 • (303) 220-0600

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CARDIFF PUBLISHING COMPANY, INC. — BPA

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INFO/CARD 9

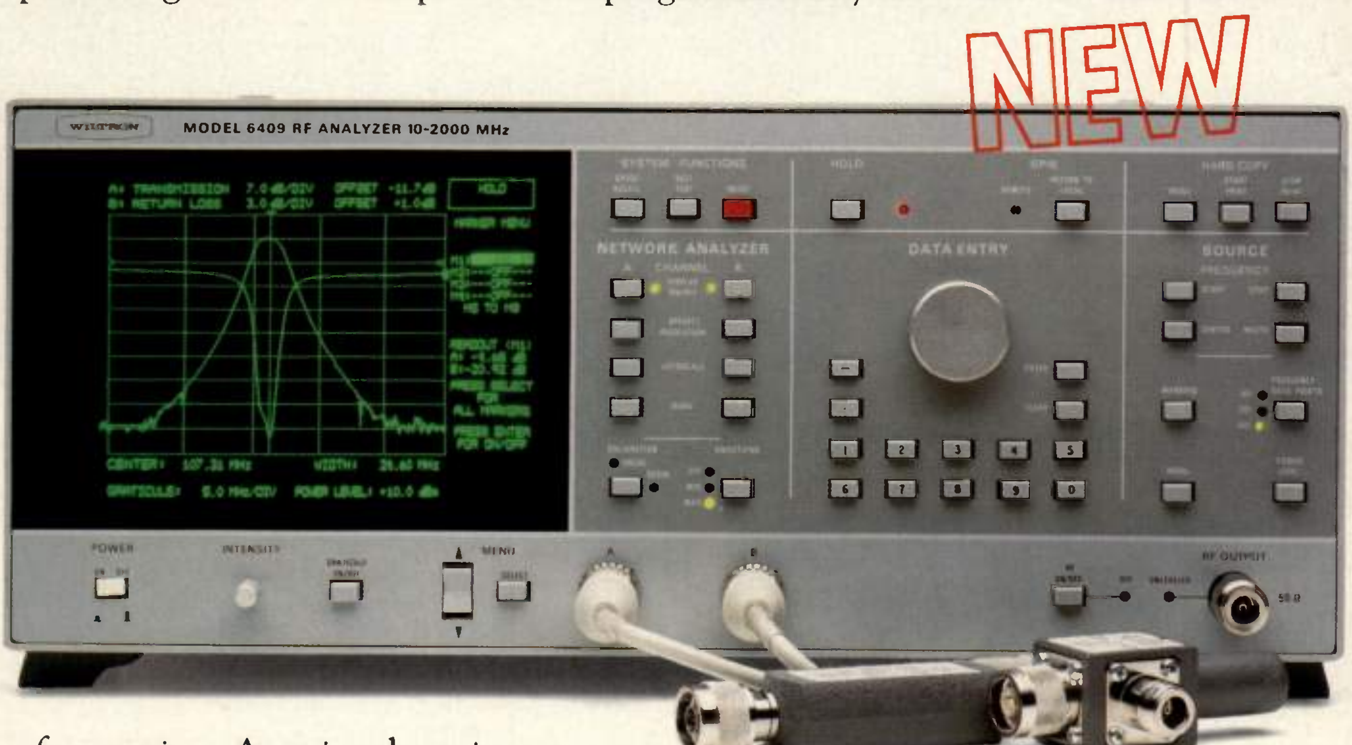
You don't g

With the NEW Wiltron RF Test System.

The new 1 to 2000 MHz Wiltron 6400 RF Analyzer. In a single, compact instrument, Wiltron brings you an affordable crystal-derived swept signal source, a scalar network analyzer, precision measurement components, and a display. Measure transmission, return loss, and absolute power.

It's a remarkable breakthrough. For far less than you would expect to pay, Wiltron gives you synthesizer-like performance over the entire 1 to 2000 MHz.

The 6400 has resolution and accuracy 10 times better than anything in its price range. It offers complete GPIB programmability and a new standard in ease



of operation. At twice the price, the 6400 would still be a bargain.

Our engineers gained exceptional stability and accuracy by "locking" the frequency to a crystal marker at the beginning of every sweep. Because frequency is always on the mark, you won't waste time looking for traces that have drifted off the screen. You'll have excellent repeatability of test data taken on very narrow bandwidth devices. Even if tests are made days apart.

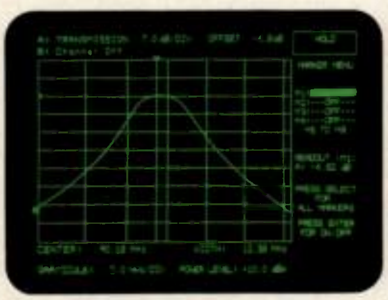
et the drift.

Dynamic range is 71 dB (+16 to −55 dBm). Use the Wiltron 6400 for the most demanding applications including TV tuner, cellular radios, filters, amplifiers, diplexers and DBS. For a permanent record, test data are plotted in graphical or tabular format on an optional ink-jet printer.

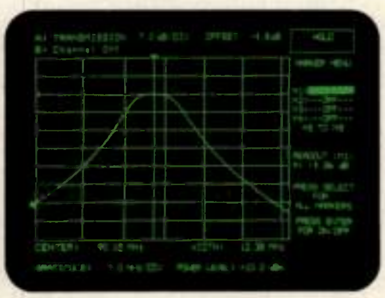
The 6400 is a joy to use on the production line, in the laboratory, or out in the field.

Autoscaling can be used to automatically select the optimum display for your device. The display is fully annotated to ensure accurate, confusion-free interpretation of test data.

Specifications
Signal Source
Frequency Range:
Model 6407: 1 to 1000 MHz
Model 6409: 10 to 2000 MHz
Frequency Accuracy: ± 100 kHz
Frequency Resolution: 10 kHz
Leveled Output Power Range: +12 dBm to +0.1 dBm
Optional attenuator: +10 dBm to −70 dBm
Harmonics: < −30 dBc
Nonharmonic spurious: < −40 dBc
Network Analyzer
Dynamic Range: +16 dBm to −55 dBm
Vertical Display Resolution: 0.003 dB maximum
Horizontal Display Resolution: 101, 201, or 401 points.
Normalization: 800 points, automatically interpolated for ranges less than full range.
Markers: up to 8.
SWR Autotesters
Directivity: 40 dB
Impedance: 50 or 75 ohms
Test Port Connector: Type N or BNC
RF Detectors
Impedance: 50 or 75 ohms
Test Port Connector: Type N or BNC



Test Data on Friday, 10:15 AM:
M1 Marker Frequency: 104.72 MHz
Passband Amplitude at M1 Marker: −4.82 dB



Test Data on Wednesday, 3:30 PM:
M1 Marker Frequency: 104.72 MHz
Passband Amplitude at M1 Marker: −4.86 dB

You get fast production test times since frequencies can be changed without recalibration. Go/no-go limit lines and up to eight markers, which can be set to test points of interest, make readings easier. Costly setup time is eliminated by storing up to nine front panel setups in memory.

In addition to the 6400's 17.8 cm (7 in.) display, there's a composite video output which will drive a larger screen. Production people love it. And with a weight of only 16 kg (35 lb), the 6400 can be carried to the most inaccessible repeater station.

Now in a single instrument, you get everything you need to make fast, accurate RF measurements. And you don't get the drift.

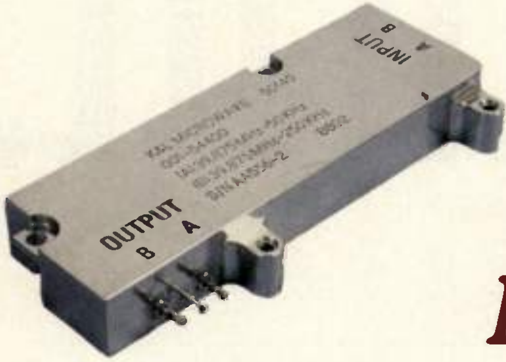
For more information, contact Wiltron, 490 Jarvis Drive, Morgan Hill, CA 95037-2809. Tel: (408) 778-2000.

WILTRON

INFO/CARD 10

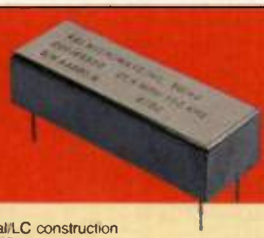
Come see us at the MTT-S Show, Booth #404.

K&L MICROWAVE. CRYSTAL FILTERS: WIDEBAND TO NARROWBAND



K&L Microwave manufactures a complete selection of **crystal filters** from **500KHz** to **160MHz**. From simple IF **Chebyshev** and **Gaussian** designs to complex custom filters, K&L can supply the filters you require. **Complete** in-house **capabilities** include the manufacture of crystals, **laser-weld sealing**, and complete **environmental testing. Call K&L** today **to discuss** your **crystal filter** requirements—wideband, narrowband, and everything in between!

STANDARD 21.4MHZ GAUSSIAN I.F. FILTERS

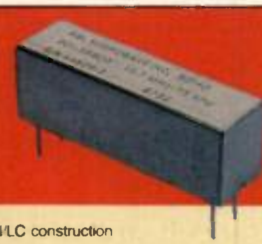


- 21.4MHz Center Frequency
- 6 Pole Gaussian Response, Crystal/LC construction
- Operating Temperature: 0° to +65°C
- Printed Circuit Board mountable

3dB BW (±10%)	60dB BW (Max)	Ins. Loss (Max)	Group Delay Variation 70% of BW3	100% of BW3	Spurious Rejection
5.0KHz	17.5KHz	4.0dB	20μS	50μS	70dB
10.0KHz	35.0KHz	3.0dB	10μS	25μS	70dB
20.0KHz	70.0KHz	3.0dB	5μS	12.5μS	70dB
50.0KHz	180KHz	3.0dB	2μS	5.0μS	70dB
100KHz	400KHz	6.0dB	1μS	2.5μS	55dB
200KHz	800KHz	7.0dB	500nS	1.25μS	50dB
500KHz	2.0MHz	12dB	200nS	500nS	70dB
1MHz	4.0MHz	7.0dB	100nS	250nS	70dB
2MHz	2.0MHz	6.0dB	50nS	125nS	70dB
4MHz	16.0MHz	4.0dB	25nS	63nS	70dB
5MHz	20.0MHz	3.0dB	25nS	50nS	70dB

INFO/CARD 108

STANDARD 21.4MHz CHEBYSHEV I.F. FILTERS



- 21.4MHz Center Frequency
- 6 Pole Chebyshev Response, Crystal/LC construction
- Operating Temperature: 0° to +65°C
- Printed Circuit Board mountable

3dB BW (±10%)	60dB BW (Max)	Ripple (Max)	Ins. Loss @ CF	VSWR Attenuation	Ultimate Rejection	Spurious Rejection
3.2KHz	9.5KHz	0.5dB	5dB	1.7:1	70dB	70dB
5.0KHz	12.5KHz	0.5dB	5dB	1.7:1	70dB	70dB
10.0KHz	25KHz	1.0dB	3dB	1.5:1	70dB	70dB
20.0KHz	50KHz	1.0dB	3dB	1.5:1	70dB	60dB
50.0KHz	125KHz	1.0dB	3dB	1.5:1	70dB	60dB
100KHz	250KHz	1.0dB	3dB	1.7:1	70dB	60dB
200KHz	500KHz	1.0dB	6dB	2.0:1	60dB	55dB
300KHz	750KHz	1.0dB	8dB	2.0:1	60dB	50dB
500KHz	1.5MHz	1.0dB	10dB	2.0:1	70dB	70dB
1MHz	2.7MHz	1.0dB	10dB	2.0:1	70dB	70dB
2MHz	5.4MHz	1.0dB	8dB	1.7:1	70dB	70dB
4MHz	10.6MHz	1.0dB	8dB	1.5:1	70dB	70dB
5MHz	13.0MHz	1.0dB	6dB	1.5:1	70dB	70dB

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rf calendar

July 5-7, 1988
Military Microwaves '88
Wembley Conference Centre,
London, England
Information: P.G. Pinches, Microwave Exhibitions and Publishers Ltd., 90 Calverley Road, Tunbridge Wells, Kent TN1 2UN, England. Tel: (0892) 44027

August 30-September 1, 1988
10th Annual Quartz Devices Conference and Exposition
Westin Crown Center, Kansas City, MO
Information: Peter Walsh, Components Group, EIA, 2001 Eye St., N.W., Washington, DC 20006. Tel: (202) 457-4930

September 12-16, 1988
10th Annual Antenna Measurements Techniques Association Meeting
Atlanta Hilton and Tower Hotel
Information: Becky Clark, 1988 AMTA Symposium, c/o Scientific-Atlanta, Inc., Mail Station ATL 28-I, P.O. Box 105027, Atlanta, GA 30348

1988 RF & Microwave Symposia
Hewlett-Packard Company
September 19, 1988, Kansas City, MO
September 21, 1988, Indianapolis, IN
September 23, 1988, Chicago, IL
October 4,5, 1988, Baltimore, MD
October 11,12, 1988, Boston, MA
Information: Contact local HP sales offices listed in the white pages of the telephone book.

September 14-15, 1988
Mountain States Electronic Expo
Denver Merchandise Mart, Denver, CO
Information: Dick Porter, Midland Exposition Group, 4501 Wadsworth Blvd., Wheat Ridge, CO 80033. Tel: (303) 424-9024

October 4-6, 1988
Northcon '88
Seattle Center Colliseum, Seattle, WA
Information: Electronic Conventions Management, 8110 Airport Boulevard, Los Angeles, CA. Tel: (213) 772-2965

October 25-27, 1988
RF Expo East 88
Philadelphia Civic Center,
Philadelphia, PA
Information: Linda Fortunato, Cardiff Publishing, 6300 S.Syracuse Way, Suite 650, Englewood, CO 80110. Tel: (303) 220-0600; (800) 525-9154

rf letters

A PPDF Correction

Editor:

The article, "A Programmable Pulse Driven Formatter", featured in the April 1988 issue, has an error I would like to correct. Figure 3, Return to One (R1), a PPDF mode, is not correct. Figure 3 is an exact duplication of Figure 2, and should be corrected to look like the oscilloscope photograph on page 30, Figure 8.

I would like to take this opportunity to say I think that your magazine is an excellent source of new and exciting ideas in the RF engineering field.

Norbert Rehm
Regency Electronics, Inc.
Indianapolis, IN

Editor:

The article "A Programmable Pulse Driven Formatter" appearing in the April 1988 Featured Technology section indeed had an error that I would like to correct. The waveforms shown on page 26 should have been as shown below.
Figure 2 was incorrectly called Figure 21, and Figure 3 duplicated the RZ waveforms from Figure 2 instead of the correct R1 waveforms.

The article looked great and we continue to receive compliments on it from our customers. Thanks for all your help!

Karl C. Zabel
Harris Microwave Semiconductor
Milpitas, CA

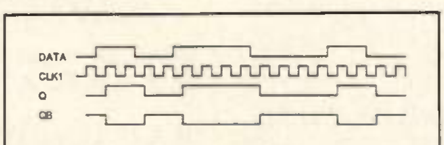


Figure 1. Typical NRZ data output waveforms.

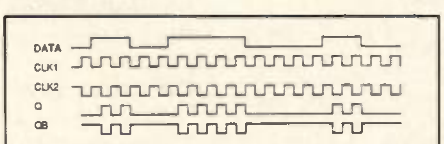


Figure 2. Typical RZ data output waveforms.

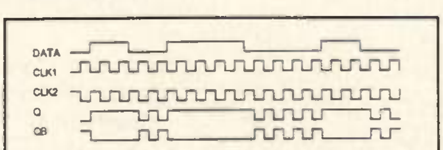
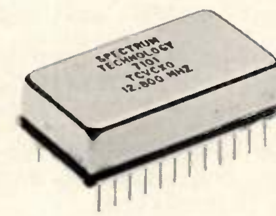


Figure 3. Typical R1 data output waveforms.



The George Washington University

Numerical Techniques in Electromagnetics: An Introduction
July 25-28, 1988, Washington, DC

Electromagnetic Interference and Control
August 1-5, 1988, Washington, DC

Electronic Warfare Systems: Technical and Operational Aspects
August 1-5, 1988, Washington, DC

Introduction to Modern Radar Technology
August 8-10, 1988, Washington, DC

Grounding, Bonding, Shielding and Transient Protection
August 8-11, 1988, San Diego, CA

Optical Fiber Communications
August 8-12, 1988, San Diego, CA
December 12-16, 1988, Orlando, FL

Information: Shirley Forlenzo, Continuing Education Program, George Washington University, Washington, DC 20052; Tel: (800) 424-9773, (202) 994-8530

Besser Associates

Principles of RF Circuit Design: Theory and Application
July 6-8, 1988, Santa Clara, CA
July 25-27, 1988, College Park, MD

Microwave Circuit Design I: Linear Circuits
August 15-19, 1988, Baltimore, MD

Microwave Circuit Design II: Non-linear Circuits
August 22-26, 1988, Baltimore, MD

Information: Eva Koltai, Besser Associates, Inc., 3975 East Bayshore Road, Palo Alto, CA 94303; Tel: (415) 969-3400

UCLA Extension

Microwave/Millimeter-Wave Monolithic Integrated Circuits
July 18-20, 1988, Los Angeles, CA

Information: UCLA Extension, P.O. Box 24901, Los Angeles, CA 90024; Tel:(213) 825-1901; (213) 825-1047; (213) 825-3344

EEsof, Inc.

Introduction to Microwave Computer Aided Engineering
September 6-7, 1988, Westlake Village, CA
November 7-8, 1988, Westlake Village, CA

Introduction to Microwave Computer Aided Layout and Design
September 8, 1988, Westlake Village, CA
November 9, 1988, Westlake Village, CA

Advanced CAE
September 12-13, 1988, Westlake Village, CA
November 14-15, 1988, Westlake Village, CA

Advanced Microwave Computer Aided Layout and Design
September 14, 1988, Westlake Village, CA
November 16, 1988, Westlake Village, CA

Nonlinear Circuit Design
September 19-20, 1988, Westlake Village, CA
November 21-22, 1988, Westlake Village, CA

Information: Sandra Scoredos, EEsof, Inc., 5795 Lindero Canyon Road, Westlake Village, CA 91362. Tel: (818) 991-7530

Integrated Computer Systems

Advanced C Programming: Hands-On Workshop
July 19-22, 1988, Boston, MA
August 2-5, 1988, Washington, DC
September 20-23, 1988, Los Angeles, CA
September 27-30, 1988, Washington, DC
October 25-28, 1988, Boston, MA
November 15-18, 1988, San Francisco, CA

Digital Signal Processing: Techniques and Applications
August 30-September 2, 1988, Washington, DC
September 13-16, 1988, San Diego, CA
October 4-7, 1988, Boston, MA
October 4-7, 1988, Toronto, Canada
October 18-21, 1988, Los Angeles, CA
November 1-4, 1988, Washington, DC

Image Processing and Machine Vision
July 26-29, 1988, Los Angeles, CA
August 30-September 2, 1988, Boston, MA
September 20-23, 1988, Washington, DC
October 4-7, 1988, San Francisco, CA
November 1-4, 1988, Los Angeles, CA

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

Georgia Institute of Technology

Microwave Antenna Measurements
July 25-29, 1988, Atlanta, GA

Techniques of Radar Reflectivity Measurement
August 2-5, 1988, Atlanta, GA

Information: Deidre Mercer, Education Extension Services, Georgia Institute of Technology, Atlanta, GA 30332-0385. Tel: (404) 894-2547.

Southeastern Center for Electrical Engineering Education

Antennas: Principles, Design, and Measurements
August 2-5, 1988, San Diego, CA

Information: Ann Beekman, SCEEE, 1101 Massachusetts Ave., St. Cloud, FL 32796. Tel: (305) 892-6146

R & B Enterprises

The R & B EMI Training Institute
August 8-19, 1988, Philadelphia, PA

Information: Greg Gore, R & B Enterprises, 20 Clipper Road, West Conshohocken, PA 19428. Tel: (215) 825-1684

Design & Evaluation, Inc.

The Worst Case Circuit Analysis Training Seminar
September 12-14, 1988, Boston, MA
October 17-19, 1988, San Francisco, CA

Information: Design & Evaluation, Inc., 1000 White Horse Road, Suite 304, Voorhees, NJ 08043. Tel: (609) 770-0800

University Consortium for Continuing Education

Modern Microwave Techniques
September 26-29, 1988, Washington, DC

Information: University Consortium for Continuing Education, 16161 Ventura Boulevard, M/S C-752, Encino, CA 91436. Tel: (818) 995-6335

New Microwave Laboratory at NJIT

Two microwave companies have made contributions towards the creation of a microwave laboratory and curriculum at New Jersey Institute of Technology. The program is intended to increase the number of degreed electrical engineers with microwave background for the state's more than 60 microwave companies.

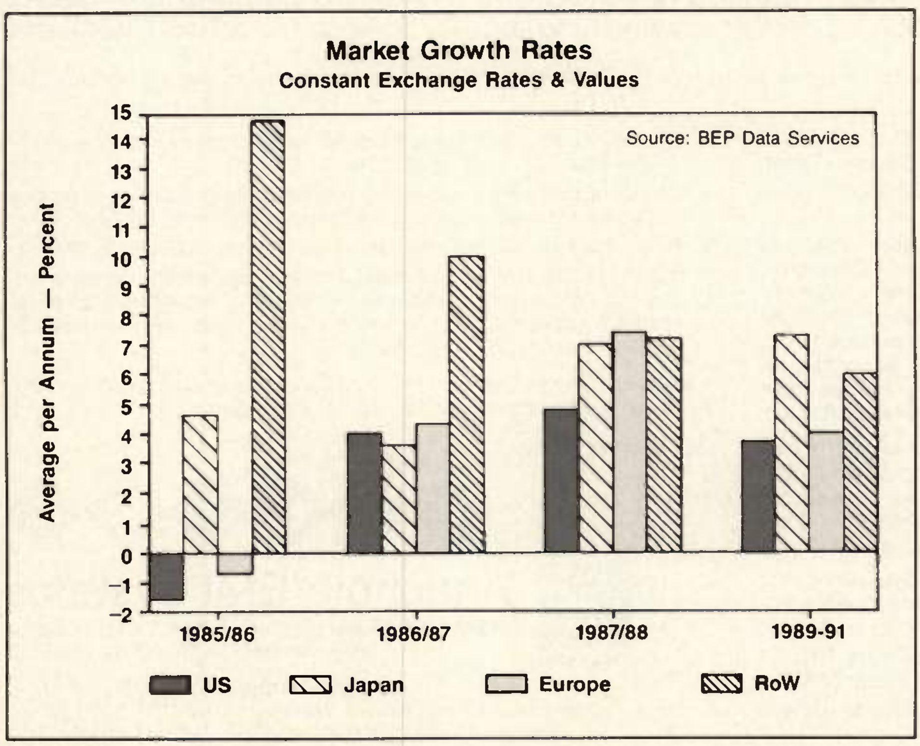
Compact Software, Inc. of Paterson and Communication Techniques, Inc. of Whippany each contributed $10,000 to support the laboratory which will be part of NJIT's Center for Microwave and Lightwave Engineering. The contributions will be used to provide microwave equipment and supplies for the laboratory. Other contributions of both cash and equipment have been promised from more than a dozen microwave equipment manufacturers throughout the New York metropolitan area.

The incentive for establishing the microwave laboratory stems from the decreasing number of microwave engineers produced every year by universities throughout the United States. According to Gerald Whitman, director of the Center for Microwave and Lightwave Engineering at NJIT, the number of graduates has not kept pace with the growth of the microwave industry, or the technological development.

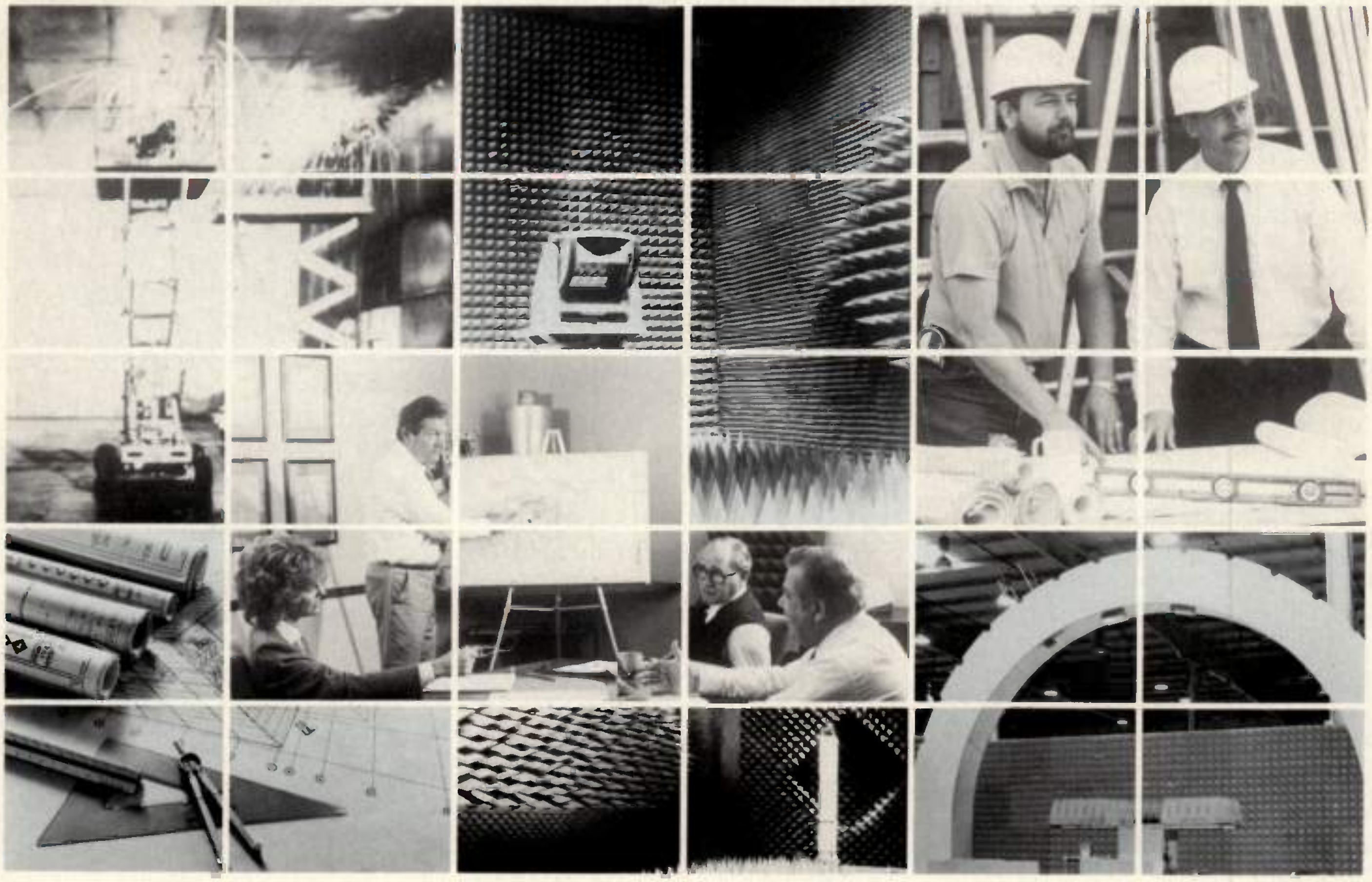
World Electronics Market to Reach $492 Billion in 1988

The World Electronics Market is forecast to reach $492 billion (U.S.) in 1988 according to a report published by BEP Data Services. This represents real growth, excluding inflation and exchange rate fluctuations, at a rate of 6 percent over 1987. The forecast calls for a growth of 4.9 percent in the United States which is higher than the 4.1 percent recorded in 1987. However, the consumer electronics products market is forecast to drop by around 1 percent. The rate of growth for the U.S. electronic market as a whole will reduce to under 4 percent per annum over the 1989 to 1991 period.

The report also indicates that Japan is projected to recover in 1988 with a real growth of 7.1 percent. The follows a poor year, by Japanese standards, in 1987 where growth was 3.7 percent due to the dampening effects of the strong yen on the industry's exports. The 14 other significant electronics markets outside Europe which BEP terms the "Rest of the World" consists mainly of Asia-Pacific, Brazil and South Africa. This market grew significantly in 1986 and 1987 with high exports of equipment from Asia-Pacific. However, the slowing market in the U.S.A. for consumer goods will adversely affect exports



TURNKEY RF Shielded Anechoic Chambers



From Concept To Reality Rantec's Anechoic/EMI Systems Group provides TOTAL SERVICES to design, construct, install and certify both small and large RF Shielded Anechoic Chambers.

These chambers include RF shielded steel enclosures, penetrations, HVAC, electrical, fire detection and suppression (water & Halon) and a completely engineered RF anechoic interior.

ENGINEERING – Rantec's Engineering Staff consists of Architectural, Electrical, Mechanical and RF Engineers. These combined talents provide complete engineering design of state-of-the-art products and facilities.

MANUFACTURING – Rantec has two modern absorber manufacturing plants, one in California and one in Oklahoma. Advanced computer controlled NC manufacturing equipment allows the production of uniformly impregnated anechoic pyramid and wedge shaped material, as well as various geometric configurations for special applications. Waveguide vents, pipe penetrations, shielded doors and 'telescoping' fire sprinkler assemblies are several other products manufactured by Rantec.

CONSTRUCTION AND INSTALLATION – Our highly trained field construction and installation crews are backed up by the best program management teams in the business. All scheduling and cost management is performed by skilled program managers utilizing the latest computer techniques.

TESTING SERVICE – Rantec provides a complete service for certification of both shielded enclosures and anechoic chambers. Measurement capabilities include:

- Shielding effectiveness testing from 30 Hz to 94 GHz at 100dB isolation levels to DOD, NSA and IEEE standards.
- Anechoic chamber reflection properties for antenna pattern measurements from 30 MHz to 94 GHz.
- Chamber backscatter properties for radar cross-section measurements from 500 MHz to 35 GHz.
- Chamber monostatic reflecting properties to determine chamber suitability for systems measurements, 500 MHz to 94 GHz.
- Axial ratio and cross-polarization properties from 100 MHz to 94 GHz.
- FCC type site attenuation measurements using both discrete frequency dipole testing and swept frequency broadband antenna testing for determining suitability of measurement site to perform to FCC, VDE, and CISPR requirements.

In summary, Rantec is the complete state-of-the-art source for turn-key RF Shielded Enclosures and Anechoic Chambers.

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for the Far East and the rate of market growth in these countries will fall to 7 percent in 1988 and down to 6 percent per annum in the subsequent three years.

The *Yearbook of World Electronics Data 1988* costs $975 and can be obtained from BEP Data Services, P.O. Box 28, Luton LU2 OBL, England.

W-J Receives $9M Order

Watkins-Johnson Company has received an order worth over $9 million for the delivery of additional subsystem equipment for the Royal Australian Navy's new construction submarine program. It includes a significant amount of Australian industry involvement. The order was made under an existing contract with Rockwell Ship Systems Australia, Pty. Limited.

Zenith Wins Cable Terminal Contract

Zenith Electronics Corporation will be producing new cable terminals to provide customers with access to a wide variety of interactive services. This cable and telecommunications system is being launched in Canada and the United States. Under the agreement (valued at approximately $14 million Canadian), Zenith will manufacture an initial order of 55,000 video terminals for Les Enterprises Videoway Ltee. The terminals will allow access to videotex data bases, teletext, electronic messaging, closed captioning and downloading of computer software via cable in addition to basic cable, pay-TV, pay-per-view and interactive television services. Zenith expects to begin shipment by the end of 1988.

MSC Expands Foundry Capabilities

Microwave Semiconductor Corporation has supplemented its small signal gallium arsenide foundry service with large signal modelling and added two new high power processes. The new 300 mA/mm higher power process is added to the existing 200 mA/mm small signal medium power process to allow design engineers to extend the range of applications for GaAs MMICs to higher power levels of operation with predictable results.

TriQuint and HP to Integrate MMIC Foundry Library

TriQuint Semiconductor announced that it has signed an agreement to incorporate its MMIC library of foundry design models into Hewlett-Packard Company's microwave CAE design system. The HP 85150A microwave design system is a software package that provides schematic capture, simulation, chip layout, and overall project documentation. The TriQuint MMIC Library models are algorithmic expressions that represents the electrical behavior of MMIC elements over a wide range of bias and operating frequency. By providing access to these models within a CAE system, a designer can simulate the operation of a MMIC to be built in the TriQuint foundry before investing in fabrication, packaging and evaluation of the actual device.

In the agreement, TriQuint is responsible for maintaining and further developing the library. The current library works on with the HP microwave design system software to represent MMIC elements built in TriQuint's HA 0.5 micron microwave and 1A general purpose IC processes. The LINMOD 3.2 library is priced at $995 and will be available in July from TriQuint. Telephone (503) 644-3535.

TIW Awarded Contract

TIW Systems, Inc., of Sunnyvale, Calif., has been awarded a contract to upgrade the tracking and antenna control system at the matura earth station by the Trinidad and Tabago External Telecommunications Company Limited (TEXTEL). TIW will replace the existing tracking and antenna control system with a microprocessor based satellite tracking drive system.

Lockheed Awards Contract to W-J

Lockheed Aeronautical Systems Group of Ontario, Calif., has awarded a $5.7 million contract to Watkins-Johnson Company. The contract calls for W-J to supply products and technology to enhance existing wideband receiving systems with the addition of a direction-finding capability. Work on the contract will be conducted at W-J's San Jose facility.

Noise Com Moves to Larger Facility

Noise Com, a supplier of noise sources, automated noise generating equipment, digitally tuned VCOs and synthesizers, has moved to a larger facility at E. 64 Midland Avenue, Paramus, NJ 07652. Their phone number is (201) 261-8797.

Rantec Opens New Manufacturing Plant

Rantec Anechoic/EMI Systems Group has opened a 94,000 square foot plant in Durant, Okla. The plant is equipped with absorber manufacturing equipment including two semi-automated impregnators and a computer controlled saw.

Leader Announces New Facility

Leader Instruments Corporation has announced the completion of a 10,000 square foot facility in Cypress, Calif. The new building houses sales, service, and warehousing.

ERA Launches Standards Program

The Electronic Representatives Association (ERA) announced the launch of Commitment to Performance, a program to articulate the professional standards that customers and principals should expect from manufacturers representatives in the electronics industry. A brochure that spells out the eight performance standards that a principal can expect from a manufacturers' representative, plus seven standards that customers can expect is available.

Rockwell Opens European Design Center

Rockwell has opened the Semiconductor Products Division of Rockwell International's European remote design center in Sophia Antipolis, France. Initial activities for the design center include hardware and software enhancements of the division's data and image, telephony, ISDN and local area network products to meet customer and European PTT specifications. Computer design equipment located in the facility will be linked directly to the division's research and development center in Newport Beach, Calif. The center is located at Les Taissounieres - B.1, Route des Doulines, Sophia Antipolis, 06560 Valbonne, France.

Penstock Opens New Sales Offices

Penstock has opened three new sales offices in Arizona, Colorado and Indiana. The new locations will cover southern Nevada and Arizona from the Tempe, Ariz., office; Colorado and Utah for the Englewood, Colo., office and Indiana and Ohio from the Indianapolis, Ind., office.

GaAs Switch Modules For High Performance Applications

By Raymond S. Pengelly,
Amin Ezzeddine and Barak Maoz
Tachonics Corporation

GaAs MMIC technology and circuit design has matured to a point where a number of products are now available commercially. Until recently these products have been single bare die or packaged single devices. Subsystem research and development centers have been building multi-chip modules for some time (ref. 1 and 2 for example), but there have been very few examples of such items being commercially available. This article describes a number of GaAs MMIC switches and the assembly of these parts into multi-chip modules built specifically as cost-effective products.

A standard 1 micron in-house fabrication technology is used to manufacture the MMICs described. The active devices, FETs and diodes, are produced using optimized selective implantation of Si resulting in planar circuits. Resistors are produced using either n or n+ implants or TaN thin-films. Capacitors are produced using Si_3N_4 dielectric which is also used for FET and other component passivation. Crossovers of second-level over first-level metallization employ air-bridges. Following thinning, through-GaAs vias are etched if necessary, the 3 inch wafers being back metallized, DC tested and sawed.

MESFETs are generally used as replacements for PIN diodes in MMICs because the technology required to produce high performance planar PIN diodes is less well understood and more difficult than that required for FETs. It is, therefore, also easier to integrate other functions on the same die, reducing fabrication complexity and increasing yields. Depletion mode FETs (normally "on") are used where the FET is pinched-off to produce its high resistance state. The low resistance achieved in the "on" state of the FET is determined by a number of technological factors including channel resistance, ohmic contact resistances and parasitic resistances between drain and source.

The GaAs FET switch requires very little current and low voltage to control it, typically −5 to −8 volts (i.e., 2 volts or so beyond pinch-off) at a few tens of microamps. The other major electrical advantage of the FET switch is its low video breakthrough from the control port (gate) to the RF line (drain and/or source). This results in the device having very low switching harmonics in the RF band. For example, a typical MESFET switch operating at 10 MHz p.r.f. with 5 nsec. rise and fall-times will have a spectral noise contribution of −60 dBm at 200 MHz without any video filtering. The switch has also intrinsically very fast switching speed, typically less than 2 nsec. The small size and relative ease of use of MMIC switches allows the replacement of PIN diode circuits at frequencies up to 20 GHz in such applications as switched VCOs, channelized receivers and phase shifters. The advantages and disadvantages of FETs versus PIN diodes used as switches are summarized in Table 1.

The MESFET used as a switch is basically a voltage controlled resistor whose resistance value is determined by the voltage applied to the gate of the device. No intentional DC voltage needs to be applied to the drain or source of the FET as in an amplifier. Figure 1 shows a simple equivalent circuit of the FET switch in its low and high impedance states. When the FET is in its "on" state the insertion loss of the switch is mainly due to the drain-to-source resistance, R_{ds}. A typical value for R_{ds} is 3 ohms for a 1 mm gate width FET having 1 μm gate length. In the "off" state the isolation is mainly determined by the corresponding R_{ds} value only at low frequencies (typically 100K ohm) and, as frequency increases by the parasitic drain-to-source capacitance (C_{ds} + ½[C_{gs} + C_{gd}], where the gate is assumed to be RF open-circuit). Typical values for this parasitic capacitance are 0.4 pF, leading to a reactance of 50 ohms at 8 GHz. In order to provide isolation at high frequencies either this capacitance has to be reson-

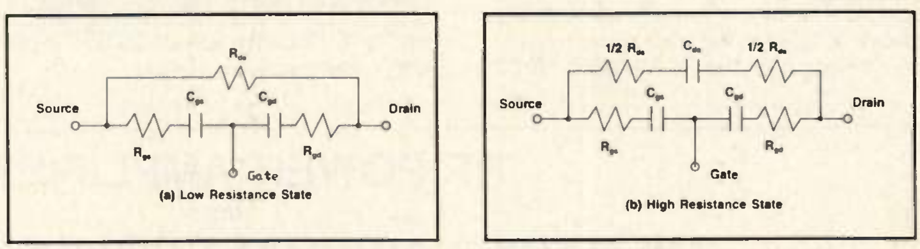

Figure 1. FET switch equivalent circuits.

Characteristic	FETs	PINs
Insertion Loss	Can be low	Usually low
Isolation	Excellent	Good
Current consumption	Very low - typ. 50 uA	Medium - typ. 20 mA
Operation to DC	Very good	Not possible
Video breakthrough	Very low without precautions	Only low with precautions
Power handling	Up to 10 watts CW	100 watts but at lower speed
Speed	Very fast - 1 nsec.	Fast - 10 nsec.

Table 1. FETs versus PIN diodes.

ated with inductance leading to relatively narrow-band operation or incorporated into a filter/travelling-wave structure to provide wider bandwidths.

The high-isolation broadband switches designed by Tachonics employ both series and shunt FETs, but without using series or shunt tuning elements. The effective source-drain capacitance of the shunt FETs is incorporated into a capacitively loaded transmission line (Figure 2). The addition of series FETs to each branch of the SPDT switch improves the low frequency isolation when they are biased to their high resistance states, while the shunt FETs biased to their low resistance states provide isolation at the higher frequencies. Many of these MMIC switches also contain switched 50 ohm loads at each throw such that the devices maintain a matched condition in both "on" and "off" states. These loads can optionally not be bonded to ground providing a switch with "open circuit" reflective VSWRs in the "off" state.

Product Examples

The TCSW-0400 SPDT switch operates over DC to 6 GHz and has been manufactured in volume production. This switch has an insertion loss of 0.8 dB at 4 GHz with a corresponding isolation of >35 dB and a 1 dB input compression point of >30 dBm. This switch has been used to produce a number of low frequency custom designs such as transfer switches and digital attenuators.

The main electrical parameters of the complete family of switch devices are shown in Table 2. Figure 3 shows the circuit diagram of the TCSW-0600 SPDT

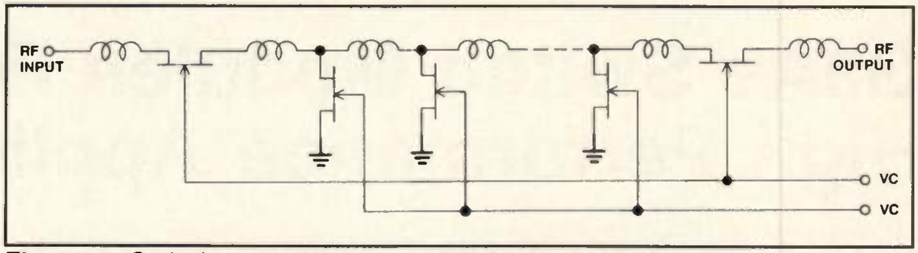

Figure 2. Switch using FETs in artificial transmission line.

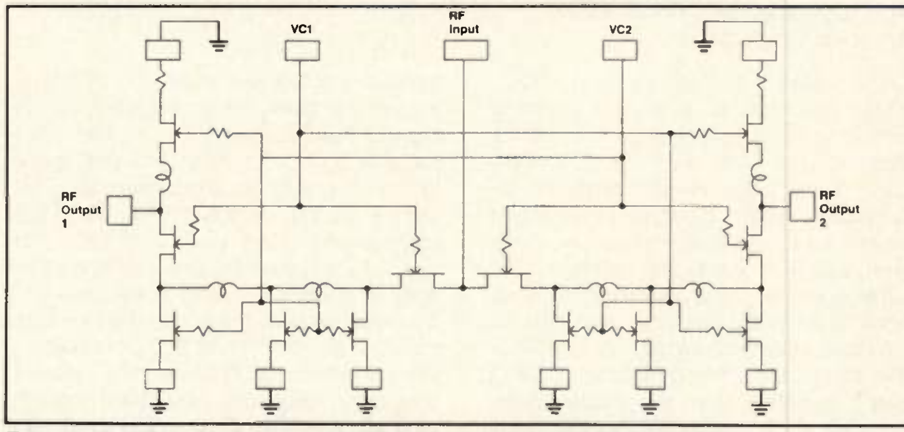

Figure 3. Circuit design of TCSW-0600 absorptive switch.

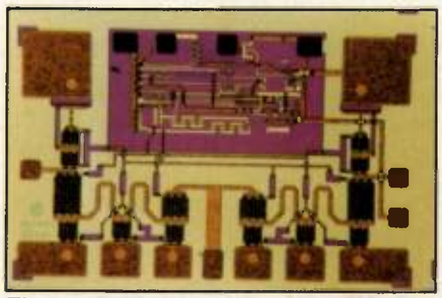

Figure 4. Photograph of TCSW-1600 SPDT switch with driver.

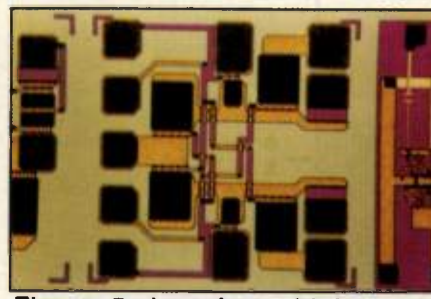

Figure 5. Low loss, high power SPDT switch (TCSW-1300).

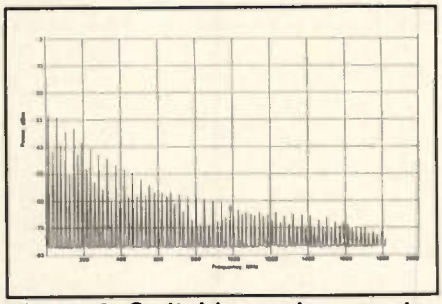

Figure 6. Switching noise spectra of TCSW-0500.

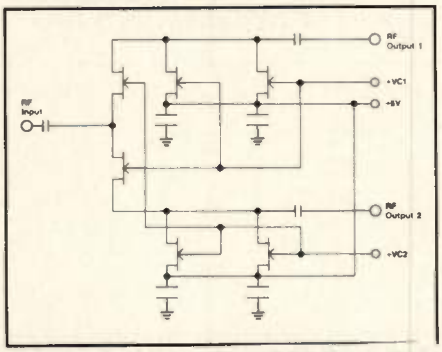

Figure 7. GaAs FET MMIC switch operated from positive voltages.

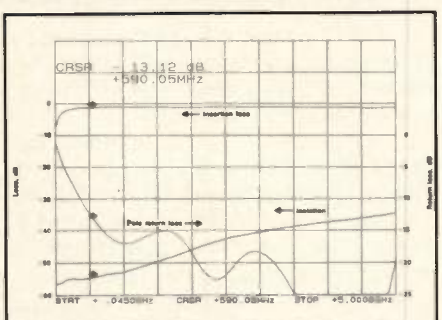

Figure 8. RF performance of positive supply configuration.

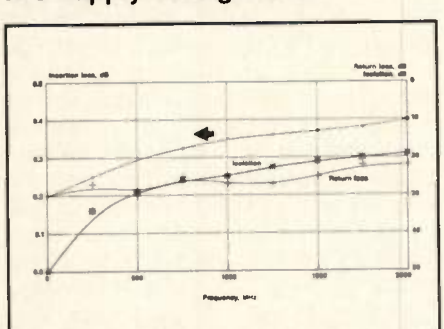

Figure 9(a). Insertion loss, isolation and return loss of TCSW-1301 SPDT switch.

switch (3). The switch can be configured to be either absorptive or reflective allowing it to be used in multithrow switch applications. The TCSW-0500 and 0600 SPST and SPDT switches have been used in a range of high isolation, fast switch modules operating up to 8 GHz. Options with GaAs on-board TTL drivers have also been dveloped. The TCSW-1600 SPDT switch with driver is shown in Figure 4. Derivatives of the TCSW-0500 through 0800 switch family are the TCSW-5300 and 5400 devices, fully integrated SP3T and SP4T die operating over 8 GHz bandwidths. These latter switches are basically combinations of SPST switches. All were designed for both single and multi-die packaging and driver interfacing.

Like PIN diode switches, MMIC counterparts can use both series and shunt FETs. In this case, drivers with complementary control voltages are required to drive the series and shunt FETs in the circuit. A number of drivers exist, such as the Teledyne TSC CMOS 420-430 series, Harris CMOS HI 5051, Maxim IH 5043 and Impellimax GX 101B2 circuits. In addition to using such external drivers, Tachonics has also developed two integrated driven switches (the TCSW-1500 and 1600, SPST and SPDT), which incorporate 1 volt threshold depletion mode gates on the same die as the RF switches.

Features of MMIC Switches

GaAs MMIC switches using MESFETs have a number of features which can be optimized during design. These features include power handling, switching speed and video breakthrough, all areas where similar attention has also been given to PIN diodes.

Power Handling. The power handling capability of MESFET switches is dependent on a number of device variables such as saturated drain current (normal FET definition), pinch-off voltage, gate-to-drain and gate-to-source breakdown voltages. These parameters are influenced by four major process dependent variables: gate recess dėpth and width, total gate width, implantation profiles and gate-to-drain and gate-to-source separations. In addition it is possible to enhance RF power handling by changing the working characteristic impedance, and by using a number of FETs in novel arrangements. The TCSW-0400 and TCSW-0600 switches, for example, have 1 dB insertion loss compression input powers of 1 and 2 watts CW, respectively. As frequency is decreased the devices are not able to handle so much CW power, particularly as the frequency goes below $1/\pi R_g (C_{gs} + C_{gd} + 2C_{ds})$, where R_g is the resistance used in series with the gate of each FET. For example, a 1μm gate width FET having a 2k ohm gate resistor, the frequency at which RF power handling starts to degrade is approximately 250 MHz.

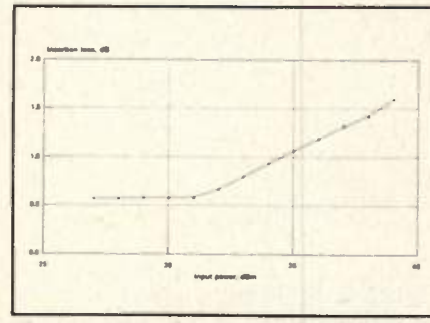

Figure 9(b). Compression characteristics of TCSW-1301 at 3 GHz.

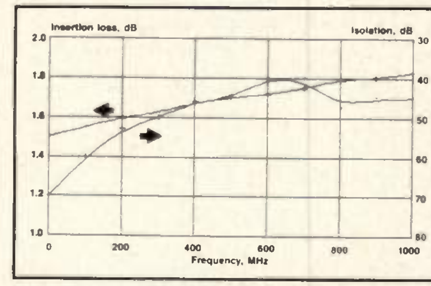

Figure 10. Performance of transfer switch module.

This knee frequency can be decreased by either increasing the gate width (at the expense of switching speed and bandwidth) or increasing the value of R_g.

Because switch power handling depends also on the instantaneous RF voltage across gate-to-drain and gate-to-source it is usual that FETs will handle RF power until either the gate diode is forward-biased during the positive half-cycle or reaches breakdown in the negative half-cycle. Thus, a careful compromise has to be made with the quiescent gate voltage that is applied in the "on" or "off" states (depending on whether the FET is in series or shunt). For a FET with a >16 volt (gate-to-source/drain) breakdown voltage, a control voltage of −8 volts will assure that the source/drain is able to handle approximately 8.7 volts or 16 volts when the gate is at −8 or 0 volts, respectively. In the simplest case of a series/shunt FET combination the switch is then able to handle approximately $16^2/100$ watts or 2.5 watts.

Tachonics has developed a 5 watt CW SPDT switch having a loss of <0.4 dB up to 2 GHz. In order to provide such power handling the switch incorporates FETs whose parameters have been optimized simultaneously by a combination of small and large signal analyses (Figure 5).

Switching Speed and Video Breakthrough. The MESFET is intrinsically a fast switch where the channel is depleted of electrons, following the time constant

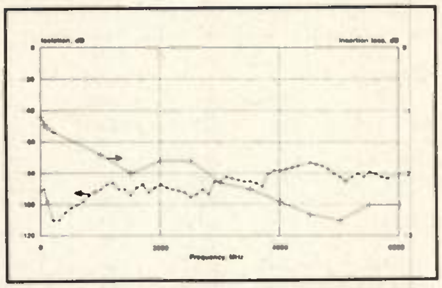

Figure 11. Isolation and insertion loss of very high isolation switch.

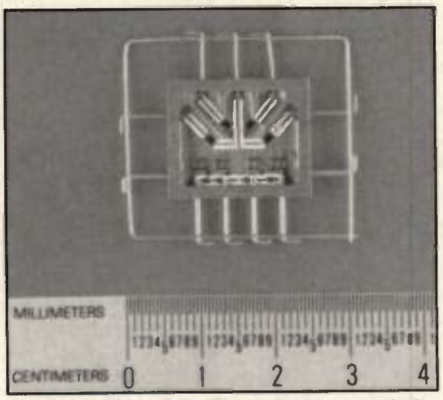

Figure 12. SP4T switch module with driver.

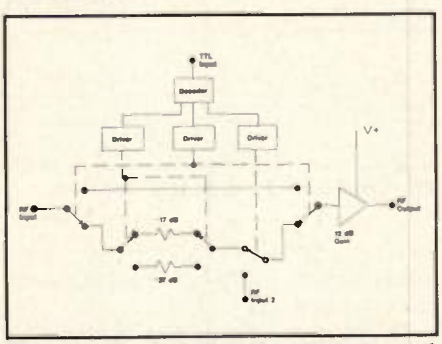

Figure 13. Schematic diagram of programmable gain module.

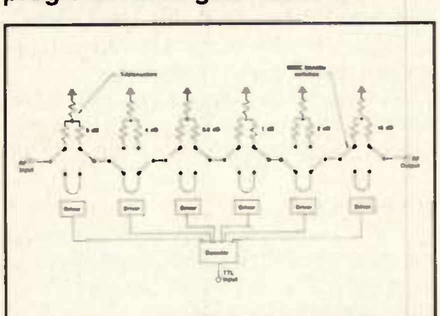

Figure 14. A 16-bit switched attenuator.

determined by the driving impedance of the gate source/drain and the total gate circuit capacitance. For a 1μm gate width FET the switching speed is approximately 0.5 nsec assuming a 2K ohm resistor in series with the gate electrode. For example, the TCSW-0600 switch consists of 5 devices per throw having a combined switching time of approximately 1.5 nsec. It is not only important to provide GaAs MMIC switches with inherently fast switching speed but also to ensure that the time constants to the FETs in the switch are equal such that video breakthrough is minimized. Such design action also ensures that the switching noise (spectral content of the video breakthrough) is minimized, a particularly important feature in maximizing dynamic range at low frequencies.

An example of the switching noise spectra of a TCSW-0500 SPST switch driven at a 15 MHz PRF (50 percent duty cycle) with complimentary control pulses from a fast TTL driver having 5 nsec rise and fall times is shown in Figure 6. No special precautions were taken in reducing the video breakthrough as would be the case for a PIN diode counterpart.,

Driving MMIC Switches from Positive Voltages. Many users need to use positive control voltages, usually for one or two reasons: either only positive supply rails are available, or they are more familiar with using positive voltages from their PIN diode experiences.

Figure 7 shows a scheme where the TCSW-0400 SPDT switch is controlled with standard TTL logic levels. The shunt FETs are raised off ground using 120 pF chip capacitors while the RF switch elements use 30 pF chip blocking capacitors. The sources of the shunt FETs are raised to a positive voltage equal to the absolute value of the control voltage (e.g., +5 or 8 volts). The RF performance of such a switch arrangement is shown in Figure 8. The switch operates well from 250 MHz to its upper design limit, but operation to DC is not possible.

Applications

High Power Switches. Commercially available MMIC switches have typically had 1 dB compression points in the ½ to 1 watt CW region. The switch shown in Figure 5 was specifically designed for higher power applications. Gate widths were chosen to handle the required peak RF currents, where the structure of the FETs was optimized for high breakdown voltage. The switch was also designed for low loss in the DC to 3 GHz frequency band, enabling its application in L- and S-band active array radar transmit/receive applications. The two throws of the switch can be bonded differently allowing high power switching on the transmit throw and high isolation (lower power) on the receive throw. Figure 9(a) shows the small-signal performance of the switch in the receive and transmit throws indicating an insertion loss for the die itself of 0.35 dB at L band. In the transmit throw the power handling is indicated by Figure 9(b) where a 1 dB compression point of 5 watts CW is shown.

Switch Modules. A range of switch modules has been built using combinations of TCSW-0400 through 0800 switch die and various drivers (CMOS, TTL, ECL) in a variety of packages. For low frequencies (<2 GHz) requiring medium isolations (>30 dB) low cost glass-to-metal seal flatpacks can be employed. Figure 10 shows the main results of a transfer switch used at radar IFs up to 1 GHz, driven by two CMOS drivers in a 14 lead flatpack. Insertion loss was <1.6 dB with a minimum isolation of 53 dB at 200 MHz. Total switching time including driver delay time was 70 nsec. The complete unit measures only 0.375 inches square by 0.11 inches deep.

Isolations in excess of 70 dB or so require special attention to be paid to both the RF and control circuits. Figure 11 shows the insertion loss and isolation of a unit which contains three packaged switches integrated onto a single microstrip carrier. In order to retain high isolation the three switches are not only housed in separated compartments but special attention was also paid to minimizing RF leakage through the control ports via the driver circuitry.

As discussed previously, SPST switches are often used to produce multithrow units. Figure 12 shows an example of a matched SP4T using 4 TCSW-0700 SPST switch die for operation to 8 GHz. This same unit can also be used as an SP3T switch where all the ports are matched even in the "all-off" state. In this unit four CMOS drivers are used with a single −12 volt rail. The module size is 0.625 inches square by 0.13 inches deep.

Table 3 summarizes some of the performance features of Tachonics MMIC switch modules.

Programmable Gain. MMIC switches and amplifiers have also been combined with chip attenuators to produce programmable gain modules. Figure 13 shows the schematic of such a unit operating over the 500 MHz to 4 GHz frequency range. In this particular unit, five TCSW-0400 SPDT die were combined with a single TCWL-0100 50 MHz to 4 GHz amplifier die allowing +10, −10 and −30 dB gains to be chosen from port 1 to port 3 or the full gain of 10 dB from port 2 to port 3. Return loss is better than 13 dB on both inputs and the output under all gain conditions.

Model Number	Frequency Range, GHz	Insertion Loss, dB @ f1 & f2	Isolation dB @ f1 & f2	Maximum On	Maximum Off	1 dB Input Power dBm
0400	DC-6	0.6/1.0	70/30	<1.5	Refl.	30
0401	DC-5	0.8/1.5	70/27	<1.5	Refl.	30
0402	DC-6	0.8/1.4	65/27	<1.7	Refl.	30
0700	DC-18	0.8/1.7	55/34	<1.6	<2.0	31
0800	DC-18	1.1/2.2	63/34	<1.9	<2.5	31
0502	DC-8	0.7/1.4	63/45	<1.5	<1.5	31
0602	DC-8	1.0/1.8	66/40	<1.5	<1.5	31
0720	DC-18	1.1/3.2	52/35	<2	<2	31
0820	DC-18	1.5/3.0	60/30	<1.9	<3.0	31
1301	DC-3	0.20/0.45	70/40	<1.2	<1.4	37
1607 (note)	DC-8	1.0/1.8	66/40	<1.5	<1.5	31

Notes:
f1 is 45 MHz for 04xx and 1301.
f2 is 3 GHz for 1301.
f2 is 6 GHz for 0400, 5 GHz for 0401 and 6 GHz for 0402.
f1 is 1 GHz for 0502, 0602 and 1607; 8 GHz for 07XX and 08XX.
f2 is 8 GHz for 05XX, 0602 and 1607; 18 GHz for 07XX and 08XX.
TCSW-1607 is a SPDT switch with integrated GaAs TTL driver.

Table 2. Summary of performance of Tachonics GaAs MMIC switches.

Product No.	TCSW-0140	TCSW-0240	TCSW-1141	TCSW-1241	TCSW-14XX
TYPE	SPST Non-reflective Undriven	SPDT Non-reflective Undriven	SPST Non-reflective Driven	SPDT Non-reflective Driven	SP4T Non-reflective Driven
Isolation	70 dB min.	70 dB min.	70 dB min.	70 dB min.	50 dB min.
Insertion Loss	2 dB max.	2 dB max.	2 dB max.	2 dB max.	2.5 dB max.
Rise/Fall Time	2 nS max.	2 nS max.	8 nS max. 5 nS typ.	8 nS max. 5 nS typ.	100 nS max.
Rep. Rate	200 MHz max.	200 MHz max.	15 MHz max.	15 MHz max.	4 MHz max.
Package Style	TC40 Drop In	TC40 Drop In	TC41 Drop In	TC41 Drop In	
Prototypes Ready By	Available	Available	Available	Available	6/30/88

Table 3. Performance characteristics of Tachonics switch modules.

Switched Attenuators. Figure 14 shows the circuit schematic for a 4 bit switched attenuator covering DC to 3 GHz employing eight TCSW-1300 SPDT die together with four thin-film chip T-attenuators providing 1 through 15 dB attenuation. The phase of each attenuator bit is held constant by equalizing the electrical length between the "straight-through" path and the attenuator pads. Using the TCSW-1300 low-loss SPDT die results in an insertion loss per bit of as low as 0.7 dB, leading to a 3.0 dB insertion loss for the complete four-bit attenuator.

Conclusions

This article has described the operation and application of a number of GaAs MMIC FET-based switch die and modules. Information on the characteristics and control of such devices has shown that such switches have now reached a relatively mature status. MMIC FET switches have a number of advantages over PIN diodes, particularly in respect to low video breakthrough, conveniently high isolations per chip and the ability to be intrinsically matched while operating with very low drive currents.

The authors would like to thank a number of their colleagues who have made significant contributions to the work described above. They include: D. Brant, J. Faguet, R. Makkay, and the wafer fabrication, assembly and test teams.

For more information on the GaAs MMIC switch modules described in this article, circle INFO/CARD #190.

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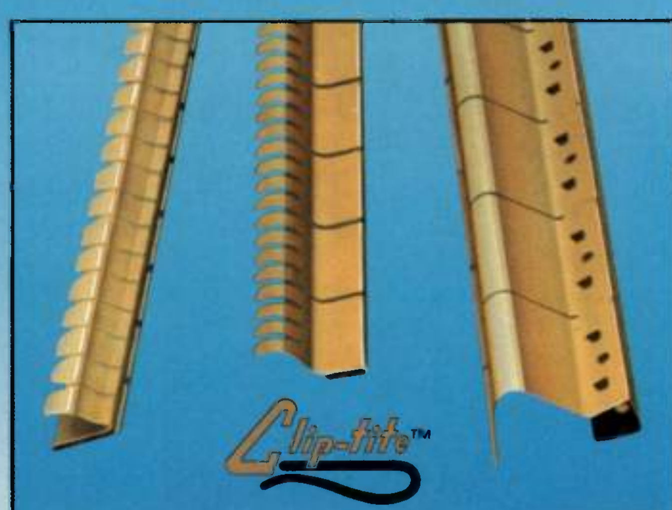

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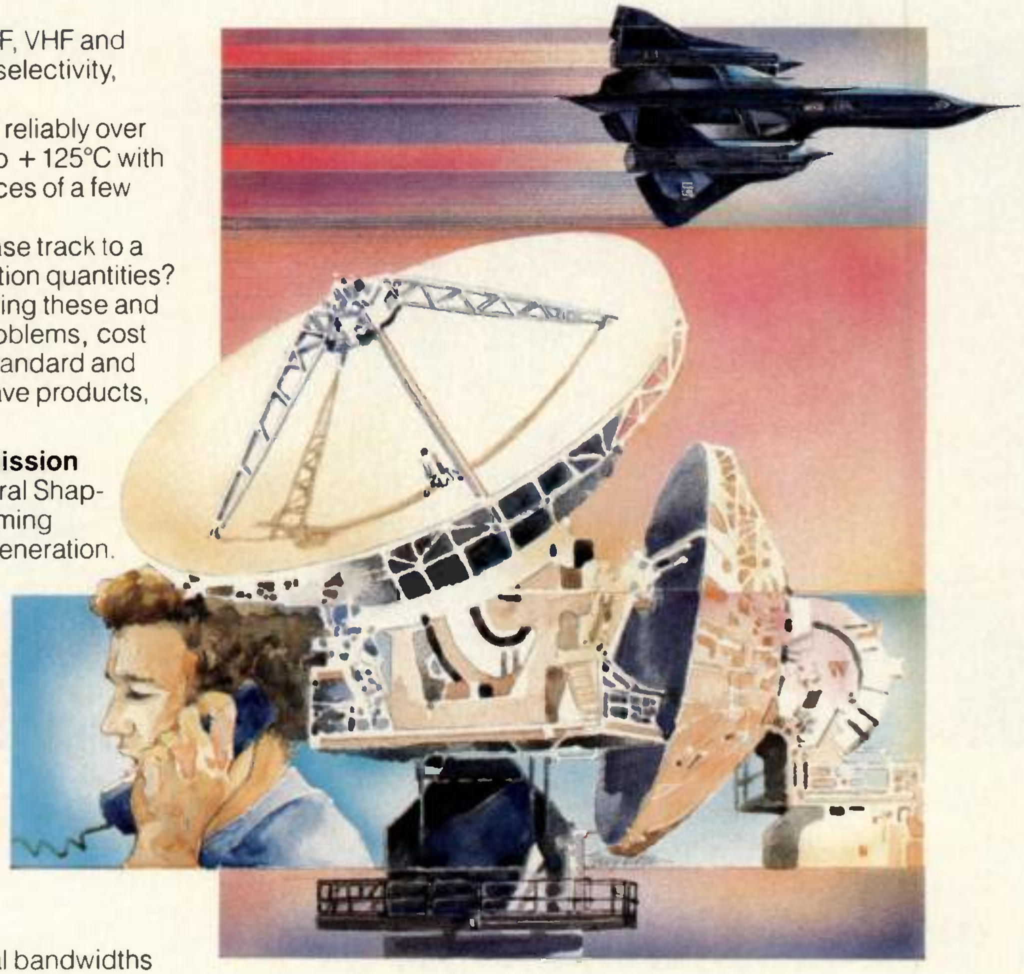

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Principles of Microstrip Design

By Alam Tam
American Microwave Technology

Microstrip is becoming a more important and popular transmission media for use in the RF and microwave industry, based upon its electrical, cost, size, manufacturability and reproducibility performance. All RF, microwave and high speed digital circuit designers should become familiar with microstrip design techniques to better their job skills. This microstrip design tutorial will enhance your understanding of the advantages, electrical characteristics and physical properties through practical applications, specific equations, useful tables and design examples.

Microstrip is a transmission line which carries the RF signal from one point to another with a unique characteristic impedance. The characteristic impedance is determined by the selected w/h ratio, plus the board or substrate material used. The physical cross-sectional construction of a microstrip above the dielectric medium is shown in Figure 1. The high frequency energy will produce a skin effect on the microstrip conductor. The current density around the conductor is then concentrated on a sheet where a skin thickness deep on the surface will be exposed to the electric field.

The transverse electric (TE) mode defines that a transmission have magnetic field components in the direction of energy flow yet the electric field is everywhere transverse. On the other hand, transverse magnetic (TM) mode defines that the transmission have the electric field components in the direction of energy flow yet the magnetic field is everywhere transverse. They are referred to as "higher order" modes for microwave transmission.

As a practical recommendation, the physical separation between the metallic cover and the actual microstrips on the substrate should be at least 10 times the substrate thickness. To avoid the higher waveguide mode excitation within the enclosure, the physical width of the housing in which the microstrip are situated, should not be more than one half of the free space wavelength at the operating frequency.

Microstrip design has proven to be a very mature technology. It provides wide operating bandwidth, good miniaturization, tremendous weight reduction, satisfactory thermal characteristics, reasonable RF power handling, ease of component integration and mass production. It is being widely used in many military and spaceborne programs. Historically, the reliability performance of microstrip designs has been successful, as predicted.

Review of Fundamental Transmission Line Equations

Since the electric and magnetic field lines and the ground plane are not entirely contained in the substrate as shown in Figure 2, the propagating mode along the microstrip is not purely transverse electromagnetic (TEM) but quasi-TEM. Assuming it is quasi-TEM, the phase velocity in the microstrip is given by:

$$V_p = C/\sqrt{\epsilon_{eff}} \qquad (1)$$

The wavelength in the microstrip line is given by:

$$\lambda_g = V_p/f \qquad (2a)$$

$$\text{Where, } \lambda_g = \lambda_o/\sqrt{\epsilon_{eff}} = C/f\sqrt{\epsilon_{eff}} \qquad (2b)$$

λ_g = microstrip wavelength
λ_o = electrical wavelength in the free air

The characteristic impedance of the transmission line is also given by:

$$Zo = 1 / V_p(C), \text{ where } C = 3 \times 10^8 \text{ m/s} \qquad (3)$$

Determination of Characteristic Impedance (Zo)

The Wheeler and Schneider formulas shall be considered because they provide accuracy better than 2 percent.

For w/h < 1,

$$Zo = \frac{60}{\sqrt{\epsilon_{eff}}} \ln(8h/W_e + .25W_e/h), \text{ where:} \qquad (4a)$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}[(1+12h/W_e)^{-0.5}+0.04(1-W_e/h)^2] \qquad (4b)$$

For w/h > 1,

$$Zo = \frac{377}{\sqrt{\epsilon_{eff}}\,[W_e/h + 1.393 + 0.667 \ln(W_e/h + 1.444)]} \qquad (5a)$$

$$W_e = W + \frac{t}{\pi}\left(\ln \frac{2h_e}{t} + 1\right) \quad \text{Effective microstrip width} \qquad (5b)$$

$$h_e = h - (2t) \quad \text{Effective thickness of the substrate} \qquad (5c)$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}[(1+12h/W_e)^{-0.5}] \text{Effective dielectric constant} \qquad (5d)$$

Example #1: What is the characteristic impedance of an 80 mil wide microstripline on a 1/32" thick Teflon fiberglass board with a dielectric constant of 2.55?

ϵ_{eff} = 1.78 + 0.775 (0.425) = 2.1

W_e = 80 + 2 = 82 mil

h_e = 31 − 2(1.4) = 28 mil
@t = 1.4 mil thickness for 1 oz. copper clad material

W_e/h=82/31=2.65, which is greater than 1 in this case:

$$\text{Thus, } Zo = \frac{377}{\sqrt{2.1}\,[82/31+1.393+0.667 \ln(82/31+1.444)]}$$

$$= \frac{377}{7.22} = 52 \text{ Ohms}$$

An alternate solution can be achieved by using the graphical design approach, referring to Figure 3. Draw a vertical line starting at w/h = 2.65 axis until it intercepts with the e = 2.55 curve. At the same point, make a line in parallel with the w/h axis until it reaches the vertical Zo axis. Therefore, the new characteristic impedance can be easily found and the result should be fairly close to that calculated in Example #1.

Electrical length of an inductive microstrip is determined by:

$$l = \frac{L \times V_p}{Zo} \qquad (6)$$

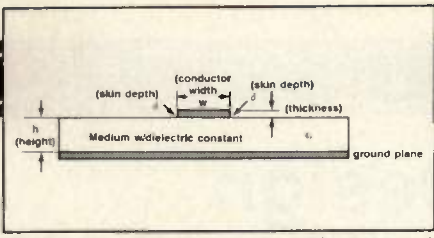

Figure 1. Cross-sectional view of microstrip.

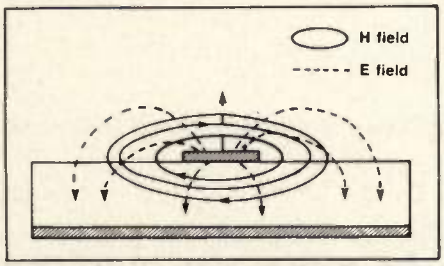

Figure 2. E and H field distribution.

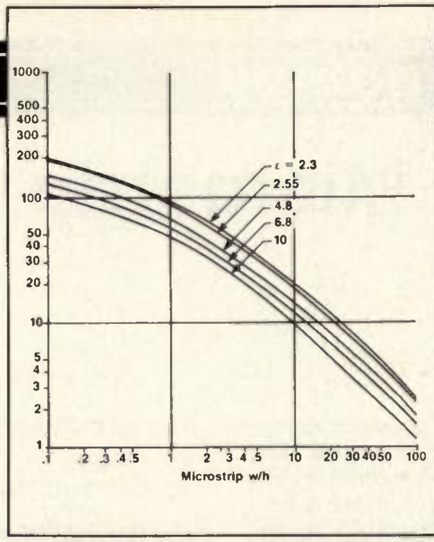

Figure 3. Characteristic impedance vs. w/h ratio.

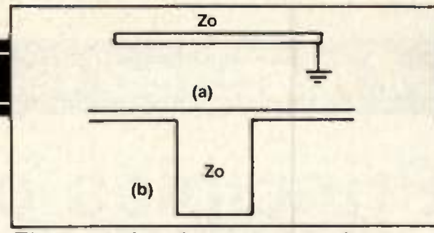

Figure 4. (a) shorted stub; (b) open stub.

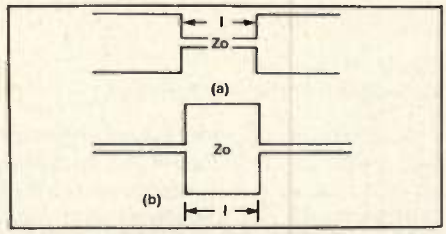

Figure 5. Electrical length (l) and Zo relationships: (a) inductor; (b) capacitor.

Example #2: What is the electrical length of a 5 mil wide microstrip on an Alumina substrate with inductance of 15 nH?

First of all, the given information is listed as below:

$\epsilon_r = 9.8$; $h = 25$ mil $w/t = .75$ mil

Using Equations 5b, 5c and 5d, $W_e = 6$ mil, $h_e = 23.5$ mil and $\epsilon_{eff} = 6.0$ can be calculated.

For $w/h < 1$, $Zo = \dfrac{60}{\sqrt{\epsilon_{eff}}} \ln (8h/W_e + .25\, W_e/h) = \dfrac{60}{\sqrt{6.0}} \times$

$\ln (8 \times 25/6 + .25 \times 6/25) = 86$ ohms

therefore, $l = \dfrac{L \times V_p}{Zo} = \dfrac{15 \times 10^{9} \times 0.41 \times 3 \times 10^{10}}{86}$

$= 2.15$ cm or 0.85 in.

Open and Shorted Circuit Reactances

Usually, the open and short circuit types of microstriplines are called stubs and they are often used as DC feeding elements and distributed elements for microwave active and passive circuit designs. The shorted stub behaves like an inductor and it normally has high characteristic impedance. On the other hand, the open stub behaves like a capacitor and it has very low characteristic impedance. Practically speaking, the electrical lengths of the shorted and open stubs are directly related to the effective wavelengths at the specific operating frequency.

$Z_{sc} = X_L = +j\, Zo \tan\theta$ (ohm) (7a)

It becomes an inductive reactance.

$Z_{oc} = X_C = -j\, Zo \cot\theta$ (Ohm) (8a)

It becomes capacitance reactance.

$\theta = \tan^{-1} (X_L/Zo)$ (7b)

$\theta = \cot^{-1} (X_C/Zo)$ (8b)

$\theta = 2\pi l/\lambda_g$ (9a)

$l = \Theta\lambda_o/360°\sqrt{\epsilon_{eff}}$ (9b)

Example #3: What will be the electrical length of a microstrip if its reactance equals the characteristic impedance?

Since $\theta = \tan^{-1}(X_L/Zo) = \tan^{-1}(1) = 45°$ or $\lambda_g / 8$.

Likewise, $\theta = \mathrm{Cot}^{-1} (X_c/Zo) = \mathrm{Cot}^{-1} (1) = 45°$ or $\lambda_g / 8$.

Then, $X_L < 90$ Ohms, $X_c > 30$ Ohms are suggested for practical circuit application.

Propagation Delay of a Microstrip

The propagation delay normally has nothing to do with the characteristic impedance of a microstrip, and is described by:

$t_{pd} = \sqrt{0.475\epsilon_r + 0.67}$ nsec/ft. (10)

Example #4: What is the propagation delay of a foot long microstrip on a G-10 fiberglass epoxy board which has a dielectric constant of 4.8?

$t_{pd} = \sqrt{0.475\epsilon_r + 0.67 \text{ nsec/ft.}} \times 1 \text{ ft.} = \sqrt{0.475(4.8) + 0.67}$
$= 1.75$ nanoseconds.

Physical and Electrical Properties

1. Conductor and Dielectric Losses — There are two major dissipative losses in any microstrip design. Dielectric loss normally is inversely proportional to the sheet resistivity (R_s) of the substrate. For a well-defined characteristic impedance, the conductor loss decreases inversely with the substrate thickness and increases with the square root of the frequency.

For Conductor Loss:

$\alpha_c = 8.68\, R_s / Zo \times w$ @$w/h > 1$, dB/cm (11a)

$\alpha_c = 23.4 \sqrt{f(\mathrm{GHz}) \times \varrho}$ dB/in (11b)

α_c = attenuation coefficient

ϱ = conductor resistivity in Ohm/cm, assuming that there is no sheet roughness on substrate

For dielectric loss:

$\alpha_d = 2.56f(\mathrm{GHz}) \left[\dfrac{(\epsilon_{eff}(f) - 1)}{\sqrt{\epsilon_{eff}(f)}}\right] (1.2^{1/3.4})(\tan\delta)$ dB/in (12)

$\tan\delta$ = loss tangent of a dielectric material

$R_s = \sqrt{\pi f_{(HZ)}\mu\varrho}$ (13)

R_s = surface skin resistivity in Ohm per unit square

σ = conductor conductivity in mho/meter = $1 / \varrho$

μ = permeability of the free space ($4\times \pi \times 10^{-7}$ Henry/meter)

Surface roughness will increase the conductor loss. Conductor losses usually greatly exceed dielectric losses for most microstrip lines, especially on alumina or sapphire substrates. However, semiconductor substrates with either silicon or gallium arsenide material result in much higher dielectric losses than conductor losses.

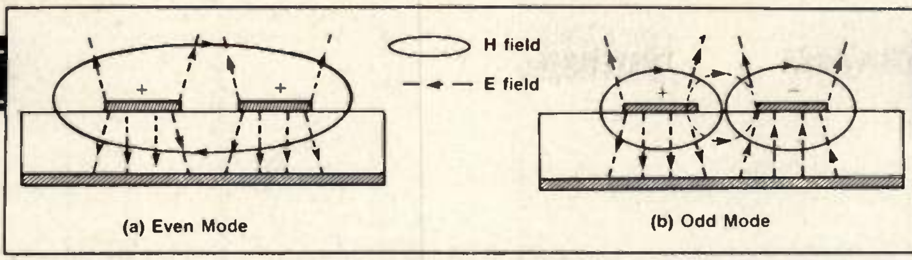

Figure 6. The electric and magnetic field distribution for the (a) even mode (b) odd mode wave excitation in the coupled microstrip lines.

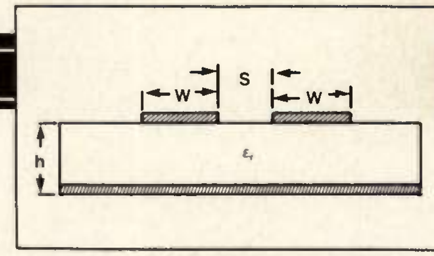

Figure 7. The cross-sectional view of coupled microstrip lines.

Example #6: What are the conductor and dielectric losses of a 21 mil wide 50 ohm microstrip on a Duroid 6010 board operating at 10 GHz assuming no sheet roughness?

Given: ϱ=2x10^{-6} ohm/cm, ϵ_{eff}(10 GHz)=7.0, tanδ=12x10^{-4} in;

$$\alpha_c = 23.4\sqrt{f(\mathrm{GHz}) \times \varrho} = 23.4\sqrt{10(2\times10^{-6})} = 0.105 \text{ dB/in.}$$

$$\alpha_d = 2.56f(\mathrm{GHz})\left[\frac{(\epsilon_{eff}(f)-1)}{\sqrt{\epsilon_{eff}(f)}}\right](1.2^{f/3.4})(\tan\delta)$$

$$= 2.56(10)\left[\frac{(7.03-1)}{\sqrt{7.03}}\right](1.2)^{2.94}(12\times10^{-4}) = 0.12 \text{ dB/in.}$$

$$\alpha_T = \alpha_c + \alpha_d = 0.105 + 0.12 = 0.23 \text{ dB/in.}$$

2. *Radiation Loss* — Microstrip is actually an asymmetric transmission line structure and it is often used in unshielded or poorly shielded circuits where the radiation energy is free either to propagate away or to induce current flow. This will result in power loss. Discontinuities such as an open end, step change, bend or corner will radiate to some extent. For lower dielectric constant substrates, radiation loss is significant at higher characteristic impedance levels. For higher dielectric constant substrates, radiation becomes significant until low characteristic impedance levels are reached. Therefore, special care by the circuit designer to reduce radiation from microstrip circuits is highly recommended. Radiation resistance of open circuited microstrip is given by:

$$R_r = 240\pi^2\left(\frac{h}{\lambda_o}\right)^2\left\{\left(\frac{\epsilon_{eff}+1}{\epsilon_{eff}}\right) - \left[\frac{(\epsilon_{eff}-1)}{2\epsilon_{eff}\sqrt{\epsilon_{eff}}}\ln\left(\frac{\sqrt{\epsilon_{eff}}+1}{\sqrt{\epsilon_{eff}}-1}\right)\right]\right\} \quad (14)$$

Example #7: What will be the resistive radiation loss of a 50 ohm microstrip on a Duroid 6010 board operating at 10 GHz?

Given: ϵ_{eff} = 6.8, h = 0.0635 cm; λ_o = 3 cm.

$$R_r = 240\pi^2\left(\frac{h}{\lambda_o}\right)^2\left\{\left(\frac{\epsilon_{eff}+1}{\epsilon_{eff}}\right) - \left[\frac{(\epsilon_{eff}-1)}{2\epsilon_{eff}\sqrt{\epsilon_{eff}}}\ln\left(\frac{\sqrt{\epsilon_{eff}}+1}{\sqrt{\epsilon_{eff}}-1}\right)\right]\right\}$$

$$= 240\pi^2\left(\frac{.0635}{3}\right)^2\left\{\left(\frac{6.8+1}{6.8}\right) - \left[\frac{(6.8-1)}{2(6.8)\sqrt{6.8}}\ln\left(\frac{\sqrt{6.8}+1}{\sqrt{6.8}-1}\right)\right]\right\}$$

$$= 1.58 \text{ dB.}$$

3. *Surface Wave Propagating Loss* — Surface Wave energy, trapped underneath the surface of the substrate dielectric medium, will be propagated away in the form of a range of TE and radial TM modes. As operating frequency increases, the surface wave conductance becomes an important loss element.

4. *Parasitic Coupling* — This primarily includes parallel microstrip resonator or line coupling, which will cause signal cross-talk and fringing capacitance. The electric and magnetic field line distribution of a quasi-TEM coupled microstrip is shown in Figure 6 and a cross-sectional view of a typical coupled microstrip is shown in Figure 7. The most important electrical characteristics depend on the coupling factor, odd mode and even mode characteristic impedances. The physical spacing between the parallel coupled microstrips can then be determined.

In order to improve the crosstalk or isolation in high speed digital systems, the coupled microstrips should have high characteristic impedances and reasonable separation, within space limitation on the board. The mutual inductance and capacitance between two lines are used to determine the crosstalk coefficient. Forward crosstalk (K_b) is normally smaller than the backward crosstalk on microstrip except for very long lines (>5 feet). Forward crosstalk does not exist at all microstrips since they are made with a homogenous medium so that the inductively and capacitively induced currents cancel. The backward crosstalk coefficient for various types of microstrip line on a G-10 fiberglass epoxy board is given by:

$$K_b = (1/4\pi t_{pd}) \times (L_m/Zo + C_m \times Zo)$$

L_m = inductive coupling

C_m = capacitive coupling

For high speed digital board designs, keep in mind that it is advantageous to have smooth, rounded line edges, constant line widths and minimum lead length for the terminating resistors.

Example #8: What is the backward crosstalk constant between two microstrips with 80 mil spacing on a 60 mil thick fiberglass epoxy G-10 board?

Using the graphical design approach by referring to Figure 8, draw a vertical line starting at s=50 mil Line Spacing Axis until it intercepts with h=59 mil curve. At the same point, make a horizontal line to the Kb axis. Therefore, the backward crosstalk constant or coefficient is found to be 0.06 as shown. the other line (passive line) would have a coupled signal of 6 percent of the amplitude from the active line in a direction opposite to that of the driving signal. The reflection coefficient in this case will be twice as much, or 12 percent.

$$C = 20\log\left|\frac{Zoe - Zoo}{Zoe + Zoo}\right| \text{dB} \quad (15)$$

$$Zo^2 = Zoe \times Zoo \quad (16)$$

$$Zoe = Zo\sqrt{\frac{1 + 10^{c/20}}{1 - 10^{c/20}}} \quad (17a)$$

$$Zoo = Zo\sqrt{\frac{1 - 10^{c/20}}{1 + 10^{c/20}}} \quad (17b)$$

C = Coupling factor

Zoe = Even mode characteristic impedance

Zoo = Odd mode characteristic impedance

$$\lambda_{ge} = 300 \times Zoe \;/\; f(\mathrm{GHz}) \times Zo1e \quad (18a)$$

$$\lambda_{go} = 300 \times Zoo \;/\; f(\mathrm{GHz}) \times Zo1o. \quad (18b)$$

λ_{ge} = Even mode wavelength

λ_{go} = Odd mode wavelength

Zoe is due to the microstrips being at the same potential and carrying equal currents in the same direction. Zoo is due to the microstrip being at equal but opposite potential and carrying equal current in opposite direction.

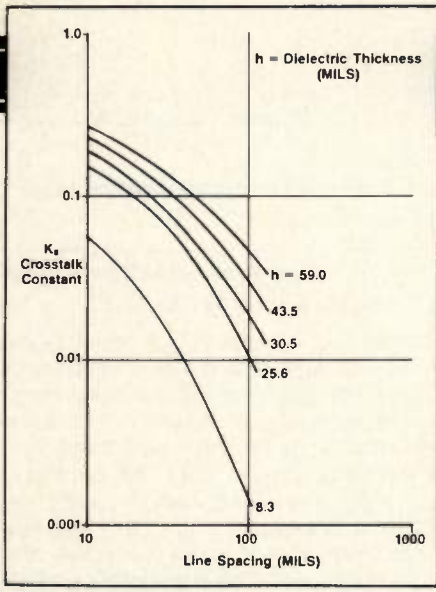

Figure 8. Backward crosstalk on G-10 board.

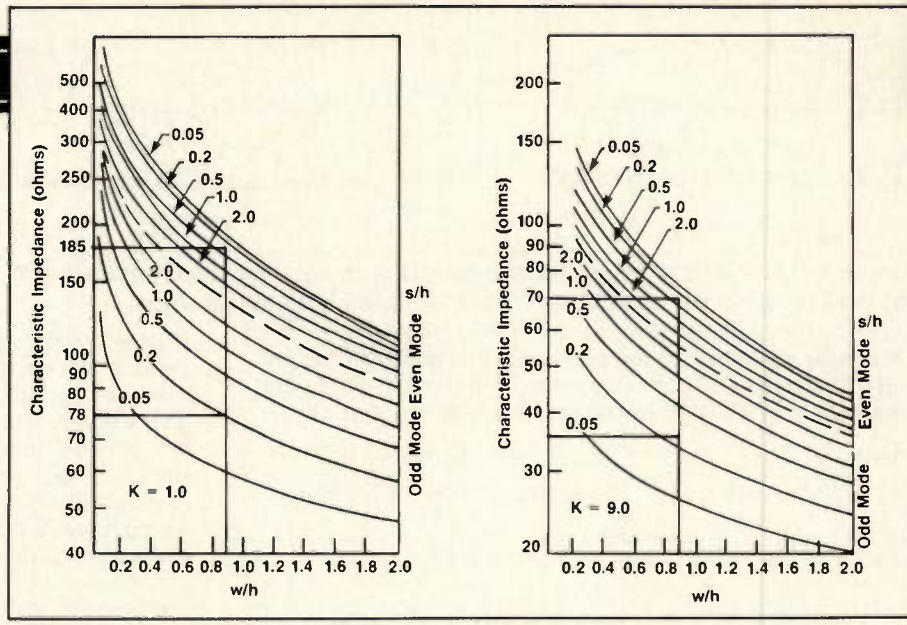

Figure 9. The Bryant and Weiss curves for (a) e = 1 and (b) e = 9.

Example #9: What should be the width, spacing and length for a 10 dB coupler design using all 50 ohm microstrip on a 40 mil thick substrate @ 4 GHz?

$$Zoe = Zo\sqrt{\frac{1 + 10^{c/20}}{1 - 10^{c/20}}} = 50\sqrt{\frac{1 + 10^{10/20}}{1 - 10^{10/20}}} = 69.5 \text{ ohm}$$

$$Zoo = Zo\sqrt{\frac{1 - 10^{c/20}}{1 + 10^{c/20}}} = 50\sqrt{\frac{1 - 10^{10/20}}{1 + 10^{10/20}}} = 36 \text{ ohm}$$

$Zo^2 = Zoe \times Zoo = 69.5 \times 36 = 50$ ohm (To doublecheck the Zo and it agrees)

Using the Bryant and Weiss curve in Figure 9b, draw two horizontal lines, one for Zoe and one for Zoo until these two lines intercept with the same s/h ratio. In this case, the s/h ratio is found to be 0.25, then the w/h ratio of 0.87 can be easily located graphically. Secondly, move on to the figure 9a using similar approach, the Zo1e and Zo1o will be equal to 185 ohm and 75 ohm respectively.

$\lambda_{ge} = 300 \times Zoe$ / f(GHz) $\times$ Zo1e = 28 mm or 1.11 in.
$\lambda_{go} = 300 \times Zoo$ /f(GHz) $\times$ Zo1o = 36 mm or 1.42 in.

The spacing = s/h × h = 0.25 × 40 mil = 10 mil

The width = w/h × h = 0.87 × 40 mil = 35 mil

Since most of the coupler designs use a quarter wavelength approach, the length should be the average of the even and odd mode wavelength divided by 4. The answer for that will be 8 mm or 0.32 in.

5. *Dispersion Effect* — At higher frequencies, the effective dielectric constant and the characteristic impedance of a microstrip line begins to change and makes the conductor dispersive. In simple words, high impedance transmission lines on thinner substrates are less dispersive. The effect of dispersion on characteristic impedance can be generally neglected. Dispersive effects raise the effective dielectric constant slightly as frequency is increased.

Getsinger's expression for Dispersion is:

$$\epsilon_{eff}(f) = \epsilon_r - \frac{\epsilon_r - \epsilon_{eff}}{1 + G(f / f_p)^2} \quad (19a)$$

$$f_p = Zo/(8\pi\, h_e) \quad (19b)$$

$$G = 0.6 + 0.009Zo \quad (19c)$$

and, f is in GHz and h = Substrate thickness (cm).
f_p = the cutoff frequency of next higher order propagation mode.

For $f_p >> f$,

$$\epsilon_{eff}(f) = \epsilon_{eff} \quad (19d)$$

Example #10: What is the effective dielectric constant of a 50 ohm microstrip on a 25 mil thick Duroid 6010 board operating at 10 GHz and the $\epsilon_{eff}(0) = 6.80$ and $h_e = 0.056$ cm?

By considering the dispersive effect because of the operating frequency,

$f_p = Zo/(8\pi\, h_e) = 50 / 8\,\pi \times (0.056 \text{ cm}) = 35.6$ GHz

$G = 0.6 + 0.009Zo = 0.6 + 0.009(50) = 1.05$

$$\epsilon_{eff}(f) = \epsilon_r - \frac{\epsilon_r - \epsilon_{eff}}{1 + G(f / f_p)^2} = 10.2 - \left[\frac{10.2 - 6.8}{1 + 1.05(10/35.6)^2}\right] = 7.06$$

An alternate solution uses the graphical design approach, referring to Figure 10. The same answer as calculated in Example #9 can be found.

6. *Discontinuities* — Any distributed circuits whether in waveguide, coaxial lines, or other types of propagation structure must inherently contain discontinuities. Although such discontinuities give very small amount of capacitances and inductances, the reactances of these become extremely important at higher microwave frequencies (above 10 GHz). Discontinuity effects and radiation loss are directly related. There are eight categories under discontinuities which are tabulated and shown in Table 1.

7. *Higher Order Modes Limitation* — The maximum frequency of operation in a microstrip line is limited by the excitation of spurious modes in the form of surface waves and transverse resonances. Surface waves are TM and TE modes which propagate across a dielectric substrate with the ground plane at the bottom. The frequency at which the extensive coupling will occur between the quasi-TEM microtripline mode and the lowest-order surface wave TM mode is defined as:

$$F_t\,(TEM1) = \frac{C}{2\pi h}\sqrt{\frac{2}{\epsilon_r - 1}}\,\tan^{-1}(\epsilon_r) \quad (20a)$$

if ϵ_r is greater than 10,

$$f_t\,(TEM) = \frac{10.6}{h\sqrt{\epsilon_r}} \text{ (GHz), where h is in cm} \quad (20b)$$

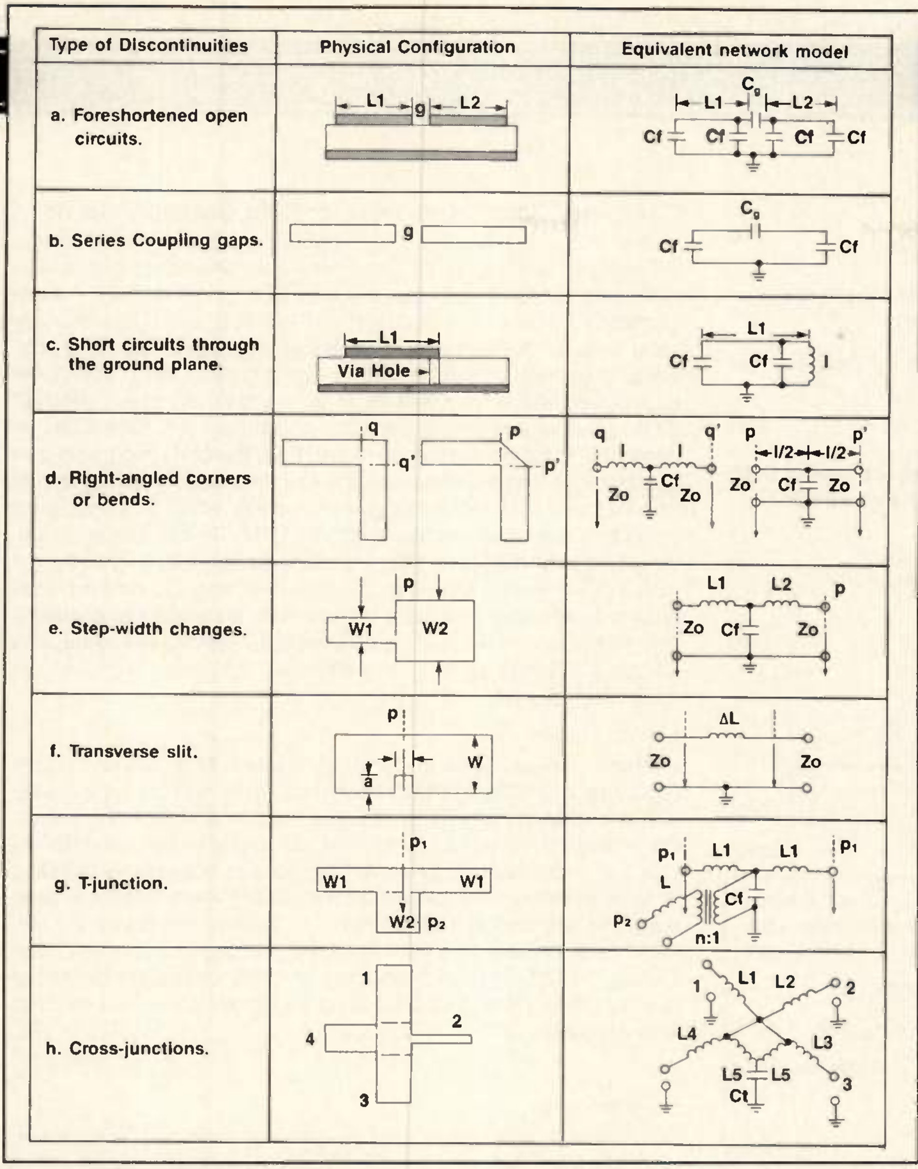

Table 1. Discontinuities.

The cutoff frequency decreases when either the substrate thickness or dielectric constant is increased. The lowest order TE surface wave mode has a lower cutoff frequency.

$$f_c(TE) = \frac{7.5}{h\sqrt{\epsilon_r - 1}} \text{ (GHz) for wide microstripline} \quad (21)$$

In summary, the first order TE mode may be excited at a frequency of about $0.71 f_t(TEM1)$ and f_t (TEM2) is about $1.5 f_t(TEM1)$;

$$f_t(TEM2) = \frac{C}{2\pi h}\sqrt{\frac{2}{\epsilon_r - 1}} \quad \frac{3\pi}{4} \quad (22)$$

Thus, the lowest order TM surface wave defines the upper limit of operating frequency for microstriplines.

For sufficiently wide microstriplines, a TE mode may exist which also couples strongly to the microstripline mode. At the cutoff frequency, the equivalent circuit is a resonant transmission line with length (w+2d) where d accounts for fringing capacitance and is of the order of 0.2h.

$$w+2d = \frac{\lambda_{TE}}{2\sqrt{\epsilon_r}} \quad (23a)$$

$$f_t(TE) = \frac{30}{\sqrt{\epsilon_r}\,(2w + .8h)} \quad (23b)$$

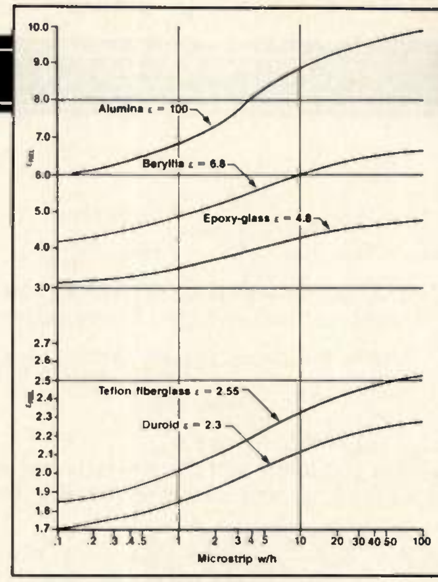

Figure 10. Effective dielectric constant vs. w/h ratio.

f_{cutoff} / $@\epsilon_r > 10$	f_t(TEM1)	f_c(TE)	f_t(TEM2)	f_t(TE)
h = 25 mil	52.3 GHz	39 GHz	83 GHz	53 GHz

Table 2. Cutoff frequencies for higher-order modes.

Material	Relative Dielectric Constant	Loss Tangent (× 10^{-4} in.)	Coefficient Of Expansion (× 10^{-6}/°C)	Thermal Conductivity (W/M °C)	Thickness Mils	Max Usable Frequency (GHz)
99.5% Alumina	9.8	1	6.0	25	15-30	8-16
99.5% BeO	6.7	3	5.7	250	10-30	10-20
RT/Duroid 5870	2.3	5	5-20	26	5-30	12-25
RT/Duroid 6006*	6.0	12	20	.4	10-30	10-20
RT/Duroid 6010*	10.5	12	20	.4	15-30	8-16
Glass Epoxy G-10	5.2	250	10-15	.3	8-30	2-4
Polymide	3.4	75	54	.5	7-30	4-10

Note: * denotes soft board.

Table 3. Common substrate characteristics.

$$f_t(TE) = \frac{10.75}{h\sqrt{\epsilon_r}} \text{ (GHz) @ w=h} \quad (23c)$$

Thus, this frequency is approximately same as f_t(TEM1).

8. Quality Factor (Q) — Although the microstrip line would appear to be an excellent choice for high Q resonant circuits, it is also limited by the radiation losses for low dielectric constant substrates, plus the surface wave coupling, depending on the characteristic impedance of the microstrip line. Notice that the thinner substrates allow higher frequencies to be used due to the surface wave modes, causing serious degradation of the Q factor, especially at the lower operating frequencies. However, a Q-factor of a couple of hundred above X band is still feasible on a standard 25 mil thick alumina substrate.

The rule of thumb for microstrip design: Q is inversely proportional to the thickness of the substrate.

$$\alpha_c = \frac{8.68\,R_s}{2\pi Z_o\,h}\,[1 - (w/4h)^2]\{1 + h/w + h/w\pi[\ln(2h/t) - t/h]\}$$

dB/unit length (24a)

$Q_c = 4{,}780\,h\sqrt{f(GHz)}$, h is in cm, for a copper conductor. (24b)

With the consideration of the dispersion effect, the unloaded Q (Q_u) can be expressed:

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} = \frac{\lambda_o(\alpha_c+\alpha_d+\alpha_r)}{8.686\pi\sqrt{\epsilon_{eff}}} \quad (25)$$

The Q_c, Q_d, Q_r are the quality factors corresponding to conductor, dielectric and radiation losses respectively.

Finally, the circuit Quality factor Q_o can be defined as:

$$\frac{1}{Q_o} = \frac{1}{Q_c} + \frac{1}{Q_d} = \frac{\lambda_o(\alpha_c + \alpha_d)}{\pi\sqrt{\epsilon_{eff}}} \quad (26)$$

This is due to the fact that the radiation losses are higher than the conductor and dielectric losses at higher frequencies.

$$\alpha_d = 27.3\left(\frac{\epsilon_{eff}-1}{\epsilon_r-1}\right)\left(\frac{\epsilon_r}{\epsilon_{eff}}\right)\left(\frac{\tan\delta}{\lambda_g}\right) \text{ dB/unit length} \quad (27)$$

$$Q_d = \frac{27.3}{\alpha_d} \quad (28)$$

$$Q_r = \frac{Zo(f)}{480\pi\left(\frac{h}{\lambda_o}\right)^2\left\{\left(\frac{\epsilon_{eff(f)}+1}{\epsilon_{eff(f)}}\right) - \left[\frac{(\epsilon_{eff(f)}-1)^2}{2(\epsilon_{eff(f)})^{3/2}}\ln\left(\frac{\sqrt{\epsilon_{eff(f)}}+1}{\sqrt{\epsilon_{eff(f)}}-1}\right)\right]\right\}} \quad (29a)$$

$$Zo(f) = Zo\,(\epsilon_{eff(0)} / \epsilon_{eff(f)})^{1/2} \quad (29b)$$

Example #11: What is the circuit Q_c and Q_u of a 50 ohm copper microstrip on a Duroid 6010 board with loss tangent of 12×10^{-6} in. and no sheet roughness at 10 GHz?

Given: ϵ_r=10.2, $\epsilon_{eff(0)}$=6.8, $\epsilon_{eff(f)}$=7.06, h=0.0635 cm.

$\lambda_g=\lambda_o/\sqrt{\epsilon_{eff}}=C / f\sqrt{\epsilon_{eff}}=3\times10^{10}/10\times10^9\times\sqrt{6.8}=0.46$ in.

$Q_c=4{,}780\ h\sqrt{f(GHz)} = 4780(0.0635\text{ cm})\sqrt{10} = 959.$

$$\alpha_d = 27.3\left(\frac{\epsilon_{eff}-1}{\epsilon_r-1}\right)\left(\frac{\epsilon_r}{\epsilon_{eff}}\right)\left(\frac{\tan\delta}{\lambda_g}\right)$$

$$= 27.3\left(\frac{6.8-1}{10.2-1}\right)\left(\frac{10.2}{6.8}\right)\left(\frac{12\times10^{-6}\text{ in.}}{0.46\text{ in.}}\right) = 0.067\text{ dB}/\lambda g\cdot$$

$Q_d = 27.3 / \alpha_d = 27.3 / 0.067 = 406.$

$$\frac{1}{Q_o} = \frac{1}{Q_c} + \frac{1}{Q_d} = \frac{1}{959} + \frac{1}{406}$$

$Q_o = 285.$

$Zo(f) = Zo\,(\epsilon_{eff(0)} / \epsilon_{eff(f)})^{1/2} = 50\,(6.8 / 7.06)^{1/2} = 49$ ohm

$$Q_r = \frac{Zo(f)}{480\pi\left(\frac{h}{\lambda_o}\right)^2\left\{\left(\frac{\epsilon_{eff(f)}+1}{\epsilon_{eff(f)}}\right) - \left[\frac{(\epsilon_{eff(f)}-1)^2}{(\epsilon_{eff(f)})^{3/2}}\ln\left(\frac{\sqrt{\epsilon_{eff(f)}}+1}{\sqrt{\epsilon_{eff(f)}}-1}\right)\right]\right\}}$$

$$= \frac{49}{480\pi\left(\frac{0.0635}{3}\right)^2\left\{\left(\frac{7.06+1}{7.06}\right) - \left[\frac{(7.06-1)^2}{2(7.06)^{3/2}}\ln\left(\frac{\sqrt{7.06}+1}{\sqrt{7.06}-1}\right)\right]\right\}}$$

$$= \frac{49}{0.676\ (0.368)} = 197$$

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} = \frac{1}{959} + \frac{1}{406} + \frac{1}{197}$$

$Q_u = 116.5$

Computer-Aided Design Approach Considerations

With the rapid software and computer hardware development, RF and microwave circuit designers can take advantage of the most popular CAD software, such as SUPER COMPACT® from Compact Software and Touchstone™ from EEsof. They not only save time but also improve the design accuracy. The CAD software provides powerful circuit optimization and fine tune capabilities with a high degree of accuracy for the designers and it can be operated in any personal computers (i.e. IBM/XT/AT or compatible) for convenience. In addition, the CAD programs can generate artworks and associated documentation for any active and passive microstrip design, especially when the operating frequency reaches greater than 10 GHz; There are so many variables to consider for the microstrip design that even a senior circuit designer will have a rough time if he wants to do it manually. Due to its lower cost, user-friendliness, technical performance and flexibility, the RF and microwave CAD system will eventually become a practical and cost-effective long-term solution for microstrip design.

Conclusion

There are quite a number of figures and tables readily available, providing important information for effective microstrip designs. Specifically, Table 3 can enhance your working knowledge about the electrical and physical characteristics of different types of substrates before the hardware subassembly process is implemented. This article also includes many practical suggestions besides the illustrative microstrip design examples which will benefit the new microstrip designers in particular. Finally, the list of technical papers and references should assist any microstrip designer who is interested in advanced reading and research. rf

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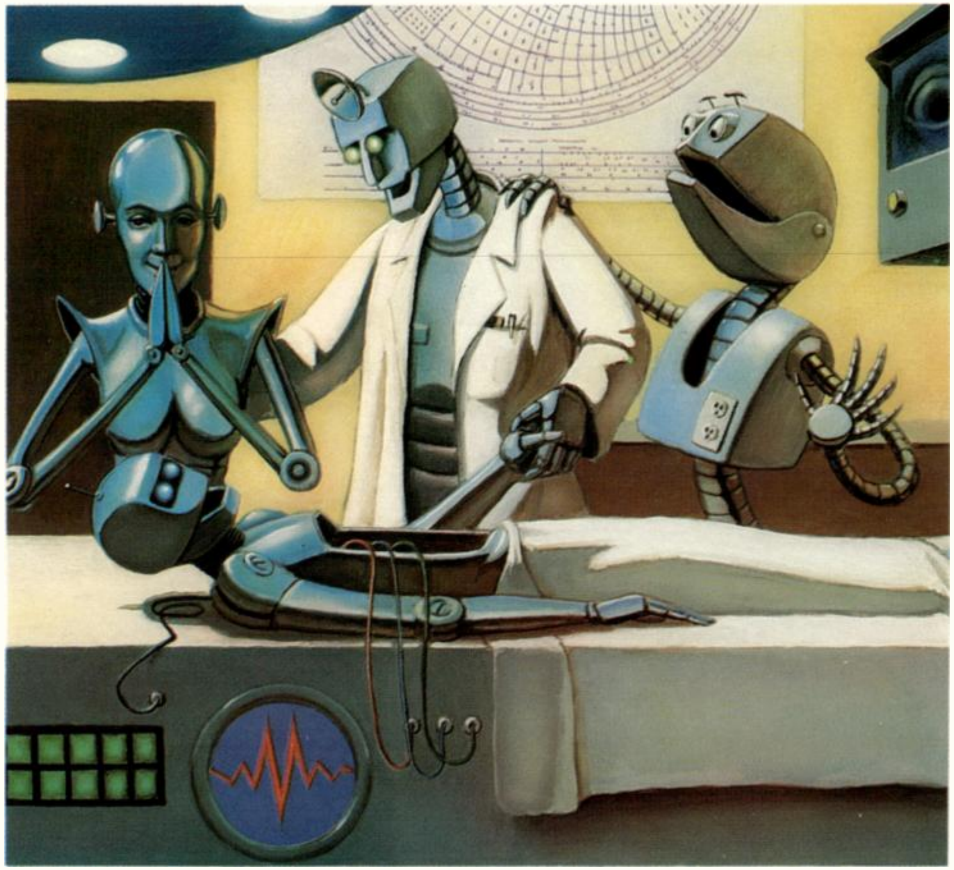

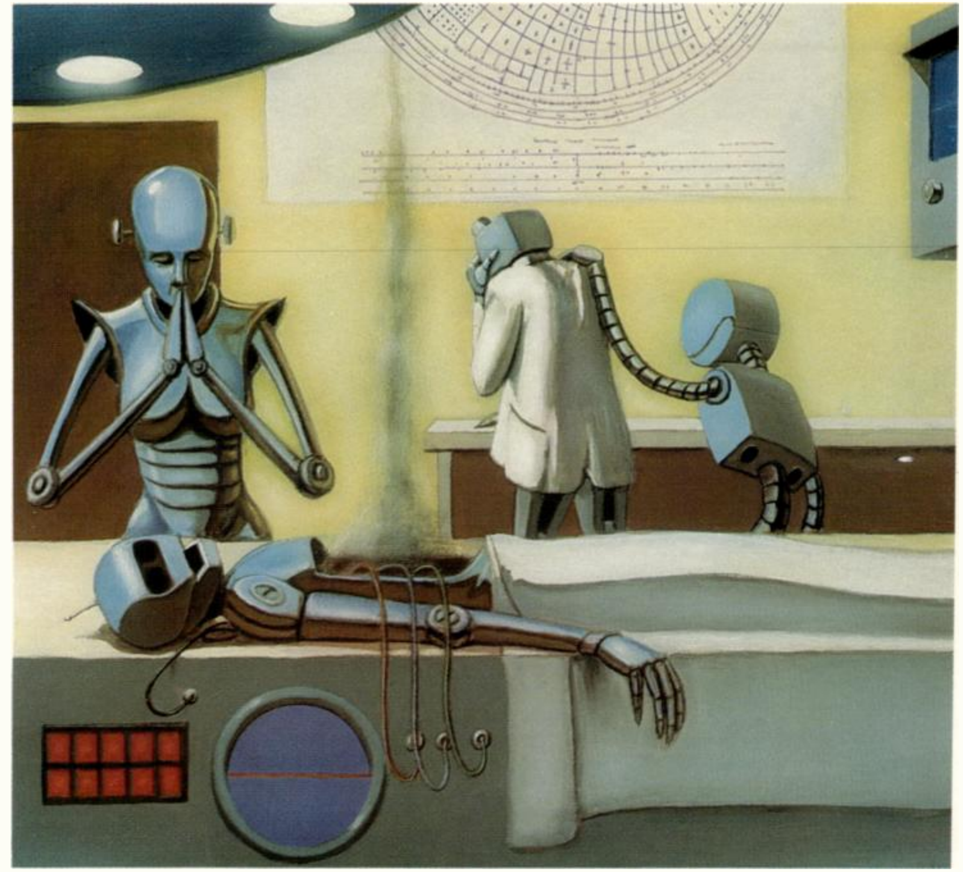

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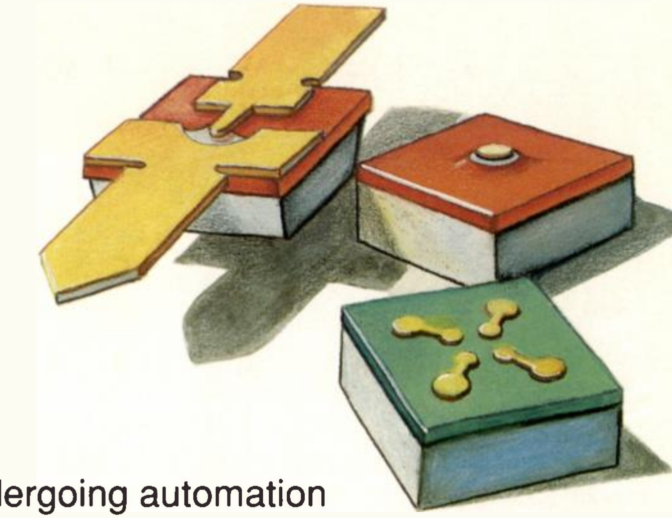

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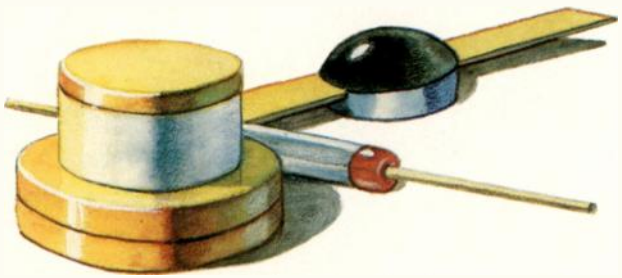

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Microstrip Analysis and Design for Various Substrate Materials

By D.R. Hertling and R.K. Feeney
Georgia Institute of Technology

As the frequency of operation of an RF circuit increases to several hundred MHz or beyond, it becomes increasingly difficult to realize lumped inductors and capacitors. Fortunately, transmission line structures can be made to duplicate the function of lumped elements and also to generate additional circuit elements that are not possible with inductors or capacitors. A strip conductor separated from a ground plane by a dielectric material (a double-sided printed circuit board) forms a microstrip transmission line system. Even when not intentionally used as circuit elements, microstrip transmission lines are always present whenever double-sided printed circuit board is employed. Even digital designers should be aware of the transmission line properties of traces on double-sided printed circuit board. This article presents a computer program in BASIC which provides information needed to design or analyze microstrip transmission lines.

The cross section of a typical microstrip transmission line together with applicable dimensions is shown in Figure 1. The analysis of wave propagation on this structure is not as simple as for coaxial cables or open-wire transmission lines. The microstrip transmission line is dispersive and cannot be described by a simple TEM mode. However, because of its practical importance, the microstrip transmission line has been extensively analyzed. Initial work was done by Wheeler(1) using conformal analysis to develop a set of descriptive equations. The equations so obtained are not very convenient for general engineering use and, consequently, considerable effort has been devoted to obtaining semi-empirical equations that are sufficiently accurate for routine engineering analysis and design. Several of these semi-empirical equations claim accuracy of 1 percent or better which is good enough for most design applications. Since several sets of equations exist, the choice of which to use is often a matter of preference of the designer. The program presented in this paper gives the user the choice of two sets of equations. One set was developed by Sobol (2) and the other set by Hammerstad (3). The authors have found both sets to be quite satisfactory. There is very good agreement between two sets of equations and for users who prefer a different set of equations, a subroutine using the preferred set can be inserted in place of a given subroutine or added as an additional subroutine.

When the program is executed, it prompts the user to choose one of five commands. The first command prints a table of characteristic impedances and velocity factors for specified board properties and a user-specified range of stripwidths. The second command is for analysis; it determines the characteristic impedance and normalized length of a microstrip line of arbitrary dimensions. The third command is used to design microstrip lines of specified characteristic impedance and normalized length. It calculates the required line width to give a desired characteristic impedance and the physical length in mils of microstrip lines at a specified frequency. Both the synthesis and analysis commands have sub-menus which prompt the user for appropriate inputs. The fourth command allows changing board parameters and the choice of equations. Finally, the last command ends the program.

Examples of Program Use

Two examples that make use of the program are presented. The first example prints a summary for 60 mil thick, two-ounce copper, Teflon-glass circuit board. The second example determines the dimensions of a 2.5 GHz Butterworth filter made on gold-alumina substrate.

Example One — For this example, the program will be used to create a summary sheet for 60-mil, two ounce, Teflon-glass circuit board material. On an 8½ by 11 sheet, approximately 50 line widths can be summarized. A listing from 20 mils to 1 inch in steps of 20 mils covers most design applications and gives, at a

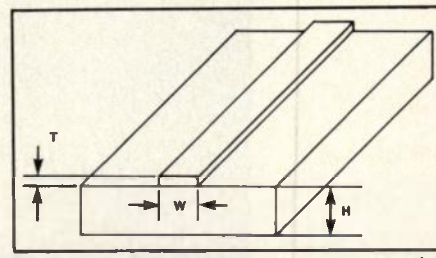

Figure 1. Dimensions of microstrip transmission line.

glance, a good idea of the variation in characteristic impedance and velocity factor over this range of microstrip widths. For finer resolution, the user can simply request smaller steps over a particular range of widths.

Upon execution of the program, the user is prompted to enter the material type, dielectric thickness, metal thickness, and relative dielectric constant. Length and width dimensions used in this program are in mils. These material parameters are retained in memory and need not be entered again during execution of the program. The user should enter TEFLON-GLASS, 60, 2.7, and 2.55 respectively. The computer then displays:

ENTER 1-LENGTHS IN DEGREES; 2 — LENGTHS IN WAVELENGHTS

Enter 1 for lengths in degrees even though this will not actually be used in Example 1. Next,

ENTER — 1 FOR SOBOL'S OR — 2 FOR HAMMERSTAD's EQUATIONS

Enter 1 for Sobol's equations; the program then displays the following menu: plays the following menu:

1 — PRINT A SUMMARY SHEET OF ZO AND VF FOR A RANGE OF WIDTHS
2 — ANALYZE (PHYSICAL TO ELECTRICAL PARAMETERS)
3 — DESIGN (ELECTRICAL TO PHYSICAL PARAMETERS)
4 — CHANGE INITIAL PARAMETERS
5 — EXIT THE PROGRAM

```
10 REM ************************************************************************
20 REM *                        MICROSTRIP DATA PROGRAM                       *
30 REM *               D. R. HERTLING AND R. K. FEENEY 10/30/87               *
40 REM ************************************************************************
50 PI=4*ATN(1)
60 C=3E+10/2.54
70 PRINT "************************************************************************"
80 PRINT
90 INPUT "MATERIAL TYPE  ",TYPE$
100 PRINT
110 INPUT "ENTER - DIELECTRIC THICKNESS (MILS)  ",H
120 PRINT
130 INPUT "ENTER - METAL THICKNESS (MILS)  ",T
140 PRINT
150 INPUT "ENTER - RELATIVE DIELECTRIC CONSTANT  ",ER
160 PRINT
170 INPUT "ENTER 1 - LENGTHS IN DEGREES ; 2 - LENGTHS IN WAVELENGTHS ",F1
180 IF F1=1 THEN L$="DEGREES" ELSE L$="WAVELENGTHS"
190 PRINT
200 INPUT "ENTER - 1 FOR SOBOL'S  OR - 2 FOR HAMMERSTAD'S EQUATIONS ",EQN
210 IF EQN = 1 THEN EQ$="SOBOL'S" ELSE EQ$="HAMMERSTAD'S"
220 PRINT
230 PRINT "************************************************************************"
240 PRINT
250 PRINT "1 - PRINT A SUMMARY SHEET OF ZO AND VF FOR A RANGE OF WIDTHS"
260 PRINT "2 - ANALYZE (PHYSICAL TO ELECTRICAL PARAMETERS)"
270 PRINT "3 - DESIGN (ELECTRICAL TO PHYSICAL PARAMETERS)"
280 PRINT "4 - CHANGE INITIAL PARAMETERS"
290 PRINT "5 - QUIT"
300 PRINT
310 PRINT "************************************************************************"
320 PRINT
330 INPUT "ENTER COMMAND  ",CMD
340 PRINT
350 ON CMD GOSUB 370,610,1010,70,1710
360 GOTO 220
370 REM SUMMARY SHEET OF ZO AND VF
380 PRINT
390 INPUT "ENTER - WIDTH INCREMENT (MILS)  ",WINC
400 PRINT
410 INPUT "ENTER - NUMBER OF CALCULATIONS  ",NCALC
420 PRINT
430 LPRINT:LPRINT
440 LPRINT "MICROSTRIP DATA FOR "+TYPE$+" USING "+EQ$+" EQUATIONS"
450 LPRINT
460 LPRINT USING "DIELECTRIC THICKNESS (MILS) ###.##";H
470 LPRINT
480 LPRINT USING "METAL THICKNESS (MILS) ##.##";T
490 LPRINT
500 LPRINT USING "DIELECTRIC CONSTANT  #.##";ER
510 LPRINT:LPRINT
520 LPRINT "WIDTH (MILS)       IMPEDANCE       VELOCITY FACTOR"
530 LPRINT
540 W=0
550 FOR I=1 TO NCALC
560 W=W+WINC
570 ON EQN GOSUB 1490,1590
580 LPRINT USING "    ####              ####.##              #.###";W,RO,VF
590 NEXT I
600 RETURN
610 REM ZO AND VF FOR A GIVEN WIDTH
620 INPUT "ENTER THE WIDTH (MILS) ",W
630 ON EQN GOSUB 1490,1590
640 PRINT
650 PRINT "************************************************************************"
660 PRINT
670 PRINT "MICROSTRIP DATA FOR "+TYPE$+" USING "+EQ$+" EQUATIONS"
680 PRINT
690 PRINT USING "FOR W =#####.# MILS ZO =####.## OHMS AND VF = #.###";W,RO,VF
700 PRINT
710 PRINT "************************************************************************"
720 PRINT
730 PRINT "1 - RETURN TO MAIN MENU"
740 PRINT "2 - CALCULATE ELECTRICAL LINE LENGTHS"
750 PRINT
760 PRINT "************************************************************************"
770 PRINT
780 INPUT "ENTER COMMAND ",CMD2
790 IF CMD2=1 THEN RETURN
800 PRINT
810 INPUT "ENTER THE FREQUENCY (MHZ) ",F
820 PRINT
830 PRINT "************************************************************************"
840 PRINT
850 PRINT "ELECTRICAL LENGTHS ARE IN "+L$
860 PRINT
870 INPUT "ENTER PHYSICAL LENGTH (MILS) - (0 TO QUIT) ",PL
880 IF PL=0 THEN RETURN
890 LAMBDA=VF*C/F/1000
900 IF F1=1 THEN EL=360*PL/LAMBDA ELSE EL=PL/LAMBDA
910 PRINT
920 PRINT "************************************************************************"
930 PRINT
940 IF F1=1 THEN GOTO 970
950 PRINT USING "FOR A LINE #####.# MILS LONG ";PL;
960 PRINT USING "THE ELECTRICAL LENGTH IS ##.### "+L$;EL:GOTO 990
970 PRINT USING "FOR A LINE #####.# MILS LONG ";PL;
980 PRINT USING "THE ELECTRICAL LENGTH IS #####.# "+L$;EL
990 PRINT:PRINT
1000 GOTO 870
1010 REM ZO AND VF FOR A GIVEN WIDTH
1020 INPUT "ENTER DESIRED ZO  ",ZO
1030 PRINT
1040 INPUT "ENTER THE FREQUENCY IN MHZ  ",F
1050 GOSUB 1420
1060 PRINT
1070 PRINT "************************************************************************"
1080 PRINT
1090 PRINT "MICROSTRIP DATA FOR "+TYPE$+" USING "+EQ$+" EQUATIONS"
1100 PRINT
1110 LAMBDA=VF*C/F/1000
1120 PRINT USING "FOR ZO = ####.## OHMS THE WIDTH = ####.# MILS";ZO,W
1130 PRINT
1140 PRINT USING "AT ####.## MHZ A WAVELENGTH IS #####.# MILS";F,LAMBDA
1150 PRINT
1160 PRINT "************************************************************************"
1170 PRINT
1180 PRINT "1 - RETURN TO MAIN MENU"
1190 PRINT "2 - CALCULATE PHYSICAL LINE LENGTHS"
1200 PRINT
1210 PRINT "************************************************************************"
1220 PRINT
1230 INPUT "ENTER COMMAND ",CMD1
1240 IF CMD1=1 THEN RETURN
1250 PRINT
1260 PRINT "************************************************************************"
1270 PRINT
1280 PRINT "ELECTRICAL LENGTHS ARE IN "+L$
1290 PRINT
1300 INPUT "ENTER DESIRED ELECTRICAL LENGTH (0 TO QUIT) ",EL
1310 IF EL=0 THEN RETURN
1320 IF F1=1 THEN LENGTH=LAMBDA*EL/360 ELSE LENGTH=LAMBDA*EL
1330 PRINT
1340 IF F1=1 THEN GOTO 1370
1350 PRINT USING "FOR A LINE ####.## "+L$+" LONG";EL;
1360 PRINT USING " THE LENGTH IS #####.# MILS";LENGTH:GOTO 1390
1370 PRINT USING "FOR A LINE #####.# "+L$+" LONG";EL;
1380 PRINT USING " THE LENGTH IS #####.# MILS";LENGTH
1390 PRINT
1400 PRINT
1410 GOTO 1300
1420 REM NEWTON-RAPHSON ROUTINE
1430 X1=10:DX=.001
1440 W=X1:ON EQN GOSUB 1490,1590:Y1=RO-ZO
1450 W=X1+DX:ON EQN GOSUB 1490,1590:Y2=RO-ZO
1460 X2=X1-DX*Y1/(Y2-Y1)
1470 IF ABS(X2-X1) <=.01 THEN RETURN
1480 X1=X2:GOTO 1440
1490 REM MICROSTRIP SUBROUTINE (SOBOL)
1500 IF W/H <.05 OR  W/H >20 THEN GOTO 1720
1510 WEFF=W+T/PI*(LOG(2*H/T)+1)
1520 A=377/SQR(ER)*H/WEFF
1530 RO=A/(1+1.735*ER^(-7.240001E-02)*(WEFF/H)^(-.836))
1540 IF (WEFF/H) <= .6 THEN GOTO 1570
1550 VF=1/(SQR(1+.63*(ER-1)*(WEFF/H)^.1255))
1560 GOTO 1580
1570 VF=1/(SQR(1+.6*(ER-1)*(WEFF/H)^.0297))
1580 RETURN
1590 REM MICROSTRIP SUBROUTINE (HAMMERSTAD)
1600 IF W/H <.05 OR W/H >20 THEN GOTO 1720
1610 IF W/H > .16 THEN WEFF=W+T/PI*(LOG(2*H/T)+1):GOTO 1630
1620 WEFF=W+T/PI*(LOG(4*PI*W/T)+1)
1630 IF W/H >1 THEN GOTO 1670
1640 EEF=(ER+1)/2+(ER-1)/2*((1/SQR(1+12*H/WEFF))+.04*(1-WEFF/H)^2)
1650 VF=1/SQR(EEF)
1660 RO=60/SQR(EEF)*LOG(8*H/WEFF+WEFF/H/4):RETURN
1670 EEF=(ER+1)/2+(ER-1)/2*(1/(SQR(1+12*H/WEFF)))
1680 VF=1/SQR(EEF)
1690 RO=377/SQR(EEF)/(WEFF/H+1.393+2/3*LOG(WEFF/H+1.444))
1700 RETURN
1710 STOP
1720 REM ERROR TRAP SUBROUTINE
1730 PRINT:PRINT "***ERROR CONDITION***"
1740 PRINT:PRINT "W/H RATIO OUT OF RANGE"
1750 PRINT:PRINT USING "W/H = ###.###^^^^ ";W/H
1760 PRINT:PRINT "EQUATIONS ACCURATE FOR .05 < W/H < 20"
1770 GOTO 220
1780 END
```

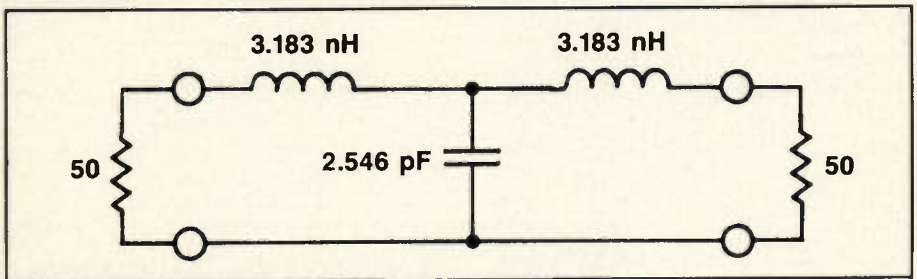

Figure 2. Lumped-element prototype network.

For this example choose command 1. The program prompts for the width increment in mils and the number of desired calculations. Enter 20 and 50 respectively as prompted. This specifies calculations from 20 mils to 1 inch in 20 mil increments. The computer prints the output shown in Table 2 and when finished, the above menu is again displayed. If desired, the user can again choose command number 1 and print a summary with a different width increment and number of points without reentering the board parameters.

Example Two — Figure 2 is a lumped element prototype of a 50-ohm*Butterworth low-pass filter with a cutoff frequency of 2.5 GHz. The microstrip equivalent of this filter is shown in Figure 3. This filter is to be constructed on a gold-alumina substrate with a dielectric thickness of 25 mils, metal thickness of 0.1 mils, and relative dielectric constant of 9.9. Since a different material is being used choose command 4 to change initial parameters. When prompted, enter GOLD-ALUMINA, 25, 0.1, and 9.9 respectively. For this example, specify normalized line lengths in degrees and choose Sobol's equations. After these initial parameters have been chosen, the main menu is displayed. In order to design the required microstrip sections, use command 3 from the main menu. First design 50-ohm lines which will be used as line stretchers on both the input and output sides of the filter. When the computer prompts for the desired ZO and the design frequency in MHz, enter 50 and 2500 respectively. The program uses a Newton-Raphson routine to iteratively solve for the line width. This routine typically takes 5 to 10 iterations and, depending on computer speed, can take several seconds. Finally, the program calculates the wavelength in inches. For the above input, the computer displays the following:

MICROSTRIP DATA FOR GOLD-ALUMINA USING SOBOL'S EQUATIONS

FOR ZO = 50.00 OHMS THE WIDTH = 23.3 MILS

AT 2500.00 MHZ A WAVELENGTH IS 1844.0 MILS

The computer then displays the design sub-menu shown below.

1 — RETURN TO MAIN MENU
2 — CALCULATE PHYSICAL LINE LENGTHS (MILS)

Since the physical line lengths of the 50-ohm sections do not matter, choose command 1 to return to the main menu. The user can now select command 1, 2, or 3 without reentering the board parameters. To design the following microstrip lines, again choose command 3. Then to design the 78 ohm lines at 2500 MHz, enter 78 and 2500. The computer displays the following:

MICROSTRIP DATA FOR GOLD-ALUMINA USING SOBOL'S EQUATIONS

FOR ZO = 78 OHMS THE WIDTH = 7.7 MILS

AT 2500 MHZ A WAVELENGTH IS 1903.3 MILS

When the design sub-menu is displayed choose command 2 in order to design physical lengths. When prompted, enter the 52.2 degree electrical length. The physical length is then displayed.

FOR A LINE 52.2 DEGREES LONG THE PHYSICAL LENGTH IS 276.0 MILS

To return to the main menu, enter a line length of zero. Next, to design the 15 ohm line select the design command from the main menu again, and enter 15 and 2500 for ZO and the frequency. By selecting command 2 in the design sub-menu, the user can find the electrical length of the 30.4 degree line. This line is 150.2 mils wide and 140.8 mils long. The dimensions of the completed filter are shown in Figure 4.

Comparison of Microstrip Equations

Some users may wish to remove the option of selecting equations and use one of the given or a user-defined subroutine. This can be easily done by removing the prompt at line 200 and substituting a statement setting the variable EQN to 1 or 2 (or 3 if a new subroutine is added). If a subroutine is added, its line number must be added to the ON EQN GOSUB statement in line 570. The program will then always use the prescribed set of equations.

Both given sets of equations are accurate for width to dielectric thickness ratios (W/H) between 0.05 and 20. If a W/H ratio out of this range is specified by the user or results from the Newton-Raphson routine, an error trap alerts the user. W/H ratios out of the allowable range are usually caused by specifying transmission lines of either very large or very small characteristic impedances. An error mes-

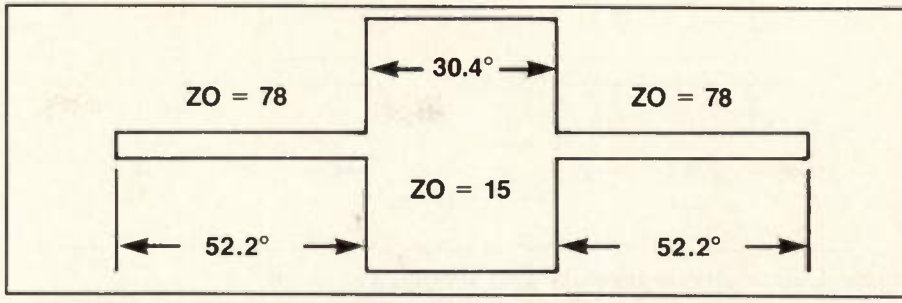

Figure 3. Microstrip equivalent in normalized dimensions.

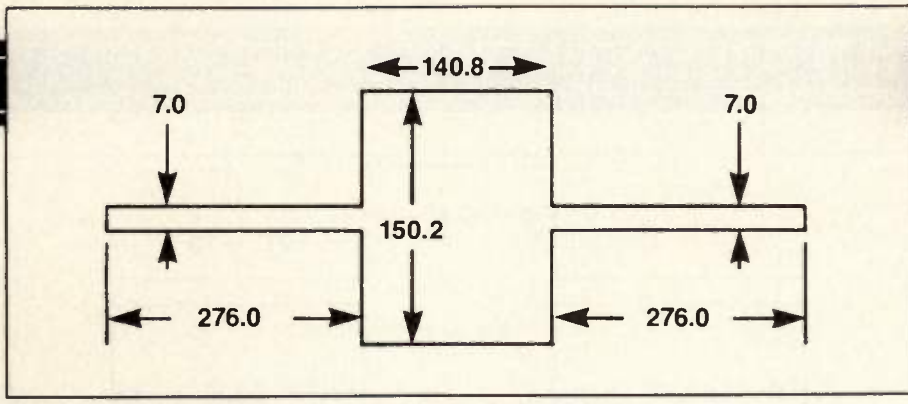

Figure 4. Microstrip equivalent with dimensions in mils.

sage is printed on the screen followed by the W/H ratio and the allowable range. The program then returns to the main menu and, since the initial data is retained, the user can select a command without reentering the substrate parameters.

Conclusions

Microstrip transmission lines are very important in modern RF design. Presented here is a simple, easy-to-use program that does both design and analysis of microstrip elements. The program may easily be changed to accommodate any desired microstrip impedance function. To receive a copy of the program on an IBM formatted diskette, send $5.00 to the authors to cover shipping and handling. rf

References

1. H.A. Wheeler, "Transmission Line Properties of Parallel Wide Strips by a Conformal Mapping Approximation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-12, No. 5, pp. 280-288, May 1964.

2. H. Sobol, "Extending IC Technology to Microwave Equipment," *Electronics*, pp. 112-124, March 20, 1967.

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CAD Amplifier Matching With Microstrip Lines

By Dr. Stanley Novak
Polytechnic University

In lumped element matching circuits, the simplest network with two elements is an L-matching network. This network offers a maximum of four solutions. In contrast, equivalent matching networks realized with two transmission lines (also in L- configuration) provides virtually an infinite number of solutions, particularly if the designer is not limited to one transmission line impedance. The variety of solutions includes a combination of open/shorted stubs at the input and output, or line-stub networks at the input combined with quarter-wave transformers and stubs at the output, or vice versa. To reduce the number of circuit options, computer analysis with one limitation on the line-stub match and one on transformer-stub match should be introduced. For practical purposes, only stub lengths below 90 and 180 degrees are considered.

The computer program presented here allows the designer to choose from a variety of solutions. The input parameters for the program are input and output impedances of a transistor (represented by a two-port network), frequency and a characteristic impedance of a connected (main) transmission line. The program operates as a self-contained unit, and was developed as an extension to the program for amplifier design published in reference (1). It operates on the CBM 64 as well as the HP 9000 series computer. Note that the variables defined for the CBM computer are not tolerated in HP BASIC, and therefore the non-dimensioned variables are changed to double variables (i.e. R to RR, I to II etc.).

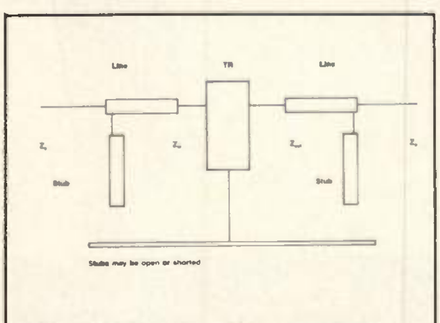

Figure 1a. Line-stub matching.

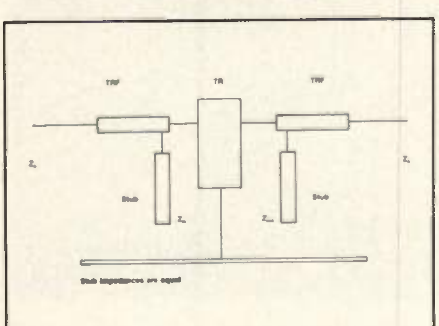

Figure 1b. Transformer-stub matching.

Matching with Stubs and Lines

This is a viable alternative to lumped element matching networks. A combination of both methods is sometimes used, usually by replacing capacitive stubs by capacitors. Transmission line matching is particularly attractive at frequencies when the magnitudes of lumped elements become too small for reliable and easy realization. The equivalent of a lumped element matching network with two pure reactances is a transmission line network with two lengths of lossless lines. The series lines represent series reactances and shunt lines (stub) represent parallel reactances. In the first case the series transmission line is connected to the input terminals of the transistor.

At the point where the real part of the input admittance of the line (with selected characteristic impedance) is equal to the admittance of the connected (main) line, another line is added in parallel (stub) to cancel the susceptance to complete the matching. The susceptance may be realized by open or shorted stub, which in general can have any value of characteristic impedance. However, in this case the computer limits the choice to the same value as the series line. A similar approach is used at the transistor output.

In the second case, the designer has to determine the input admittance of the transistor and add directly to the input terminal length of the open or shorted line

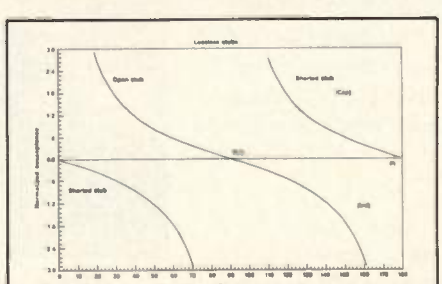

Figure 2. Electrical length versus susceptance.

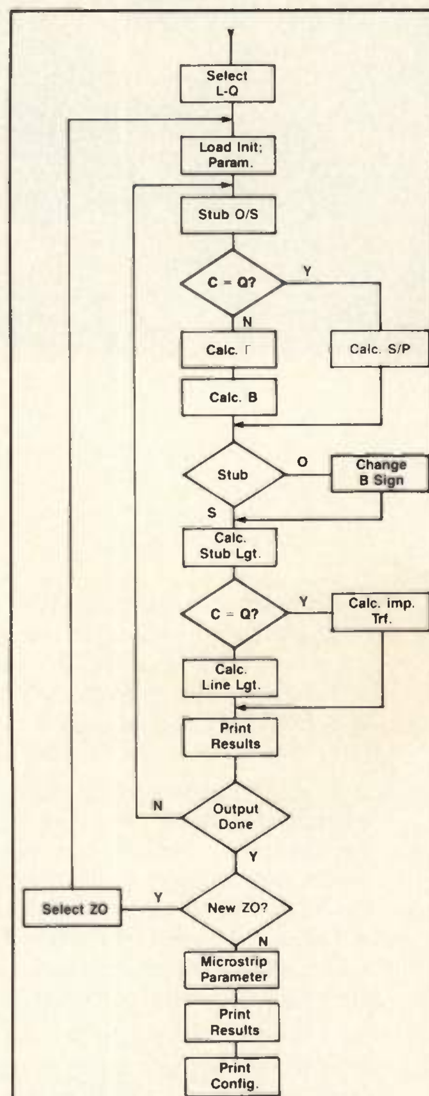

Figure 3. Flowchart for the microstrip match program.

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```
[illegible] REM MICRO[illegible]TRIP DESIGN, S. NOVAK, OCT 1986
[illegible] PRINT"MICROSTRIP-LINE MATCH DESIGN"
[illegible] READ TRF,RS,XS,RL,XL
[illegible]
[illegible]
[illegible] DIM [illegible] A(9)
[illegible] PRINT TS"FREQUENCY=";F/1000000;"MHZ","Z0=",Z0,"OHMS
[illegible]
[illegible] PRINT"INPUT IMP (RS,XS)=",RS,XS
[illegible] PRINT"OUTPUT IMP (RL,XL)=",RL,XL
[illegible] GOTO [illegible]
[illegible] REM COMPL NO DIVIDE ••••••••••••••••••••••••••••••••
[illegible]
[illegible] D
[illegible] D
[illegible] RETURN
[illegible] REM RECT TO POLAR ••••••••••••••••••••••••••••••••••
[illegible]
[illegible]
[illegible] THEN 1910
[illegible] *180/PI+A(J)*(1-SGN(R(J)))
[illegible] RETURN
[illegible] REM CALC DISTRIBUTED ELEMENTS ••••••••••••••••••••
[illegible] INPUT"MATCH STUB-LINE OR QUARTER WAVE TRANSFORMER?[L/Q]";C$
[illegible] IF C$="L" THEN PRINT"STUB AND LINE MATCH",
[illegible] IF C$="Q" THEN PRINT"QUARTER W.TRANSF AND STUB MATCH",
[illegible] PRINT" AT FREQUENCY";F/1000000;"MHZ"
[illegible] IF C$="L" THEN B$="LINE"
[illegible] IF C$="Q" THEN B$="TRF."
[illegible] DIM T(4)
[illegible] REM GL=REAL PART OF TERM.IMPEDANCE [LINE=50OHM]**
[illegible]
[illegible]
[illegible] -XL
[illegible] -XS
[illegible]
[illegible] FOR J=8 TO 9
[illegible] IF J=8 THEN PRINT"INPUT ******
[illegible] IF J=9 THEN PRINT"OUTPUT ******
[illegible] INPUT"OPEN OR SHORTED STUB?[O/S]";D$
[illegible] IF D$="O" THEN G$="OPEN"
[illegible] IF D$="S" THEN G$="SHORTED"
[illegible] IF C$="Q" THEN 3350
[illegible] REM CALC NEW REFL COEFF ••••••••••••••••••••••••••
[illegible]
[illegible]
[illegible] GOSUB [illegible]
[illegible]
[illegible] GOSUB [illegible]
[illegible] REM CALC B STUB ••••••••••••••••••••••••••••••••••••••
[illegible] B=(M(J)*M(J)*(Y0+GL)*(Y0+GL)-(Y0-GL)*(Y0-GL))/(1-M(J)*M(J))
[illegible] IF B<0 THEN PRINT"NO SOLUTION FOR Z0=";Z0;"OHMS"
[illegible] IF B<0 THEN 3270
[illegible] B=SQR(B)
[illegible] REM CALC STUB ••••••••••••••••••••••••••••••••••••••
[illegible] IF D$="S" THEN B=-B
[illegible] BL=ATN(-Y0/B)*180/PI
[illegible] IF BL<0 AND C$="L" THEN BL=90+BL
[illegible] IF BL<0 AND C$="Q" THEN BL=90-BL
3110 T(J-7)=BL/360
3120 IF C$="Q" THEN 3400
3130 AA=A(J)
3140 REM CALC LINE ••••••••••••••••••••••••••••••••••••••
3150 R1=Y0-GL:I1=-B
3170 R2=Y0+GL:I2=-B
3190 GOSUB 1750
3200 R(J)=R:I(J)=I
3220 GOSUB 1900
3230 AA=(A(J)-AA)/2
3240 IF AA<0 THEN AA=AA+180
3250 T(J-5)=AA/360
[illegible] GOTO 3450
[illegible] NEXT J
[illegible] INPUT"NEW LINE IMPEDANCE OR REPEAT CALCULATIONS?[Y/N]";E$
[illegible] IF E$="N" THEN 3610
[illegible] INPUT"ENTER LINE IMPEDANCE IN OHMS [IF REPEAT PRESS ENTER]";Z0
3310 FOR J=1 TO 4:T(J)=0:NEXT J
3340 GOTO 2790
3350 REM SER/PAR CONVERSION ••••••••••••••••••••••••••••
3360 U=(I(J)/R(J))*(I(J)/R(J))
3370 R1=R(J)*(1+U)
3380 B=-U/(I(J)*(1+U))
3390 GOTO [illegible]
3400 REM QUARTER-WAVE TRANSFORMER ••••••••••••••••••••••
3410 V(J)=SQR(R1/GL)
3420 Z1=V(J)
3430 T(J-5)=.25
3440 AA=90
3450 REM PRINT RESULTS •••••••••••••••••••••••••••••••••
3460 PRINT B$;" LENGHT=";INT(T(J-5)*E)/E;"LAMBDA 0",
3470 PRINT ",EL.LENGHT=";INT(AA*E)/E;"DEG.,IMPEDANCE=";INT(Z1*E)/E;"OHMS"
3480 PRINT G$;" STUB=";INT(T(J-7)*E)/E;"LAMBDA 0",
3490 PRINT ",EL.LENGHT=";INT(BL*E)/E;"DEG.,IMPEDANCE=";Z0;"OHMS"
3500 IF J=8 THEN H$=G$
3510 GOTO 3270
3520 REM CALC.MICROSTRIP WIDTH ••••••••••••••••••••••••
3530 DE=EXP(Z0*SQR(1+ER)/42.4)-1
3540 NE=8*SQR(DE*((7+(4/ER))/11)+((1+(1/ER))/.81))
3550 W=H*NE/DE
3560 REM CALC.EFF.DIEL.CONSTANT ••••••••••••••••••••••
3570 [illegible]F=((ER+1)/2)+((ER-1)/2)*(1/SQR(1+(10*H/W)))
3580 REM LAMBDA FREE SPACE=LM,IN SUBSTRATE=LG ••••••••
3590 LG=10*LM/SQR(EF)
3600 RETURN
3610 PRINT:PRINT"ENTER SUBSTRATE PARAMETERS"
3630 INPUT"SUBSTRATE REL DIEL CONSTSTANT";ER
3640 INPUT"SUBSTRATE THICKNESS [MM]";H
3650 LM=3E+10/F
3660 GOSUB 3520
3670 PRINT
3680 PRINT"PARAMETERS FOR MICROSTRIP LINES @";F/1000000;"MHZ CENTER FREQUENCY"
3690 PRINT"SUBSTRATE THICKNESS=";H;"[MM]"
3700 PRINT"SUBSTRATE REL DIEL CONST=";ER
3710 PRINT"LINEWIDTH FOR";Z0;"OHMS=";INT(W*E)/E;"[MM]"
3720 PRINT H$;" STUB-IN LENGHT=";INT(T(1)*LG*E)/E;"[MM]"
3730 PRINT G$;" STUB OUT LENGHT=";INT(T(2)*LG*E)/E;"[MM]"
3740 IF C$="Q" THEN 3780
3750 PRINT B$;" LENGHT-IN=";INT(T(3)*LG*E)/E;"[MM]"
3760 PRINT B$;" LENGHT-OUT=";INT(T(4)*LG*E)/E;"[MM]"
3770 GOTO 3840
3780 Z0=INT(V(8))
3790 GOSUB 3520
3800 PRINT"LINEWIDTH FOR TRF.IN ";Z0;"OHMS=";INT(W*E)/E;"[MM]";"LENGHT=";INT(T(3
)*LG*E)/E;"[MM]"
3810 Z0=INT(V(9))
3820 GOSUB 3520
3830 PRINT"LINEWIDTH FOR TRF.OUT ";Z0;"OHMS=";INT(W*E)/E;"[MM]";"LENGHT=";INT(T(
3)*LG*E)/E;"[MM]"
3840 PRINT
3850 Z0=1/GL
[illegible] GOSUB 3520
[illegible] PRINT"LINEWIDTH FOR MAINLINE";Z0;"OHMS=";INT(W*E)/E;"[MM]"
3880 PRINT"CIRCUIT CONFIGURATION ••••••••••••••••••••••••"
3890 PRINT:IF C$="Q" THEN 3960
3900 PRINT"GEN. *S*** LINE **** TRANS **** LINE ***S* LOAD"
3910 PRINT"    T                        T"
3920 PRINT"    U                        U"
3930 PRINT"    B                        B"
3940 PRINT"   ";H$;"                ";G$
3950 GOTO 4100
3960 PRINT"GEN ***** TRF **S* TRANS *S** TRF ***** LOAD"
3970 PRINT"              T        T"
3980 PRINT"              U        U"
3990 PRINT"              B        B"
3995 PRINT"            ";H$;"     ";G$
4000 REM TRANSISTOR DATA STORAGE ••••••••••••••••••••••
4010 REM 2N3570,750E6,9.[illegible]
4020 DATA MRF571,1E9,2.[illegible]
4100 END
```

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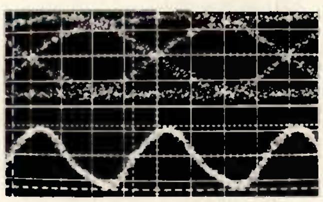

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UPG703B	Four Stage Ripple Counter	500 ps	2.5 GHz
UPG704B-15	4:1 Multiplexer	800 ps	1.5 GHz
UPG704B-20	4:1 Multiplexer	800 ps	2.0 GHz
UPG704B-25	4:1 Multiplexer	800 ps	2.5 GHz
UPG705B-15	1:4 DeMultiplexer	800 ps	1.5 GHz
UPG705B-20	1:4 DeMultiplexer	800 ps	2.0 GHz
UPG705B-25	1:4 DeMultiplexer	800 ps	2.5 GHz
UPG706B-1	High Speed Flip Flop	400 ps	4.0 Gbps
UPG706B-2	High Speed Flip Flop	400 ps	4.0 Gbps
UPG707B	Laser Diode Driver	400 ps	3.0 GHz

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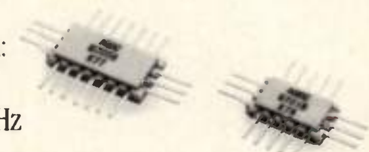

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(stub). This cancels the reactive part of the admittance and uses a series line quarter-wave transformer to convert the remaining resistive part to the characteristic impedance of the connecting transmission line (which is 50 ohms in most cases). This is repeated at the output and both cases are illustrated in Figure 1.

The only limitation on matching line impedances is the substrate material, which gives the practical boundaries on the realizable width of the lines. The exception is the quarterwave transformer whose impedance is given by the real part of the transistor input/output impedances and impedance of connected transmission line.

In the case of stubs, use of either the open or shorted configuration is determined by circuit requirements such as biasing. When circuit size is a consideration, the selection of stub configuration is usually critical since one method may have a shorter stub over another. Note that adding half wavelengths to the calculated value will change an open stub to a shorted stub and vice versa.

Calculations of Stub Impedances

For short sections of lines, the designer can assume that the losses could be neglected and the results from lossless analysis of transmission lines can be used. In this case, operating with parallel stub elements, the admittance of the open and shorted stub is:

$$Y_{os} = j\ Y_o \tan\theta \quad (1)$$

$$Y_{ss} = -j\ Y_o \cot\theta \quad (2)$$

Note that the resulting values are pure susceptances, and the only difference between tan and −cot functions is 90 degrees or $\pi/2$ radians. This is reflected in equation 3;

$$\tan(90 + \theta) = -\cot\theta \quad (3)$$

If open capacitive stubs shorter than 90 degrees with a positive sign for susceptance are desired and a negative value for θ is obtained, the designer has to add 90 degrees to obtain the desired solution. In the case of shorted (inductive) stubs, shorter than 90 degrees with negative susceptance value, 90 degrees may have to be added to θ if necessary. This is done automatically in the program.

The relationship between the functions for open and shorted stubs is shown in Figure 2. From Figure 2 note that useful areas for realization of stubs is below 60 degrees of electrical length at the frequency of design, (or below $\pi/3$ radians or .167 lambda free space). Impedance above this value rises too rapidly for reliable realization. This limit should be taken as a guidance when determining which computed value is suitable for realization of practical matching networks.

The angle θ in the equations actually represents the following relationship:

$$\theta = \beta l = 2\pi l/\lambda \text{ (rad)} \quad (4)$$

or

$$\theta = \beta l = 360 l/\lambda \text{ (degrees)} \quad (4a)$$

From this, for known susceptances the required length l can be calculated using (1) and (2) respectively. Considering that for shorted stubs (<90 degrees) the susceptance is negative, from (2);

$$Y_{ss} = -jB_{ss} = -j\,Y_o \cot\theta \quad (5)$$

or

$$\tan\theta = Y_o/B_{ss} \quad (6)$$

from which,

$$\beta l_{ss} = \theta = \tan^{-1}(Y_o/B_{ss}) \quad (7)$$

Note that equation 7 gives the value of βl in degrees or radians depending on the conversion used. For open stubs shorter than 90 degrees the value of susceptance needs to be positive and,

$$Y_{os} = jB_{os} = jY_o \tan\theta \quad (8)$$

or

$$\tan\theta = (B_{os}/Y_o) \quad (9)$$

leading to,

$$\beta l_{os} = \tan^{-1} (B_{os}/Y_o) \quad (10)$$

From equation 7 the length of the shorted stub becomes;

$$l_{ss} = \lambda/2\pi \tan^{-1}(Y_o/B_{ss}) \quad (11)$$

and from equation 10 for open stub;

$$l_{os} = \lambda/2\pi \tan^{-1}(B_{os}/Y_o) \quad (12)$$

The wavelength can be obtained from frequency of design by the following;

$$\lambda = 3.10^8/f \quad (13)$$

which when substituted into equations 11 and 12 gives the required stub lengths in free space. To calculate lengths of microstrip lines the designer should evaluate the effective dielectric constant of the lines and correct the free space wavelength for each case using the equations below;

$$l_m = l/\sqrt{\varepsilon_{eff}} \quad (14)$$

This concludes the stub design.

Quarter-Wave Transformers

When designing with quarter-wave transformers, first convert input (output) impedance of the transistor to its parallel admittance equivalent circuit. The required matching susceptance may be capacitive or inductive, and can be realized by open or shorted stub. For example, to realize inductive susceptance (Figure 2), open stub lengths in the $90 < \theta < 180$ degrees range are used and compared with inductive shorted stubs in the $0 < \theta < 90$ degrees region which provide for the same match. In the case of capacitive susceptance the situation is reversed. Therefore, matching stubs longer than 90 degrees are sometimes necessary. Fortunately, due to symmetrical character of the $\tan\theta$ and $-\cot\theta$ functions similar solutions are obtained by trigonometry manipulation.

Note that capacitive stubs are sometimes preferred to lumped capacitance, in the form of chip capacitor or by some tunable version. The required value is then determined from the susceptance as;

$$C = B/(2\pi f)$$

Microstrip Lengths and Width Calculations

When the evaluation of free space lengths and impedances of the lines is completed, the next step is the selection of dielectric substrate material for the final realization of the circuit. After the material is selected, the lengths and widths of the lines and stubs may be evaluated. This is done using Wheeler's [2] equations, assuming for simplification zero thickness of the conductive layer. Then from the chosen material parameters and known lengths and impedances of the lines, each line is evaluated for the required length and width. Width is determined by characteristic impedance of the line and applicable effective dielectric constant.

Using substrates that have a permitivity range of two to ten, the line impedance has to be maintained between 20 and 150 ohms since lines below this range are too wide and lines above this range are too narrow to be reliably etched on the substrate. When designing with quarter wave transformers, impedance generally exceeds this range. In such cases a solution is to calculate intermediate impedance as a square of the input and output impedances, and use two transformers in series.

The bandwidth of amplifiers designed by using only two matching elements is usually restricted to about 10 percent. In case where this is unsatisfactory it is possible to use analysis programs with optimization facilities that extend bandwidth. Obviously this is achieved by reduction of the overall gain.

Program Logistics

The program is based on a short review of basic principles used in matching circuits with transmission lines. Further information is detailed in references 3,4 and 5. Processing of entry data is shown in Figure 3.

After loading the input and output impedances and operating frequency of the transistor, the program designs a matching network. After the operator selects the type of network desired (line and stub or transformer and stub), the program finds the data for input network, selects the stub for output network, and displays the results. Calculations are done for the standard 50 ohm environment. However, the operator is offered a choice of impedance values for matching lines. The operator can also repeat calculations for the same impedance while changing requirements for stubs. If a new impedance is selected, the calculations are repeated with a new selection of stubs. After a satisfactory solution is obtained, the user may exit by refusing a new value of Z_0. The program is then redirected to the final evaluation of widths and lengths of lines in the selected substrate environment.

The final configuration of the circuit is

Table 1. MRF 571 at 1000 MHz with 50 ohm lines.

displayed together with the selected stub elements. In cases where quarterwave transformer and stub matching is selected, the values of transformers impedances and line parameters are shown together with linewidth of the mainline microstrip (50 ohm). Examples are illustrated in Tables 1 and 2.

Note that in some cases the match of two transmission line networks is not realizable. When this happens, the computer displays a message indicating that for chosen characteristic impedance Z_0, a solution is not available.

Conclusion

The program presented above offers significant time savings for the design of narrow band amplifier matching circuits. When used on computers with graphic facilities, simple adaptation provides for graphic display of all available combinations for match within a chosen range of line impedances.

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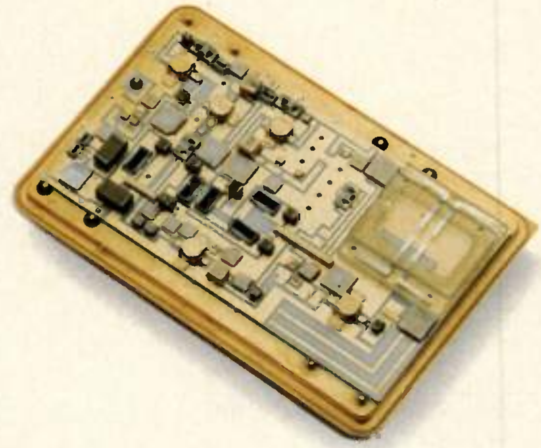
1. S. Novak, "Computer Enhanced Amplifier Design," *RF Design*, Feb. 87, pp. 97-109.
2. H.A. Wheeler, "Transmission Line Properties of a Strip on a Dielectric Sheet on a Plane," *IEEE Trans. on MTT*, Aug. 77, pp. 631-647.
3. T.T. Ha, *Solid State Microwave Amplifier Design*, Chap. 3-4, Wiley 1981.
4. R.S. Carson, *High Frequency Amplifiers*, Wiley 1975.
5. G.D. Vendelin, *Design of Amplifiers and Oscillators by the S-Parameter Method*, Chap. 1, 2, 3, Wiley 1982.

Table 2. MRF 571 using 20 ohm lines and 100 ohm stubs.

6. S. Novak, "Amplifier Matching with Transmission Lines," *1987 International Symposium/Brazil.*

About the Author

Dr. Stanley Novak is industry professor, director EE Laboratories at Polytechnic University, 333 Jay Street, Brooklyn, NY 11201. He can be reached by telephone at (718) 260-3476.



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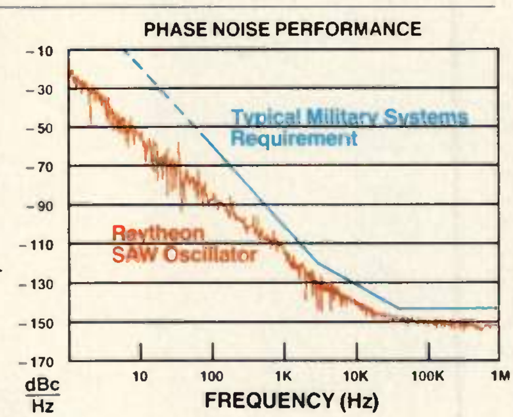

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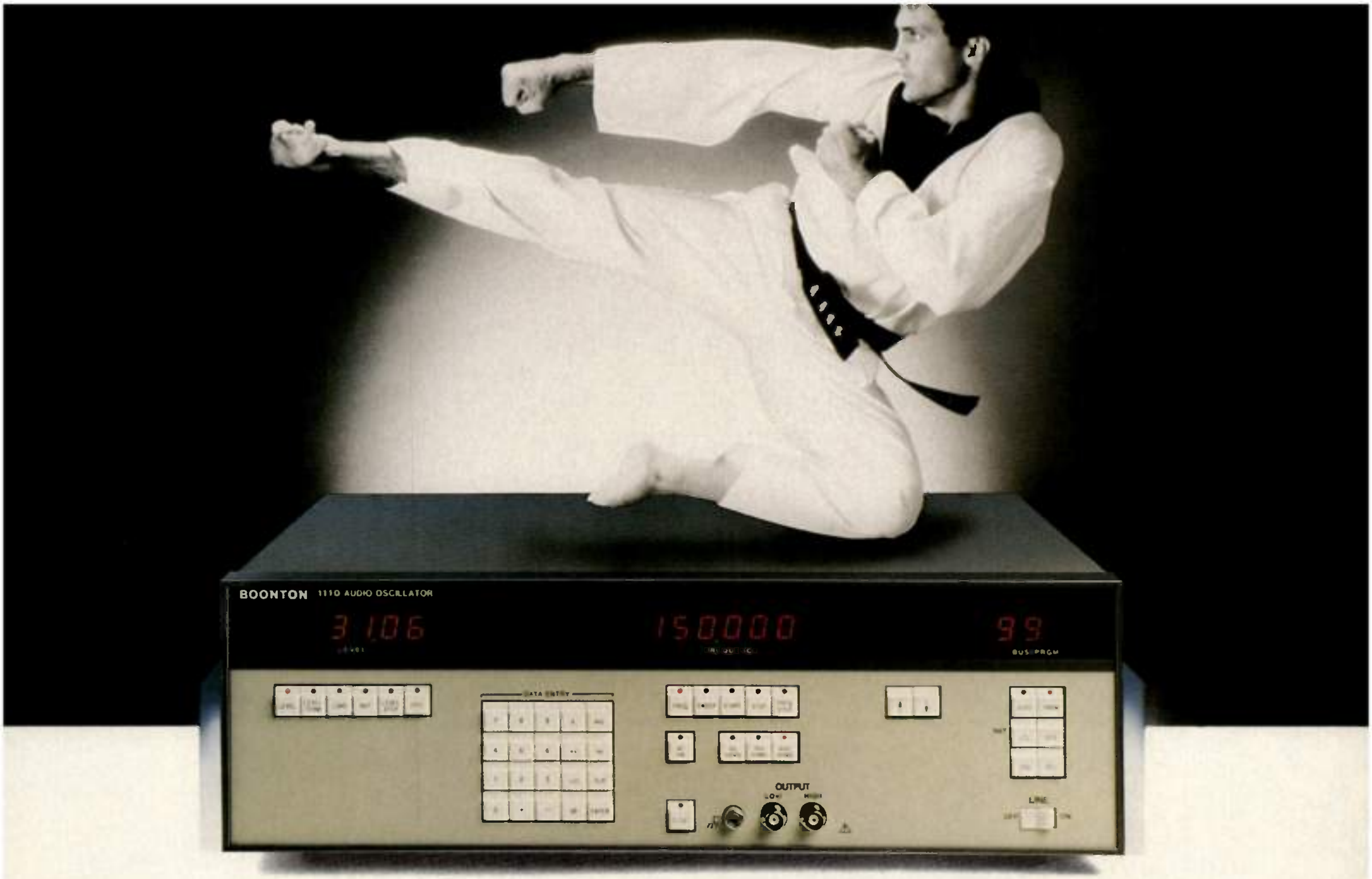

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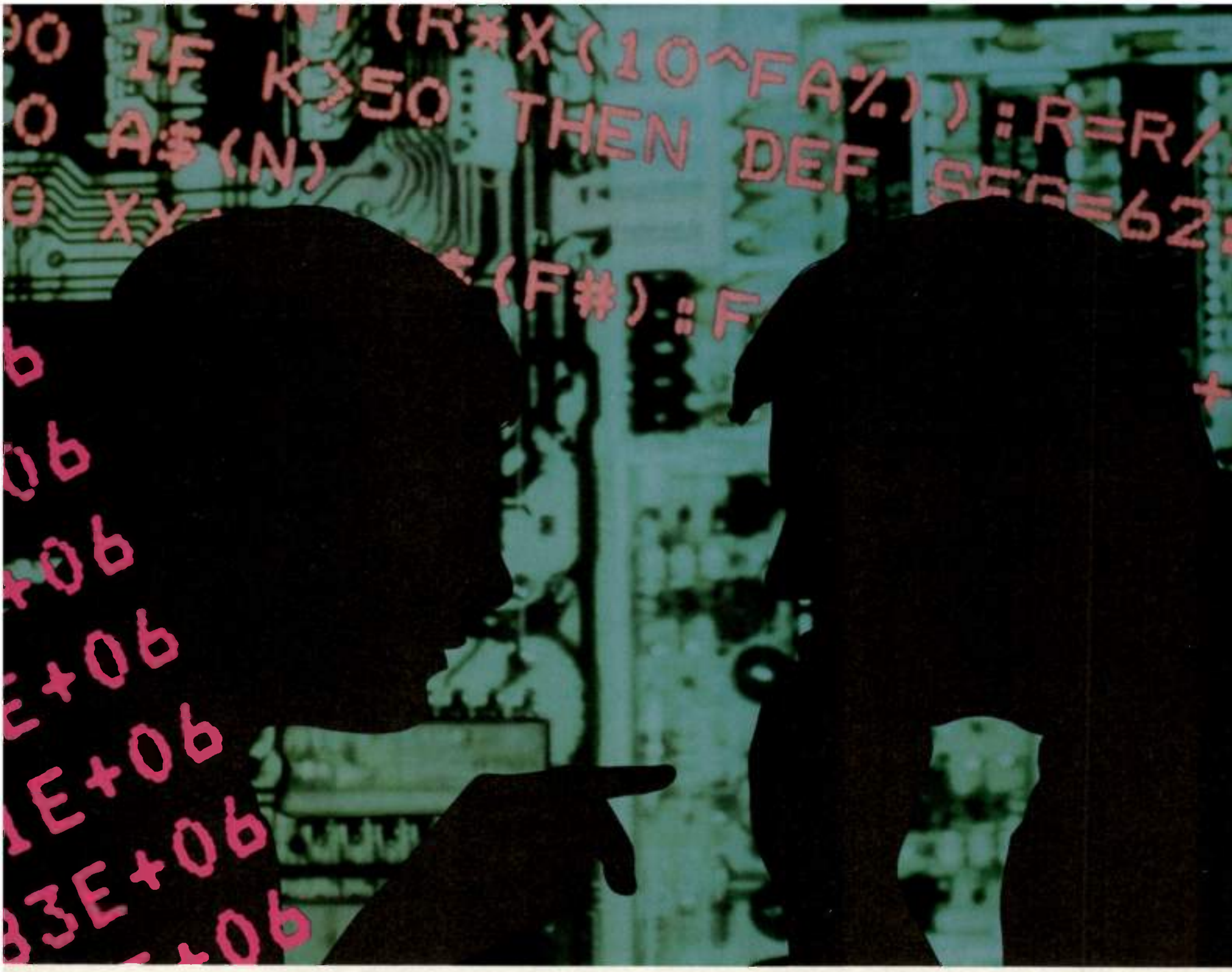

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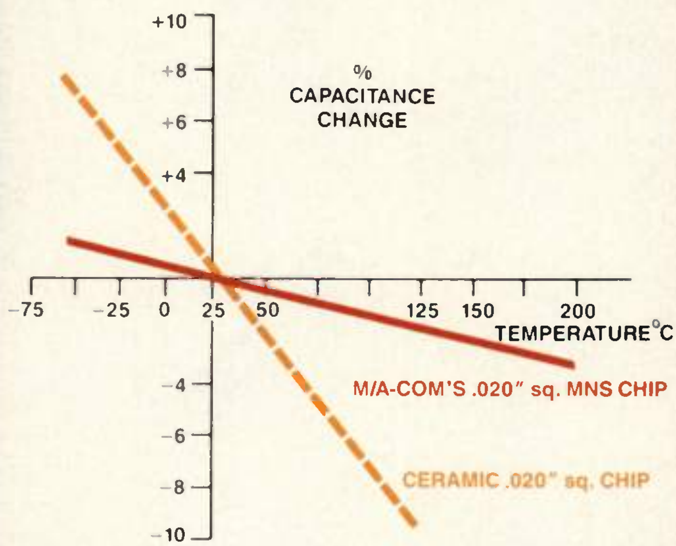
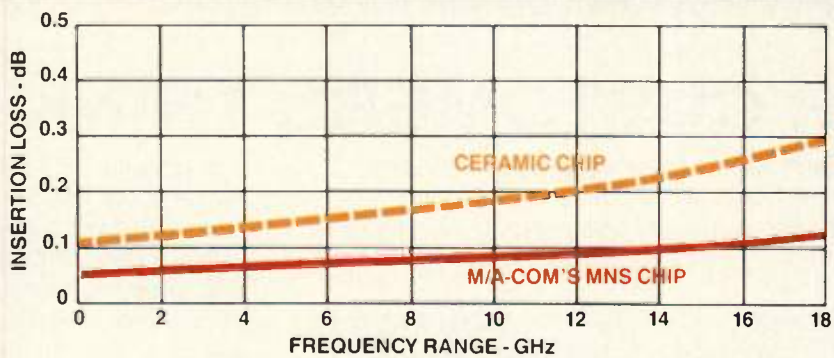


Capacitance Change for 20 pF Capacitors M/A-COM'S MNS VS. Ceramic



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New Products at MTT-S 1988

New York Show Spotlights RF and Microwave Offerings

Toggle Switch Attenuators
Kay Elemetrics

A line of toggle switch attenuators utilizing surface mount technology will be introduced. The devices feature a 3 watt power rating with a frequency range of up to 3 GHz. These attenuators are useful for test calibration. **Kay Elemetrics Corp., Pine Brook, NJ. INFO/CARD #206.**

Tuned Filters and Multicouplers
K&L Microwave

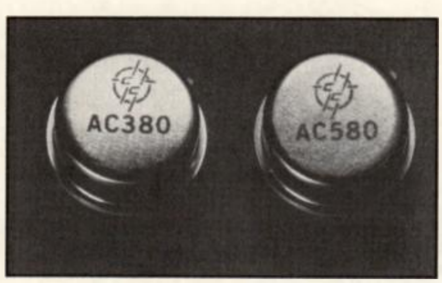
K&L will be showing a line of digitally and manually tuned filters and multicouplers including a 225-400 MHz frequency agile hopping multiplexer. The filters can be tuned in two modes; the normal mode and active mode. The normal mode directs the filters to frequencies previously selected through a frequency management system utilizing digitally controlled stepping motors. In the active mode, individual filters hop in a 12 MHz band about the frequency selected from the normal mode. The multicoupler handles 30 watts average with peak specification of 120 watts or 50 watts CW. **K&L Microwave, Inc., Salisbury, MD. Please circle INFO/CARD #205.**

GaAs Switch
Daico Industries

The P/N DS0602 is a low current, broadband, GaAs FET SPDT switch with a frequency range of 5 to 2000 MHz and VSWR of 1.5:1. The device draws 150 microamps and switches in 26 ns. From 5 to 20 MHz, the isolation is 55 dB. Other features include internal 50 ohm termination and 4 ns transition time. **Daico Industries, Inc., Compton, CA. Please circle INFO/CARD #204.**

Cascadable Amplifiers
Cougar Components

Models AC380 and AC580 are thin film cascadable amplifiers that operate from 10 to 250 MHz and 10 to 500 MHz, respectively. Typical gain is 25 dB on the 380 and 23 dB on the 580. Noise figure ranges from 1.7 dB to 2.2 dB depending on the model. Operating current at 15 V is 17 mA on the 380 and 18 mA on the 580. The amplifiers are packaged in 4-pin TO-8 packages. **Cougar Components, Sunnyvale, CA. INFO/CARD #203.**



Tuning Sticks
American Technical Ceramics

ATC unveils a tuning stick — a device that makes on-board capacitor value selections. It consists of an ATC 100 Series Superchip® radial wire leaded capacitor labeled with its specific value and attached to a non-conductive holder. The values range from 0.1 pF to 1000 pF and price is $49.95 per kit. **American Technical Ceramics, Huntington Station, NY. INFO/CARD #202.**

MMIC Design Workstation
EEsof

The MMIC Workstation™ is a broad-based computer-aided tool that is designed for use with Apollo and Sun platforms. The workstation allows users to perform schematic capture, linear and non-linear simulation, full-custom layout, and design verification. **EEsof, Inc., Westlake Village, CA. INFO/CARD #201.**

Digital Receiver System
Steinbrecher

ACCUVERTER™ is a digital receiver system that converts RF signals into digital words while preserving more than 96 dB of available spurious-free dynamic range without the use of AGC. It serves as an interface between RF signals and digital signal processing. **Steinbrecher Corp., Woburn, MA. INFO/CARD #200.**

Wideband Power Divider Merrimac

Merrimac Industries unveils the PDM-27-10G power divider with a frequency range of 1.5 to 18 GHz. It measures 1.79" × 1.0" × 0.4" and costs $550 in small quantities.

The Tacan coupler system is a high power sub-system designed to monitor the forward and reflected power of a Tacan radar transmitted signal. Two detected outputs for each direction are provided. The system measures 15,000 watts peak over the 960 to 1215 MHz range. Coupling is within 0.2 dB and directivity is at least 20 dB over the whole band. **Merrimac Industries, Inc., West Caldwell, NJ. INFO/CARD #199.**

PBW Discriminator Aydin Vector

The Aydin Vector MMD-91 airborne discriminator is used to convert FM multiplexed subcarrier signals to the original channel information. It features circuits for the input bandpass filter, pulse averaging

detection circuit and output lowpass filter. Specifications include ±7.5 percent deviation for the IRIG PBW signals and stability of ±1.0 percent. **Aydin Vector Division, Newtown, PA. INFO/CARD #198.**

Triax Connectors AMP Inc.

These miniature and subminiature triax connectors offer termination to both cable and printed circuit boards. They use crimp technology for easy assembly, reduced rejects and lower applied costs. Performance is rated to 500 MHz with good EMI/RFI shielding characteristics. **AMP Inc., Harrisburg, PA. INFO/CARD #197.**

Instrumentation Amplifier Hewlett-Packard

HP introduces a 100 kHz to 3 GHz instrumentation amplifier with 25 dB gain and 20 dBm output power. Output power is adjustable over a +2 dBm to +20 dBm range. With built-in internal leveling, output flatness is held to ±1.5 dB over the full band. The HP 8347A is priced at $3,950.

The HP 5371A is an instrument designed to analyze and characterize time-varying signals to 500 MHz. It allows users to understand the dynamics of frequency, phase, time interval and jitter of complex signals. **Hewlett-Packard Company, Palo Alto, CA. INFO/CARD #196.**

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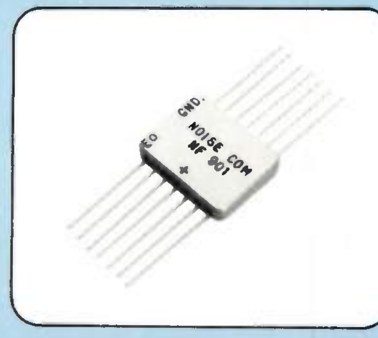

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SAW Oscillators
Andersen Laboratories

Andersen unveils a line of SAW oscillators that operate up to 2.4 GHz. The frequency determining elements are fabricated on quartz substrates for optimum stability. The specifications include a carrier frequency range of 1.2 GHz to 2.4 GHz, output power of 13 dBm ±2 dB, spurious outputs at −60 dBc max. and SSB phase noise of −90 dBc/Hz max. at 1 kHz offset. **Andersen Laboratories, Inc., Bloomfield, CT. INFO/CARD #191.**

GaAs Chip Set
Anadigics

This GaAs chip set is intended for applications in excess of 2 Gbit/sec and consists of the ALD30010 laser driver, the ATA30010 transimpedance amplifier, and the ACP10010 0.5 ns decision circuit. **Anadigics, Warren, NJ. Please circle INFO/CARD #195.**

Automated Tuner
Maury Microwave

A 3.5 mm automated tuner covering the 4 to 26.5 GHz range will be introduced for use with the Maury automated tuner system (ATS). The tuner can be controlled via the GPIB ATS controller. **Maury Microwave Corp., Cucamonga, CA. Please circle INFO/CARD #194.**

Hermetic Packages
Coors Ceramics

Coors Ceramics introduces a line of hermetic packages for microwave, fiber optic, power and hybrid applications. Applicable technologies include matched seal and compression seal glass-to-metal packaging utilizing F-15 alloy and stainless steel. **Coors Ceramic Company, Golden, CO. Please circle INFO/CARD #192.**

Internally Terminated Switches

The S-50-005 is a PIN diode RF switch with integral TTL drivers. It has a frequency range of 10 to 500 MHz and insertion loss is 1.3 dB (max) from 10 to 300 MHz. Isolation from 10 to 100 MHz is 50 dB and VSWR is measured at 1.4:1. Input power for 1 dB compression is +3 dBm while switching speed is 20 us. **JFW Industries, Inc., Indianapolis, IN. Please circle INFO/CARD #187.**

MMIC Active Multipliers

Frequency Doubler Uses Inexpensive, Stable Devices.

By Jerry Hinshaw

This article describes a practical, inexpensive and unconditionally stable frequency multiplier design suitable for a wide range of VHF through low microwave applications. A single silicon MMIC stage provides conversion gain as a doubler. Several stages may be cascaded to provide a binary multiplication factor, with the output signal at a useful level. Good spectral purity and fair tuning range are additional positive features of this approach.

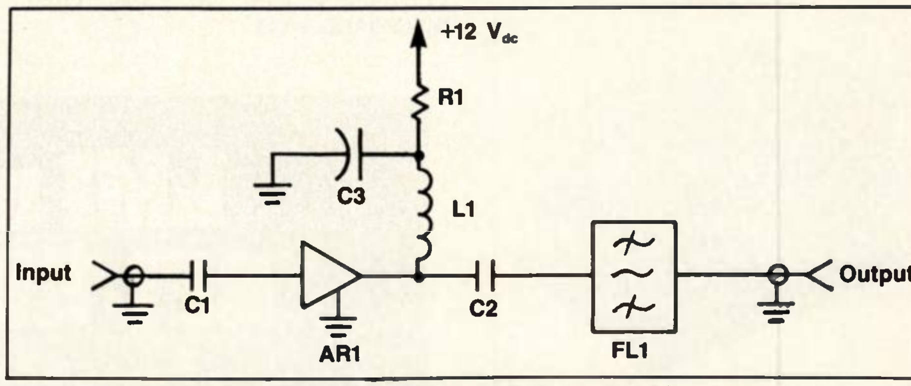

Figure 1. Schematic diagram of the prototype doubler.

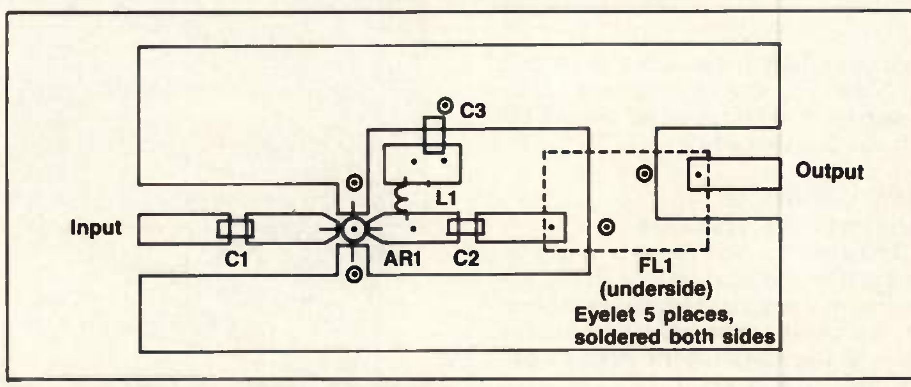

Figure 2. Component layout sketch.

Device	Quantity	Cost
Amplifier MMIC	1	0.99
Helical Filter	1	3.10
Chip Capacitors	3	0.36
Resistor	1	0.11
Inductor	1	0.27 (optional)
Circuit Board	—	0.40 (at $1 per in^2)
TOTAL		$5.23

Table 1. Cost estimates for double circuit, in 100 quantity.

The idea which led to the construction of this circuit was the discovery that the second harmonic output of a moderately driven MMIC amplifier is at or above the input level. This suggested that the device can be used as a unity gain doubler. The MMIC devices are unconditionally stable, so an output filter cannot drive the MMIC into oscillation. There are no tuned idlers to restrict bandwidth, so the multiplier has the same bandwidth as the output filter, up to the theoretical 50 percent. (Maximum bandwidth of a single-output multiplier is 1/N, where N is the multiplication ratio. At greater bandwidths, other harmonics will appear at the output.)

By contrast, earlier methods of harmonic multiplication have some shortcomings. Instability, tuning difficulties, temperature problems, cost, losses, and complexity are some of the difficulties faced by designers of transistor or diode multipliers. MMIC stages, with their stability and broadband gain, minimize or eliminate these problems. The only real shortcoming of today's MMIC blocks is that their resistive biasing and feedback schemes result in moderate power consumption. Except for battery-powered equipment, the power requirements are not too restrictive. To fully appreciate the appeal of this MMIC design, let us review several other methods of frequency multiplication.

One comparable method uses step recovery diodes (SRDs). These have been common for a quarter-century, and for many years were one of the best, if not only, solid-state methods of producing moderate power at microwave frequencies. In an SRD multiplier, energy is stored, usually in a small inductor, then "dumped" into a resonant output circuit in a small fraction of an RF cycle by the fast-switching diode. The rapid transition from open to conduction creates an output rich in harmonics. An output filter selects one of the harmonics and rejects the others.

An SRD multiplier has few parts, and can have fairly low losses, but never gain. Disadvantages include a specialized, and therefore expensive, diode. Matching the input and output can be tricky, especially in applications where moderate bandwidth and operation over a wide temperature range are required. The output spectrum "breaks up" into undesired harmonics as the port impedance of the diode shifts with changes in RF drive and temperature. In short, tuning and stabilizing an SRD multiplier can be a major headache.

A second method of frequency multiplication in the lower microwave region is the operation of a transistor stage as a nonlinear amplifier with the input tuned to the fundamental and the output matched at the second (or higher) harmonic. The transistor is usually biased as a Class C amplifier, so the input signal drives the device through the highly non-linear region of the device's I-V junction response near the origin. This produces an output rich in harmonics. The transistor provides gain, and the harmonic power level can be as great or greater than the fundamental drive power, as with the MMIC.

However, a single discrete transistor stage will often be unstable, especially with the reactive terminations needed to filter the undesired harmonics. As with the SRD, a transistor multiplier can produce oscillatory spurious outputs at certain drive levels, especially as temperature changes shift the operating point and alter the junction characteristics. The need for tuned input and output networks adds to the size and cost of such multipliers, and they have never been especially popular.

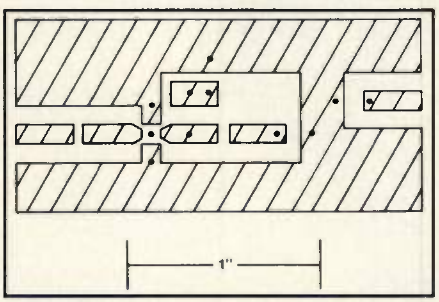

Figure 3. 1:1 artwork master for test board.

Compared to these two methods, the MMIC doubler design has some real advantages. The MMIC gain block is very small, and its stable characteristics mean that a production circuit can give repeatable performance with minimal adjustment. the circuit will operate reliably over the full operating temperature range with only small variations in output power and without spurious generation. The variation in output power versus temperature seems even smaller for MMIC stages with high drive levels, probably because the saturation characteristics vary less than the small-signal gain as temperature changes.

Circuit Description

To test this MMIC design idea, I built a simple VHF multiplier stage. This circuit used a readily available helical resonator filter at the output to select the desired second harmonic. The result was a low-cost, small doubler stage which performed as expected. This test circuit is representative of typical applications in the VHF and UHF range.

The basic multiplier has one active component, a filter, three capacitors and one resistor, as shown in Figure 1. An input signal applied to the MMIC amplifier produces an output at the input frequency as well as the second harmonic. At the output, a filter tuned to twice the input frequency passes the second harmonic energy and reflects the fundamental (x1) signal back into the MMIC, where it may contribute to more distortion. (The x2 output is, after all, really just desired distortion.)

The output frequency of the test circuit was chosen to utilize a 440 MHz bandpass filter that was on hand. This filter, manufactured by Toko, is small and inexpensive, but has very good skirt selectivity and only about 2 dB passband loss. It seemed a good candidate for combining with a MMIC. Thus, the test circuit doubles a 220 MHz input to a 440 MHz

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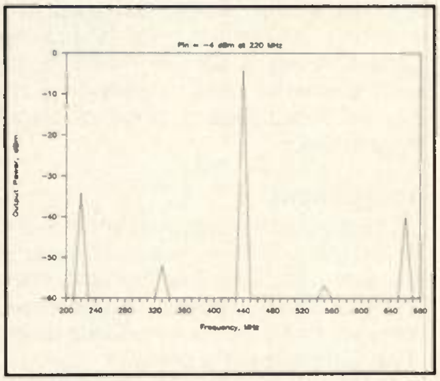

Figure 4. Output frequency spectrum plot.

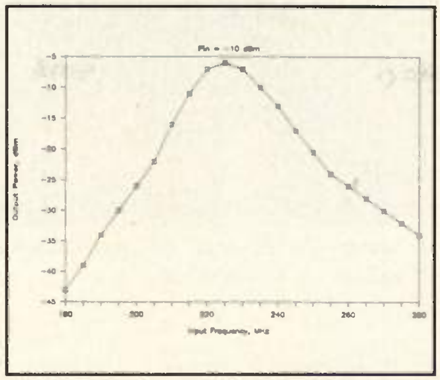

Figure 5. Output bandwidth plot.

output. No attempt was made to reduce the size of this prototype, but the total area occupied by the components is small. The filter used is small, but even smaller filters using ceramic-loaded resonators are available.

The multiplier was hastily built on a hand-cut board. A simple layout (Figures 2 and 3) was drawn at 2:1 scale, reduced to 1:1 and used to guide a hobby knife blade in scoring the copper on one side of a 1/16 inch glass-epoxy PC board. After scoring, the copper is easily peeled away to leave isolated microstripline traces. The other side of the board is left undisturbed as a ground plane. Several eyelets couple the top and bottom ground planes together in areas needing a good ground, such as near the MMIC leads and the filter connections. Details of the construction are painfully visible in the photographs, Figures 6 and 7.

Test Results

The prototype doubler tests were simple and pleasing. The MMIC bias was normal, about 4.5 volts at the output lead and 17 milliamperes current. A test signal at 220 MHz immediately produced a strong output at 440 MHz, with undesired harmonics well attenuated. These data are presented in Figure 4, which shows the output frequency spectrum for a constant power 220 MHz input. The 220 MHz fundamental is over 30 dB below the second harmonic output, with other products lower yet. The other low level products shown are due to leakage from a 110 MHz crystal oscillator that was part of the test setup. No tuning of the filter was necessary, as the factory preset adjustments put it on frequency.

The output power varies with input power, but above -5 dBm drive level there is little change. This indicates that the saturation level for harmonic output is fairly constant, a desirable characteristic for easier cascading of several stages.

The doubler circuit has a fairly narrow bandwidth, as shown in Figure 5. This is as expected from the sharp helical resonator filter alone, with no significant bandwidth shrinkage that might be attributed to the MMIC stage. No instabilities were observed as the input frequency was swept. For a narrow-band application, this

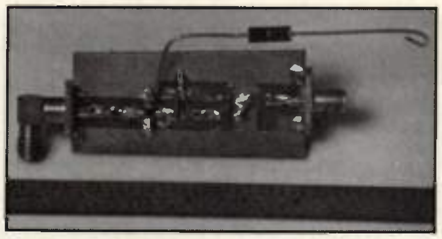

Figure 6. Photo of prototype doubler — topside.

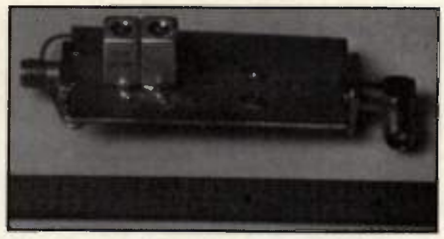

Figure 7. Photo of prototype doubler — underside.

response produces maximum rejection of undesired harmonics. For a broader bandwidth use, a filter with wider bandwidth is needed. The input frequency can then vary to create a range of output frequencies.

Applications

There are many potential applications for this MMIC doubler design. In general, it can be used whenever low cost, small size, stability and moderate bandwidth are required, and where the moderate power supply drain is not a problem.

As an example, VHF and UHF local oscillator (LO) chains for mobile radios can be built with this technique, using cascaded doublers. Narrowband stages are ideal for single-frequency LOs, since they maximize the spectral purity of the final output. For a cascade of several doublers, the input drive power should be relatively strong, so the output level of each stage is saturated.

For multiple frequency use, a low-frequency synthesizer could drive a cascade of wider-band doublers. At present, low- cost synthesizer components work up to about 1 GHz. Above this, MMIC doublers could easily increase the range to 2 to 4 GHz. For example, a synthesizer covering 732.5-737.5 MHz can be doubled to 1465-1475 MHz. This signal can then be used to downconvert the 1535-1545 MHz mobile satellite band to a fixed 70 MHz IF for demodulation. The lower synthesis frequency can be achieved at lower cost and lower power consumption than it would directly at L-band. Phase noise at the output of the doubler will, of course, be increased by the familiar 20 log N (dB), where N is the multiplication ratio. However, this degradation would probably be seen in a practical synthesizer, as well. For narrowband voice and data applications, the MMIC design will certainly suffice.

The range of potential uses for silicon MMIC multipliers seems wide, and should remain so even as GaAs devices become more available. The cost of silicon MMICs will doubtless remain below that of GaAs for some time. The simplicity of this design, and its ease of production, is an improvement over earlier frequency multiplication schemes. rf

About the Author

Jerry Hinshaw is a senior staff engineer at Bendix Communications Division, 1300 E. Joppa Road, Towson, MD 21204. This article is his 1987 RF Design Awards contest entry.

Unequal Power Division with a Lumped Element Divider

By David H. Burgess
Honeywell, Inc.

The Wilkinson power divider is widely known and many variations are used in microwave systems today (1). Its most useful characteristics are good impedance matching at each port and high isolation between output ports. This device, usually implemented using transmission lines, can also be realized with lumped elements, making it useful for VHF applications (2). For some applications, an unequal power split between the two output ports is desirable. Such a design is described for hybrid Wilkinson power dividers by Parad and Moynihan (3). This paper discusses the design of a lumped element version of an unequal split power divider.

The design equations for the Wilkinson power divider are derived in terms of the power split ratio, k, the characteristic impedance, Z_o, and the center frequency, ω. The proposed circuit is shown in Figure 1. A sample design is verified by computer simulation using Touchstone™ and the measured response of a prototype circuit is presented.

By forming the equivalent circuit shown in Figure 2, the circuit can be analyzed by employing the method of even and odd mode analysis outlined by Reed and Wheeler (4). To achieve a power splitting ratio of

$$K = \frac{\text{Power out Port 2}}{\text{Power out Port 3}} \geq 1$$

the impedance level from port 1 to port 3 is constrained to be k times the level from port 1 to port 2. This results in

$$Z_{12} = \frac{1 + K}{K} Z_o$$

$$Z_{13} = KZ_{12} = (1 + K)\, Z_o$$

$$Z_2 = Z_o$$

$$Z_3 = KZ_o$$

where Z_o is the input impedance looking into port 1. Z_{12} and Z_{13} were calculated from the requirements that Z_{12} in parallel with Z_{13} equals Z_o and $Z_{13} = kZ_{12}$. Note also that the output impedance of port 3 is no longer Z_o and must be transformed back if desired.

For the odd mode, equal voltages of opposite phase are applied to ports 2 and 3 resulting in a virtual ground along the line of symmetry. From this, the simplified circuit of Figure 3 can be drawn. At the design center frequency, ω_o, each port should be matched.

So from figure 3a

$$R' = Z_o \qquad (1)$$

$$\omega_o L_1 = \frac{1}{\omega_o C_2} \qquad (2)$$

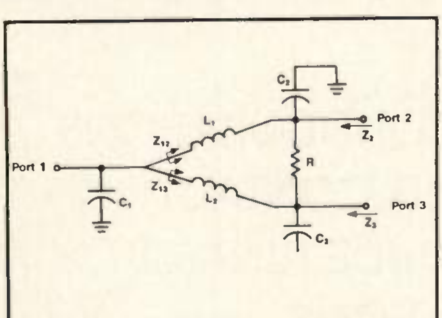

Figure 1. Wilkinson power divider.

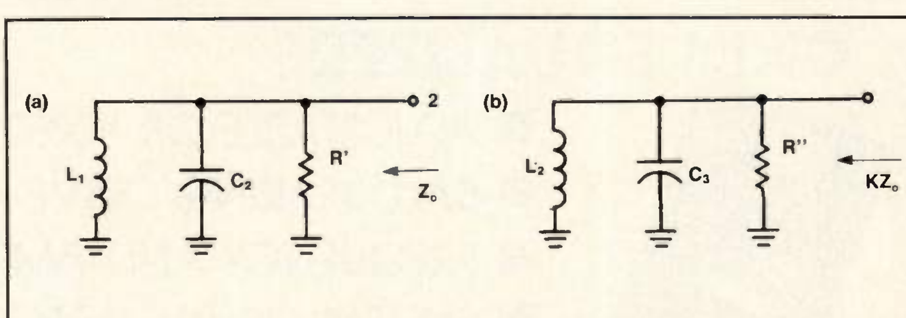

Figure 3. Odd mode circuit.

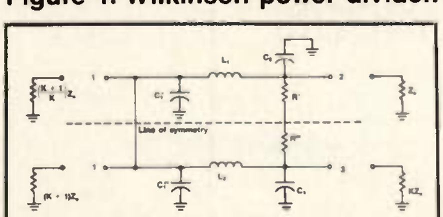

Figure 2. Equivalent circuit.

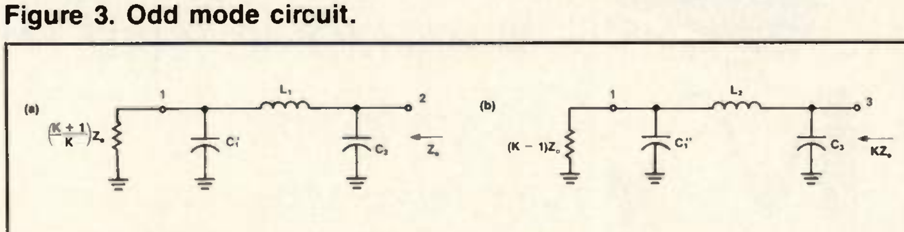

Figure 4. Even mode circuit.

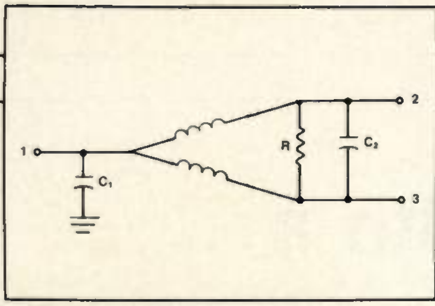

Figure 5. Alternate circuit.

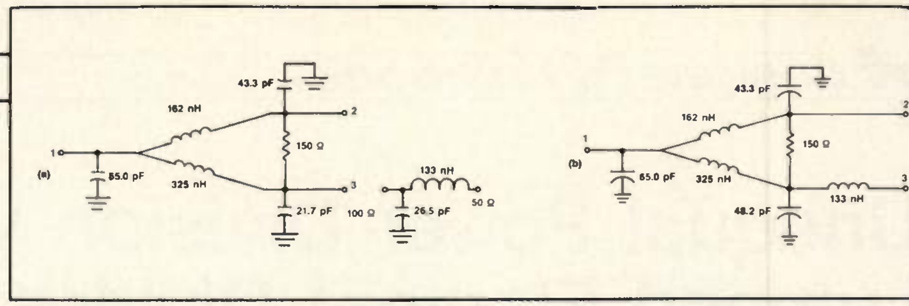

Figure 6. The final circuit.

and from Figure 3b $\qquad R'' = KZ_o \qquad (3)$

$$\omega_o L_2 = \frac{1}{\omega_o C_3} \qquad (4)$$

Also from Figure 2 $\qquad R = R' + R''$

and substituting (1) and (3) $\qquad R = Z_o + KZ_o$

or $\qquad R = (K + 1)\, Z_o$

In the even mode, voltages of equal amplitude and phase are applied to ports 2 and 3. This results in an open circuit along the line of symmetry and the simplified equivalent circuits are given in Figure 4. Again, the ports should be matched at ω_o.

From Figure 4a

$$Y_o = j\omega_o C_2 + \frac{\left(\frac{K}{K+1} \quad Y_o + j\omega_o C_1'\right) \frac{1}{j\omega_o L_1}}{\left(\frac{K}{K+1} \quad Y_o + j\omega_o C_1'\right) + \frac{1}{j\omega_o L_1}}$$

where $Y_o = \dfrac{1}{Z_o}$

which after sufficient manipulation yields

$$\omega_o L_1 = \frac{1}{\omega_o C_1'} = \sqrt{\frac{K+1}{K}}\, Z_o \qquad (5)$$

Similarly from Figure 4b

$$Y_o/K = j\omega_o C_3 + \frac{\left(\frac{1}{K+1} \quad Y_o + j\omega_o C_1''\right) \frac{1}{j\omega_o L_2}}{\left(\frac{1}{K+1} \quad Y_o + j\omega_o C_1''\right) + \frac{1}{j\omega_o L_2}}$$

which yields $\omega_o L_2 = \dfrac{1}{\omega_o C_1''} = \sqrt{K(K+1)}\, Z_o \qquad (6)$

Using equations (1) through (6), each component can now be solved for in terms of k, ω_o, and Z_o. The resulting design equations are summarized below.

$$R = (K + 1) Z_o \qquad (7)$$

Touchstone (TM) - Ver(1.30-Jun-18-85) - Ser(15858-1768- 1000) -
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FREQ-MHZ	DB[S11] PD	DB[S22] PD	DB[S33] PD	DB[S21] PD	DB[S31] PD	DB[S32] PD
30.0000	-13.510	-23.240	-9.931	-1.961	-5.111	-9.375
35.0000	-14.459	-21.980	-10.943	-1.877	-5.142	-10.908
40.0000	-15.607	-20.902	-12.383	-1.828	-5.101	-12.730
45.0000	-17.147	-20.907	-14.425	-1.800	-5.013	-15.069
50.0000	-19.531	-22.381	-17.486	-1.783	-4.907	-18.416
55.0000	-24.244	-26.676	-22.993	-1.769	-4.813	-24.289
60.0000	-69.657	-67.799	-57.694	-1.761	-4.771	-70.756
65.0000	-21.364	-23.694	-21.362	-1.781	-4.837	-24.087
70.0000	-14.005	-16.506	-14.452	-1.889	-5.094	-18.275
75.0000	-9.409	-12.053	-10.093	-2.177	-5.646	-15.247
80.0000	-6.234	-8.957	-7.006	-2.742	-6.587	-13.632
85.0000	-4.044	-6.798	-4.835	-3.625	-7.938	-12.992
90.0000	-2.638	-5.323	-3.357	-4.770	-9.630	-13.049

Figure 7. Touchstone™ results.

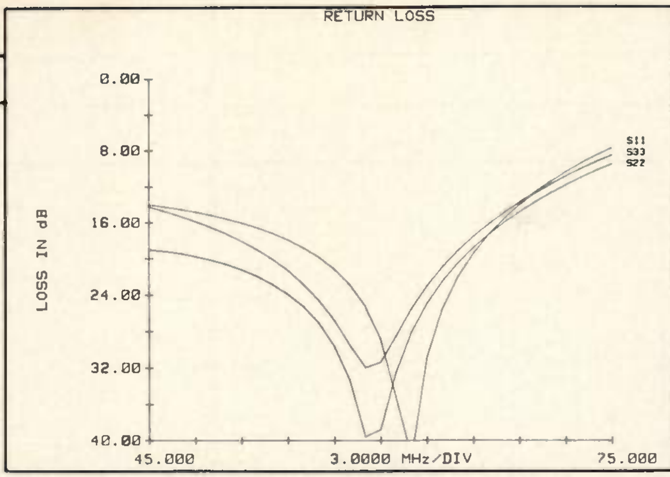

Figure 8. Return loss versus frequency.

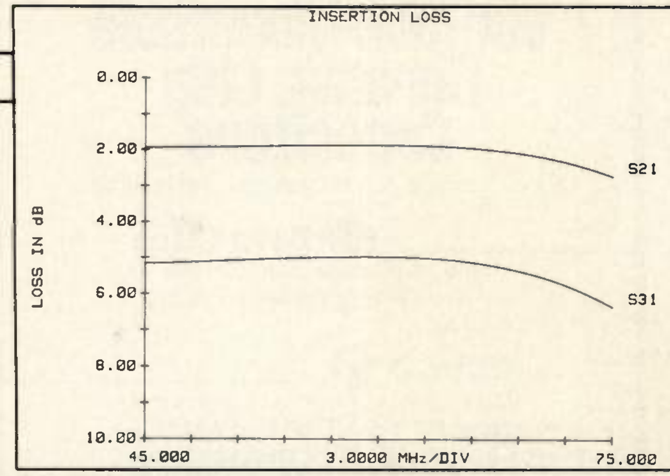

Figure 9. Insertion loss versus frequency.

$$C_1 = \sqrt{\frac{K+1}{K}}\,\frac{1}{\omega_o Z_o} \qquad (8)$$

$$L_1 = \sqrt{\frac{K+1}{K}}\,\frac{Z_o}{\omega_o} \qquad (9)$$

$$L_2 = \sqrt{K(K+1)}Z_o/\omega_o \qquad (10)$$

$$C_2 = \sqrt{\frac{K}{K+1}}\,\frac{1}{\omega_o Z_o} \qquad (11)$$

$$C_3 = \frac{1}{\omega_o \sqrt{K(K+1)}Z_o} \qquad (12)$$

An alternate circuit is shown in Figure 5. A similar analysis results in the design equations given below.

$$R = (K + 1)Z_o$$

$$C_1 = \frac{1}{\omega_o \sqrt{K}\, Z_o}$$

$$L_1 = \frac{Z_o}{\omega_o \sqrt{K}}$$

$$L_2 = \frac{\sqrt{K}\, Z_o}{\omega_o}$$

$$C_2 = \frac{\sqrt{K}}{\omega_o (K+1) Z_o}$$

Computer Simulation

A power divider was designed using equations (7) through (12) with $k = 2$ and $f_o = 60$ MHz. Additionally, a 100 ohm to 50 ohm "L" matching network was added to port 3. By choosing a matching network with a shunt capacitor followed by a series inductor, the shunt capacitor can be combined with C_3, thereby requiring the addition of only one component to match port 3 to 50 ohms. The calculated circuit values are displayed in Figure 6.

At 60 MHz all three ports should be closely matched to 50 ohms, and ports 2 and 3 should be well isolated. The calculated values for S_{21} and S_{31} are −1.76 dB and −4.77 dB, respectively. The circuit was simulated on Touchstone and the printout is listed in Figure 7. Considering that only three significant figures were retained for the component values, the results are essentially exact, which they should be if the design equations are valid. The fact that this power divider is constructed of low pass type structures is clearly seen in the frequency response displayed by the computer simulation. Note that the high end performance degrades much more rapidly than the low end.

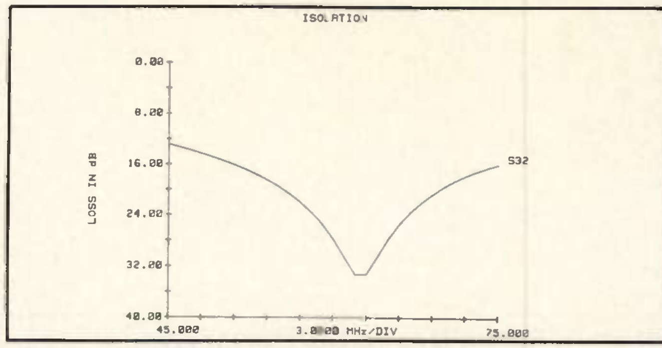

Figure 10. Isolation versus frequency.

Test Results

A prototype power divider was constructed using standard capacitor and resistor values and hand-wound toroidal inductors. The prototype circuit was measured on a network analyzer. Figure 8 shows the return loss at each port to be in excess of 14 dB (VSWR of 1.5:1) up to 69 MHz. The measured transmission loss at 50 MHz from port 1 to port 2 was 1.9 dB and the loss from port 1 to port 3 was 4.9 dB. This is in close agreement with the results of the computer simulation which did not take into account component losses due to finite Q's. Note the 3 dB difference, or 2 to 1 ratio, between S_{21} and S_{31}. Finally, the isolation between ports 2 and 3, shown in Figure 10, was greater than 20 dB from 55 to 69 MHz, giving the device a useful bandwidth greater than 20 percent.

Summary

Equations which allow the design of lumped element power dividers with arbitrary power splitting ratios while preserving matched conditions at each port and high isolation between the output ports have been presented.

These equations were verified by computer simulation and were used to build a prototype circuit that performed in close agreement with theory.

The author wishes to thank Dennis Francis for his assistance in constructing and testing the prototype circuit.

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

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Fundamentals of Red/Black System Engineering

Basic Information on TEMPEST Requirements

By Michael L. Brooks
Litton Data Systems

For a secure communications program, the task of system engineering includes describing the overall TEMPEST engineering requirements. Within the context of this task is the requirement to define the Red/Black system engineering methodology. This article provides the fundamental concepts for determining this methodology in order to illustrate the necessity of a front-end Red/Black engineering definition for a TEMPEST system design.

To achieve a successful Red/Black-engineering design, system engineers must have the necessary background to enable them to define Red/Black engineering tasks for a secure communications, or TEMPEST, program. Unfortunately, Red/Black engineering is overlooked by many engineers due to their lack of understanding of the applicable TEMPEST requirements and the consequent tasks required in determining the Red/Black system engineering methodology. This aspect of system engineering is important for national security and mission success of military programs. This implies the necessity of increasing the understanding of system engineers (and technical managers) in the Red/Black design process.

The basic units of a secure communications, or TEMPEST, system are the Black and Red equipment types. The Black equipment are those which process data not containing any classified (national security sensitive) information, whereas Red equipment processes data with classified content. By definition, a TEMPEST system will include both Black and Red equipment types. (However, one possible exception is a satellite system which may be defined totally as Red, with only its space environment defined as Black.)

By definition, the transfer of Red data between Red and Black units is not permissible. However, Black and Red units cannot be connected directly, because some type of interface is required between these equipment to prevent the inadvertent transfer of classified information. The Red/Black interface contains the necessary circuitry (such as filters and isolation devices) and the required mechanical design techniques (such as shielding and low-impedance bonds) to prevent this illegal transfer of data. The reference provides a complete discussion of the Red/Black interface and related terms.

This Red/Black interface is separate from the Red and Black units (assuming that these units are existing designs, which were not originally engineered with Red/Black constraints, and are not modifiable), and serve a single purpose of achieving directional Black-to-Red information transfer. The exception to this single-purpose function are encryption devices, which serve a dual role as Red/Black interfaces. First, these devices encrypt the Red signals and convert them into Black signals, and also de-encrypt incoming Black (encrypted-Red) signals and convert these back into the plain-text Red format. Second, the encryption device provides the required Red/Black separation and isolation needed to prevent the coupling of the plain-text Red signals onto the encrypted-Red or other Black lines.

Table 1 is an interconnection matrix indicating the different possibilities for the transfer of Red and Black data within a system. Note that while Red-to-Red and Black-to-Black signal transfers are acceptable, the transfer of Black data between Black and Red units may be accomplished only via a Red/Black interface ("OK,?"). In some cases, Red-to-Red signal interconnection may not be permitted if these distinct Red signals have been given different classification levels. Of course, the transfer of Red data to a Black unit is not permitted.

From:	To: Red Unit	Black Unit
Red Data @ Red Unit	OK	No
Black Data @ Red Unit	OK	OK,?
Black Data @ Black Unit	OK,?	OK

Table 1. Red/black interconnection matrix.

Ground Rules

Table 2 lists the ground rules for Red/Black system engineering. The system engineer must be able and willing to pay the price to ensure a satisfactory and complete TEMPEST system design for the secure communications program. Included in this price for a successful design is the requirement for the system engineer to acquire a thorough understanding of the program, TEMPEST requirements and their implications to the Red/Black engineering methodology. Then, an understanding of the functional operation of each equipment unit or subsystem in the system must be obtained in order for the system engineer to differentiate between the Red and Black signals and equipment types.

Armed with this background in system operation, Red signal flow patterns and equipment designations, the system engineer is then able to determine if the conceptual or preliminary system design is adequate for providing a sufficient number of Red/Black interfaces. If a sufficient number of these interfaces is not provided in the system, then it is imperative that the system engineer work with the program office personnel and electical and mechanical design engineers to ensure that an adequate number of Red/Black interfaces is included in the design.

It is necessary for the system engineer to enlist the assistant of a program TEMPEST engineer to educate these individuals, as well as himself or herself, in

TEMPEST terminology and in the requirements for Red/Black interfaces and their electrical/mechanical design constraints. The requirements for these interfaces must be sufficiently detailed for the electrical and mechanical engineers, so that they will be capable of implementing the correct design methodology at each different interface.

After the Red/Black engineering methodology is established for the system, the system engineer must be willing to maintain a constant interaction with these engineers to ensure that the TEMPEST system requirements are completely understood. Finally, the system engineer must coordinate all aspects of the system design with the program TEMPEST engineer to avoid conflicting design methodologies, and utilize him or her as a technical resource to verify the accuracy and completeness of the TEMPEST system design.

Conclusion

The system engineer has an important role in the TEMPEST design process for a secure communications system. Not on-

1. Understand the TEMPEST system requirements.
2. Analyze the system architecture for Red and Black signal flow.
3. Differentiate between the Red and Black equipment types.
4. Determine if a sufficient number of Red/Black interfaces are provided in the system.
5. Clarify the Red/Black interface design constraints to the equipment electrical and mechanical engineers.
6. Follow-up the system engineering design tasks with interactions with all engineers to ensure a satisfactory design.
7. Coordinate the system design approach with the program TEMPEST engineer to avoid conflicting design methodologies and to verify the accuracy and completeness of the design.

Table 2. Red/black system engineering groundrules.

ly must he or she obtain a good understanding of the Red/Black design requirements and their implications to the system design, but must also be willing to assist the program TEMPEST engineer in educating those involved in the design process to ensure that all engineers and managers appreciate these implications and the methods of their implementation. Complete and sufficient TEMPEST system designs that will satisfy the program requirements are imperative to ensure mission success and the maintenance of national security. rf

References

1. Michael L. Brooks, "Understanding TEMPEST Requirements — Part 1," *RF Design*, June 1986, p. 69.
2. Michael L. Brooks, "Understanding TEMPEST Requirements — Part 2," *RF Design*, August 1986, p. 32.

About the Author

Mike Brooks is a systems EMC/TEMPEST engineer with Litton Data Systems, 8000 Woodley Avenue, Van Nuys, CA 91409. He may be contacted at (818) 904-2448.

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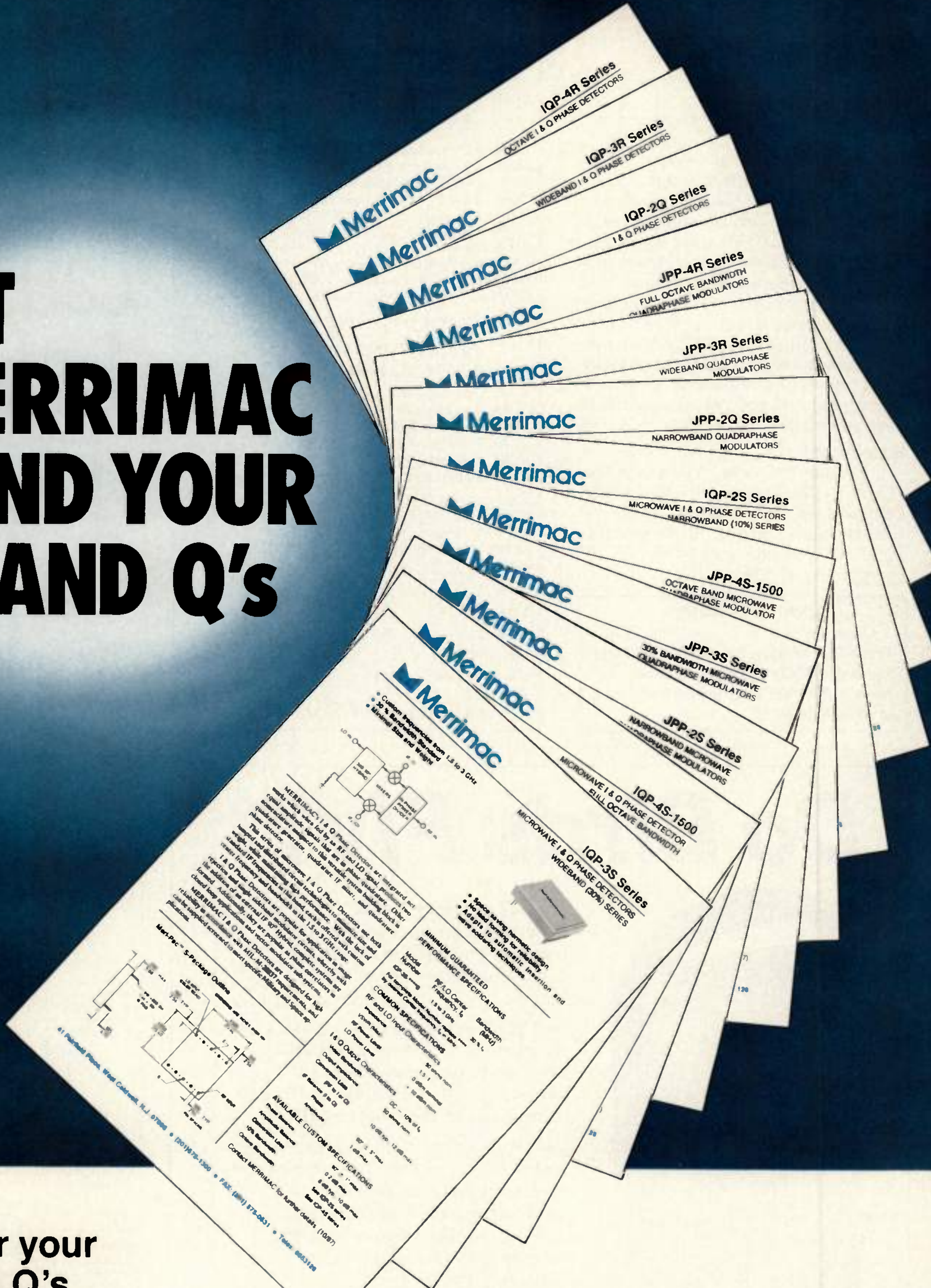

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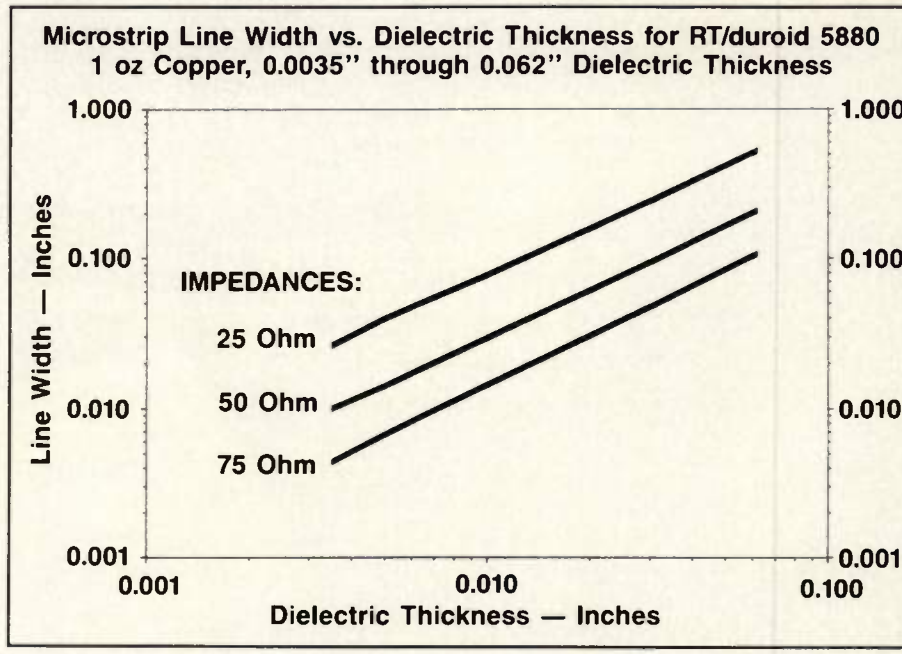
Rogers Introduces a PTFE Composite

RT/duroid® 5880 glass microfiber reinforced PTFE composite is designed for stripline and microstrip circuit applications. It contains glass reinforcing microfibers which are randomly oriented to maximize benefits of fiber reinforcement in final circuit applications. Normally supplied as a laminate with electrodeposited copper, the material composites can be clad with rolled copper foil if required. Cladding with aluminum, copper or brass plate is also available.

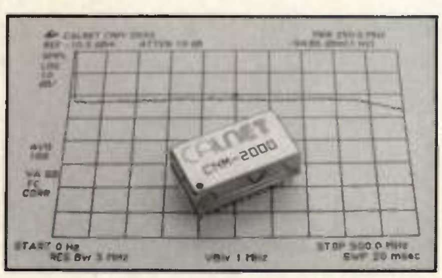
This laminate has a thickness of 0.0035" and is useful in applications requiring a low loss laminate. This includes antenna covers, innerlayers in three-layer couplers, and suspended substrates such as those in high-Q filters.

The dielectric constant is 2.20 ±0.02 at 10 GHz and dissipation factor is 0.0009 at 10 GHz. Other thicknesses available range from 0.005" to 0.375". **Rogers Corporation, Chandler, AZ. Please circle INFO/CARD #188.**



Wideband Noise Generator

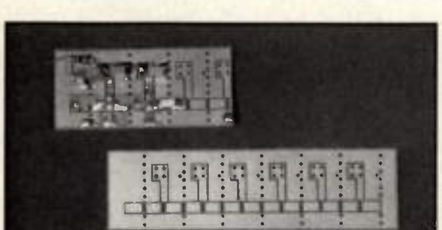
Calnet introduces the Model CNM-2000 noise generator module that produces true white Gaussian noise from 10 kHz to



500 MHz into a 50 ohm load. It uses shot and thermal noise as its source. In single quantities, the unit is priced at $149. **Calnet Electronics Inc., Kanata, Ontario. Canada. INFO/CARD #186.**

RF/Microwave Prototyping Boards

RF Prototype Systems introduces prototype boards for evaluation and verification purposes. The boards are double sided



and have plated thru holes. The LPF1 is a general filter that accommodates filters with up to seven sections including lowpass, highpass and narrow bandpass. The GBI, another board, is a gain block layout that provides a 50 ohm interconnection and DC bias for MMIC amplifiers. For evaluating TO-8 voltage controlled oscillators and amplifiers, the TO81 board with holes for SMA connectors and power supply decoupling components is available. In single quantities, the price ranges from $4.50 to $9.75 depending on the board. **RF Prototype Systems, San Diego, CA. INFO/CARD #185.**

Log-Periodic Antenna

Model AT1100 log-periodic antenna provides power gain over an isotropic of 6.5 dB (min). Gain flatness is 1.0 dB while

VSWR is 1.8:1 (max) and bandwidth is 100 to 1000 MHz. The antenna is 68 inches from front to back and costs $2,800. **Amplifier Research, Souderton, PA. Please circle INFO/CARD #184.**

Voltage Controlled Oscillator

This TO-8 oscillator is available for frequencies from 100 MHz to 6000 MHz. Wideband (octave range) and narrowband (±10 percent of center frequency) units with an optional buffer stage are available.

Frequency variation over the −55°C to +85°C is typically ±0.075 percent for the narrowband and ±0.15 percent for the wideband units. **Micropac Industries, Inc., Garland, TX. INFO/CARD #183.**

Tracking Generators

Avcom introduces the MTG-8566A microwave tracking generator which is designed to be utilized with the HP

8566A. The MTG-8566A has a phase locked cavity oscillator referenced to an ovenized crystal oscillator. IF feedthrough at 2050 MHz or 3621.4 MHz is under −65 dBm with a tracked signal response of ±1.8 dB. A 100 dB attenuator is optional. Prices for the MTG series begin at $1,435. **Avcom, Richmond, VA. Please circle INFO/CARD #182.**

Logarithmic Amplifier

The AD9521 is a 7 to 250 MHz, 4.7 dB noise figure logarithmic amplifier. Voltage gain range for this amplifier is flat to 1.2 dB from 30 to 160 MHz. Typical applications include radar signal receivers, electronic countermeasures, sonar equipment and miniaturized log strips. **Analog Devices, Norwood, MA. INFO/CARD #181.**

TV Receiver Chip

LM1822 is a video IF amplifier/PLL detector system which contains all the functions needed for video IF signal processing for TV receivers and cable converter equipment. It incorporates a five stage gain controlled IF amplifier, a phase

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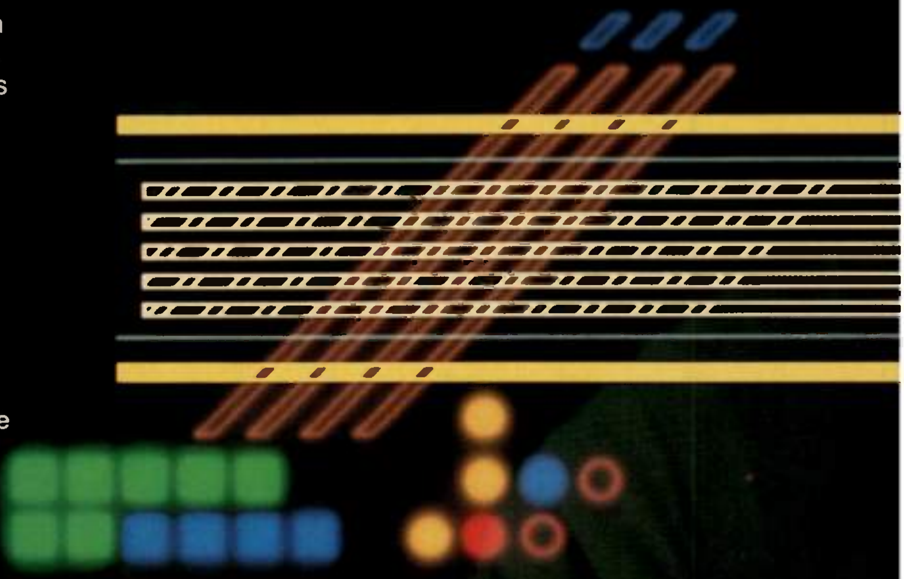

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Dissipation Factor	.0009	.0009
Coefficient of Thermal Expansion		
Test Method ASTM D-3386		
Conditions 15°-35°C		
Units mm/M		
Dimensions		
X	0.6	0.9
Y	0.6	1.8
Z	2.8	6.9
Dimensional Change After Etch		
Units in/in	.00005	NA (.001**)

* Meets Mil P-13949G

** Industry-accepted value for non-woven materials. Data not published by Rogers Corporation.

* RT/duroid is a Registered Trademark of Rogers Corporation.

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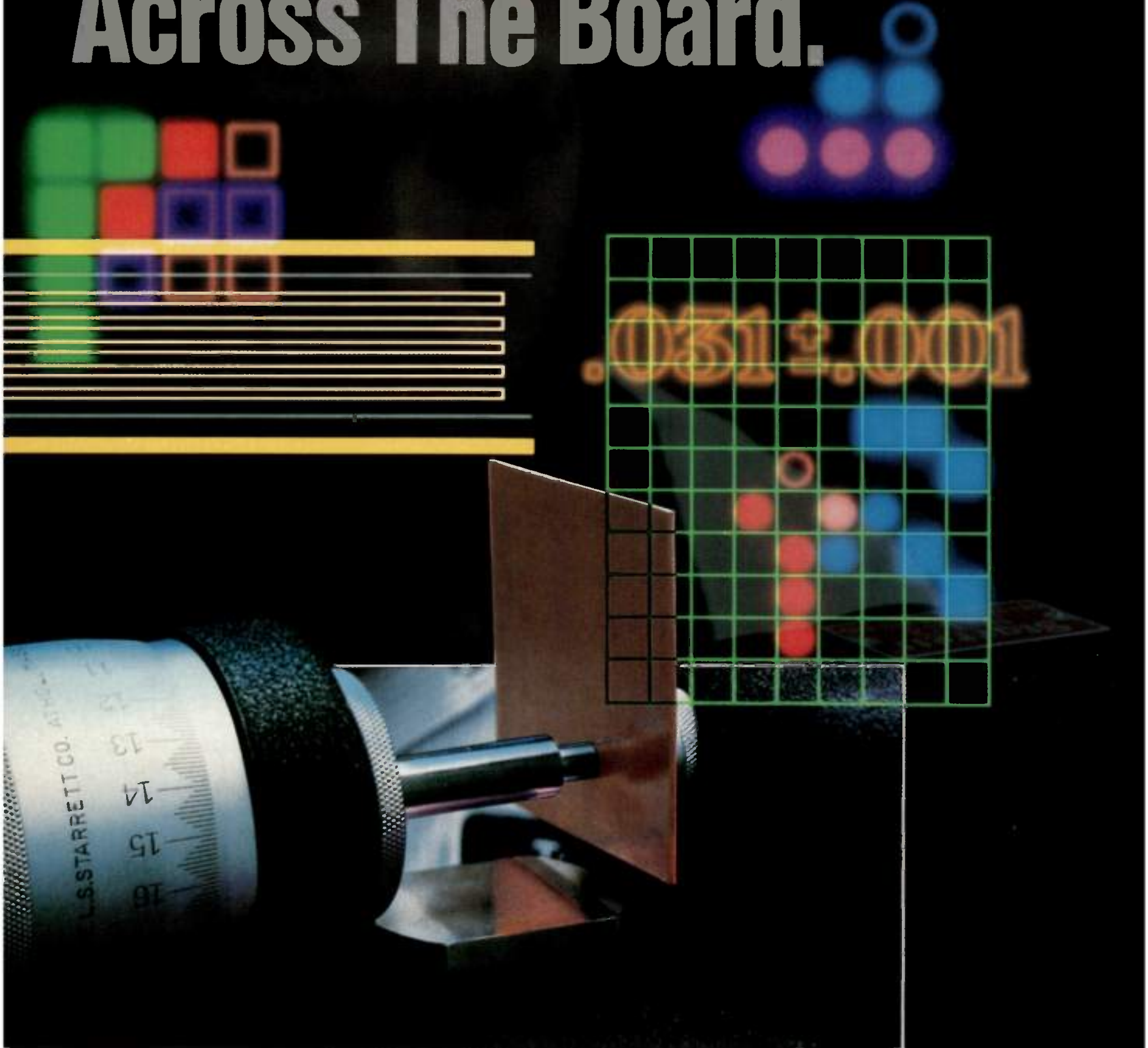

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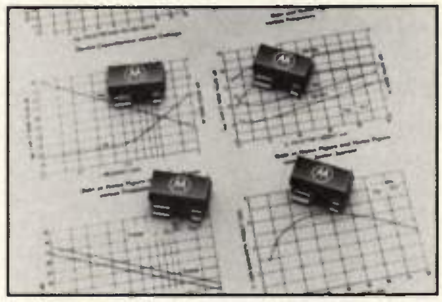
locked loop synchronous detector with white spot noise inversion, an AFC detector and gated AGC. The device accepts IF input signals from SAW filters. In quantities of 100, the IC is priced at $2.95 each. **GE Solid State, Somerville, NJ. Please circle INFO/CARD #180.**



Small Signal Transistor

MRF0211 is a low noise, high gain, small signal transistor packaged in a four lead surface mount SOT-143 package. The current gain bandwidth is 5.5 GHz and collector base capacitance is 0.7 pF while collector-emitter breakdown voltage is 15 volts (min). The 1 GHz noise figure is specified at 1.8 dB. **Motorola, Inc., Phoenix, AZ. INFO/CARD #178.**

Tunable Notch Filters

Microwave Filter Company unveils the 6367 Series of tunable notch filters for 30 to 900 MHz which cover an approximate 2:1 frequency range with an adjustable 3 dB bandwidth. Units are available with 50 ohm BNC connectors or 75 ohm F connectors . The price ranges from $139 to $179 depending on the frequency range required. **Microwave Filter Company, Inc., East Syracuse, NY. Please circle INFO/CARD #179.**

Numerically Controlled Oscillator

Stanford Telecommunications introduces the Model STEL-1172B CMOS numerically controlled oscillator. The device generates digitized sine and cosine functions and can be used in conjunction with a D/A converter in analog signal generation and digital signal processing applications. It outputs a phase continuous signal

which can be continuously switched between frequencies in a microsecond. Other features include a 50 MHz clock frequency, 32-bit frequency resolution, −55 dB spur levels, 8-bit sine and cosine outputs or 12-bit phase output and a microprocessor bus interface. The STEL-1172A is packaged in a 40-pin DIP and costs $225 when purchased in quantities above 100. **Stanford Telecommunications, Inc., Santa Clara, CA. INFO/CARD #177.**

Dual-Channel Millivoltmeter

Model URV5 is a dual-channel millivoltmeter which measures high impedance RF voltages from 20 kHz to 1 GHz, thru-line coaxial voltages from 9 kHz to 2 GHz, power levels from 1 MHz to 18 GHz (50 or 75 ohm), and DC voltages up to 400 V. The instrument has probes and sensors which are automatically sensed for the

proper display of results. Each channel can be displayed separately, as the ratio of one channel to the other, or referred to any reference. A separate analog display allows interpretation of measurement trends. The cost is $3960 less probes and sensors. **Rohde & Schwarz, Inc., Lanham, MD. INFO/CARD #176.**

Calibrated Attenuator Set

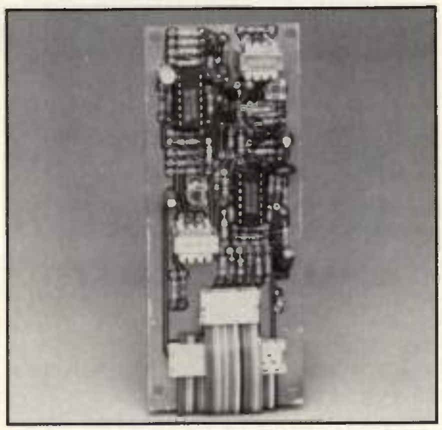
RLC Electronics unveils a precision type N calibrated attenuator set. Model A-18-C-N consists of four (3, 6, 10 and 20 dB) fixed attenuators designed to meet the requirements of MIL-A-3933. The average power rating is 2 watts with 500 watts peak. The complete set is available for $360. **RLC Electronics, Inc., Mt. Kisco, NY. INFO/CARD #175.**

Hi-Rel Preamplifiers

Model MLA24M is a hi-rel preamplifier that covers from 5 MHz to 1000 MHz with a 3 dB noise figure, linear power output of 18 dBm and a gain of 20 dB. The device features an aluminum case with female SMA connectors and two mounting holes. Lightning, static and reverse polarity protection is included. **Wi-Comm Electronics, Inc., Masssena, NY. Please circle INFO/CARD #174.**

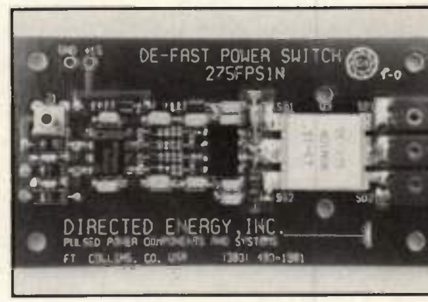
Audio Interface Assembly

Neulink has developed an interface assembly to process audio information for either speech or data. The data unit can transmit or receive 700 to 2400 baud manchester coded data, while the speech unit is optimized for passing speech signals. The units are available with Neulink's 450 to 470 MHz or 928 to 960 MHz RF links and interface through a standard 15-pin "D" style connector. **Celltronics, San Diego, CA. INFO/CARD #173.**



Switch Module

FPS1N is a switch module designed for switch mode, pulsed and low frequency RF applications. It produces a voltage slew rate of 200 kV/us and a current slew rate of 10,000 A/us. The switch is designed for DC to 1 MHz power conversion, as a driver for image intensifiers, Impatt



diodes, laser diodes, acoustic transducers, TWT and planar triode grid drivers, and as a lab pulse generator. **Directed Energy, Inc., Fort Collins, CO. INFO/CARD #172.**

Variable Active Attenuator

Janel Labs introduces two variable attenuators using PIN diode circuitry with power capability to +23 dBm and maximum VSWR of 2.0:1. Models AT882 and AT883 provide attenuation of 2.0 dB to 30 dB over 5 to 500 MHz and 2.7 dB to 20 dB over 500 to 1000 MHz. In single quantities, the attenuators are $62. **Janel Laboratories, Inc., Corvallis, OR. Please circle INFO/CARD #170.**

RF Vector Voltmeter

The HP 8508A is an RF vector voltmeter useful for RF voltage and phase measurements. The standard version comes with two high impedance probes and operates from 100 kHz to 1 GHz while the optional version has two 50 ohm type N inputs with a 300 kHz to 2 GHz range. With either input channel, the instrument can directly read voltage or power. By connecting the second input elsewhere in the circuit under test, gain or loss and phase difference between the two nodes can be measured. Signals as low as 10 microvolts (−87 dBm) can be measured and dynamic range is 90 dB. The basic voltmeter costs $5,500. **Hewlett-Packard Company, Palo Alto, CA. Please circle INFO/CARD #171.**

Notch Filter

Model 6165 from Microwave Filter Company is a notch filter that eliminates broadband transmitter sideband interference to VHF receivers at the same site. The notch frequency is 47.005 with a minimum depth

of 112 dB and insertion loss of 0.5 dB (max) at 49.595 MHz. At this frequency, power handling is 10 kW CW while impedance is 50 ohms. Price is $8,680. **Microwave Filter Company, East Syracuse, NY. INFO/CARD #170.**

8-Bit A/D Has 180 MHz Bandwidth

A monolithic 8-bit flash analog to digital converter that provides typical word rates of 100 MHz with TTL compatible digital outputs is available from Analog Devices. The AD9012 has a minimum encoding rate of 75 MHz, while its 180 MHz bandwidth allows sampling of signals beyond the Nyquist rate. The input capacitance is 16 pF, signal to noise ratio is greater than 46 dB, and harmonic suppression is 54 dB from DC to 1.23 MHz. Applications for this converter include radar, digital oscilloscopes, digital radio, and electronic warfare systems. Pricing begins at $70 in 100-piece quantities. **Analog Devices, Norwood, MA. INFO/CARD #169.**

Two-Way Power Divider

PDM-02S-4G is a stripline power divider covering multi-octaves. The amplitude balance is 0.2 dB max., phase balance is 2° and insertion loss is 0.9 dB. Output port isolation is 17 dB over the 0.5 to 7.5 GHz frequency range. In small quantities, the power divider is $995. **Merrimac Industries, Inc., West Caldwell, NJ. Please circle INFO/CARD #168.**

Coax Stripper

This coaxial cable stripping machine strips coaxial, fiber-optic, semi-rigid, triaxial and concentric multiple pair. It accepts cable ranging in size from 0.040" to 0.450" o.d. Price is $1495. **Western Electronic Products Co., San Francisco, CA. INFO/CARD #167.**

SPST RF Switch

SWTF1101 is a miniaturized thick film switch packaged in a 8-pin header. The frequency range is 50 MHz to 1 GHz, VSWR is less than 1.5:1, and isolation is greater than 40 dB. When measured between 50 percent logic input to 90 percent or 10 percent RF output, switching speed is less than 100 ns. **KDI Electronics, Whippany, NJ. INFO/CARD #166.**

Video Shift Registers

NSC unveils the DP8515V-350 and DP8516V-350 video shift registers that feature a parallel load rate of 30 MHz and maximum shift rate of 350 MHz. Both devices are parallel-in, serial-out 16-bit units that can act as two 8-bit shift registers through a tap at the eighth bit. They operate from a single ±5 V power supply and feature four 16-bit words of FIFO buffer, essential for high-speed multiple board graphics systems. In 100-unit quantities, the price is $33 each. **National Semiconductor Corp., Santa Clara, CA. INFO/CARD #165.**

Analog to Digital Conversion System

Plessey Semiconductors announces the availability of a single chip analog to digital conversion system. Designated the SP94308, the device offers an 8-bit resolution at an 18 MHz sampling rate, with a minimum analog bandwidth of 6 MHz without preceding sample and hold circuit. When conversion of luma or full composite video signals is required, the device can digitize both PAL and NTSC standards. It is packaged in 28-pin plastic DIPs and costs $12.24 each in quantities of 1,000. **Plessey Semiconductors North America, Irvine, CA. INFO/CARD #164.**

Time Interval Counter

The SR620 is a reciprocal interpolating counter-time with a 4 ps single shot resolution for time intervals and 11 digits of resolution for frequency. It can measure time interval, period, phase, pulse width, risetime, falltime, and frequency to 1.3 GHz. Options include a high stability ovenized crystal time base and PC control software. Price for the SR620 is $3,850. **Stanford Research Systems, Inc., Sunnyvale, CA. INFO/CARD #163.**

High Speed Op Amps

CLC205 and CLC206 are high speed op amps that feature −3 dB bandwidths of 170 MHz and 180 MHz, respectively. The 205 has harmonic distortion of −57 dB (20 MHz), slew rate of 2400 V/us, and settling time of 22 ns to 0.1 percent. The 206 features −3 dB large signal bandwidth of 70 MHz (20 $V_{p\text{-}p}$), harmonic distortion of −59 dB (20 MHz), 3400 V/us slew rate and settling time to 0.1 percent of 19 ns. Cost ranges from $72 to $177 in single quantities depending on package purchased. **Comlinear Corp., Fort Collins, CO. INFO/CARD #191.**

Remote Transfer Switch

RLC introduces the Model SR-TC-R-D-40 remote transfer switch that operates from DC to 40 GHz. VSWR ranges from 1.3 to 2.0, insertion loss goes from 0.25 dB to 1.0 dB and isolation goes from 45 dB to 70 dB depending on frequency range. Prices start at $525 in unit quantities. **RLC Electronics, Inc., Mt. Kisco, NY. INFO/CARD #190.**

PBW Discriminator

The MMD-91 airborne discriminator is used to convert FM multiplexed subcarrier signals to the original channel information. Specifications include ±7.5 percent deviation for IRIG PBW signals and stability of ±1.0 percent for full scale output. **Aydin Vector Division, Newtown, PA. INFO/CARD #189.**

Receiver Simulation Program

CommView 1.0 allows receiver cascades to be created and simulated while including the effects of excess broadband and discrete noise at each stage. CommView also accepts broadband and CW jammer inputs and calculates the associated performance degradation. It allows the user to sweep the input signal level and provides AGC voltage, S/N_o, S/N, E_b/N_o, E_b/N and bit error rate versus input level. Signal power, noise density, S/N_o, and S/N are provided stage by stage. E_b/N_o, E_b/N and bit error rate can be determined for AM, FM, FSK, PSK, and QAM. **Webb Laboratories, North Lake, WI. INFO/CARD #169.**

Circuit Simulation Software

ECA-2 from Tatum Labs is now available for the Apple Macintosh. This analog circuit simulator features AC, DC, transient, Fourier, temperature, Worst-case, and Monte-Carlo analyses. The software has the capability to plot graphics as the points are being computed in real time. This package is priced at $675 and a free demo disk is available. **Tatum Labs, Inc., Ann Arbor, MI. INFO/CARD #209.**

Active Filter Design Package

PMSS Active Filter Design Tools 2.0 features on screen design and component selection with the results shown in Bode plots and comparisons of specific components to ideal situations. Highpass, lowpasss, bandpass, Butterworth, Chebyshev, Bessel, and elliptic filters are supported in the 1 to 50 kHz range. Seven different slope options are available in the Chebyshev mode and filters with up to six poles can be designed. This IBM compatible software is available for $55. **Power Mountain Software Systems, Cora, Wyoming. INFO/CARD #208.**

Communications and System Simulator

TESS™ is a general purpose communications and system simulator for the IBM PC and compatibles. The simulator handles systems that contain filters, mixers and VCOs as well as digital logic. A library of over fifty devices is featured. With MODGEN™, a companion package, engineers can modify or add models with a few lines of code. TESS is $495 and MODGEN is $245. **Tesoft, Roswell, GA. INFO/CARD #207.**

Brochure Details Test Instruments

The listings in the brochure include specifications on oscilloscopes, adapters and calibrators for oscilloscopes, IC testers, digital testers, probes, multimeters, function generators, pulse generators, multifunction counters, power supplies, video testers, stereo generators, and components testers. A section on accessories is also included together with summary comparison charts and selected product applications. **B&K-Precision, Chicago, IL. INFO/CARD #219.**

Low Power MOS Catalog

Siliconix has published a low power MOS catalog detailing its line of N-channel enhancement mode, P-channel enhancement mode and N-channel depletion mode devices. The parameters listed are product summary, absolute maximum ratings, thermal resistance ratings, electrical characteristics, and source-drain diode ratings and characteristics. **Siliconix, Inc., Santa Clara, CA. INFO/CARD #220.**

Dielectric Resonator Catalog and Guide

A Designer's Guide to Microwave Dielectric Ceramics contains a detailed design and application note with illustrations and references as well as five new dielectric products. The products range from dielectric materials in various configurations to tuning screws, bonding adhesives and a T.C. tuning kit. A selection of characteristics and specifications together with performance examples are featured. **Trans-Tech, Inc., subsidiary of Alpha Industries, Inc., Woburn, MA. INFO/CARD #218.**

Analog IC Catalog on Disk

Precision Monolithics has introduced a data disk catalog covering its line of analog signal conditioning and data conversion ICs. The *Precision Decision* catalog is user friendly, menu driven and can be run on IBM PC compatible machines. It can be used as a design tool for pinpointing the optimum device for specific applications. The selection process is based on a parametric spec search. The resulting list includes data such as package options and pricing. Competitive cross-referencing is also accessible. **Precision Monolithics, Inc., Santa Clara, CA. INFO/CARD #217.**

Signal Conditioning Filter Catalog

Volume 31 of the *Active and Passive Signal Conditioning Filter Catalog* is available from TTE. The filters listed include both passive and active in various configurations such as Butterworth, Chebyshev, Subminiature, TTE, anti-aliasing and various notch forms. Filter specification worksheets together with a glossary of terms, filter test procedure, and cross reference numbers are included. **TTE, Inc., West Los Angeles, CA. Please circle INFO/CARD #216.**

Application Note on Temperature Rise Calculations for Circuit Boards

A report from Rogers Corp. provides formulas to estimate temperature rise of conductor traces built in microstrip or stripline on RT/duroid. It reviews simplifying assumptions which should be taken into account when doing temperature rise estimations. A calculation for current heating in a bias line and another for RF resistive heating in a microstrip transmission line is provided. **Rogers Corporation, Chandler, AZ. INFO/CARD #215.**

Coaxial Connector Catalog

Applied Engineering Products is offering its 1988 Subminiature Coaxial Connectors and Cable Assemblies catalog for military and OEM use. It depicts the company's product line together with dimensions, specifications, cross referencing, assembly tooling, assembly instruction and plating options. **Applied Engineering Products, New Haven, CT. Please circle INFO/CARD #214.**

Microwave Counters Brochure

The brochure describes the 2440 Series of microwave counters form Marconi. The specifications together with features and available accessories are listed. The frequencies supported start at 0.1 Hz and extend to 26.5 GHz depending on the specific model. **Marconi Instruments, Allendale, NJ. INFO/CARD #213.**

Short Form Catalog Lists Military Connectors

U.S. Components is offering a short-form catalog that lists standard PC connectors, special design PC connectors, standard rack and panel connectors, and special rack and panel connectors. An introduction to the various connectors is featured. **U.S. Components, Inc., Bohemia, NY. INFO/CARD #212.**

Engineering Reference Guide

This wall chart showcases an engineering reference guide for high precision data acquisition. A data converter's resolution is presented in terms of LSB weight, parts per million, percent of full scale range and a voltage reading. The chart also details Datel's high speed and precision component product line. Products shown include D/A converters, A/D converters, sample-and-hold devices and operational amplifiers. Brief descriptions of available technical and product literature are also provided. **Datel, Inc., Mansfield, MA. INFO/CARD #211.**

Medium Power Amplifiers Featured in Brochure

A brochure describing low noise, medium power, DC to microwave amplifiers is available from Trontech. Specific types featured include silicon and GaAs FET low noise amplifiers, medium and high power RF and microwave amplifiers, ultra-wide band low noise and medium power amplifiers. Frequency response, gain flatness, noise figure, output power, saturated output, gain compression, power requirement, input power and case style specifications are given where appropriate. **Trontech, Inc., Neptune, NJ. INFO/CARD #168.**

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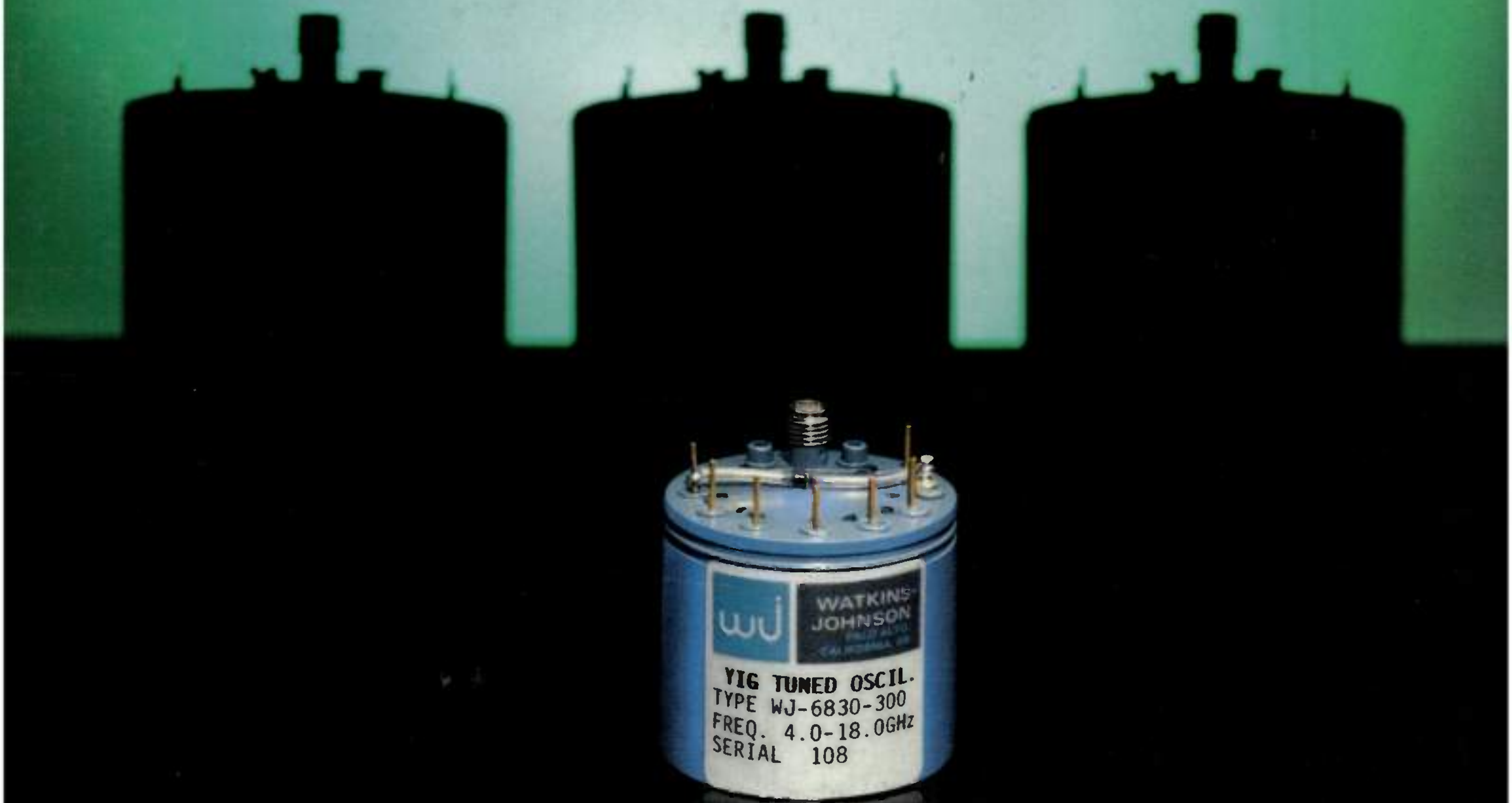

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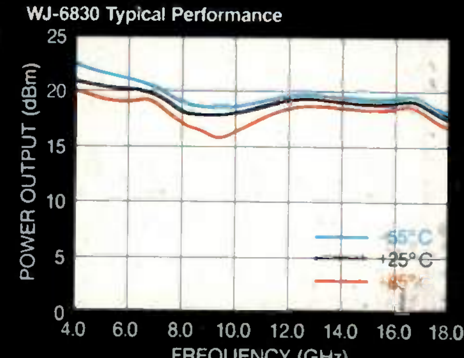

For complete information on the WJ-6830 series of YIG oscillators, contact the Watkins-Johnson Field Sales Office in your area, or telephone Ferrimagnetic Devices Applications Engineering in Palo Alto, California, at (415) 493-4141, ext. 2252.

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