JOSEPH L. ABITA

MICROWAVE/MILLIMETER WAVE TECHNOLOGY

In the course of technology evolution, a ''quantum leap'' may occur during a period of characteristic S-curve growth. The sudden advance can be brought about by a single discovery or by a combination of several factors. Microwave systems and technology have been experiencing such a period of rapid growth, promising a similar trend for high-frequency and high-speed systems. This article presents factors contributing to that surge, and an overview of microwave electronics activities at APL.

INTRODUCTION

Microwave-electronic science and technology have been a part of the work of APL for many years (Fig. 1). In 1940, APL was founded to develop radio proximity fuzes at the time of the earliest beginnings of radar. Knowledge gained in the development of radar fuses led to advances in guided-missile defense using the Navy shipborne surface-to-air missiles—Terrier, Tartar, and Talos. APL continued work on the development of advanced systems for radar; communications; navigation; command, communications, and control; geodesy; and tracking—all of which are based on radio-wave generation and processing systems. Major innovations came about as a result of in-house microwave capability.[1] Over the past several decades, APL has continued its work in microwave technology, trying to keep up with the rapid pace of development by major systems houses,

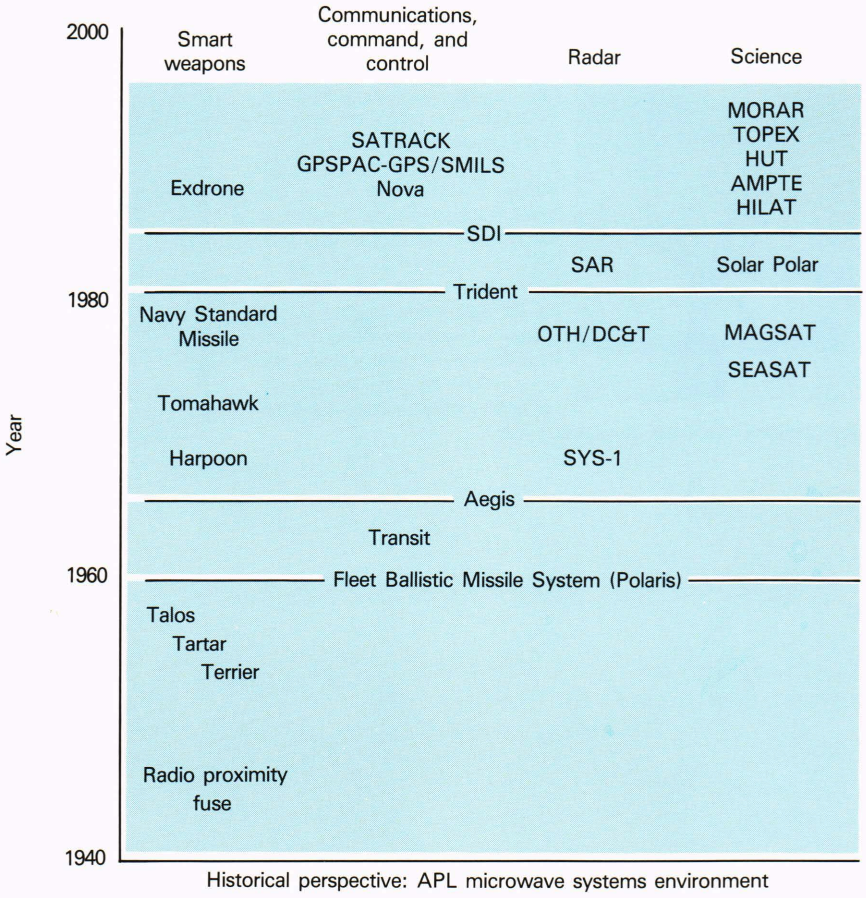


Figure 1—A historical overview of microwave systems work at APL.

and meeting the funding requirements for facilities and equipment. Microwave technology is essential in the long-range evolution of Navy systems, and the support of those systems is the primary mission of APL.

NAVY SYSTEMS AND MICROWAVE TECHNOLOGY

The Department of Defense has instituted a tri-service effort in microwave electronics in order to maintain technological superiority to aid in the defense of the United States. The total investment by the Department of Defense, industry, and the academic community over the next five years is in the billions of dollars. The microwave/millimeter-wave monolithic-integrated-circuit initiative (MIMIC) complements the very-high-speed integrated-circuit (VHSIC) digital program of the past seven years. Although there are many parallels between those programs, there are several important differences. The VHSIC program strongly emphasized technology development, it was conducted by several major systems houses, and it depended on the "obvious benefits of the technology" to encourage enthusiastic embrace by the military services for technology transfer and insertion. In comparison, the MIMIC program emphasizes systems usage to improve technology and insists on team arrangements of participants from systems houses (prime contractors), commercial technology support ventures (foundries, computer-aided-design companies, component/package suppliers, etc.), and universities, and is promoting education and awareness of tri-service program management to encourage technology transfer and insertion.

Microwave systems can be categorized in the areas of radar, communications, command, control, and electronic warfare. Phase 1 of the MIMIC program proposes advanced microwave technology for over 50 major systems: "... it has become increasingly evident to program managers in the Department of Defense that the microwave and millimeter wave circuits needed for use in the 'front end' of many military electronic systems are often unavailable. In some cases, the required component simply does not exist as a manufacturable product. In other cases, the cost of the product is unacceptably high for the intended application. Consequently, both the performance and cost of a weapons system are adversely affected."[2]

Specific Navy systems (areas) targeted for MIMIC technology insertion are listed in Table 1. APL will participate in the future development of microwave technology because of its mission and goals.

Table 1—Major Navy systems developments plan to incorporate MIMIC technology. The trend is toward millimeter-wave operation to meet the performance demands of an electromagnetically hostile environment.

Communications

Mark XV • MILSTAR • GPS • JTIDS • ICNIA
Antijam Data Links • Tactical Radio • MMW
Spacelinks

Radar

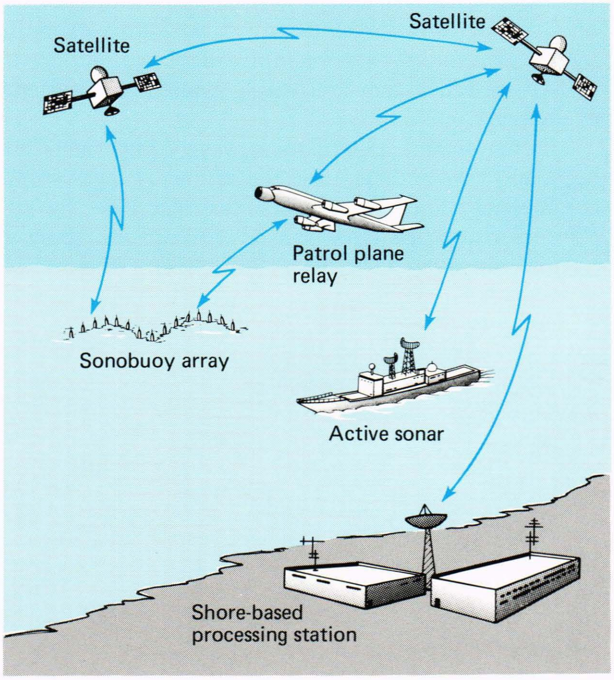
SBR • ATA • ASAP • Airborne Multimode
Phased Array • Shared Aperture

Autonomous/Smart Weapons

AMRAAM • OABM • HARM • EX60 • INEWS
Low Cost Seeker • Standard Missile

Electronic Warfare

ALR-77 • APR-39 • ASAP • ALQ-136, -165, -126
INEWS • RWR • ADVCAP • GEN-X • NVLKA
AAED • ASPJ • Expendable Decoys



A NEW ERA

For over 40 years microwave engineering developments have resulted in growth of the market, the technology, and the microwave community. Over the past several years, major advancement and expansion has taken place because of an ability to deal with the complexity of microwave circuit analysis, to accurately characterize components, and to package and integrate systems. This is because of the rapid growth in the use of computer-aided design, engineering, and testing; test and measurement methods; and equipment, materials, and processes. Currently, the pace of microwave electronics advancement is being accelerated because of problems such as limited frequency-allocation opportunities; major initiatives such as the Strategic Defense Initiative, MIMIC, Global Positioning System, and the Military Strategic/Tactical and Relay system have had a similar effect. Performance and physical demands of modern commercial and military systems, coupled with the high levels of integration and the fusion of different technologies, offer exciting challenges to the microwave engineering community.

As an example, Fig. 2 shows a completely solid-state transmit/receive module for a phased-array radar developed by ITT Defense Technology Corporation.[3] The module provides 30-dB gain at 20% efficiency, operating at 12-W peak output power at 5 to 6 GHz. It contains a six-bit programmable phase shifter and transmitter/receiver switch; a power amplifier and two drivers; and a low-noise preamplifier with transmit/receive switch. This development unit measures 3.8 × 2.5 × 12.7 cm and weighs 170 g; future versions are expected to be half that size and weight.

Texas Instruments has developed a one-chip monolithic transmit/receiver module at X band.[4] Operating at 8 to 12 GHz, the single-chip 13 × 4.5-mm integrated-circuit module consists of a 4-bit phase shifter, a 4-stage power amplifier, a 3-stage low-noise amplifier, and two transmit/receive switches. The module provides 500-mW output with 26-dB gain and 12.5% efficiency in transmit, and 18-dB gain with a 5.5-dB noise figure in the receive mode.

Figure 3 shows a MIMIC component, the HMM 11810. The HMM 11810 is a commercial product (Harris Semiconductor) used in wideband applications. It provides 5-dB gain over the 6- to 18-GHz band with ±0.75-dB flatness, 50-mW output power, and a 6.5-dB noise figure. This is only one example of a large number of MIMIC products that are readily available for systems engineering.

The major end user of microwave components has been, and will continue to be, the military. Large-volume commercial markets promised in the early 1980s for satellite television and data transmission did not come to pass as competing technology (for example, fiber optics) and market factors made the economics unattractive. The lost opportunity threatened the survival of technology expected from emerging commercial microwave ventures.

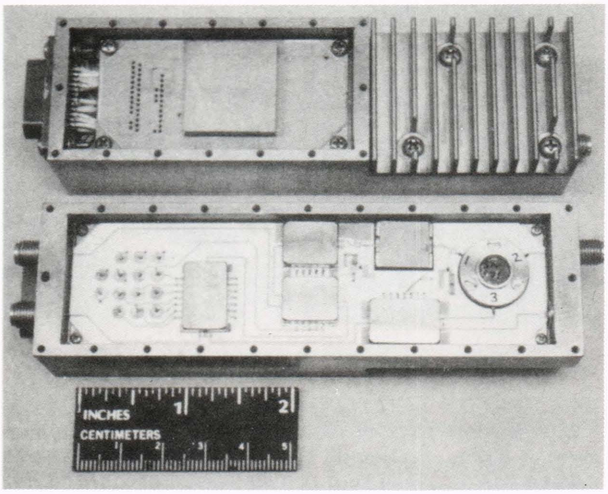


Figure 2—The active-array antenna transmit/receive module is a major focus for MIMIC. This module, developed by ITT, integrates power supply and digital control with the microwave transmit and receive channels. (Courtesy *Aviation Week & Space Technology.* © McGraw-Hill, Inc., 1986 and 1987. All rights reserved.)

In spite of less-than-encouraging predictions, it appears that the microwave field will still have vast commercial opportunities. Collision-avoidance systems for automobiles[5] and aircraft have been realized; those microwave (or millimeter-wave) systems are highly integrated with real-time decision-making and reaction using digital processing and robotic control. In the area of air-traffic control and environmental monitoring (to detect wind shear, for example), one article[6] points out that "The nation's air traffic control and navigation system is about to undergo extensive modernization ... $15 billion by the end of the century ..." The modernization will include Mode S beacon and transponder air-to-air and air-to-ground communication and data links, the microwave landing systems, collision-avoidance systems, and ground-station upgrades. There are also very-small-aperture terminals, remotely piloted vehicles, and mapping and locating pathfinders, to name several more commercial ventures. To be incorporated in such applications, cost, size, weight, and reliability must meet consumer product demands.

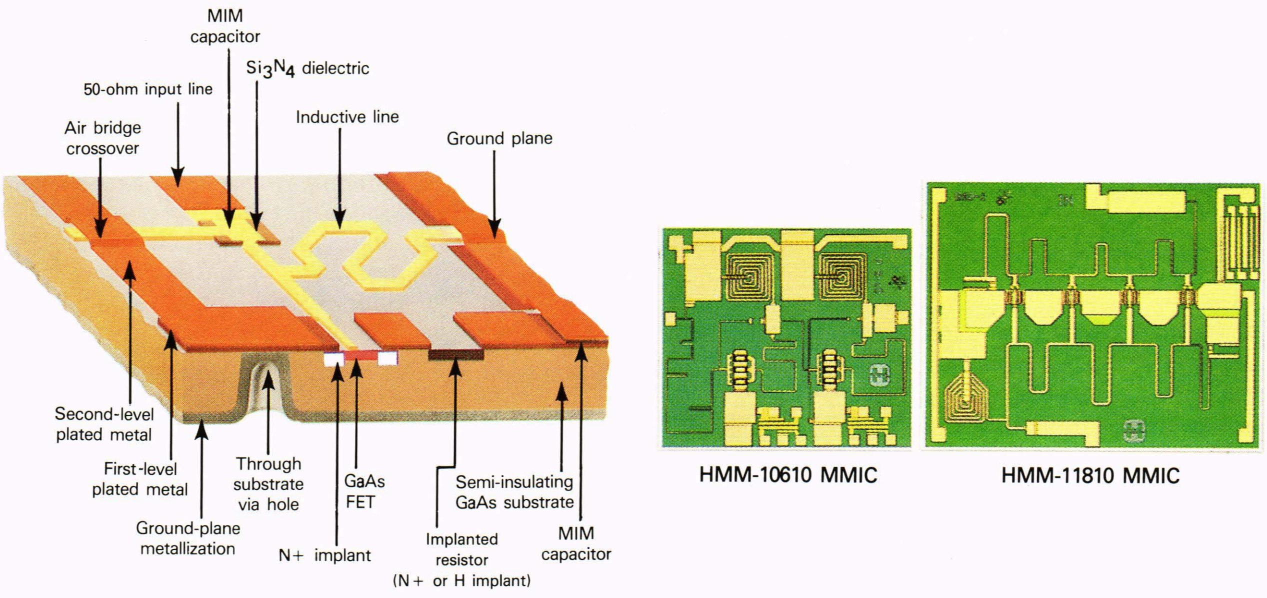
It is difficult to measure and define the extent of worldwide microwave activity. The trend is reflected in recent statistics[7] that forecast growth in MIMIC from $25.2 million in 1986 to $2.29 billion in 1997, a 100-fold increase. Major conferences in that field have grown from several hundred participants a decade ago to several thousand attendees now. Another indicator of that trend is the fact that The Johns Hopkins University Whiting School of Engineering microwave curriculum has grown from 4 to 12 courses, and from 60 to about 500 registrants over the past five years.

APL INITIATIVE

APL participates in the Strategic Defense Initiative, advanced radar and telecommunications, space stations, military systems (command, control, communications, and intelligence; electronic countermeasures; battle management; environmental surveillance and characterization; etc.) and national programs for the advancement of science and technology. In order to contribute to future state-of-the-art concepts and their implementation, APL must refine, expand, and extend its electronics expertise and capability.

APL has a broad base for electronic design, fabrication, test, packaging, and analysis; in addition, fundamental research and development is conducted on electronic materials, processes, and devices. In general, emphasis has been on low-frequency analog and digital circuits; consequently, there is a need to re-establish a microwave electronics capability. The APL executive committee has selected microwave/millimeter-wave miniature microwave circuit technology as an area for future work, with the following objectives:

- Establish a program at APL to pursue state-of-the-art microwave-electronics efforts.



Features of a typical MMIC chip

HMM-10610 MMIC

HMM-11810 MMIC

Electrical specifications

Model no.	Frequency band (GHz)	Small-signal gain (dB)		Gain flatness (over full BW) (dB) Max	1 dB gain compression output power (dBm) Typ	Noise figure (dB) Typ	VSWR Max
		Min	Typ				
HMM-10610	2 to 6	10	12	±0.5	+19	6	Input 2:1 Output 1.75:1
HMM-11810	6 to 18	4.5	5	±0.75	+16.5	6.5	2:1

V_{DD} = 5V, I_{DD} = 120 mA (typical, HMM-10610)/100 mA (typical, HMM-11810)

Figure 3—A broad range of functions is commercially available as MMIC (monolithic microwave integrated circuit) chips. The elements of an MMIC are monolithic-lumped and distributed resistors, inductors, capacitors, transmission lines, and active devices. Ground-plane vias and air-bridge crossovers are elements that allow high-frequency operation of transformers and transistors. One wideband design approach made practical by MIMIC is the distributed-transmission-line amplifier. (Reprinted with permission of the Harris Corporation.)

- Identify and define specific internal and external applications of MIMIC technology.
- Develop an in-house program for the design, fabrication, packaging, test, analysis, and quality assurance of microwave subsystems.
- Conduct research and development in new and novel microwave applications and devices.
- Provide education and training of personnel.
- Establish a cooperative Homewood–APL program in microwave electronics.

APL's microwave initiative inherits resources for accelerated microwave circuit and module development that are already in place. Hybrid microwave circuits, miniature quasi-monolithic circuits, and passive microwave monolithic integrated- circuit[7] networks can be fabricated in-house. The typical high cost of MIMIC technology is largely offset by existing electronic and mechanical engineering resources, including processes, assembly and machine tools, and test facilities. But those resources must be tailored to meet new specific requirements. Effective microwave engineering design using captive and external fabrication is being developed.

APL will integrate and test available MIMIC components and develop fully custom microwave circuits when the need arises.

MIMIC IN APL SYSTEMS

The application of advanced microwave technology is critical to many APL programs. Two examples are given below.

APL's Space Department has made world-acclaimed contributions to space science. One instrument that is part of the Space Department heritage is the radar altimeter, which provides both orbital and planetary surface data. The trend for radar altimeters is toward higher operating frequencies and smaller volume, weight, and power consumption, while raising performance levels.

Altimeters now being developed in the Space Department use MIMIC technology. The Topography Experiment for Ocean Circulation program includes the development of an altimeter with a measurement precision of 2 cm that operates at 20 GHz, with a peak power output of 20 W. An altimeter planned for the Mars Observer Radar Altimeter and Radiometer operates at 14 GHz, and would measure both surface-height variations and surface temperature (the latter is made possible by integrating a microwave radiometer into the radar electronics). Both instruments are solid-state space-qualified applications of advanced microwave technology.

For such one-of-a-kind systems, technology is selected and incorporated based on performance, reliability, and schedule. But in other, more general cases, additional considerations are associated with applications, such as the feasibility of mass production, low-cost, maintenance, and survivability.

At APL, active arrays and missiles (such as Harpoon, Tomahawk, and the Standard Missile) are natural users of MIMIC technology. Seeker and fusing functions of those modern missiles are being developed so as to have autonomous behavior for identification, friend or foe; targeting; and intercept. Given the volume, reliability, and economic constraints associated with missiles, meeting performance goals will require systems that integrate MIMIC and VHSIC.

That application is ideal for illustration of the new technology. Figure 4 shows an example of the benefits of the new technology. With thousands of units involved, it is important that the microwave design be suitable for manufacture.

MIMIC Technology

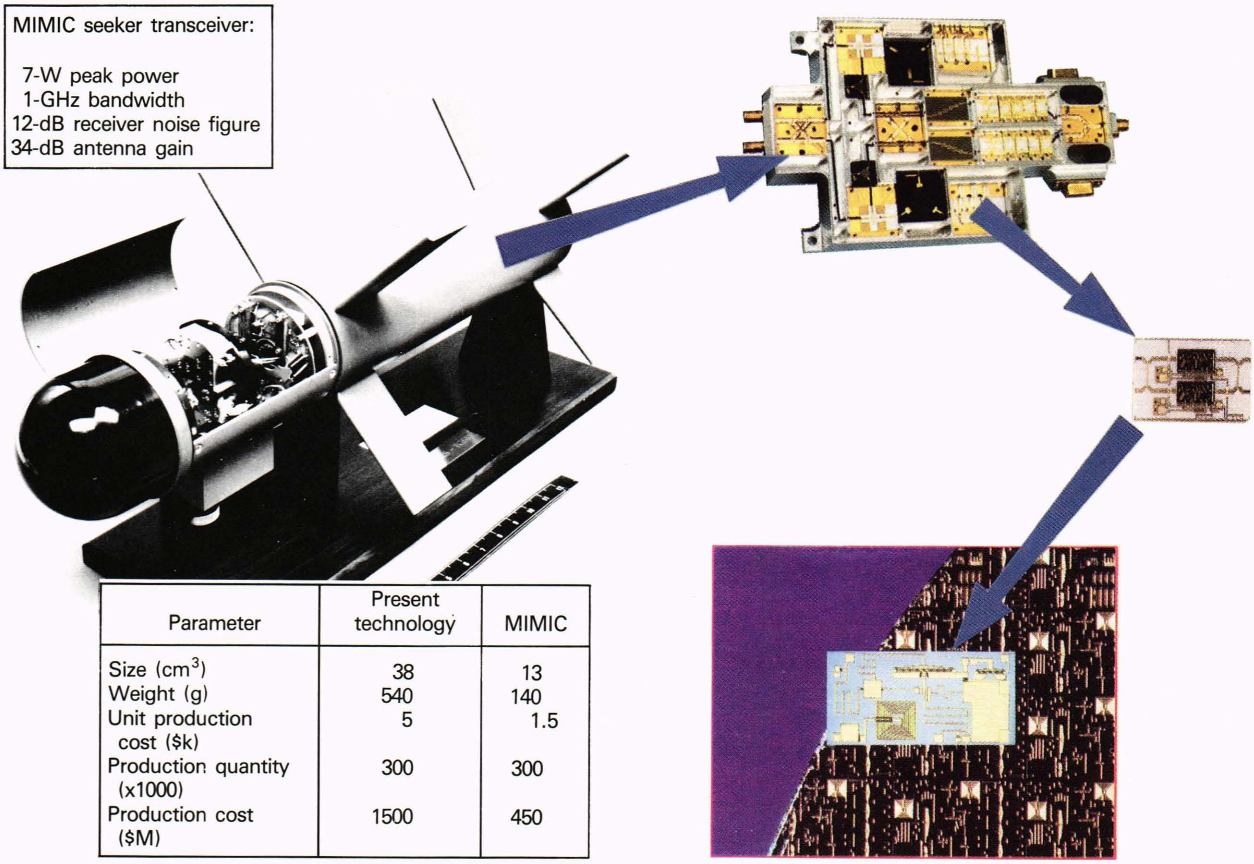
As mentioned earlier, the MIMIC program consists of efforts in the areas of specification, design, measurement and characterization, acquisition, fabrication, packaging, and test and evaluation. These areas, while different from one another, are inseparable and interdependent, although any of them could exist as a standalone activity. At APL, resources are evolving in all of those areas of technology.

Specification

Several tiers of specification are related to application to MIMIC technology. Figure 5 shows the connectivity and complexity in deriving specifications, as exemplified by considerations for a V-band (60-GHz) phased array.[8] Microwave experience and expertise is necessary at this initial phase to generate a development guide with adequate detail and definition for effective technical implementation. High-capacity computer-aided-engineering design stations allow for the storage, recall, and distribution of experience.

Design

The first commercial microwave computer-aided-engineering program was offered in 1971 by Tymeshare. It



MIMIC seeker transceiver:

7-W peak power
1-GHz bandwidth
12-dB receiver noise figure
34-dB antenna gain

Parameter	Present technology	MIMIC
Size (cm^3)	38	13
Weight (g)	540	140
Unit production cost ($k)	5	1.5
Production quantity (x1000)	300	300
Production cost ($M)	1500	450

Figure 4—An example of improvement in performance and cost by using MIMIC.

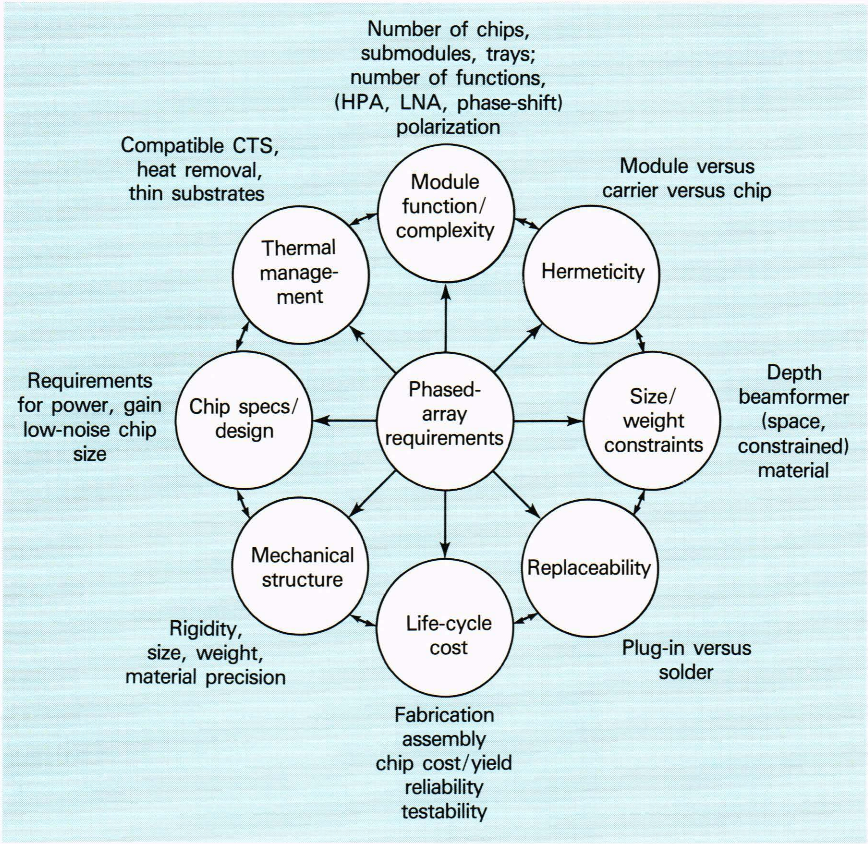


Figure 5—Microwave system development presents a challenge to integrate all the facets of electrical, mechanical, thermal, environmental, cost, and operational design.[8] (Reprinted with permission of *Microwave J.*, from the January 1987 issue, © 1987 Horizon House–Microwave, Inc.)

performed two-port cascade analysis and incorporated a small number of standard elements (electrical parameters). Shortly thereafter, the popular Compact software (from Compact Engineering) became available. It had nodal and two-port analysis, optimization, transmission line synthesis, S-parameter data files, and noise analysis. It was used for linear, small-signal, steady-state circuit design. At that time, computer power was far below what it is today.

The rapid evolution of microcomputers from 8-bit to 32-bit workstations serendipitously supported a similar pace in the development of microwave engineering software. Today, fourth-generation software is offered by EEsof, Compact Engineering, Hewlett–Packard, and others, with impressive capabilities (for example, menu environment, full-screen editing, high-resolution color graphics, large libraries of standard and user-definable elements, optimization, and tuning). Reasonably priced personal computers can now accommodate linear and nonlinear mixed analysis, steady-state and transient performance evaluation, thermal and process considerations, systems-level to device-level focus, network synthesis, computer-generated pattern layout, interactive design–test interfacing, and foundry application-specific integrated-circuit definition.

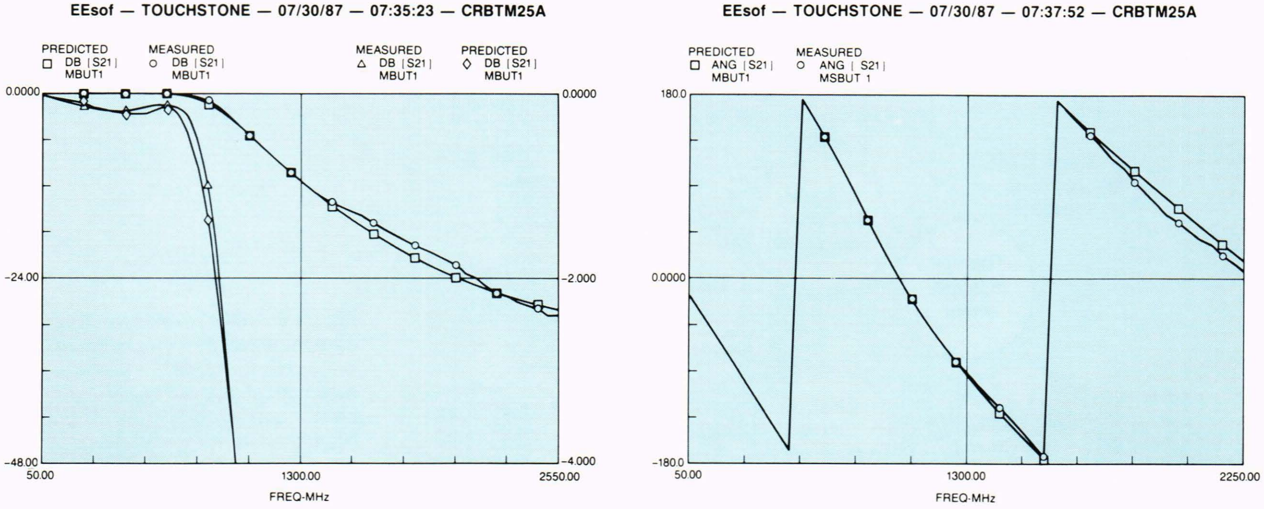
APL has established modern microwave-design resources that couple microwave software with powerful workstations, pattern generators, and test equipment to provide such features.

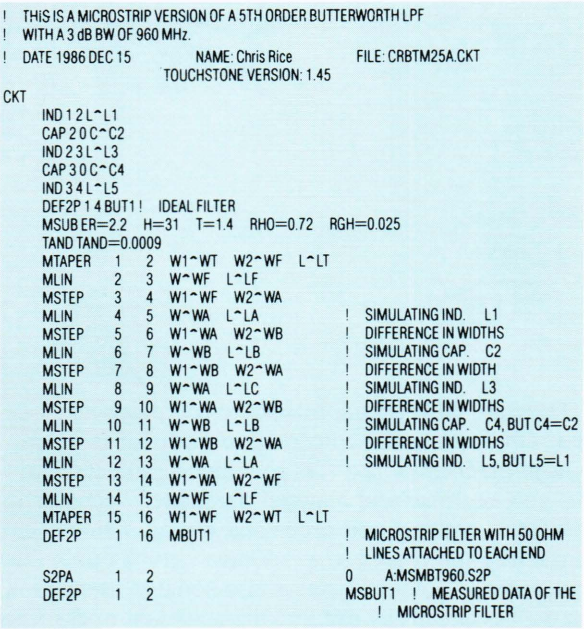
There are different approaches to computer circuit design. One uses nodal construction and circuit descriptions in the form of text files containing element descriptors and electrical and material parameters, entered according to a structured order and syntax. Circuits can be defined and reused so as to have virtually unlimited complexity. Another scheme is also nodal in foundation, but defines circuits by pictorial manipulation of elements on a displayed schematic. This latter method is similar to computer-aided drafting, wherein electrical parameters are treated as attributes entered as part of the schematic object. Performance output (measurements) can be selected from a myriad of presentations in tabular or graphic display. Figure 6 shows an example of the screen environment for each of these.

Rapid advances are being made in the accuracy of microwave computer-aided engineering. Those include advances in verified elemental models, user-defined elements, active-device models, and other aspects of microwave design.

MICROWAVE MEASUREMENTS

Understanding the nature and behavior of microwave circuit elements is critical to successful design. Test and measurement of millimeter-wave frequencies, perhaps the most difficult aspect of microwave engineering, offers challenges in the areas of calibration standards and techniques, test fixture design, instrumentation, and analysis. Computer-aided testing enhances systemic error correc-





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!   WITH A 3 dB BW OF 960 MHz.
!   DATE 1986 DEC 15          NAME: Chris Rice          FILE: CRBTM25A.CKT
                           TOUCHSTONE VERSION: 1.45
CKT
    IND 1 2 L^L1
    CAP 2 0 C^C2
    IND 2 3 L^L3
    CAP 3 0 C^C4
    IND 3 4 L^L5
    DEF2P 1 4 BUT1 !   IDEAL FILTER
    MSUB ER=2.2   H=31   T=1.4   RHO=0.72   RGH=0.025
    TAND TAND=0.0009
    MTAPER   1   2  W1^WT   W2^WF   L^LT
    MLIN     2   3  W^WF   L^LF
    MSTEP    3   4  W1^WF   W2^WA
    MLIN     4   5  W^WA   L^LA                !  SIMULATING IND.   L1
    MSTEP    5   6  W1^WA   W2^WB              !  DIFFERENCE IN WIDTHS
    MLIN     6   7  W^WB   L^LB                !  SIMULATING CAP.   C2
    MSTEP    7   8  W1^WB   W2^WA              !  DIFFERENCE IN WIDTH
    MLIN     8   9  W^WA   L^LC                !  SIMULATING IND.   L3
    MSTEP    9  10  W1^WA   W2^WB              !  DIFFERENCE IN WIDTHS
    MLIN    10  11  W^WB   L^LB                !  SIMULATING CAP.   C4, BUT C4=C2
    MSTEP   11  12  W1^WB   W2^WA              !  DIFFERENCE IN WIDTHS
    MLIN    12  13  W^WA   L^LA                !  SIMULATING IND.   L5, BUT L5=L1
    MSTEP   13  14  W1^WA   W2^WF
    MLIN    14  15  W^WF   L^LF
    MTAPER  15  16  W1^WF   W2^WT   L^LT
    DEF2P    1  16  MBUT1                      !  MICROSTRIP FILTER WITH 50 OHM
                                               !  LINES ATTACHED TO EACH END
    S2PA     1   2                             0     A:MSMBT960.S2P
    DEF2P    1   2                             MSBUT1   !   MEASURED DATA OF THE
                                                    !   MICROSTRIP FILTER
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MiCAD layout of the microstrip filter

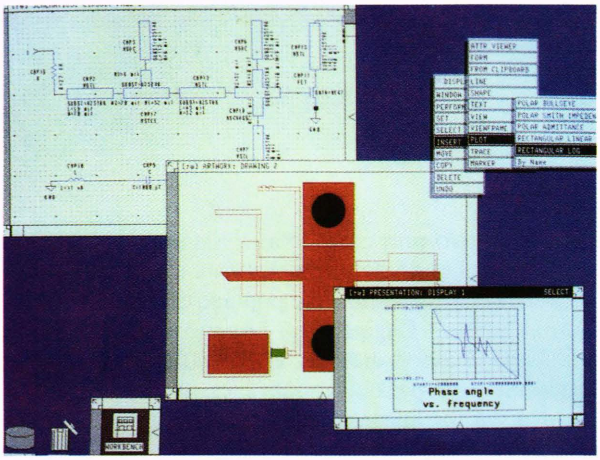


Figure 6—One of the most significant factors responsible for the rapid pace of modern microwave technology is computer-aided engineering. Text description and pictorial schematic capture are two approaches to the design environment. (Reprinted with permission of EEsof and Hewlett-Packard.)

tion and the characterization of test fixtures. Test data output is compatible with computer-aided-engineering design software so that measurements can be directly injected into circuit-analysis programs.

Testing uncertainty is often caused by interaction between the device under test and the test fixture; progress is being made in this area in several directions. Better test fixtures and (on-chip) standards[9] are available now than were available several years ago, alternate methods of calibration and test-fixture characterization are possible, and advances in high-frequency probes and probe systems allow direct high-frequency access to device ports. Modern automatic network analyzers with a high-frequency probe station can perform direct chip-on-wafer measurements to millimeter-wave frequencies.[10]

Acquisition

This function (usually underemphasized) can be as basic as ordering capacitors or as complex as assuring the timely receipt of performance-verified, reliable monolithic devices. The performance of components for microwave applications is influenced by construction, material, and operating frequency. Unfortunately, because of this situation, there is a "uniqueness of part" in microwave engineering that must be taken into consideration. In addition to component acquisition, there are selection and evaluation of external commercial processing and packaging services. Process variations are intrinsic to these areas and must be incorporated into performance sensitivity analysis as part of the design process.

Process

Monolithic microwave integrated circuits (MMICs) and hybrid microwave-circuit designs are implemented using substrates from a broad and diverse range of microwave circuit materials. Processes and materials used affect performance, whether it is a single-layer printed circuit on Teflon or a gallium-arsenide monolithic integrated circuit.

Major advances in microwave technology have been brought about by the development of reliable processes for materials growth and preparation and circuit fabrication. Just as components and packaging considerations must be incorporated as an integral part of the electronic design, processes must also be incorporated. The microwave designer is familiar with the behavior and influences associated with processes used to produce a circuit, and aware of how they relate to achieving the design specifications. Modern process equipment at APL deposits materials that are patterned by high-resolution lithographic techniques to form the elements of an MMIC chip (Fig. 3).

Organizations working on microwave technology must consider process control and standardization; in addition, characteristic process data must be made available to designers.

Three basic process levels can be defined, according to the type of substrate: soft materials for spatially distributed circuits, hard materials for distributed circuits, and materials for monolithic or quasi-monolithic distributed–lumped circuits.

APL has a background in electronic processing of materials that is immediately applicable to microwave-circuit fabrication. Its resources are extensive and are suitable for work ranging from simple printed circuits to quasi-monolithic components on exotic materials. Because of the different requirements of high-frequency circuits (as compared to hybrid or digital circuits), microwave-specific processes are under development. The radar-array module mentioned earlier can be fabricated at APL.

The Eisenhower Research Center recently installed a metal organic chemical vapor deposition reactor used in the preparation of engineered materials—layered microstructures (2 to 20 nm) of doped semiconductors make possible high-electron-mobility transistors that operate at frequencies above 100 GHz.

Packaging

In addition to the mechanical, the thermal, and environmental aspects typical of electronic integration, there are many other considerations, such as electromagnetic compatibility, cavity resonance, surface waves, isolation, crosstalk, spurious modes, and parasitics. Self-contained modules also require direct-current bias supplies that do not affect the microwave function. They must be regulated, filtered, and isolated, yet must be in close proximity to high-frequency circuit regions.

The subject of microwave packaging is too complex to be dealt with in this article. In general, close attention must be given to microwave input and output connectors and transitions, compartmental package design, ground integrity, component and substrate attachment, undesirable coupling, and requirements stemming from application constraints.

Figure 7 shows a chip package used for MMIC mounting,[11] and a transmit/receive module integration scheme.[8] Note the integration of microwave, optical, and digital technology in the same module. Packaging for high-frequency or high-speed operation in a systems environment continues to be a challenge and a limiting factor for microwave systems. Standardization is not likely to occur beyond MMIC chip carriers.[12]

APL has extensive microwave design, machines, processes, materials, assembly, and test resources for chip-level to system-level insertion of MIMIC/VHSIC technology; packaging is a strong point in engineering experience. Current and future efforts will draw on packaging expertise and experience in microwave system integration.

SYSTEMS CONSIDERATIONS

There are two types of MIMIC insertion—replacement insertion and beneficial insertion. The former is usually a direct substitution (form, fit, and function) for an existing unit. Replacement insertion objectives are useful and can direct technology growth. It can build experience, confidence, reputation, and awareness; unfortunately, replacement insertion does not nuture and sustain technology development.

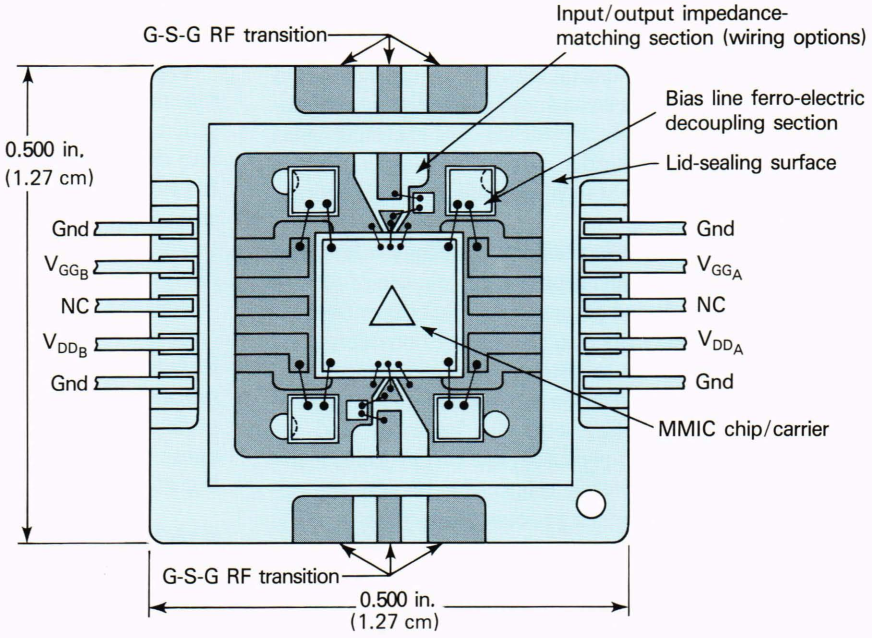
Beneficial insertion sustains and encourages the growth of technology. Thus, the benefits of using MIMIC result in system improvements.

MIMIC technology will continue to grow because it can provide performance improvements that would be otherwise unattainable, especially for radar.[13] But it has also been pointed out that:

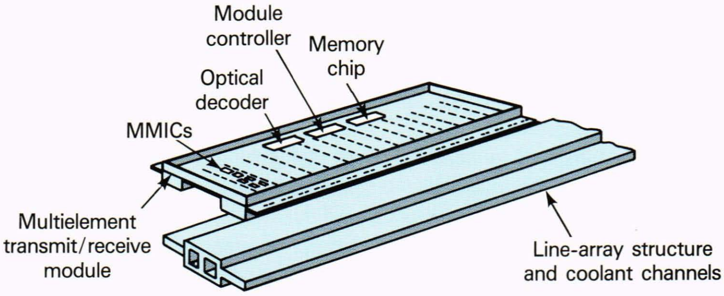
> "At the outset, designers must decide whether MMIC technology is a viable candidate for their circuit function—if the circuit elements required are available in MMIC form with adequate performance characteristics. Second, designers must look at cost and reliability considerations."[14]

Figure 8 shows an example of benefits to be realized with MIMIC; in addition, there are the obvious associated improvements in weight, volume, efficiency, and reliability.[15] Hybrid microwave circuits have been used for over 20 years, and their reliability and failure mechanisms are fairly well established. The availability of gallium-arsenide monolithic circuits has encouraged reliability evaluations that show that MMIC modules are even more reliable than hybrid microwave circuits.[16] (In passing, it should be noted that both microwave and high-speed digital circuits based on gallium arsenide are radiation-hardened to levels approaching 10^8 Rad.[17])

There is an especially positive attribute of using monolithic microwave circuits in large quantities where consistent performance is necessary (for example, an active array having thousands of elements). The consistent and exacting processes of microelectronic fabrication methods coupled with the distributed–lumped nature of MMICs result in excellent chip-to-chip performance con-



(a) MMIC power amplifier package assembly detail.



(b) V-band brick module concept.

Figure 7—Perhaps the most challenging aspect of microwave design is packaging. Whether a single chip or a complex multi-technology module, a high degree of interaction and interdependence must be managed to interface and integrate circuitry.((a) reprinted with permission of *Microwave J.*, from the November 1987 issue, © 1986 Horizon House-Microwave, Inc.; (b) reprinted with permission of *Microwave J.,* from the January 1987 issue, © 1987 Horizon House-Microwave, Inc.)

sistency. Test data for an MMIC 2- to 6-GHz amplifier cell shows excellent consistency of the small-signal gain for 29 chips selected from the same run (Fig. 9).[18]

One major consideration for future high-performance systems is cost. Historically, microwave modules have a major proportion of their cost associated with assembly, test, and adjustment of performance to meet specification tolerances. Those necessities make some microwave systems economically impractical to build and maintain. For example, current active phased-array hybrid microwave transmit/receive modules cost about $2000 to $4000, in quantity. Not counting the array-integration costs, an X-band, 3000-element array face would cost $12 million. One goal of the Department of Defense MIMIC initiative is to achieve improved-performance MMIC transmit/receive modules at a cost of $250 per module.[19] This would reduce the aforementioned array-face module cost to $750,000, with operational costs also reduced considerably because of improved reliability, efficiency, and availability, and replacement ease.

Table 2 shows the MMIC components that are available and their performance level.[20] Performance and yield of MMICs have increased dramatically over the past 10 years; the range of products and number of commercial suppliers have done the same,[21] as have the attention and investment by all the major systems houses. All are strong indicators of the importance and future impact of MIMIC technology.

SUMMARY

MIMIC is a new technology for advanced system development. APL's MIMIC initiative is:

- To realize beneficial insertion of MIMIC technology.
- To develop components applicable to microwave systems.
- To package and integrate commercially available MIMIC components.

Table 2—Typical performance of MMIC components.

MMIC Component	*Frequency Range (GHz)*	*Noise Figure (dB)*	*Performance Gain (dB)*
Small-signal amplifiers (narrow band)	3–5	1.5	22
	10–12	2	30
	28–30	7	14
Small-signal amplifiers (wide band)	2–18	5–7.5	6
	8–26	4–6	6
	2–30	7.5–8.5	9

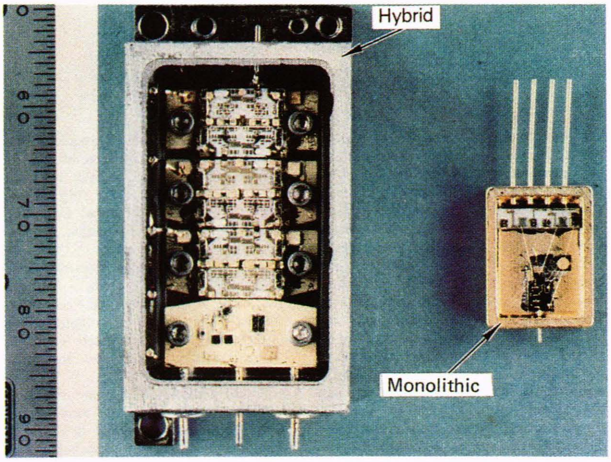
MMIC Component	*Frequency Range (GHz)*	*Power output (W)*	*Gain (dB)*	*Efficiency (%)*
Power amplifiers (narrow band)	(4-stage) 7.5	1.3	32	30
	(1-stage) 10.0	2.0	4	15
	(3-stage) 16.5	2.0	12	20
	(1-stage) 28.0	1.1	3	10.8
Power amplifiers (wide band)	(2-stage) 3.5–8	2.0	10	20
	(1-stage) 2–20	0.8	4	15

MMIC Component	*Frequency Range (GHz)*	*Conversion loss (dB)*
Mixers	15	10
	30	6
	95	7.5

MMIC Component	*Frequency Range (GHz)*	*Power output (dBm)*
Power source	0–10	15
	30–35	30
	60–70	−4

MMIC Component	*Frequency Range (GHz)*	*Insertion loss (dB)*
Phase shifter (6-bit)	5–6	9.5 (±1-dB ripple)
(5-bit)	17.7–20	3–4 (±6° phase error)

MMIC Component	*Frequency Range (GHz)*	*Isolation (dB)*	*Loss (dB)*
SPDT switch	DC–4	35	0.8
	0–20	30	2.0



Comparison task	Hybrid module	Monolithic module
Number of gold wires	253	18
Number of piece parts	117	10
Assembly time (h)	16	1
Tune time (h)	10	No tuning required
RF parameters	Same as monolithic	Same as hybrid
Cost (1984)	$2500 (primarily labor)	$500 (primarily parts)

Figure 8—Department of Defense MIMIC program will accelerate transition from hybrid microwave integrated-circuit technology to the smaller, potentially much-lower-cost monolithic technology. Shown is a hybrid voltage-controlled oscillator (above left) and its monolithic counterpart (right), produced by Texas Instruments. Below is a comparison of the number of piece parts and labor content for each technique.[15] (Courtesy of *Aviation Week & Space Technology,* © McGraw-Hill, Inc., 1986 and 1987. All rights reserved.)

- To conduct materials research on high-temperature superconductive films and engineered materials for device and component development.

Future projects may develop in microwave, digital, acoustic, and optic integration for signal processing and sensors.

An effective MIMIC effort at APL requires work in two major areas: (1) development of broad functional microwave capability, resources, and technology, and (2) demonstration, implementation, and beneficial insertion of MIMIC. New microwave technology has been and will continue to be very important at APL.

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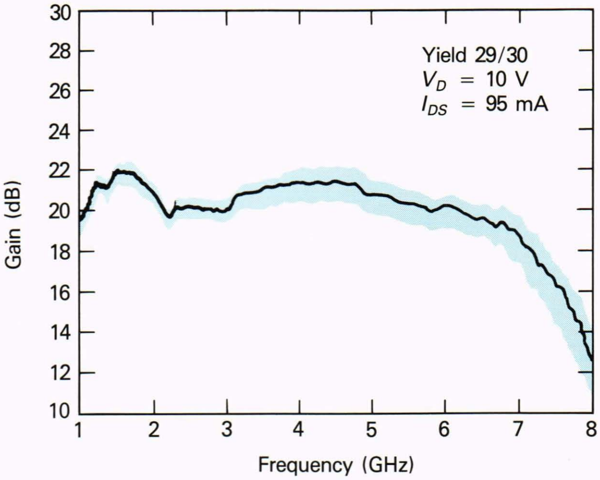

Figure 9—Consistent performance without tuning is a benefit of MIMIC. Excellent qualitative and good qualitative performance is characteristic of this 2- to 6-GHZ MMIC amplifier chip.

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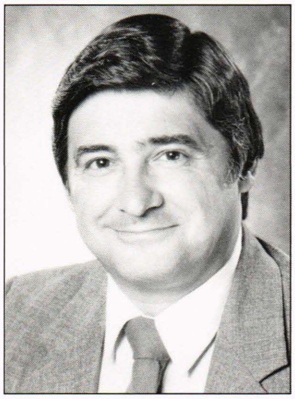

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