JOSEPH L. ABITA

MICROWAVE TECHNOLOGY

As technology evolves, a sudden advance can be brought about by a single discovery or by an especially favorable combination of conditions. Microwave technology has been advancing rapidly, promising a similar trend for the performance of high-frequency and high-speed systems at microwave frequencies. This article presents elements contributing to that acceleration and gives an overview of current microwave electronics technology at APL.

INTRODUCTION

In 1942, APL was founded to develop radio proximity fuzes based on the application of emerging radar technology. That innovative work led to participation in guided-missile defense and contributed to the advance of early Navy shipborne surface-to-air missiles (Terrier, Tartar, and Talos). The Laboratory continued work on the development of advanced systems for radar; navigation; command, communications, and control; geodesy; and tracking. Major innovations resulted from in-house microwave expertise. Over the past several decades, APL has continued its work in microwave technology and has tried to keep up with the rapid pace of development by major systems houses. Microwave technology is essential to the long-range evolution of Navy systems, and the support of those systems is a primary mission of APL.

The Department of Defense microwave/millimeter-wave monolithic integrated circuit (MIMIC) initiative complements the very high speed integrated circuit (VHSIC) digital program. Although many parallels exist between those programs, they differ in several important aspects. The VHSIC program, conducted by several major systems houses, strongly emphasized technology development, and it depended on the often touted "obvious benefits of the technology" to encourage technology transfer and insertion by the military services. In comparison, the MIMIC program emphasizes systems use to improve technology and requires team participation by industry, commerce, and universities. It encourages education of tri-service program managers to promote technology transfer and insertion.

CURRENT TRENDS IN MICROWAVE TECHNOLOGY

Four decades of microwave engineering developments have resulted in the expansion of microwave markets and technology and an increase in the number of people working in the field. Major recent advancement has occurred because of an ability to deal with the complexity of microwave circuit analysis and to characterize components accurately. Our expertise has evolved from the rapid growth in microwave computer-aided design, test, and measurement. Also, modern materials, processes, and equipment contribute to reliable circuit fabrication, packaging, and integration. The pace of microwave electronics advancement is driven by the need to meet performance goals, which arise, for example, from frequency-allocation limitations and major programs such as the Strategic Defense Initiative, the Global Positioning System, and the Military Strategic/Tactical and Relay System. Performance and physical demands of modern commercial and military systems, coupled with high levels of integration and the fusion of different technologies, offer exciting challenges in microwave engineering.

Several notable microwave products that exemplify current microwave technology apply microwave integrated circuit (MIC) and monolithic microwave integrated circuit (MMIC) technology, both of which are embraced by the MIMIC program. For example, a completely solid-state transmit/receive module for a phased-array radar was developed by ITT Defense Technology Corporation.[1] The module provides 30-dB gain at 20% efficiency, operating at 12-W peak output power at 5 to 6 GHz. Texas Instruments has developed a one-chip monolithic transmit/receiver module at X band.[2] Operating at 8 to 12 GHz, the single-chip 13 × 4.5 mm integrated-circuit module provides 500-mW output with 26-dB gain and 12.5% efficiency in the transmit mode and 18-dB gain with a 5.5-dB noise figure in the receive mode. Another example is the HMM 11810, a commercial product of 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. Many other MMIC products are commercially available for electronic systems engineering.

Whereas MIC technology is akin to surface-mounted technology, MMIC technology is fully monolithic: the material properties of gallium arsenide extend operation well beyond the frequency limits of silicon-based devices.

The availability of advanced microwave components is critical to military applications. Relative to typical silicon semiconductor production, the military market for gallium arsenide is low in volume and does not provide incentives for timely yield/cost improvements or standardization—consequences very important to the use and insertion of this technology. Large-volume markets, on the other hand, may not promote improvements in product performance. Commercial applications, although providing large-volume opportunity, do not typically require the high performance levels that some military and space systems strive for. But those same military and space applications do not offer the large-volume incentive conducive to good yield/cost and standardization. Negatively affected by this dichotomy will be the commercial availability of functional, high-performance microwave components. Thus, companies engaged in development of custom high-performance systems must maintain their own microwave technology.

Large-volume commercial markets are important to the companies that sell microwave components and circuits. The facilities, products, and experience of these companies are important to continued development of high-performance microwave systems at affordable cost. Suitable markets have not yet solidified, but the microwave field promises vast commercial opportunities. Collision avoidance systems for automobiles[3] and aircraft have been realized. These 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 air safety (to detect wind shear, for example), "The national air traffic control and navigation system is about to undergo extensive modernization . . . $15 billion by the end of the century . . . "[4] The modernization will include air-to-air and air-to-ground communication and data links, microwave landing systems, collision avoidance systems, and ground-station upgrades. Very-small-aperture terminals, remotely piloted vehicles, and mapping and locating pathfinders are other projected commercial ventures. To be incorporated into such applications, systems and components must meet the demands and constraints of consumer markets as to cost, size, weight, and reliability.

The trend in microwave electronics is reflected in recent statistics[5] that forecast growth in MIMIC technology from $25.5 million in 1986 to $2.29 billion in 1997, a 100-fold increase. The number of attendees at major conferences in this field has increased from several hundred a decade ago to thousands now. Another indicator of the trend is that the microwave curriculum at The Johns Hopkins University G.W.C. Whiting School of Engineering has grown from 4 to 14 courses (which include design and foundry fabrication of custom MMIC's in gallium arsenide), and registrants have increased from 60 to about 500 over the past five years.

MICROWAVE ELECTRONICS AT APL

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

Over the years, APL has established a broad base for electronic design, fabrication, test, packaging, and analysis, complemented by fundamental research and development on electronic materials, processes, and devices. In general, emphasis has been on low-frequency (less than 1 GHz) analog and digital circuits; consequently, a need exists to establish a microwave electronics capability for use of the spectrum up to frequencies of 100 GHz and beyond.

The Executive Committee of APL has selected MIMIC technology for independent research and development with the following objectives:

1. Establish expertise at APL to participate in state-of-the-art microwave electronics.
2. Identify and define specific internal and external applications of MIMIC technology.
3. Develop an in-house program to design, fabricate, package, test, analyze, and qualify microwave subsystems.
4. Conduct research and development for novel microwave applications and devices.
5. Provide education and training in microwave technology.
6. Promote and enhance cooperative microwave electronics research and development between The Johns Hopkins University Homewood Campus and the Applied Physics Laboratory.

The Laboratory's microwave initiative inherits resources for microwave circuit and module development that are already in place. Hybrid, miniature quasi-monolithic, and passive MMIC networks can be fabricated in-house. The typical high cost of establishing MIMIC technology is largely offset by these existing electronic and mechanical engineering resources, including processes, assembly, machine tools, and test facilities. But those resources must be tailored to new levels of sophistication to bring the Laboratory's microwave engineering expertise in line with the state of the art in knowledge, "tools," and skills.

MIMIC IN APL SYSTEMS

Because the application of advanced microwave technology is critical to many APL programs, we must integrate and test available advanced MIMIC components and develop custom microwave circuits when needed. This conclusion is supported by the nature of APL's mission and is typified by several examples.

Our Space Department has a long heritage in space-based radar altimeters, which provide orbital and planetary surface data. The trend for radar altimeters is toward higher operating frequencies, increased performance levels, and smaller volume, weight, and power consumption. Altimeters being developed in the Space Department necessarily use MIMIC technology; they represent solid-state space-qualified applications of advanced microwave technology. For example, the Topography Experiment for Ocean Circulation program requires a small solid-state altimeter with a precision of 2 cm that operates at 20 GHz and a peak power output of 20 W. For such one-of-a-kind efficient systems, technology is selected and incorporated on the basis of performance, reliability, and schedule. Additional considerations are associated with applications, such as the feasibility of production, cost, maintenance, and survivability.

At APL, active arrays and missiles (such as Harpoon, Tomahawk, and the Standard Missile) are "must use" opportunities for MIMIC technology. Seeking and fuzing functions of these modern missiles are being developed to provide autonomous behavior for identification (friend or foe), targeting, and interception. Given the volume, reliability, and economic constraints associated with missiles (and active array radars), performance goals will require systems that use and integrate MIMIC and VHSIC. Figure 1 shows the cost and performance benefits of MIMIC technology when applied to missile electronics. With thousands of units involved, microwave systems must be designed for manufacture from the inception of system development. Such a requirement can be met only by having successful experience in "beginning-to-market" microwave technology implementation from initial idea to marketplace.

MIMIC TECHNOLOGY

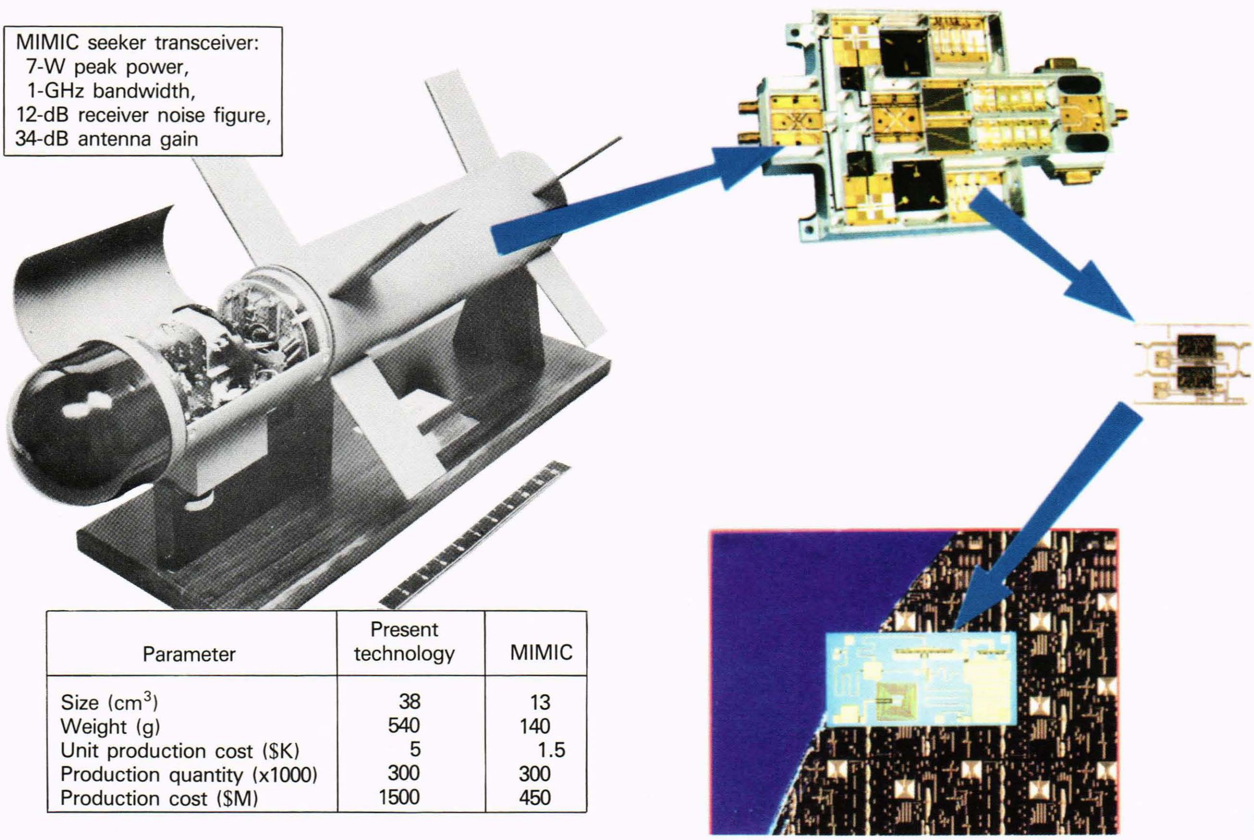
The MIMIC program consists of work in applications specification, design, measurement and characterization, acquisition, fabrication, packaging, and test and evaluation. These areas are inseparable and interdependent when applied to microwave electronics and systems. At APL, resources and capability are evolving in all those areas of technology.

Specification

Several tiers of specification are related to the application of MIMIC technology. Figure 2 shows the connectivity and complexity of deriving specifications, exemplified by considerations for a V-band (60-GHz) phased array.[6] Microwave experience and expertise are necessary at this initial phase to generate a development guide with adequate detail and definition for effective technical implementation.

Design

The rapid advance of microcomputers from 8- to 32-bit workstations helped make possible a similar rapid pace in the development of microwave engineering software. Today's fourth-generation software has impressive abilities, such as screen icon and menu command environment, full-screen editing, and high-resolution color graphics. Personal computers now accommodate linear and nonlinear mixed analysis, steady-state and transient performance evaluation, thermal and process considerations, system- to device-level focus, network synthesis, computer-generated pattern layout, interactive design-test interfacing, and foundry application-specific integrated-circuit definition. The accuracy of computer-



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 1. An example of improvement in performance and cost by using MIMIC technology.

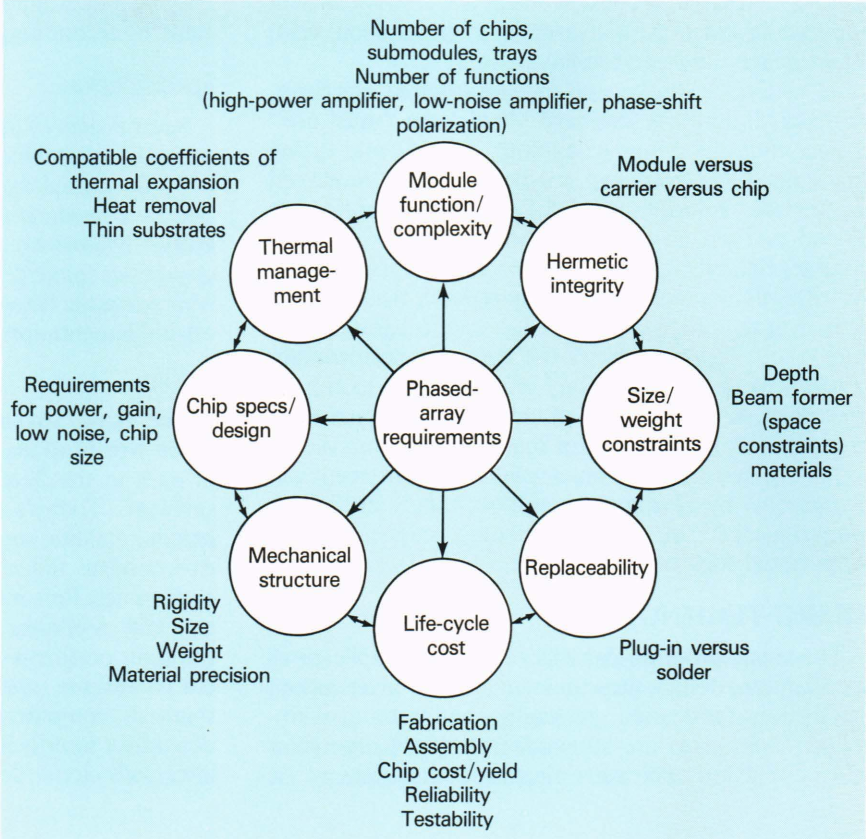


Figure 2. Microwave system development presents a challenge to integrate all the facets of electrical, mechanical, thermal, environmental, cost, and operational design.[6] (Reprinted with permission of *Microwave J.*, from the January 1987 issue, © 1987 Horizon House–Microwave, Inc.)

aided microwave engineering is improving. Progress has also been made in verified elemental models, user-defined elements, active-device models, and other aspects of microwave design.

Microwave Measurements

The accuracy and validity of models developed to represent the nature and behavior of microwave circuit components must be determined by comparing predicted performance against measured data. Test and measurement at millimeter-wave frequencies are perhaps the most difficult aspects of microwave engineering. Uncertainty in test data is caused by interaction between the device under test and the test fixture; progress is being made in this area in several directions. Computer-aided testing enhances systematic error correction and the characterization of test fixtures. Over the past several years, better test fixtures and (on-chip) standards[7] have become available, and several new approaches to calibration and test fixture characterization have evolved. Advances in high-frequency probes and probe systems allow direct high-frequency access to device ports. Modern automatic network analyzers with high-frequency probe stations can perform direct chip-on-wafer measurements to millimeter-wave frequencies.[8] Test data output is compatible with computer-aided-engineering design software, so that measurements can be directly injected into circuit-analysis programs.

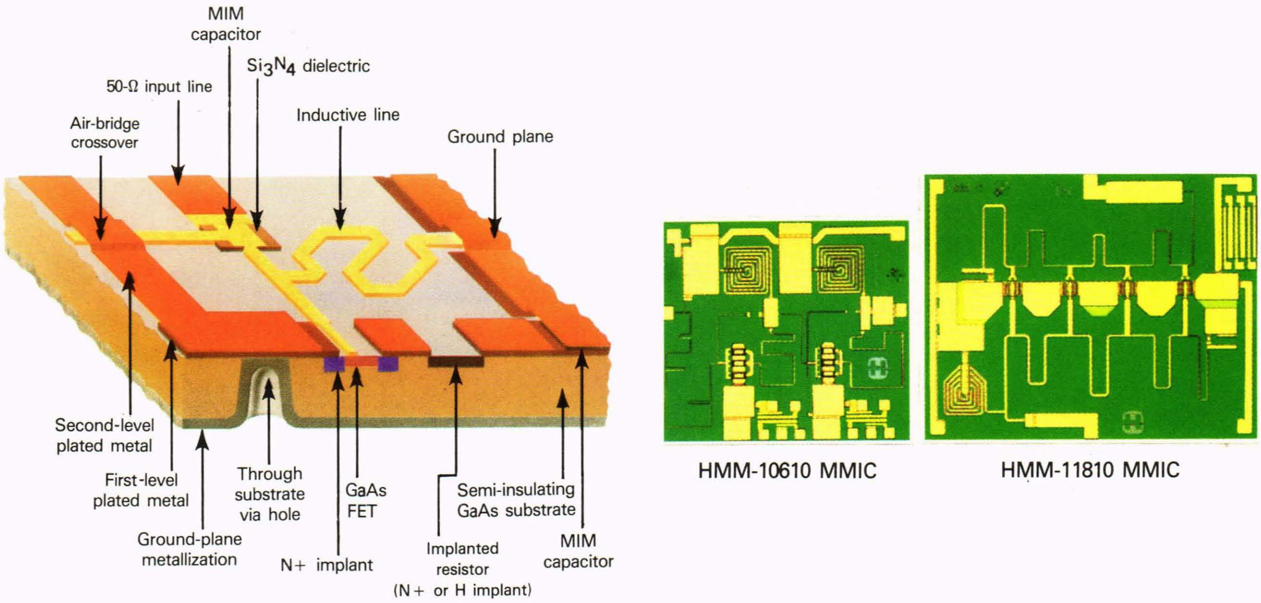
Acquisition

Performing this function can be as basic as ordering capacitors or as complex as ensuring the timely receipt of performance-verified, reliable monolithic devices. A "uniqueness of part" in microwave engineering must be considered; that is, each of a given type of component can have significantly different high-frequency network design parameters. In addition to component acquisition, selection and evaluation of external commercial processing and packaging services also are available at APL.

Process

Major advances in microwave technology have resulted from the development of reliable processes for materials growth and preparation and circuit fabrication. Just as components and packaging considerations must be integral to the electronic design, processes must also be incorporated. Modern process equipment at APL deposits materials that are patterned by high-resolution lithographic techniques to form the elements of a MMIC chip (Fig. 3).

The Laboratory has extensive resources for microwave circuit fabrication, suitable for work ranging from simple printed circuits to quasi-monolithic components on exotic materials. Because of the different requirements of high-frequency circuits (compared with hybrid or digital circuits), microwave-specific processes are under development.



Model no.	Frequency band (GHz)	Small-signal gain (dB) Min	Small-signal gain (dB) Typ	Gain flatness (over full bandwidth) (dB) Max	1-dB gain compression output power (dBm) Typ	Noise figure (dB) Typ	Voltage standing-wave ratio Max
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

Figure 3. A broad range of functions is commercially available as MMIC chips. The elements of an MMIC are monolithic-lumped and distributed resistors, inductors, capacitors, transmission lines, and active devices. Through-the-substrate connections (vias) and air-bridge crossovers are elements that allow high-frequency operation of transformers and transistors. One wide band design approach made practical by MMIC technology is the distributed transmission-line amplifier. Features of a typical MMIC chip (top) (GaAs FET, gallium arsenide field-effects transistor; MIM, metal-insulator-metal). Electrical specifications (bottom) (drain voltage, 5 V; drain current, 120 mA [typical, HMM-10610], 100 mA [typical, HMM-11810]). (Reproduced by permission, Harris Corporation.)

Packaging

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 4 shows a chip package used for MMIC mounting[9] and a transmit/receive module-integration scheme. Note the integration of microwave, optical, and digital technology in the same module. Standardization is not likely to occur beyond MMIC chip carriers;[10] therefore, packaging for high-frequency or high-speed operation in a systems environment will continue to be a challenge and a limiting factor for microwave systems.

The Laboratory 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 strength of APL's engineering experience. Current and future efforts will draw on this packaging expertise and experience in microwave system integration.

SYSTEMS CONSIDERATIONS

Over the past several years, independent research and development and program support have enhanced APL's ability to develop microwave electronics systems. We will use available microwave technology to accomplish our mission and will maintain effective levels of expertise. This purpose sets the scope and level of effort dedicated to APL's captive microwave technology. We intend to use commercial MMIC's, realize custom-distributed hybrid MIC's, and use commercially available gallium arsenide for custom APL-designed MMIC's. Figure 5 shows examples of these different modes of our direct participation in microwave technology.

Performance improvements are offered by MIMIC technology that would be otherwise unattainable, especially for radar.[11] Figure 6 shows an example of benefits to be realized with MIMIC technology; associated improvements in weight, volume, efficiency, and reliability also are seen.[12] Hybrid microwave circuits have been used for over 20 years, and their reliability and failure mechanisms are well-established. The availability of gallium ar-

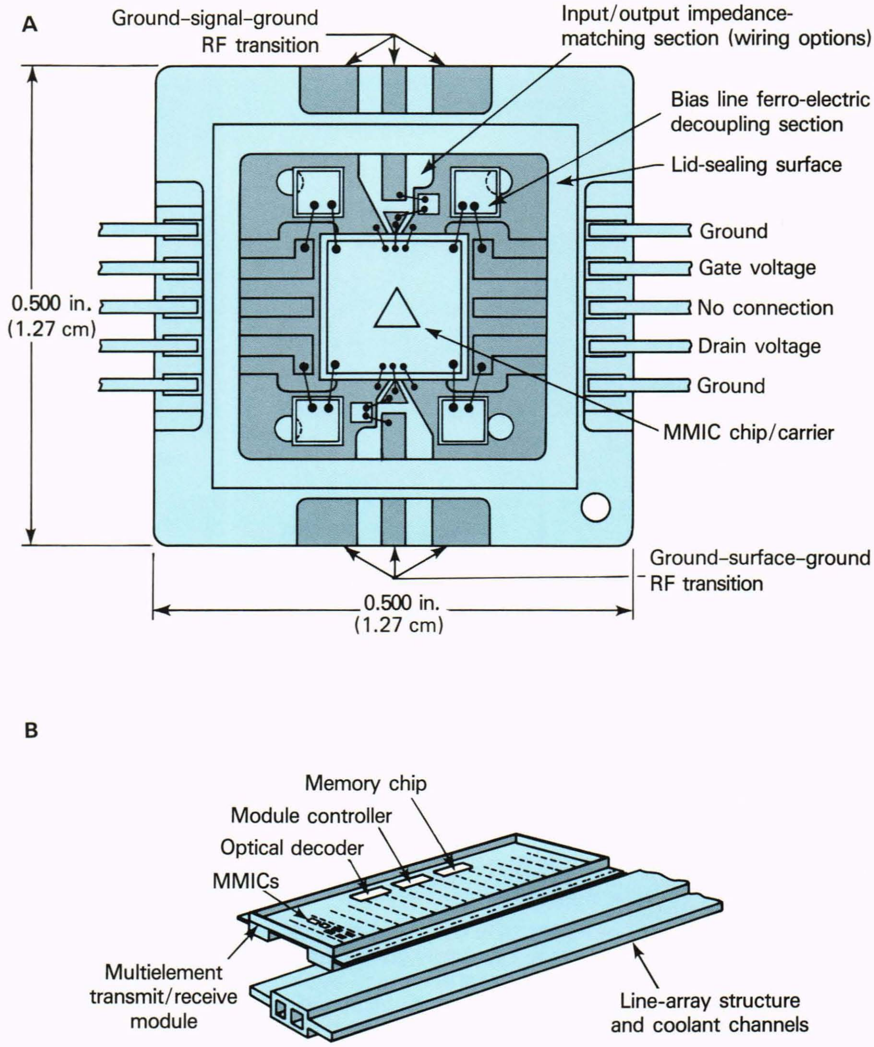


Figure 4. Perhaps the most challenging aspect of microwave design is packaging. Whether a single chip or a complex multi-technology module, a high degree of interaction and interdependence is necessary to integrate circuitry. **A**. A package assembly of an MMIC power amplifier. (Reprinted with permission of *Microwave J.*, from the November 1986 issue, © 1986 Horizon House-Microwave, Inc.) **B**. V-band brick module concept. (Reprinted with permission of *Microwave J.*, from the January 1987 issue, © 1987 Horizon House-Microwave, Inc.)

senide monolithic circuits has encouraged evaluations that show MMIC modules to be very reliable and rugged.[13] (Both microwave and high-speed digital circuits based on gallium arsenide are radiation-hardened to levels approaching 10^8 rad.[14])

The use of monolithic microwave circuits in large quantities is especially beneficial when consistent performance is necessary (for example, in active array radar having thousands of elements). The consistent and exacting processes of microelectronic fabrication, coupled with the distributed-lumped nature of MMIC's, result in excellent chip-to-chip reproducibility of performance (Fig. 7).[15]

One major consideration for future high-performance systems is cost. Historically, the major proportion of the cost of microwave modules has been associated with assembly, test, and adjustment of performance to meet specification tolerances, making some microwave systems economically impractical to build and maintain. One goal of the Department of Defense's MIMIC initiative is to achieve improved performance of MMIC transmit/receive modules at $250 per module.[16] This would make active array radar affordable and reduce operational costs because of improved reliability, efficiency, availability, and replacement ease.

Table 1 shows the available MMIC components and their performance levels.[17] Performance and yield of MMIC's have increased dramatically over the past 10 years; the range of products and number of commercial suppliers have also increased,[18] as have the attention and investment by the major systems houses. All are strong indicators of the importance and future impact of this technology.

SUMMARY

With the new MIMIC technology for advanced system development, APL strives to achieve the following:

1. Realize beneficial insertion of MIMIC technology.
2. Develop custom microwave components as appropriate and necessary.

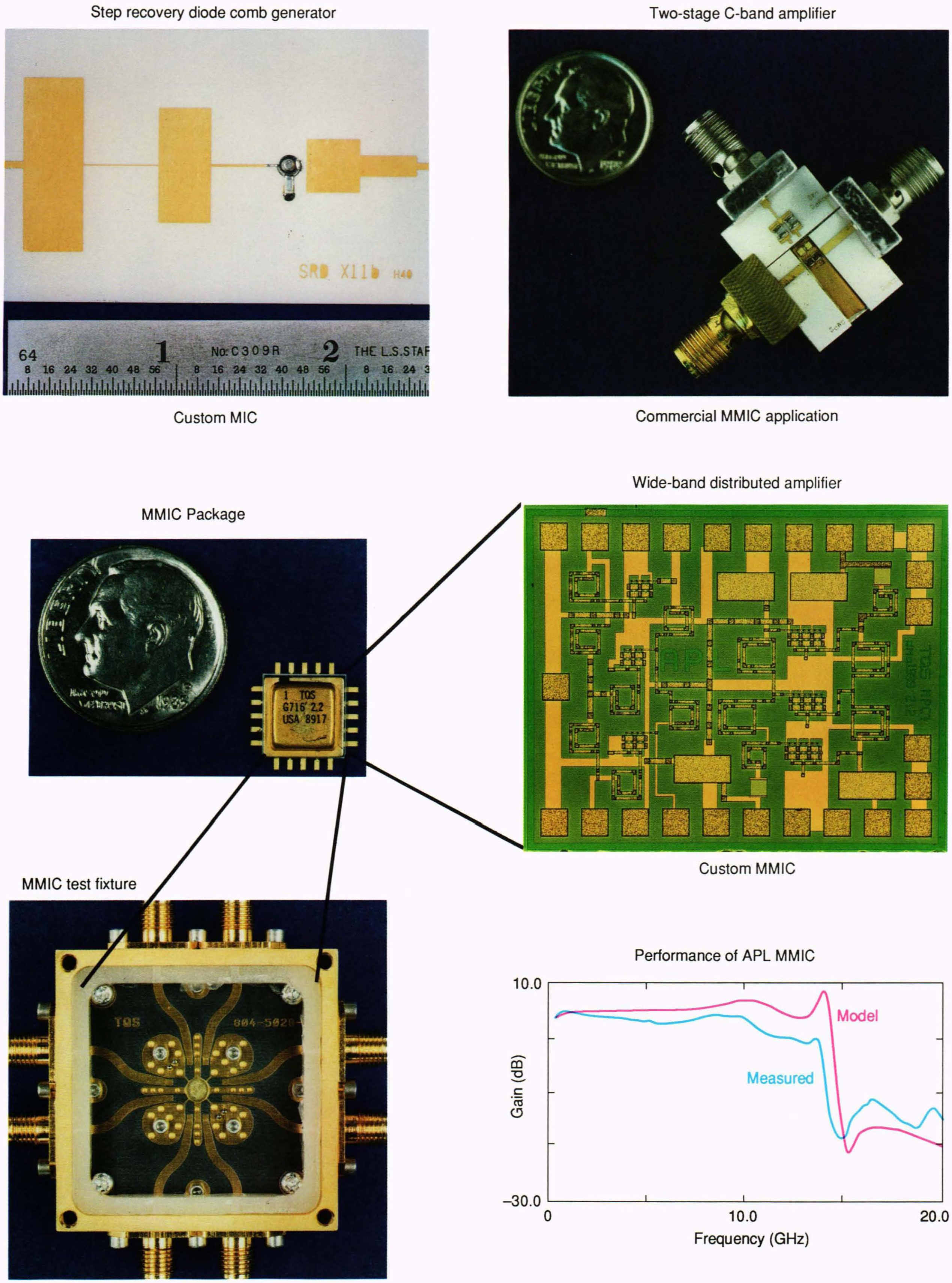


Figure 5. The Laboratory has established expertise in applying commercially available microwave technology and in developing custom microwave modules and circuits at MIC to MMIC levels of implementation.

Table 1. 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 (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)**	
Single-pole double-throw switch	DC–4	35	0.8	
	0–20	30	2.0	

3. Package and integrate commercially available MIMIC components.

4. Contribute to the advance of microwave technology.

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 important to the Laboratory's mission.

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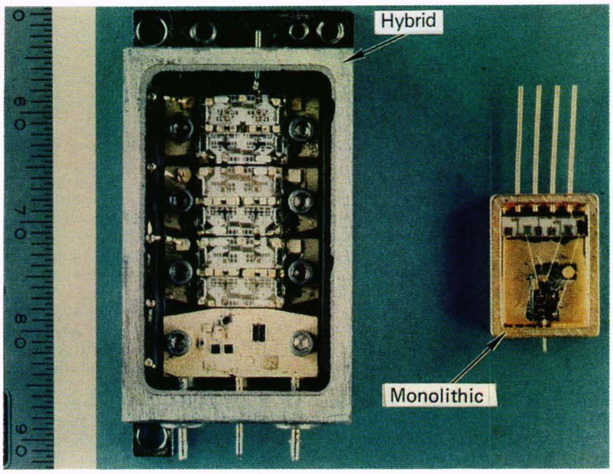

Comparison task	Hybrid module	Monolithic module
Number of gold wires	253	18
Number of piece parts	117	10
Assembly time (h)	16	1
Tune time (h)	10	No tuning required
RF parameters	Same as monolithic	Same as hybrid
Cost (1984)	$2500 (primarily labor)	$500 (primarily parts)

Figure 6. The Department of Defense MIMIC program will accelerate transition from hybrid MIC technology to the smaller and potentially less expensive monolithic technology. Shown is a hybrid voltage-controlled oscillator (above left) and its monolithic counterpart (above right), produced by Texas Instruments. Below is a comparison of the number of piece parts and labor content for each technique.[12] (Courtesy of *Aviation Week & Space Technology*, © McGraw-Hill, Inc., 1986 and 1987. All rights reserved.)

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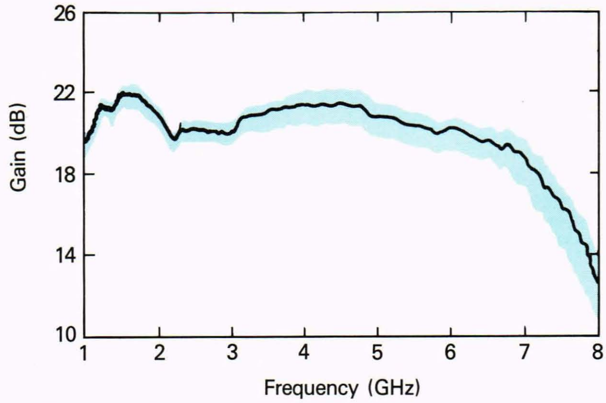

Figure 7. Consistent performance without tuning is a benefit of MMIC technology. Excellent performance is characteristic of this 2- to 6-GHz MMIC amplifier chip (yield, 29/30; drain voltage, 10 V; saturation drain current, 95 mA).

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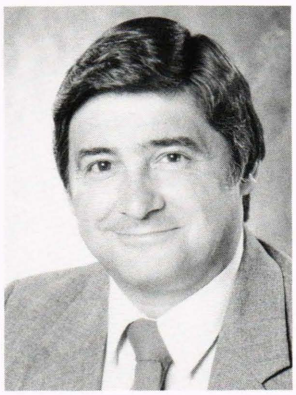

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MICROELECTRONICS: Further Reading