Microwave and Millimeter-Wave Integrated Circuits

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Invited Paper

***Abstract*—A historical sketch of microwave integrated circuits, monolithic microwave integrated circuits, and their application is presented in this paper.**

***Index Terms*—Applications, circuits, communication, electronic warfare, hybrid, integrated, microwave, monolithic, radar, systems.**

I. Introduction

MICROWAVE and millimeter-wave integrated circuits have experienced a tremendous growth over the last 50 years. Circuits have become smaller, highly integrated, lower cost, and have found extensive applications in radar, electronic warfare, and the commercial field. This historical review is divided into three sections: microwave integrated circuits (MICs), monolithic microwave integrated circuits (MMICs), and MIC and millimeter-wave integrated-circuit applications authored, respectively, by Bahl, Pucel, and Niehenke.

II. MICs

A. Introduction

We will divide the historical development of MICs into two categories: microwave printed circuits (MPCs) and hybrid MICs. The MPC technology is exclusively applied to a wide variety of microwave passive components including manifolds for power distribution, filters, couplers, baluns, and printed antennas. The hybrid MIC technologies are commonly used for fabricating active, passive, and integrated microwave functions. Basic building blocks for MICs are planar transmission lines such as stripline, microstrip, proximity-coupled stripline and microstrip, slotline, coplanar waveguide, and finline. Fig. 1 shows cross-sectional views of these lines. They are normally characterized by four basic parameters, i.e., characteristic impedance, phase velocity or effective dielectric constant, attenuation constant, and power-handling capability. The parameters are evaluated in terms of their cross-sectional dimensions, properties of the dielectric substrates, and the conductor materials used.

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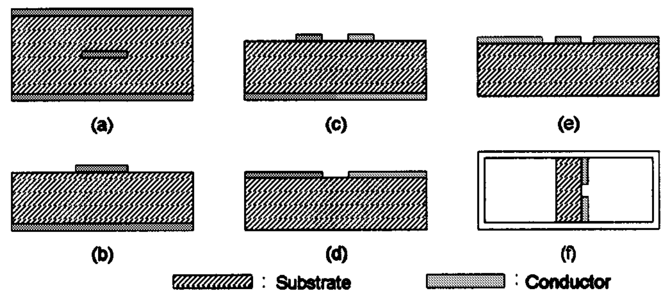

Fig. 1. Planar transmission lines for MICs. (a) Stripline. (b) Microstrip. (c) Coupled microstrip. (d) Slotline. (e) Coplanar waveguide. (f) Finline.

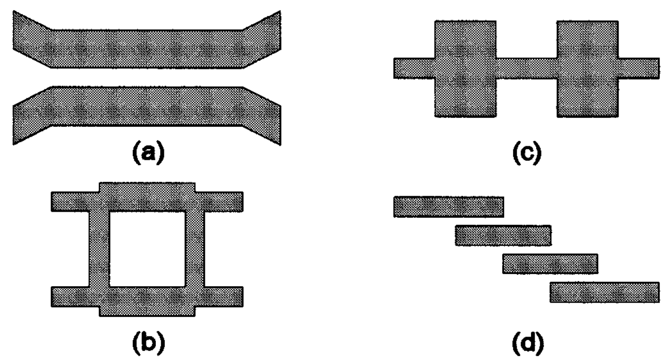

Fig. 2. Stripline components. (a) TEM-line proximity coupler. (b) Branch-line coupler. (c) Low-pass filter. (d) Bandpass filter.

B. MPCs

An excellent historical overview on MPCs is given in the literature [1]–[3]. The stripline is the basic building block for MPCs. The work on stripline was first reported in 1951 [4], and papers on theoretical design information including characteristic impedance, junction discontinuities, and coupled striplines were published during 1954–1956 [5]–[15]. The first stripline design manual *A Handbook of Tri-plate Microwave Components* was available in 1956 [16]. The first book, entitled *Stripline Circuit Design*, was published in 1974 [17]. Historical accounts of stripline directional couplers and filters are given by Cohn and Levy [18] and Levy and Cohn [19], respectively. Fig. 2 shows popular configurations of these components.

Numerous papers were published in the 1950s and 1960s describing the theory, design, fabrication, and measured data for the TEM-line edge-coupled directional couplers. Among stripline components, directional couplers are the most popular. These couplers can provide coupling in the 8–40-dB range.

Early work on these homogeneous couplers (single and multisections) can be found in [20]–[22]. These couplers are also known as backward-wave couplers because the coupled wave on the secondary line travels in the opposite direction compared with the incident wave on the primary line when excited with a microwave signal.

In several applications, a tight coupler such as a 3-dB coupler is required and is difficult to realize as the very tight spacings needed are limited by current photo-etch techniques. This problem was solved by using three-dielectric layer broadside coupled striplines [13] and offset broadside coupled striplines [14] and led to the development of tight stripline couplers. Narrow-band couplers can also be realized using the branch-line configuration.

Pioneering work in TEM stripline filters was performed in the 1950s, 1960s, and 1970s, and an extensive reference list is given by [19]. The most popular configurations are low–high impedance low-pass filters, and end-coupled, hairpin-line, parallel-coupled, interdigital, and combline bandpass filters. Stripline bandpass filters are widely used in microwave systems.

The early work on stripline served as the seeds for the successful growth of MPCs and the introduction of hybrid MICs. Over the past 30 years, MPC technology is steadily improving in the areas of new materials, high-resolution etching, milling circuit patterns, accurate modeling, automatic manufacturing, and cost effectiveness.

C. Hybrid MICs

Most high-volume microwave applications are either served by hybrid MICs or MMICs or both used together. Traditionally, in MICs, active and passive discrete components such as transistors, inductors, capacitors, and resistors are attached externally to an etched circuit on alumina (the most common microwave ceramic) or some soft substrate. The etched alumina or soft substrate may also have other distributed passive components such as filters, couplers, and combiners. In such circuits, sections of planar transmission lines are the basic building blocks.

The evaluation of hybrid MICs began in 1955 when the microstrip line was introduced [23]–[25]. During the 1960s and 1970s, numerous papers were published on microstrip-line characteristics including characteristic impedance, phase velocity and dispersion, losses, junction discontinuities, coupled microstrip lines, microstrip antennas, and other planar lines. Major evolutionary events included Wheeler's paper on microstrip line characteristics [26], accurate data for coupled lines using a variety of substrate materials [27], introduction of lumped elements for microwave circuits [28], microstrip compatible 3-dB Lange coupler [29], and several new MIC lines, e.g., slotline [30], coplanar waveguide [31], and finline for millimeter-wave applications [32]. In the 1970s, several special issues of this TRANSACTIONS appeared and four books on this subject were published [17], [33]–[35]. Fig. 3 shows microstrip configurations for a 3-dB Lange coupler and a two-way divider.

The growth of MIC technology took off after the development of techniques for printing microwave circuits on alumina substrates and the availability of GaAs FETs. By the mid-1970s, the technology had matured to the extent that microwave single-function circuits (including amplifiers, oscillators, switches, phase shifters, and mixers and multifunction circuits, e.g., transmitter and receiver modules for military and aerospace systems) were in large-scale production. During this period, MICs brought about a revolution in the microwave industry because so many microwave functions could be packaged into a small space and batch fabricated for large volume production. Several factors contributed to the success of MIC technology including the availability of good quality polished alumina substrates, the evolution of cost-effective processes for thin-film metallization and high-resolution photoetching, the development of alumina drilling and cutting tools, and the proliferation of good quality GaAs FETs. MIC technology has steadily improved in the areas of modeling, automatic manufacturing, multilayer production, and cost effectiveness. During the past 30 years, MIC technology has played a key role in the growth of microwave applications.

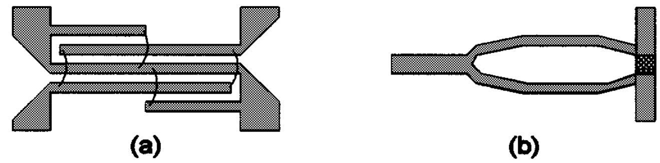

Fig. 3. (a) 3-dB Lange microstrip coupler. (b) Two-way Wilkinson microstrip divider.

The two most common MIC technologies are thin and thick film. Thin-film MICs are made via a sputter and etch process. Thin-film MICs are robust to standard manufacturing processes, exhibit very repeatable performance, and provide excellent performance into the millimeter spectrum. In the early 1980s, a thin-film technology variant was introduced and called the miniature hybrid MIC [36]. Miniature hybrid MIC technology is based on thin film in which the multilevel passive circuits are batch fabricated on the substrate and only solid-state devices are externally attached to these circuits. The advantages of this circuit technology are small size, lightweight, have excellent heat dissipation, and exhibit broad-band performance.

Thick-film MICs are manufactured using various inks pressed through patterned silk screens. Thick-film MICs are inexpensive and are generally limited to the microwave spectrum. Around the time of the introduction of the hybrid miniature MIC, a thick-film variant called low-temperature cofired ceramic (LTCC) was also introduced [37]. The LTCC manufacturing process is similar to the thick-film process, except it does not use a base substrate. Dielectric layers are in the form of unfired ceramic tape (or green tape) instead of paste. This technology also enables the printing of reliable capacitors and resistors.

LTCC technology due to its multilayer process offers several advantages over conventional thin-film, thick-film, and high-temperature cofired ceramic (HTCC) technologies. These advantages include a higher level of integration of components; e.g., capacitors, resistors, inductors, transmission lines, and bias lines, and greater design flexibility by enabling the realization of different types of transmission-line media such as microstrip, stripline, coplanar waveguide, and rectangular

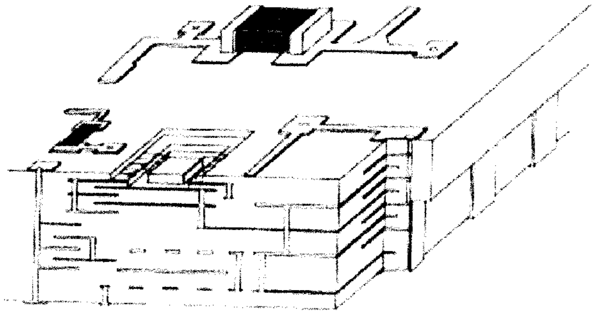

Fig. 4. 3-D view of the LTCC module.

TABLE I
SUMMARY OF TYPICAL MATERIALS AND PROCESSES USED TO FABRICATE MICS

Materials/ Processes	Microwave Printed Circuit	Thin Film	Thick film	Cofired Glass-Ceramic (LTCC)	Cofired Ceramic (HTCC)
Base substrates	PTFE glass fiber, PTFE ceramic, hydrocarbon ceramic, polyester glass	Al_2O_3,AlN, BeO, quartz, glass/ceramic	Al_2O_3, AlN, BeO	N/A	N/A
Conductors	Cu	Au, Al, Cu	Au, PdAu, PtAu, Ag, PdAg, PtAg, PtPdAg, Cu	Au, Ag, PdAgCu	W, Mo
Dielectrics	N/A	SiO_2, polyimide, benzocyclobutene (BCB)	Glass-ceramics, recrystallizing glasses	Glass-ceramic tape	Ceramic (Al_2O_3) tape
Resistors	N/A	NiCr, TaN	RuO_2 doped glass	RuO_2 doped glass	N/A
Processes	Photolithography, etch, collate sheets, bonding	Sequentially vacuum deposit, spin coat, and/or plate conductors, dielectrics, and resistors; photolithography; etch	Sequentially print, dry, and fire conductor, dielectric, and resistor pastes	Punch vias, print and dry conductors on tape, collate layers, laminate, cofire	Punch vias, print and dry conductors on tape, collate layers, laminate, cofire

coax. Passive components, matching networks, bias lines, and shielding of RF lines can be combined in LTCC technology using several available ceramic and metal layers. Finally, solid-state low-power devices are attached on the top surface to realize active or passive circuits. High-power devices can be integrated with LTCC by attaching the devices directly to the next level assembly chassis through holes fabricated in the LTCC MIC. Fig. 4 shows the three-dimensional (3-D) view of the LTCC module with embedded passive components and bias lines.

MIC technology is very diverse in its application of materials and processes to implement a broad array of functions. Table I summarizes these materials and processes. The circuit functions enabled by MIC technology include oscillators, doublers, amplifiers, mixers, receivers, transmitters, and transmit/receive modules. Examples of these circuits are found in Section IV.

The current trend in the MIC technology is to reduce the system cost by integrating as many components and circuit functions on a single substrate. Various MIC technology contenders emerging for such applications are thick film, LTCC, and multilayer system-on-a package (SOP) [38]–[40]. In general, thick film is suitable for low frequency, LTCC for high integration, and SOP for high-performance applications.

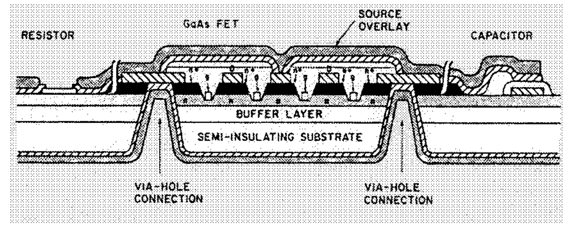

Fig. 5. Illustration of technologies used in MMICs.

III. MMICs

A. Introduction

The last half-century has witnessed the emergence of a plethora of scientific and engineering developments relevant to the growth of the microwave field. Many of these developments can trace their origin to earlier work in the two decades preceding this period. Much of this earlier work was related to government-sponsored activities pertaining to military applications, and to research conducted in several industrial and university laboratories [41]–[43].

This background as a base was supplemented by the emergence of the newly christened semiconductor technology at pre-mid-century and by the genesis of the digital computer a short time earlier. Building upon all of these developments, a significant new microwave field emerged. This field, i.e., MMICs, is the subject of this section.

Before proceeding, it is appropriate that we define what we mean by a MMIC. We have adopted the following definition [44]

> "A monolithic microwave integrated circuit is an active or passive microwave circuit formed *in situ* on a semiconductor substrate by a combination of deposition techniques including diffusion, evaporation, epitaxy, and other means."

Fig. 5 is a cross-sectional view of a hypothetical MMIC, which illustrates the technologies inferred in the above definition. It is essential to note that the *raison d'être* for this technology was to fulfill the following objectives:

1) cost reduction by batch processing;
2) higher reliability and improved reproducibility;
3) size and weight reduction;
4) circuit design flexibility and multifunction performance;
5) multioctave operation.

These objectives, to a lesser or greater degree, have been fulfilled over the past decades. In particular, the first four objectives were attained for the same reasons that digital computer circuits have achieved them. In that sense, MMIC technology, simply speaking, is an extension of existing computer chip technology to the microwave bands. The fifth objective follows from the compact circuit configurations possible, which minimize bandwidth-limiting parasitic capacitances and inductances, and from the confinement of electromagnetic fields within the semiconductor substrate. An in-depth presentation of these topics can be found in several references, i.e., [45] and [46].

B. MMICs—A Brief History

We proceed with our historical sketch by tracing the evolution of the MMIC field from its inception in the 1960s to the present time.

We have chosen, for pedagogical reasons, to divide the historical development of MMICs into several logical periods. Because of editorially imposed space limitations of this paper, coupled with the abundance of contributions to this field over the last four decades, we shall studiously avoid in the text, citing names of individual contributors to the field whenever possible, lest we slight many of those who would unavoidably remain unmentioned. In this way, we shall minimize any bias that may find its way into this paper. However, to compensate for this, we shall refer to a number of comprehensive historical references where such information may be obtained. In essence, then, only milestone results will be stated in order that the nonspecialist may be given a general view of the field, rather than its details, which can be found elsewhere [44], [45], [47].

Genesis (1950–1964): The concept of microwave circuit integration did not begin with MMICs. Its origin can be traced to two earlier developments discussed in Section II. The first, the printed circuit approach, based on low dielectric-constant insulating sheets upon which interconnection patterns were etched onto a metallic coating, were confined, essentially to passive circuitry. Since the insulating substrate, grounded on its bottom side, served as a transmission-line medium, some wavelength reduction was achieved. An excellent historical presentation on this approach is given in the literature [7].

The printed circuit approach provided little size reduction and rather limited integration because of the dearth of integrable active elements. These problems were addressed some ten years later when two-port solid-state active elements became available and alternative higher dielectric-constant substrates, such as sapphire and alumina, were employed [28]. Passive components in planar form, such as thin-film capacitors and inductors, added another degree of integration. This approach, known as the hybrid integrated circuit, is still popular to this day and has attained a high level of sophistication, as described in Section II.

Incubation (1965–1979): The origin of the MMIC approach can be traced back to 1964 to a government-funded program based on silicon technology, which had as its objective a transmit–receive (TR) module for an aircraft phased-array antenna [47], [48]. Unfortunately, the results were disappointing because of the inability of semiinsulating silicon to maintain its insulating properties through the high-temperature diffusion processes required for the formation of active components such as bipolar junction transistors (BJTs). Thus, very lossy substrates resulted, which were unacceptable for microwave circuitry. Nevertheless, the program established that the basic technology of circuit integration on a semiconductor chip developed for digital circuitry [49] could be applied to analog microwave circuitry. An excellent description of this program is given in [47].

The problems associated with silicon substrates put a halt to MMIC efforts utilizing this material. However, a few years later, research based on the 3–5 compound gallium arsenide (GaAs) showed promise that the lossy substrate problem could be resolved. This material, in its semiinsulating state, was, for all practical purposes, a good insulator and could be used as the base material for MMICs. However, no GaAs-based two-port active device existed at the time.

The first GaAs MMIC was demonstrated in 1968 with a 94-GHz receiver front-end utilizing high-frequency Gunn and Schottky barrier diodes [50]. It took another 8–10 years for the next development in GaAs MMICs to appear, in this case, an X-band amplifier [51]–[53] employing metal Schottky-gate field-effect transistors (MESFETs) [54].

The arrival of the MESFETs during this transition period to GaAs MMICs was perfectly timed since it was the first two-port solid-state device developed to overcome the frequency limitations of the silicon BJT. Thus, this planar GaAs amplifying device operable in the microwave band would open the door to a wide variety of active circuits in MMIC format. Indeed, as it would turn out later, the fortuitous arrival and concurrent development of the GaAs MESFET would be the major factor in the rapid growth of the MMIC effort in the years to follow.

The quality of GaAs material, however, left much to be desired. Intensive effort was necessary to bring it up to the standards of silicon technology. The early feasibility demonstrations of GaAs MMICs provided the necessary incentive for a period of intense materials research and development to improve the quality of GaAs as a device material. This research took place at laboratories worldwide during the coming years.

Rapid Growth (1980–1986): The dearth of high-quality GaAs did little to stem the effort in MMIC technology. Indeed, the next six years witnessed a worldwide scramble to demonstrate GaAs MMICs in a variety of circuit configurations over the entire frequency band up to 35 GHz. Circuits ranging from direct-coupled amplifiers to low-noise and power amplifiers, signal generators, oscillators and mixers, direct broadcast satellite (DBS) receivers, altimeters, and others were demonstrated [45]. These results served as proof of concept. There was no attempt to achieve production ready products. This latter objective had to await improvement and control of the GaAs material and processing technology and also the development of a design methodology.

The design of this wide-ranging variety of circuits exhibited a sufficient degree of complexity that could no longer be met by simple Smith chart manipulations. A more sophisticated approach, employing computer-aided design (CAD) techniques, was necessary because “tweaking” of the circuit, once fabricated, was out of the question. Some software intended for microwave design was available, but needed upgrading in the areas of device modeling and in synthesis and optimization features. The need for these improvements soon became evident to designers during this period and vendors began to respond. This was just the beginning. Other papers in this issue describe the intensive effort that ensued, and continues to this day, in the evolution of ever more powerful microwave CAD software to handle the sophisticated designs of contemporary MMICs. It can be said that without microwave CAD software, the MMIC industry, as we know it, could not have developed as rapidly as it did, if it would have developed at all.

A measure of the progress in MMIC technology during this brief period can be gauged by the increase in circuit

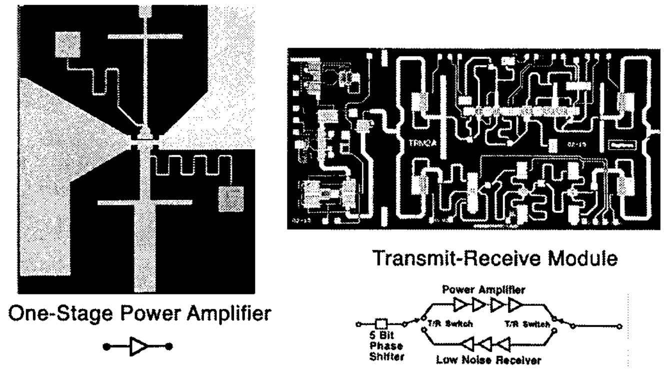

Fig. 6. Illustration of increase in MMIC complexity during the 1978–1986 period. Both chips have approximately the same area.

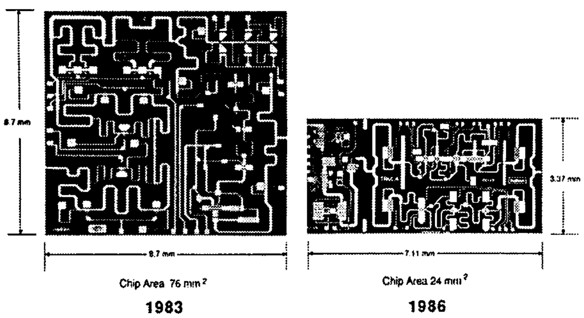

Fig. 7. Illustration of chip size reduction in MMICs from 1983 to 1986.

complexity and in the reduction in circuit size achieved. Fig. 6 presents a photograph of a one-stage X-band power amplifier demonstrated in 1978. Eight years later, on a GaAs chip of approximately the same area, an entire TR module was fabricated consisting of two switches, a three-stage receiver chain, and a four-stage transmitter chain. Fig. 7 illustrates, for the same TR module, the 50% reduction in circuit area achieved in a mere three-year interval during this period.

A significant portion of the MMIC effort in the U.S. during this era was supported in part by a series of Department of Defense (DoD) contracts. This continued interest on the part of the DoD is not surprising since it was a natural follow-up in its support of integrated circuit development that began in the 1960s.

MIMIC Era (1987–1995): The DoD, in its review of the preceding period, identified the potential applications of the MMIC technology to solution of military objectives. The TR modules described earlier are one example of such applications funded under DoD contracts.

It was also concluded that the MMIC technology could not be advanced through an assortment of uncoordinated and, often, overlapping programs, as was true for the preceding period. What became evident in this review was that a focused effort would be required to solve the myriad problems in materials and device technology and production and in the limitations of design methodology and CAD software. Major investments well beyond the scope of individual companies would be necessary.

The DoD realized that a structured program was needed to achieve economy of scale in the research and development areas, as well as in the production process, not unlike what its very high-speed integrated circuit (VHSIC) program did

TABLE II
MIMIC PHASE I CONTRACTORS

Prime	Team Members
Hughes/GE	E-Systems, AT&T, M/A Com, Harris Microwave, Eesof, Cascade
ITT/Martin Marietta	Alpha, Harris Systems, Pacific Monolithics, Watkins-Johnson
Raytheon/TI	Aerojet, Airtron, Compact, Consilium, General Dynamics, Magnavox, Norden, Teledyne
TRW	Honeywell, Hittite, General Dynamics

for digital technology. Thus, in late 1986, the Microwave and Millimeter-Wave Integrated Circuit (MIMIC) program was launched. It was to dominate the MMIC field for much of the next decade [55], [56].

The MIMIC approach brought together the system houses, foundries, software firms specializing in microwave CAD development and circuit simulation, and laboratories skilled in device physics and modeling. Whereas, in the previous period, the DoD was concerned primarily with performance goals, the MIMIC program made manufacturability goals its thrust. During the period of this program, major advances were made across the board in all phases of MMIC technology and design.

The MIMIC program, a tri-service effort, sponsored by the Defense Advanced Research Projects Agency (DARPA) was organized in four phases, three of which ran concurrently and was assigned a budget of $536 million. The first phase, i.e., Phase 0, was a one-year program definition phase beginning in January 1987. This was followed by two consecutive three-year hardware development phases. The first of these Phase I, was performed by three prime contractors. Each prime contractor was supported by a group of subcontractor team members, as indicated in Table II. The total contract award value was $225.6 million.

The second prime contractor did not participate in Phase II, which had a total award value of $228.1 million. The subcontractor mix was also somewhat different. Note the extensive scope of industrial involvement. Parallel efforts were also funded to provide the necessary technology support in areas such as lithographic and test equipment development, CAD, and packaging.

The principal objective of the MIMIC program was to make reliable microwave and millimeter-wave monolithic circuits available for military use at affordable cost. To achieve this goal, a number of supporting tasks were carried out including: 1) extension of research and development results already achieved in the laboratory; 2) establishment of an adequate supply of wafers possessing the needed electrical properties; 3) substantial improvement of CAD models and software; 4) successful integration of results of the design process with the manufacturing process; 5) selection of chips and chip design approaches for a wide range of military applications; 6) reliability assurance of MMICs; 7) provision of appropriate package designs; 8) extension of automated test procedures; and 9) establishment of pilot production facilities for high-yield low-cost MMICs, which would provide the framework for high-volume production.

TABLE III
MILESTONES IN MMIC DEVELOPMENT

DATE	FUNCTION	FREQUENCY BAND	SUBSTRATE			DEVICE BASIS		
			Si	GaAs	InP	FET	HEMT	HBT
1965	PIN switch	X	•					
1968	Mixer/oscillator	V		•				
1974	Low-power amplifier	X		•		•		
1978-79	power amplifier	X		•		•		
	Low-noise amplifier	K		•		•		
1980	switches	X		•		•		
1981	traveling-wave amplifier	X		•		•		
	T/R module (multi-chip)	X		•		•		
1982	phase shifter	X		•		•		
1984	T/R module (single chip)	X		•		•		
	DBS receiver	X		•		•		
1986	Power amplifier	Q		•		•		
1987	Multi-octave switch	DC - Q		•		•		
1988	Low-noise amplifier	V		•			•	
1989	Power amplifier	X		•				•
	Power amplifiers	X, I-J		•			•	
1990	Multi-octave TWA	5-100 GHz			•		•	
1992	LNA/power amplifier	W					•	
1994	Power amplifiers	I-J		•				•
2000	Low-noise receiver	183 GHz			•		•	

The applications addressed by the MIMIC program were broadly based across four system areas, namely: 1) smart weapons; 2) electronic warfare; 3) radar; and 4) communications. The technology base developed under the MIMIC program brought microwave monolithic circuits from experimental proof-of-concept demonstrations to the status of high-yield low-cost products produced on highly automated fabrication lines.

Maturity (1996–): The MMIC field had reached a certain level of maturity by this time. A spectrum of problems addressed by the MIMIC program and by parallel, though smaller, efforts in the U.K. and Asia had been solved, at least in the technology area. For example, MMICs based on silicon and indium–phosphide (InP) substrates joined GaAs. In addition, FETs had been supplemented by high electron-mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs).

Table III is illustrative of some of the key milestones in MMIC circuit development. Note the gradual increase in the frequency band of operation and the eventual inclusion of devices other than the FET. The list is by no means inclusive or exhaustive.

Aggressive effort are in progress to develop multilayer packaging techniques and still more sophisticated CAD device models and design software based on such concepts as electromagnetic simulation and the neural-network approach. Military applications of MMICs continue, but are now augmented by a proliferation of commercial applications including personal communications, DBS systems, satellite-to-satellite communications, and intelligent vehicle highway systems. These and other applications, all spinoffs from the MIMIC program, will be covered in Section IV.

C. Summary

The technology of MMICs is well established. Although initially based on GaAs, it has now been expanded to include other materials such as InP. Ironically, it also now encompasses silicon, though currently at the low end of the microwave band where the substrate is not utilized as a propagation medium. The initial active elements, namely, Schottky barrier diodes and MESFETs, have been supplemented by HEMTs, HBTs, and recently, MOSFETs.

Contemporary CAD software is very sophisticated both in the improvement of its models and also in its inclusion of an extensive configuration of circuit topologies.

The MMIC field is now secure as a major component of the microwave industry. It has delivered on its early promise to be a viable alternative to hybrid integrated circuits. The MMICs advantages of small size, low cost and weight, as well as it applicability at extremely high frequencies and over multioctave bands has been realized.

The MMIC field has a very bright future indeed, especially in communications, both wired and wireless, with its emphasis on bandwidth. It continues, of course, to serve as an important technology in military applications. MMIC design concepts also will play an important role in future high-speed computer circuitry.

IV. MICROWAVE AND MILLIMETER-WAVE INTEGRATED CIRCUITS APPLICATIONS

A. Introduction

The development of integrated microwave and monolithic circuits is linked to the progress of MPCs, hybrid microwave

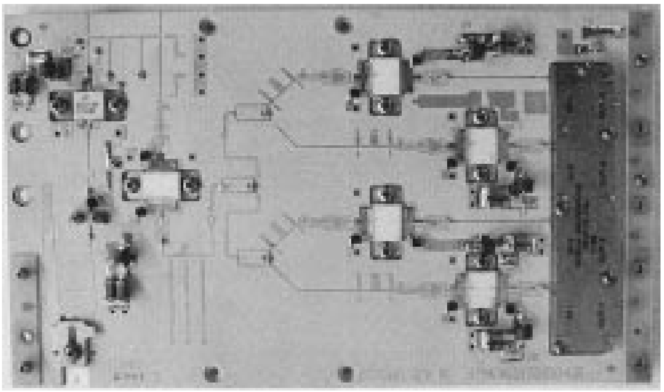

Fig. 8. ASR-12 airport traffic control radar transmitter module uses four SiGe BJTs for 700-W output power over 2.7–2.9 GHz (courtesy of the Northrop Grumman Corporation).

circuits, and MMICs, as described in Sections II and III. The advance in solid-state device technology has profoundly influenced the applications of MIMICs. This section will cover the historical applications for the circuits, including radar, electronic warfare countermeasures (ECMs), and communications.

B. Radar Applications

Radar [57] is used in many commercial and military applications. Military applications include target location, mapping, and surveillance. Commercial applications include weather mapping, motion detectors, speed measurement (radar guns), collision-avoidance automotive radar, and airport radars. The early radar transmitters used the magnetron, developed for World War II. Later, tube-type amplifier-type transmitters were introduced for added stability and capability like the crossed-field tube, the klystron power amplifier (KPA), and the traveling-wave tube (TWT). Solid-state transmitters were first introduced into radar applications with the availability of the high-power silicon BJT in the 1970s.

Radars are used routinely in airport air traffic control as a federal safety requirement with the exploding level of air traffic. An example of such radar is the ASR-12 Solid State Radar developed in the 1990s by the Northrop Grumman Corporation, and currently in use in six countries. Fig. 8 illustrates the transmitter air-cooled microstrip power module, which combines four silicon germanium (SiGe) power transistors for 700-W peak power over the 2.7–2.9-GHz radar band. The use of SiGe developed in the 1990s allows higher frequency operation with improved gain and efficiency compared to the Si BJTs. The next higher assembly combines four modules to provide a 2500-W power level, complete with energy storage and control logic for pulse-shaped electromagnetic interference (EMI) control. The 2500-W plug-in panels are combined in parallel to develop a 20-kW transmitter. The fully solid-state transmitter achieves vastly higher availability than older vacuum tube designs. The improvement is partly due to the inherent reliability of solid-state devices, and also because 99% of the transmitter components and assemblies can be repaired or replaced online, without disrupting radar operation.

Airborne radars also are used to detect wind shear. Fig. 9 illustrates a Northrop Grumman MODAR solid-state 75-W X-band transmitter module developed in the 1990s. This module uses GaAs field-effect transistors (FETs) serially combined using a stripline soft board assembly. FET MMICs are used with external matching for low loss. The stripline serial combiner provides an efficient and compact low-loss combining technique for a large number of elements.

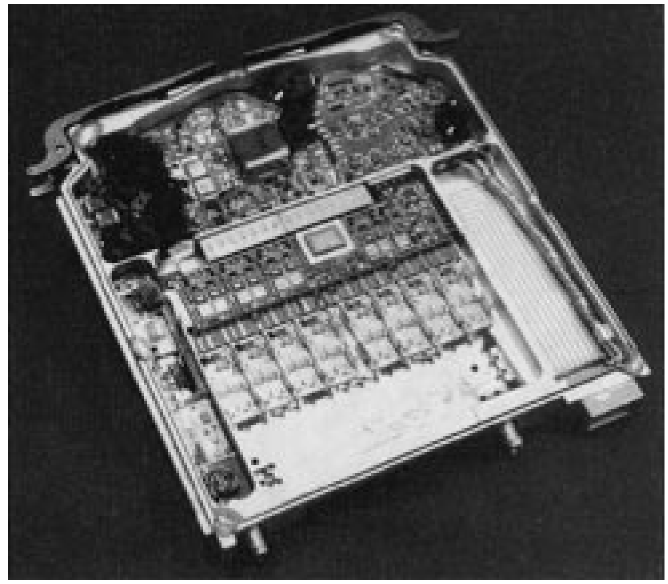

Fig. 9. Modar X-band airborne radar transmitter module uses MMIC FETs serially combined to develop 75 W (courtesy of the Northrop Grumman Corporation).

During the 1980s and 1990s, HEMTs, and later the pseudomorphic high electron-mobility transistors (pHEMTs) were developed providing very low noise figures for receiver applications and very efficient power amplifiers for transmitter applications. The GaAs pHEMT has been used to frequencies in the 100-GHz range. In addition, the power capability of the silicon BJT was extended in frequency from 3 GHz to around 20 GHz with the introduction of the GaAs HBT.

Radars are also used in automobiles for collision avoidance. A frequency of 77 GHz has been adapted for this application. Such a transceiver module is shown in Fig. 10 [58]. Developed by M/A-COM in the 1990s, it uses a glass-on-silicon (GMIC) substrate. This media contains low-loss microstrip transmission lines, biasing circuits (spiral inductors, capacitors, resistors), air bridges, gold ground planes, heat removal and ground areas for the MMICs, and can accept flip-chip devices. The monolithic nature of this circuit is inherently low cost and allows batch processing for repeatability. The transceiver consists of a microstrip 19-GHz dielectric-resonator oscillator (DRO), amplifiers, multipliers, mixers, and p-i-n MMIC switches with a waveguide output.

Radars are used for missile applications and use millimeter waves due to packaging constraints and resolution characteristics. At these frequencies, the use of MMICs is required in order to obtain the performance, low cost, and packaging densities (small and compact size). Fig. 11 [59] illustrates a W-band transceiver developed by the Northrop Grumman Corporation in the 1990s. The transceiver has a 1-in diameter, is 0.25-in thick, and contains a four-element circularly polarized patch antenna,

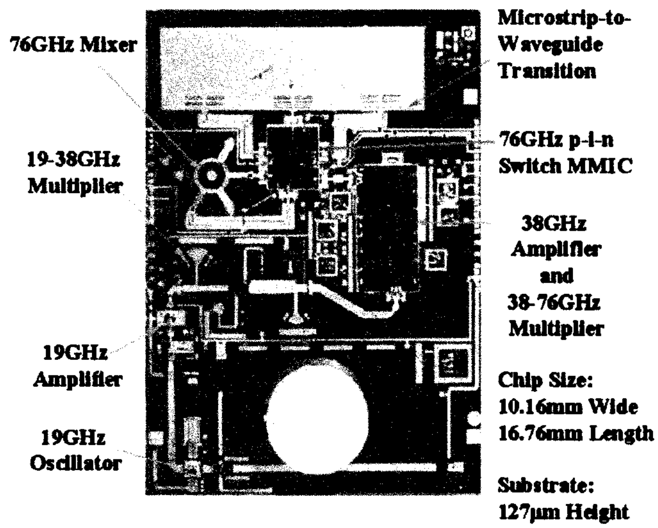

Fig. 10. Complete 76–77-GHz transceiver module fabricated on a GMIC substrate (courtesy of M/A-COM).

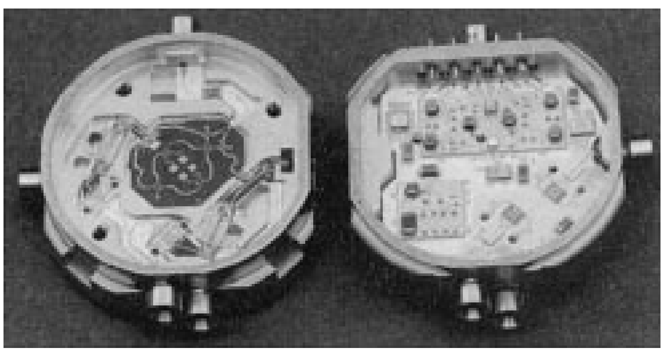

Fig. 11. W-band missile radar two-sided transceiver is complete with four circularly polarized patch antennas, two-axis monopulse comparator, MMIC T/R switch, and MMIC receiver channels (courtesy of the Northrop Grumman Corporation).

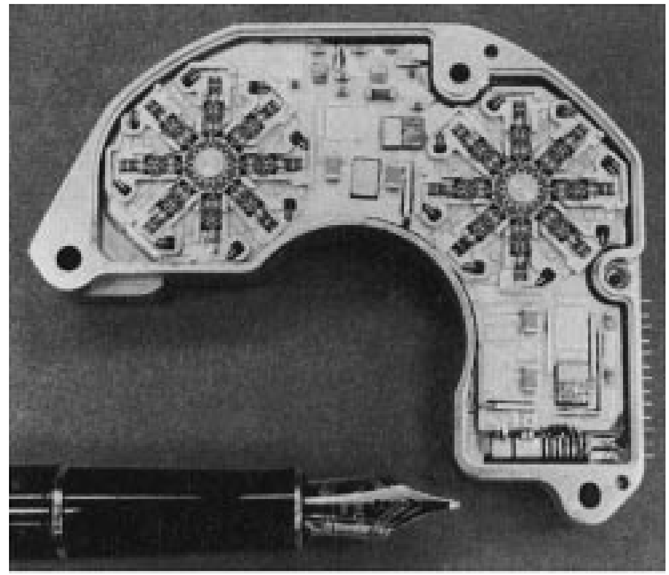

Fig. 12. W-band missile radar 1-W transmitter combiner side (courtesy of the Northrop Grumman Corporation).

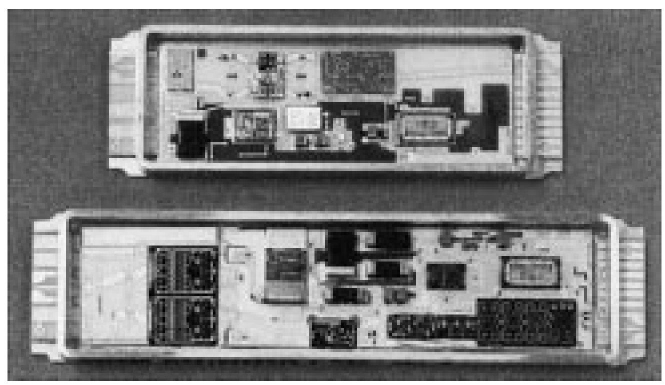

Fig. 13. X-band transmitter (bottom) and receive (top) module (courtesy of the Northrop Grumman Corporation).

a monopulse comparator, two all MMIC receiver channels, one for the sum and a switchable difference in either azimuth or elevation. Two MMIC p-i-n diode switches provide the TR and the difference switching. Each MMIC receiver channel has a balanced low-noise amplifier, an image enhanced/reject subharmonic mixer, and an IF amplifier. The double-sided transceiver uses an optimal arrangement of quartz, alumina, and LTCC as its substrate medium. GaAs pHEMTs are used for all the MMIC amplifiers and mixers. The development and insertion of an InP MMIC LNA was found to improve the overall noise figure.

Fig. 12 [60] illustrates a W-band miniature 1-W 2.4-oz 1.3-in^3 transmitter developed in the 1990s by the Northrop Grumman Corporation for missile applications. Integrated circuit media in this assembly consist of microstrip, stripline, radial line, and waveguide. The transmitter input Ku-band input signal is doubled, amplified, and split into two eight-way outputs. Each eight-way output is amplified, tripled, amplified, and combined in a radial combiner. Each of the two radially combined outputs is then combined in a waveguide magic tee. Quartz-type LTCC is used as the substrate integrated medium to route the dc and control signals to the active MMIC circuits. GaAs pHEMTs are used for all the MMICs.

The radar circuitry described above all use a single transmitter and single-channel or multichannel receivers. The power can be directed to and received from an antenna that can be mechanically or electrically scanned. Later developments of radar systems use many solid-state TR modules [61], each module having its own transmitter, receiver, phase/amplitude control, and antenna, comprising a solid-state phased-array system. Examples of operational phased-array systems include AN/SPY-1 (Aegis), PATRIOT, Electronically Agile Radar (EAR), Airborne Warning and Control System (AWACS), Multifunction Electronically Scanned Adaptive Radar (MESAR), AN/TPS-70, AN/TPQ-37, PAVE PAWS, COBRA DANE, COBRA JUDY, F22, and Theatre High Altitude Air Defense (THAAD—formerly ground-based radar). Fig. 13 illustrates a prototype transmit (bottom) and receive (top) module used in an F22 airborne active aperture radar. All active circuits are in MMIC form for low cost.

C. ECM Applications

ECM is used to render radars ineffective. Examples of passive ECM are chaff, decoys, or other reflectors that require

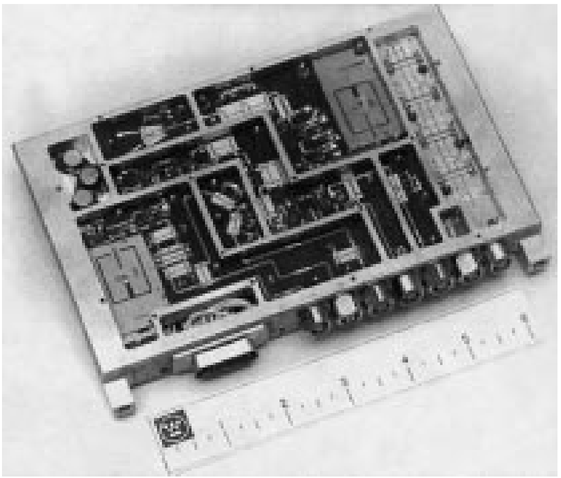

Fig. 14. Wide-band ECM multifunction module (courtesy of the Northrop Grumman Corporation).

no prime power. ECM uses both jamming and deception techniques. The deception ECM is the intentional and deliberate transmission or retransmission of the amplitude, frequency, phase, or otherwise intermittent or continuous-wave (CW) signals for the intention of misleading the interpretation or use of information by electronic systems [62]. Fig. 14 [63] illustrates an example of a wide-band ECM multifunction module developed in the 1980s that used soft and hard substrate material employing microstrip, slot line, and coplanar waveguide. Integrated functions include coupling, limiting, up-conversion, down-conversion, broad-band amplification, amplitude modulation, switching, gating, and stable frequency generation. Various frequencies are used in the circuit functions and include S-, C-, X-, and Ku-bands. ECM systems developed in the 1990s made extensive use of commercially available wide-band MMICs.

D. Communications Applications

MICs and millimeter-wave circuits find extensive use commercial applications. These include two-way radios, pagers, cellular telephones, line-of-sight communication links, satellite communications, wireless local area networks (WLANs), Bluetooth, local multipoint distribution systems (LMDS), and navigation—global positioning system (GPS).

The two-way radio provided a convenient way to communicate and, in 1941, Motorola introduced the first commercial line of FM two-way radio systems and equipment. The FM technology provided a significant improvement in range and quieter operation than AM technology. In 1955, Motorola introduced a new radio communications product—a small receiver called a Handie-Talkie radio pocket pager—that selectively delivered a radio message to a particular individual. Pagers soon began to replace public announcement systems in hospitals and factories. In 1962, Motorola introduced the fully transistorized Handie-Talkie HT200 portable two-way radio and, in 1983, Motorola's first DynaTAC analog cellular system, which began commercial operation in 1985.

In the 1990s, digital technology was introduced to the cellular radio (second generation), which provided more radio channels for the same bandwidth with improved voice quality [64]. Two operating bands are used around 800–1000 and 1750–1900 MHz. Many phones operate at both frequency bands in analog, as well as digital modes. The digital modes include global system for mobile communication (GSM), time-division multiple access (TDMA), and CDMA. The third-generation cellular telephones under development will provide higher data rates with the Internet access and built-in Bluetooth module, which allows wireless connection to a compatible computer without cables. RF circuits are highly integrated and work on both frequency bands. The transistors used for power amplifiers for nonconstant envelope modes require linear operation. The GaAs HBT and pHEMT were found to work well for linear mobile handheld operation for the 1-W levels and the silicon laterally diffused metal oxide semiconductor (LDMOS) is typically used for the base-station for higher linear power levels.

Line-of-sight tower communication links have been used since the 1940s to communicate at microwave frequencies for telephone conversations, video, and data. Author C. Clarke first suggested the satellite communications in 1945. Satellite communications [65] over the last 30 years has experienced an explosive growth due to the rapid increase in global demand for voice, video, and data traffic. Fixed satellite services (FSSs) like the INTELSAT provide communication between the satellites and a large number of relatively large Earth stations. Terrestrial landlines connect to these earth stations. S-, C-, and Ku-bands, as well as 30/20 GHz are used. INTELSAT I (early bird) was launched in 1965 and provided 240 voice channels, and the INTELSAT VI series of satellites launched from 1989 onward provided a carrying capacity of 33 000 telephone circuits. With digital compression and multiplexing, 120 000 two-way telephone channels and three television channels are supported.

The DBS services use relatively high-power satellites to distribute television programs to subscriber homes or to community antennas where the signal is distributed to homes by cable. The original system was at the C-band and required a large dish, while the Ku-band system very popular today requires a very small dish. The Mobile Satellite Services (MSSs) transmits between a large fixed Earth station and a number of smaller earth terminals fitted on vehicles, ships, boats, and aircraft. The IMMARSAT 2 series of satellites started launching in 1989 and provides 150 simultaneous transmissions. The IMMARSAT 3 provides a tenfold improvement to that system. These satellite systems operate at high Earth geo-static positions. Other satellite systems operate in low Earth orbit (LEO) between 600 and 800 km (Iridium, Ellipso, Globalstar) or at intermediate (10 000 km) altitude in circular orbit (ICO). These systems provide communication between the satellite and handheld units. In all of these satellite systems, reliable operation is paramount. Many reliable MMIC and transponder designs have been reported [66], [67] and qualified for the space environment using transistors, microwave passive circuits, and MMICs [68].

WLANs developed in the 1990s has applications for high data-rate connections in homes, schools, and office buildings. The IEEE 802.11 Standard is primarily used with a frequency around 2400 MHz with 20-dBm RF power and 50-m range.

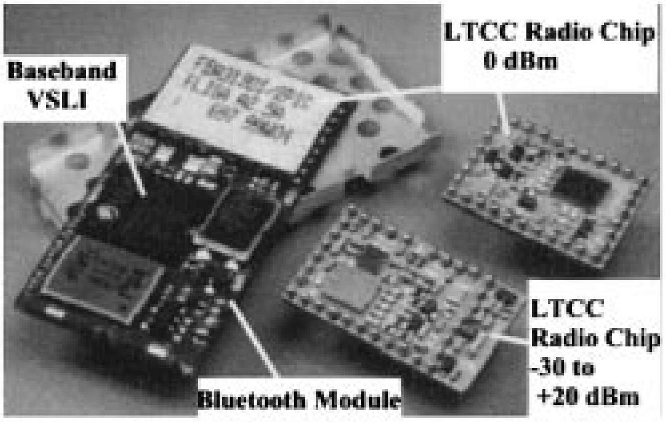

Fig. 15. Bluetooth module includes LTCC Bluetooth 0-dBm radio chip and baseband very large-scale integration. Also shown is a −30- to +20-dBm higher power LTCC radio chip for extended range (courtesy of Ericsson).

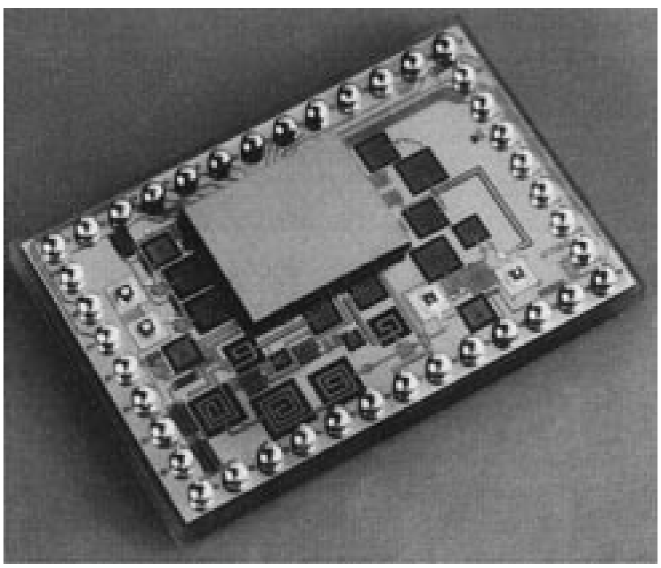

Fig. 16. Bluetooth radio module uses thin-film integrated passives and a flip-chip active integrated circuit (courtesy of the Intarsia Corporation).

Bluetooth was developed in the early 2000s as a low-cost wireless means of interconnecting computers with peripheral devices and other applications. Bluetooth also operates on the 2400-MHz band with 0-dBm power and 1–10-m range. With additional amplification to 20 dBm, it can have a range of 50 m. Fig. 15 illustrates a complete Bluetooth radio module manufactured by Ericsson that used LTCC and Fig. 16 shows a module developed by Intarsia that uses thin-film integrated passives and a flip-chip active integrated circuit [69].

LMDS is used to provide a terrestrial multimedia delivery system, to send and receive two-way broad-band transmission to and from cells about 3–6 mi in diameter. The bandwidth of 1300 MHz in the 28–31-GHz band was allocated in 1998 by the FCC for this application. The LMDS provides high-speed Internet access, television broadcasts, video conferencing, video, audio, and telephony. Hybrid pHEMT [70] and MMIC pHEMT [71] power amplifiers have been developed with 2 W of power in this band. 3-D MMIC up–down-conversion chip sets [72] have also been reported for this application.

The GPS is very popular as a navigation aide and is available in handheld units. Integrated silicon BJT MMIC chips [73], [74] have been developed to down convert and process the 1.575-GHz GPS signal.

V. Conclusions

The last 50 years have been witness to the development and growth of an entirely new and exciting microwave field. The initial impetus for this development was a response to the needs of new military systems under development. This field is still expanding at a rapid rate, though now promoted by a variety of commercial applications including the new demands of the Information Age with its emphasis on high-speed and large-bandwidth requirements.

VI. Future Trends

In the future, the use of multilevel interconnects to realize vertically integrated RF, microwave, and millimeter-wave circuitry is expected to become a routine feature. Future development will focus on higher level of integration using optimum hybrid technologies on a single substrate. Hybrid circuits will become more like monolithic circuits. MMICs will combine more circuit functions for that one-chip solution. Silicon CMOS integrated circuits for low-cost RF applications and InP integrated circuits for millimeter-wave circuits will become more mature and commonplace. Microwave and millimeter-wave circuits will use more digital circuits in their overall implementation.

Acknowledgment

The authors dedicate this paper to all of their colleagues in the MIC and MMIC fields whose contributions have made their mark in the developments of this exciting new field over the past five decades. The authors would also like to acknowledge the generosity of E. D. Cohen, former Director of the MIMIC program, and W. C. Pittman, Redstone Arsenal, for supplying copious documentation on the historical aspects of the MIMIC program.

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