Microwave Integrated Circuits—An Historical Perspective

HARLAN HOWE, JR., FELLOW, IEEE

I. Introduction

BEFORE ATTEMPTING an historical view of microwave integrated circuits, it was necessary to consider just what a microwave integrated circuit is. If someone can come up with a clear, noncontroversial, universally accepted definition, he's a better man than I am. In the broadest sense, a microwave integrated circuit is any combination of circuit functions which are packaged together without a user accessible interface. This definition, however, opens the door to great kluges of waveguide bends and components which have been brazed or welded together, and that is clearly not the intent of this review. I have, therefore, limited the scope to planar integrated circuits which make use of process control manufacturing techniques for a significant portion of the integrated circuit. This would include such transmission-line techniques as stripline, microstrip, slotline, finline, co-planar waveguide, and to a slightly lesser extent, lumped element circuits, image guide dielectric waveguides, and planar waveguide packages which are becoming a viable technique for integrated circuits at millimeter-wave frequencies.

II. The Early Years

The evolution of microwave integrated circuits must begin with the development of planar transmission lines. The earliest event that I was able to trace came from a conversation with Harold Wheeler in which he indicated that in 1936 he had put two flat co-planar strips side by side to make a low-loss transmission line that could be rolled up to save space. Harold also remembered that in 1942 he had built a trombone line-stretcher operating at 150 to 200 MHz for a Navy IFF program. He used a strip transmission line between parallel plates and loaded it with a high-dielectric constant material in order to make it smaller at these low frequencies. This device actually had production quantities associated with it. In a footnote in the paper "Microwave Printed Circuits—A Historical Survey" [1], Robert M. Barrett commented, "The flat coaxial transmission line was first used, insofar as this author has been able to determine, by V. H. Rumsey and H. W. Jamieson and was applied to a production antenna system during World War II as a power division network (this work is described in a report by V. H. Rumsey published by the Combined Research Group NRL during the war years and in a U.S. Navy antenna instruction book)." Whether it was Wheeler or Rumsey and Jamieson who were first to make a stripline is an exercise which is left to the reader. In any event, it would appear that this early work was largely empirical because again, according to Barrett, the original analysis of strip transmission line was reported for the first time in a Hughes Aircraft internal technical memo #234, entitled "Theoretical and Experimental Studies of a Strip Transmission Line." It was dated May 12, 1950, and was authored by N. A. Begovitch and A. R. Margolin.

While this work was going on, the people of Federal Telecommunication Laboratories in Nutley, NJ, were working on microstrip. Their results were first reported in a trio of papers [2]–[4] which were published in the December 1952 *Proceedings of the IRE*. The lead paper was entitled "Microstrip—A New Transmission Technique For The Kilomegacycle Range." It was written by D. D. Grieg and H. Engelmann. It was followed by a paper by Assadourian and Rimai, entitled "Simplified Theory of Microstrip Transmission Systems." The third paper on microstrip components was authored by J. A. Kostriza. The three papers covered the concept, theory, and practical realization of a wide variety of microstrip circuits. The microstrip had been born and was here to stay.

The first Symposium on the specific subject of microwave strip circuits (stripline, microstrip tri-plate, microwave printed circuits, etc.) was held on October 11 and 12, 1954, at Tufts College, under the co-sponsorship of the Air Force Cambridge Research Center and the Research Laboratory of Physical Electronics of the Department of Physics at Tuft's College. Twenty-one papers were presented over the two-day period by a group of contributors that now reads like "Who's Who" in the microwave industry. In March of 1955, the MTT-S put out its first Special Issue of the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and printed the papers presented at this Symposium. The editor at that time was Ted Saad. That issue is the most worn-out one in my collection of MTT TRANSACTIONS. It contained a wealth of solid basic information including the landmark paper by Seymour Cohn, "Problems in Strip Transmission Lines." [5]

In reviewing the references and acknowledgements in the papers published in MTT-3, it was fascinating to notice how many times acknowledgement of support was given to Robert Barrett, who was then Chief of the Airborne Antenna Section at the Air Force Cambridge Research Center. Among other areas, Barrett was supporting work both at

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The author is with MA/COM, South Avenue, Burlington, MA 01803.

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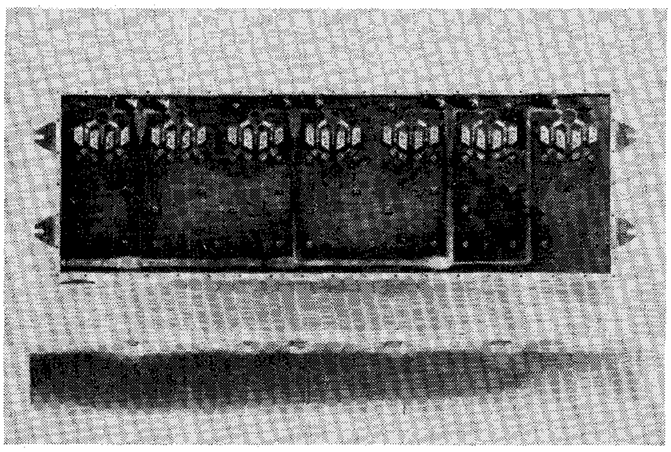

Fig. 1. Inside view of a 7-channel *C*-band stripline mixer developed in 1955. (Photo courtesy of Eaton Corp., AIL Division.)

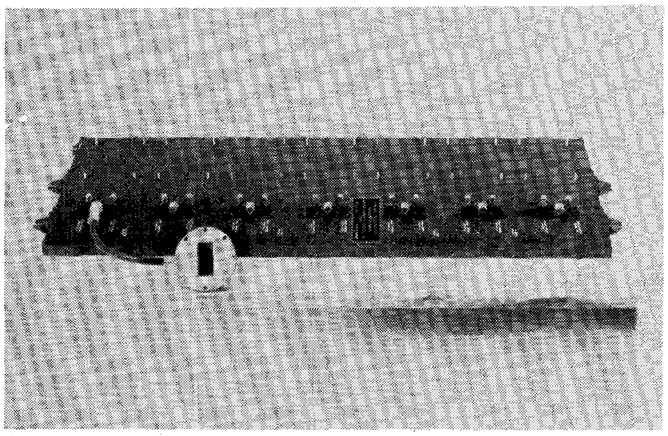

Fig. 2. An outside view of the mixer assembly shown in Fig. 1. Note the threaded studs on the back of the assembly which we used to hold 7 vacuum-tube preamplifiers. (Photo courtesy of Eaton Corp., AIL Division.)

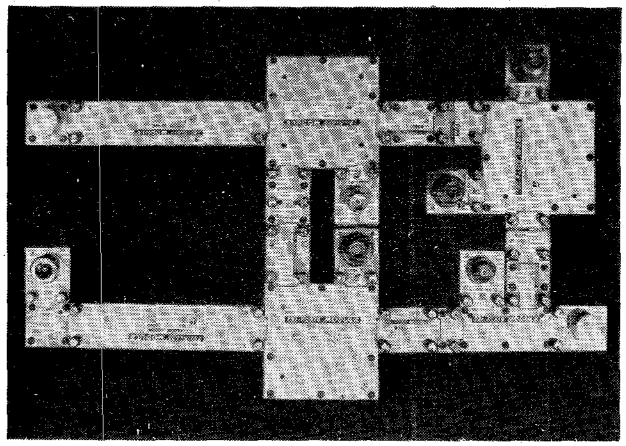

Fig. 3. A selection of Tri-plate modules which were sold as individual components which could be interconnected, circa 1957. (Photo courtesy of Sanders Associates.)

Fig. 4. This photograph was on the cover page of the Tri-plate Manual published in 1956 and shows the comparison of a Tri-plate circuit with its waveguide equivalent. (Photo courtesy of Sanders Associates.)

Sanders Associates and at Airborne Instruments Laboratories. AIL was working with a different type of strip transmission line making use of a thin substrate of dielectric material which was suspended between two ground planes and had a double registered pattern on it. Thus, the major dielectric material was air. In 1955, AIL coined a trademark for this form of construction. They called it Stripline. Over the years AIL failed to defend its trademark, however, and in due course of time stripline became the generic term that it is today for any flat transmission line in between two shielded ground planes. AIL was doing not only basic research but actually started to build complex subassemblies or integrated circuits using this suspended substrate stripline technique. The first of these to be commercially sold was a seven-channel, *C*-band, balanced mixer assembly with a local oscillator distribution network. It was delivered to Sperry Gyroscope Company in Lake Success, Long Island, who used it on the MSG-5, which was an Army surveillance radar using a stacked beam arrangement with a lens. A photograph of the inside of this first "stripline" MIC is shown in Fig. 1. The outside of the finished assembly is shown in Fig. 2.

Sanders Associates in Nashua, NH, had been working since 1952 on another type of strip transmission line. It was trademarked Tri-plate and was a solid dielectric two-layer construction. Although intended primarily for integrated circuits, Sanders produced a number of Tri-plate modules which were sold as individual components that could be breadboarded together from a kit. Some of these are shown in Fig. 3. Similar kits of microstrip modules, with the same idea, were also produced and sold by Federal Telecommunications Laboratories Inc. (ITT). In 1956, Sanders Associates published *A Handbook of Tri-plate Microwave Components* [6]. A photograph of a tri-plate integrated circuit compared to a waveguide circuit included in the frontispiece of that book is shown in Fig. 4. The Tri-plate Handbook compiled much of the information which had been presented and previously published, along with the work preformed by the Sander's group during the

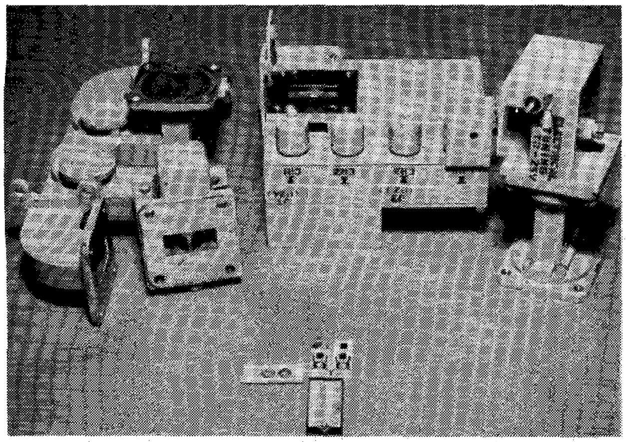

Fig. 5. A comparison of ceramic microstrip integrated circuits with their waveguide equivalent, circa 1965.(Photo courtesy of M/A-COM, Inc.)

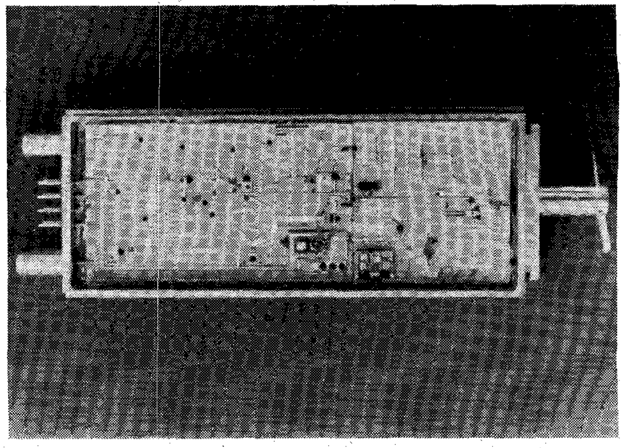

Fig. 6. The complex receive–transmit module for the MERA radar produced in the mid-1960's. (Photo courtesy of Texas Instruments.)

previous four years. It was the only text on stripline design available until my book, *Stripline Circuit Design*, [7] was published 18 years later.

These then were the early activities in the planar transmission-line area which were to serve as the seeds for the rapid growth and acceptance of microwave integrated circuits as the key building blocks for the families of microwave systems which we know today.

III. The Middle Age of MIC's

The 1960's were a period of rapid growth for MIC activity. It was also a period in which the proponents of various techniques proselytized and defended them with a degree of religious fervor not normally associated with the microwave industry. By and large, the people working on a given MIC technique were convinced that it was the only way to go and would be the only one to survive. As we know now, in looking back, they were all wrong.

Materials had been a key drawback to MIC development during the 1950's. During the 1960's, material manufacturers started to improve the uniformity of their product, to reduce the loss tangent, and to introduce new microwave materials for stripline and microstrip applications. While much of the early work had been done on cross-linked polystyrene and glass-reinforced polystyrene, stripline circuits shifted into woven teflon fiber glass and a new microfiber teflon fiber glass called Duroid™. Microwave-quality 99-percent pure alumina, which could be polished and metallized for thin-film circuits, emerged, and this was the major impetus towards the development of microstrip MIC's. The reduction in size, due to the high-dielectric constant and the mechanical stability which made it possible to mount semiconductors, made alumina microstrip an extremely attractive approach towards MIC's. Fig. 5 is a photo very similar to that shown in the Tri-plate Handbook, but it shows a microstrip circuit produced at Microwave Associates which was supposed to have the same performance as the three waveguide assemblies behind it. It never did. The metallization was thick film and lossy and there were problems with reliable attachment of semiconductor devices. The project was an ambitious one which was ahead of its time. The same job could be done today with no difficulty.

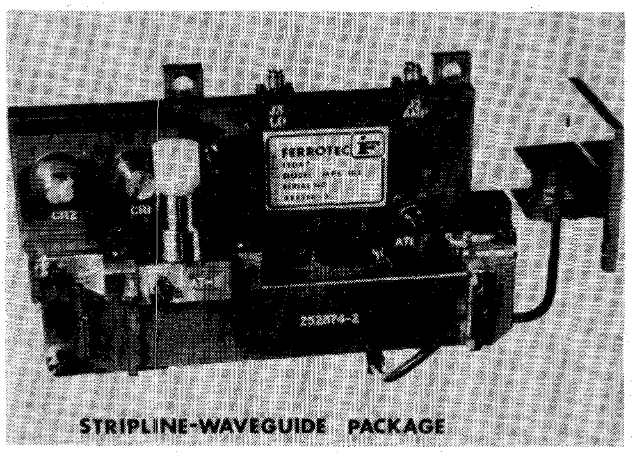

Fig. 7. A stripline MIC with integrated ferrites and some peripheral waveguide components, circa 1967. (Photo courtesy of M/A-COM, Inc.)

In September of 1964, Texas Instruments, under Air Force Avionics Laboratory support, began the development of the transmit/receive modules for an active phased-array radar called MERA. This module, which is shown in Fig. 6, was built in alumina microstrip using thin-film techniques. It was, for the time, extraordinarily complex and contained an *S*-band preamplifier, two phase-shift networks, two $\times 4$ multipliers, a pulsed amplifier, a TR switch, a mixer, and a 500-MHz preamp. Between the starting date and late 1968, over 600 modules were completed to build to the prototype array. To the best of my knowledge, this is the first time that any substantial quantities of MIC's of this complexity were produced.

While the spotlight of glamour was shining on the ceramic microstrip people, progress was also being made in stripline integrated circuits. Ken Carr, at Ferrotec, solved the problem of economical integration of ferrite devices into stripline assemblies and began to champion this, along with the use of multimedia techniques to build assemblies such as the one shown in Fig. 7. These techniques were put into production around 1969 and several hundred thou-

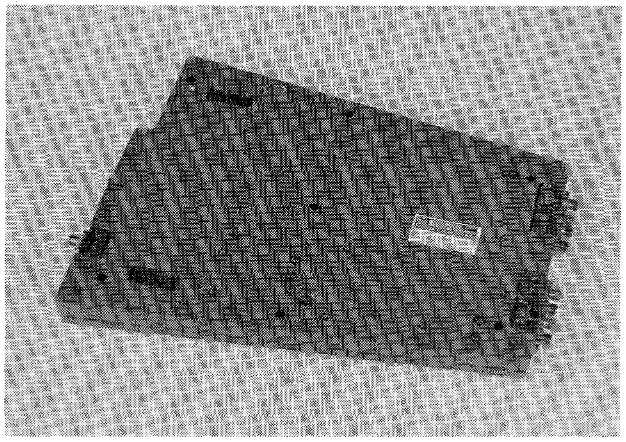

Fig. 8. A nine-layer bonded wide-band stripline assembly using the techniques of Shelton and Mosko. (Photo courtesy of M/A-COM, Inc.)

sand MIC's using them were built in the decade that followed.

In 1966, a trio of papers appeared in the MTT-S TRANSACTIONS which paved the way for wide-band, multi-octive stripline integrated circuits. The first of these, which was entitled "Impedances of Offset Parallel Coupled Strip Transmission Line," by J. Paul Shelton, Jr., appeared in January of 1966 [8]. It described the design equations for a three-layer form of construction which allowed continuously varying coupling by offsetting a pair of center conductors so that they could have either a gap, a partial overlap, or a full overlap according to the degree of coupling needed. It was a simple, practical technique which permitted multiple-section circuits to be readily constructed. In October of 1966, Shelton published again, this time with the help of Joe Mosko at the Naval Weapons Center, China Lake, CA. Their paper, "Synthesis and Design of Wide-Band Equal Ripple TEM Directional Couplers and Fixed Phase Shifters," [9] used the Shelton technique to build multi-octave couplers and phase shifters. This, in combination with the tables [10] published by Crystal and Young the year before, gave a new set of tools to wide-band circuit designers. Those tools were further improved in December of 1966 when the definitive paper on nonuniform-line techniques was published by Carl Tresselt [11]. These ideas, in combination with the concept of bonding stripline circuits together under heat and pressure, made it possible to produce chassisless assemblies with extremely great bandwidth, such as the one shown in Fig. 8.

In the same way that Shelton's coupling technique was an important step forward for stripline integrated circuits, a major breakthrough occurred for the microstrip side of the house in 1969 when Julius Lange of Texas Instruments published a letter on a new interdigital stripline quadrature coupler [12] which was ultimately to bear his name and win him the Microwave Applications prize. This technique, which permitted octave-band, quadrature couplers to be made in a microstrip configuration, solved the bandwidth problem that microstrip designers had been fighting for some time. In combination with a new and more accurate technique for calculating impedances and coupling presented by Bryant and Weiss in 1968 [13], it propelled microstrip integrated circuits into a new arena of wide-band phase shifters, couplers, balanced amplifiers, filters, and the other building blocks which are so common in MIC's that are in production today. The original illustration of the Lange coupler is shown in Fig. 9.

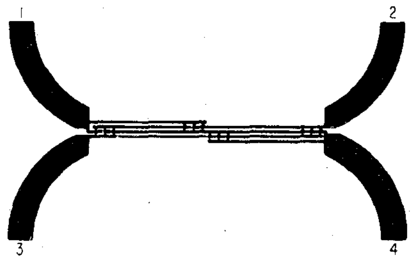

Fig. 9. Illustration of the Lange coupler from Lange's original correspondence in the MTT-S TRANSACTIONS.

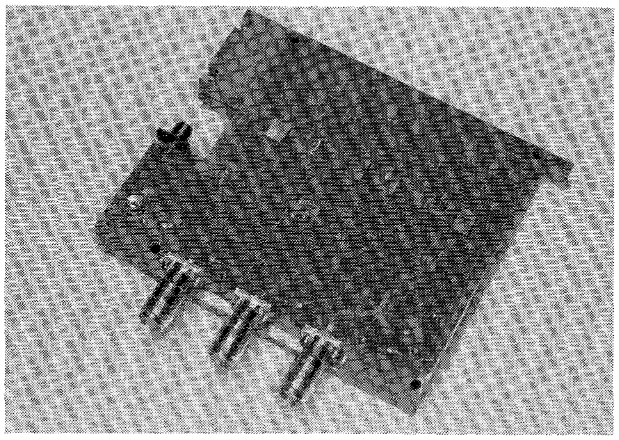

Fig. 10. A typical stripline assembly of the 1970's with integrated ferrites, filters, and semiconductor modules. (Photo courtesy of M/A-COM, Inc.)

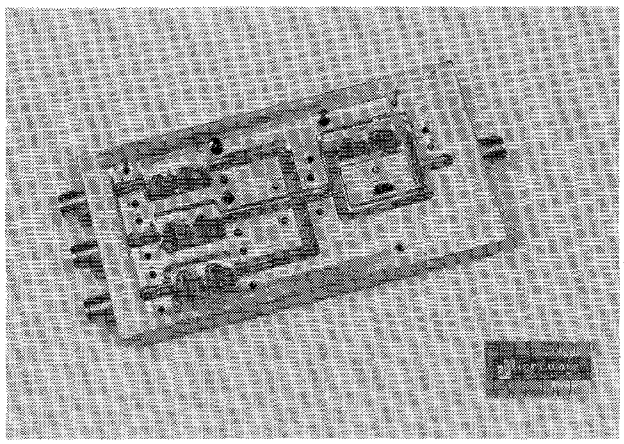

Fig. 11. A low-dielectric microstrip assembly with directly integrated semiconductor chips, and a channelled construction for high isolation, circa 1975. (Photo courtesy of M/A-COM, Inc.)

As we moved into the 1970's, stripline and microstrip assemblies, such as those shown in Figs. 10–12, became commonplace and accepted as the everyday method of building microwave integrated circuits. New forms of transmission lines were on the horizon, however. In 1974,

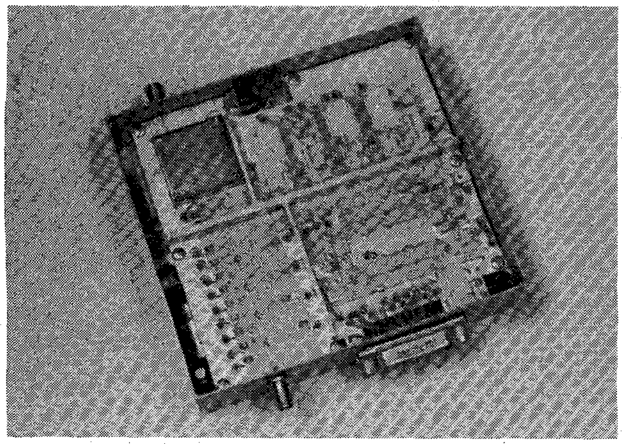

Fig. 12. A ceramic microstrip L-band receive–transmit module from the early 1970's making use of high-power amplifiers and Lange couplers in a hermetically sealed enclosure. (Photo courtesy of M/A-COM, Inc.)

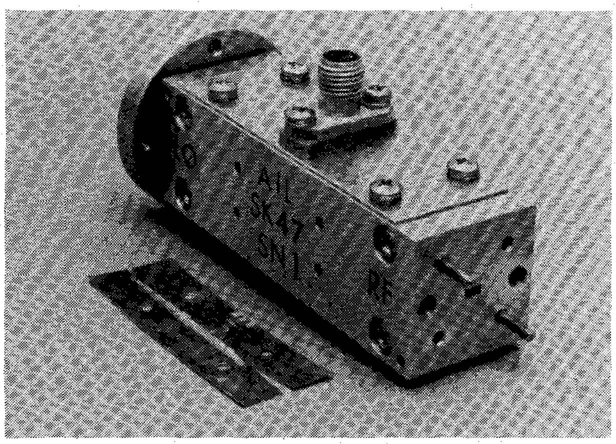

Fig. 13. A W-band subharmonic mixer built in finline with transitions to waveguide. (Photo courtesy of Eaton Corp., AIL Division.)

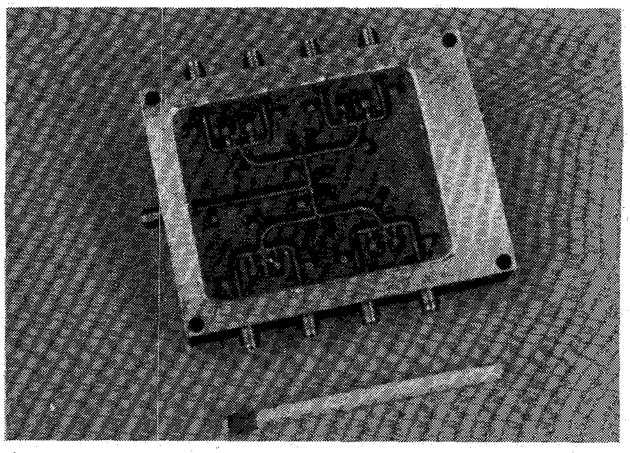

Fig. 14. A 26–40 GHz low-dielectric microstrip switch made in 1983 using CAD/CAM techniques without intermediate drawings. (Photo courtesy of M/A-COM, Inc.)

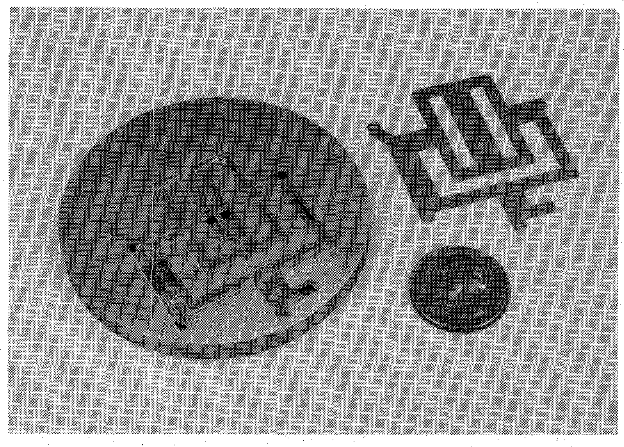

Fig. 15. 94 GHz monopulse front end using planar waveguide computer-aided manufacturing techniques. (Photo courtesy of M/A-COM, Inc.)

Paul Meier described a variety of new integrated-circuit components in a transmission line he called finline [14]. This structure was particularly useful for integrated circuits using planar techniques in an E-plane construction at millimeter-wave frequencies. A typical finline circuit is shown in Fig. 13. Other more exotic techniques, such as dielectric waveguide integrated circuits, described by Bob Knox [15], will undoubtedly have greater impact on the industry in the years ahead.

The period from 1960 to 1980 was a time of prolific development in the area of MIC's. Three Special Issues of the MTT-S TRANSACTIONS devoted entirely to microwave integrated circuits were published during this time. The first (in July of 1968) was edited by Sy Okwit, the second (in July of 1971) was edited by John Horton, and the third (in October of 1978) was edited by Reinhart Knerr. In addition, there were many special issues in the various trade journals devoted to this subject.

IV. TODAY AND TOMORROW

The planar transmission-line techniques which underwent so much basic research during the 1950's and early 1960's are common tools in normal use today. Current engineering concerns itself primarily with more efficient ways to design and build this type of circuit and in particular the application of CAD/CAM techniques. The channeled microstrip circuit, shown in Fig. 14, was done entirely without drawings by using direct transfer from a design computer for both artwork generation and NC tape development for the machining of the parts. This appears to be the trend for this type of construction. The technique of rapid and precision machining of complex patterns is also causing the re-emergence of waveguide as a tool for MIC's, particularly at millimeter-wave frequencies where the transmission characteristics of other forms of lines are unacceptable. Fig. 15 is a planar waveguide MIC which contains monopulse arithmetic, drop-in chip carrier mixer substrates, and ferrite elements. The application of NC techniques and laser welding permits circuits of this type to be made in an economical fashion. An excellent review of the techniques currently being used to build MIC's and super components is contained in six papers which are part of a special report in the November 1983 issue of the *Microwave Journal* [16].

Major R&D efforts currently under way are directed at such areas as image guide, co-planar waveguide, finline, and dielectric waveguide, all with emphasis on techniques which can be applied to monolithic integrated circuits. The

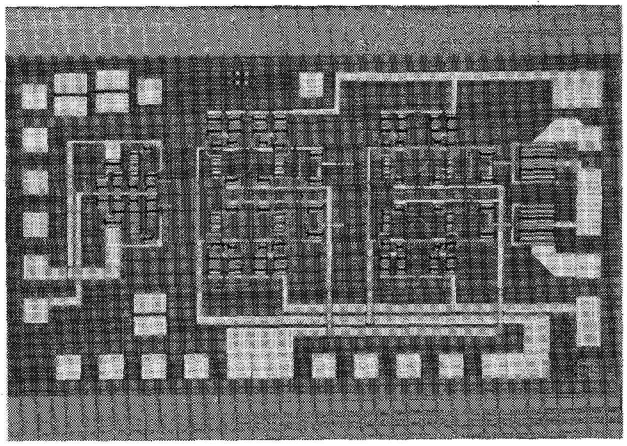

Fig. 16. A Gallium Arsenide monolithic microwave integrated circuit. This chip is a divide-by-4 digital divider which will work to 4 GHz. (Photo courtesy of M/A-COM, Inc.)

application of Gallium Arsenide to microwave monolithic integrated circuits has grown so explosively in the past few years that we now have a separate Symposium on Microwave and Millimeter-Wave Monolithic Circuits held in cooperation with the annual MTT-S International Symposium. These monolithic circuits encompass all of the traditional microwave functions of analog circuits, as well as new digital applications which are illustrated by chips such as the divide-by-4 monolithic circuit shown in Fig. 16. Perhaps the best way of illustrating the degree of activity and the level of research being done on monolithic integrated circuits is to suggest that the reader review the digest of papers for the 1983 Microwave and Millimeter-Wave Monolithic Circuit Symposium [17]. This, to my mind, is clearly the direction we are heading in the decade ahead.

Acknowledgment

I would like to take this opportunity to thank Ted Saad for the opportunity to participate in this historic issue of the MTT-S Transactions, as well as to thank those who contributed material. I have written this from my personal perspective as a worker in field, rather than that of a trained historian. I would, therefore, like to apoligize in advance to the hundreds of authors and workers who have made significant contributions to the field and who, unfortunately, were not mentioned.

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Harlan Howe, Jr. (M'64–SM'69–F'80) received the B.S. degree in optics from the University of Rochester in 1957.

He spent the early years of his career at the Sperry Gyroscope Company and the LEL Division of Varian Associates. He joined Microwave Associates in 1967 and currently serves as Vice President of Advanced Technology in the M/A-COM Corporate Component Technology Center.

He is the author of over 30 papers, as well as the book, *Stripline Circuit Design* (Artech House, Dedham, MA, 1974). He was elected a Fellow of the IEEE in 1980 for "contributions to microwave integrated circuits." He is past Chairman of the Boston Chapter of MTT-S and was the General Chairman of the 1983 MTT-S International Symposium, which was held in Boston. He has served as a member of the MTT-S AdCom for the past eight years, and is currently Vice President of the MTT-S.