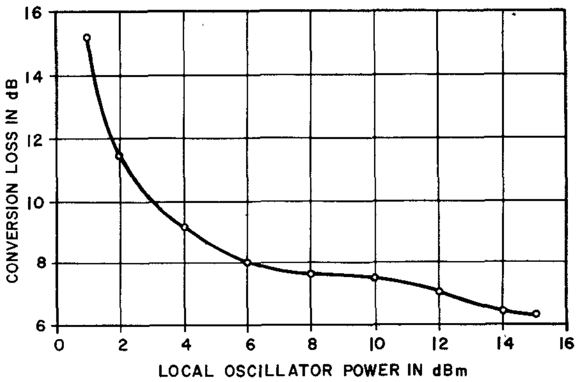

Fig. 6. Conversion loss of downconverter as a function of the pump power of the subharmonic local oscillator. The conversion loss at a power of +15 dBm or 15 mW per diode is 6.3 dB.

the circuit also shows good pump-to-signal port isolation. The pump frequency does not reach the signal input port because it is below cutoff in the signal waveguide and the second harmonic of the pump frequency measured at the signal port is 30 dB below the power at the pump port.

The conversion loss and the noise figure of the downconverter can be further improved if the stripline signal filter is removed and replaced by a novel waveguide-to-stripline transition [6]. The new transition shows a very small insertion loss at the signal frequency, and the rejection at the image frequency is better than 20 dB. The resulting conversion loss and noise figure for such a converter is improved by approximately 2 dB.

VI. Summary

It is shown that hybrid integrated millimeter-wave downconverters with good noise performance and bandwidth can be built using a stripline circuit and a pair of beam-leaded Schottky-barrier diodes which are pumped at a subharmonic of the conventional local oscillator frequency. The circuit meets the requirements of a digitally modulated system and looks attractive for use in the frequency range from 10 to 100 GHz.

Acknowledgment

The authors wish to thank W. C. Ballamy and D. C. Redline for providing the polyisolated beam-leaded devices. They also wish to thank T. F. McMaster and R. F. Trambarulo for helpful comments.

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Dielectric Waveguide Microwave Integrated Circuits—An Overview

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Invited Paper

Abstract—**An integrated circuit technique for microwave and millimeter wavelengths which uses refractive-type waveguides and signal processing coupled with planar integration techniques characteristic of microstrip microwave integrated circuits (MIC's) is described. Following a comparison of the optical and millimeter approaches to this circuit technique, a discussion of transmission lines and components for millimeter wavelengths is presented. System applications are also described.**

Manuscript received February 3, 1976; revised June 7, 1976.
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I. Introduction

A MICROWAVE integrated circuit (MIC) technique which uses a refractive dielectric waveguide has been emerging for the past several years. Research on this microwave technique has been less extensive than that in the optical dielectric integrated circuit (ODIC) technique. However, practical circuit results and demonstrated system applications have been achieved. A comparison between the microwave and ODIC techniques will be made. Transmission

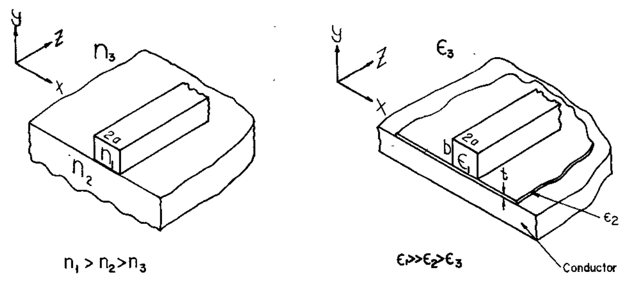

Fig. 1. (a) Strip dielectric waveguide for ODIC's. (b) Insular dielectric waveguide for microwave dielectric integrated circuits (MDIC).

TABLE I
TYPICAL PROPERTIES OF MICROWAVE AND OPTICAL DIELECTRIC WAVEGUIDES

	MICROWAVE	OPTICAL
Dielectric Materials (ϵ_1)	Alumina, Semiconductors	Glass; Semiconductors
Dielectric Materials (ϵ_2)	Plastic	Glass; Semiconductors
Dielectric Constant (ϵ_1)	10-15 or higher	2-4; 12
Dielectric Constant (ϵ_2)	2.5	2-4; 12
Index Ratio $\sqrt{\epsilon_1/\epsilon_2}$	2	1.1 - 1.01
Waveguide Width (in λg)	0.5	2-10
Degenerate E^x_{11} mode suppressed?	Yes	No
Radius of Curvature (in λg)	2-5	30-1000

line properties will be considered together with several passive transmission line components. Methods of mounting active devices are illustrated in various experimental circuits and integrated assemblies. Advantages of the dielectric waveguide integrated circuits will be presented and a comparison will be made with microstrip MIC's and metal waveguide circuits.

II. MICROWAVE AND OPTICAL DIC'S

A comparison of optical and microwave DIC waveguides is shown in Fig. 1. A rectangular core waveguide having an index of refraction n is surrounded by one or more media which generally have lower indicies [1]. In Fig. 1(a), the strip is in air ($n_3 = 1$) and is supported by a substrate having an index n_2, where n_2 is only incrementally lower than n_1. Other forms of ODIC waveguide are made where the core is partially or totally immersed in the substrate [2]. The purpose of having n_2 only incrementally smaller than n is to allow for single-mode operation ($E_{11}{}^y$ is the fundamental mode) while the width of the waveguide is several wavelengths. The use of a large index ratio would require a guide dimension on the order of one-half the guide wavelength. Since this dimension would be submicron for optical circuits, the fabrication problem becomes extremely difficult.

There exists for any rectangular dielectric waveguide a degenerate (or nearly degenerate) mode, the $E_{11}{}^x$ mode, which has a polarization transverse to the $E_{11}{}^y$ mode. Imperfections, discontinuities, or bends will cause coupling of these modes. The $E_{11}{}^x$ mode can be suppressed over a limited frequency range through the use of an aspect ratio $2a/b$ which is somewhat greater than 1. However, the preferred method for achieving single-mode operation is to introduce a grounding plane (mirror) so that the electric field of the $E_{11}{}^x$ mode is shorted [2]. The use of metal clading for optical dielectric waveguide has been investigated [3]. However, considerable loss is added at optical wavelengths by a conducting plane.

The dielectric waveguide structure for use in MDIC applications is similar in configuration and in principle of operation, but rather different in materials and practical implementation. The "insular" waveguide [4] is a general waveguide configuration used for MDIC's and is shown in Fig. 1(b). The special case of the insular guide, where the thickness of the low dielectric medium ϵ_2 (where $\epsilon = n^2$) is zero, is known as the image waveguide. The acronym MILIC has been used to describe the microwave insular (image) line integrated circuits. The insular waveguide is operated truly single mode because the ground or image plane is used to increase the cutoff frequency of the $E_{11}{}^x$ mode to a frequency substantially higher than that of the $E_{11}{}^y$ mode.

The principal differences between the microwave and optical dielectric waveguides are identifiable from Table I. The optical dielectric waveguides are generally made of glass or semiconductors and are formed using techniques such as sputtering, ion implantation, diffusion, reverse sputtering, or ion beam or chemical etching. Guide widths are typically a few microns. The microwave dielectric waveguides are usually made of high-purity alumina or high-resistivity semiconductor materials, and are formed using various machining methods. Alumina, however, lends itself to low-cost manufacturing because the waveguide or components can be fabricated in the green state prior to firing into final form. Dielectric constants are 10–15 for the materials which typically have been used for microwave guides.

The higher dielectric constant ratio (ϵ_1/ϵ_2) between the guide and surrounding media is practical at microwave or millimeter wavelengths because the guide wavelengths (and therefore the guide dimensions) are not unreasonably small for economical manufacture. The use of a higher dielectric constant ratio provides substantially better field confinement and, therefore, a much smaller radius (in wavelengths) may be used in the layout of planar integrated circuits without unacceptable levels of radiation. The table shows that optical MIC's having low index ratio would have to use radii which are large in wavelengths to prevent radiation.

It is not the intent here to provide an in-depth comparison of MDIC's and ODIC's. Blum has recently pointed out that the major difficulty with advancing the ODIC technology is that of fabricating a number of devices in compatible materials systems and integrating them into a single circuit [5]. To this could be added the observation that many practical circuit device problems must be resolved which result from the use of radii having tens to hundreds of wavelengths. Furthermore, the degenerate mode problem

TABLE II
THEORETICAL ATTENUATION CHARACTERISTICS OF INSULAR, MICROSTRIP, AND METAL WAVEGUIDE TRANSMISSION LINES

Description	Frequency (GHz)	λ_g (cm)	2a (cm)	t (cm)	α (dB/cm)	α (dB/λg)	Q_u	Q_{ins}/Q_u	Reference
Insular Waveguide Alumina	15	0.955	0.534	0.053	0.0093	0.0089	3063	1	6
	30	0.476	0.268	0.027	0.0224	0.0107	2551	1	6
	60	0.237	0.134	0.013	0.0554	0.0131	2072	1	6
	90	0.158	0.090	0.009	0.0955	0.0151	1802	1	6
Microstrip-Gold on Fused Quartz (50 ohm)	15	1.210	0.108	0.054	0.0200	0.0242	1124	2.72	7
	30	0.605	0.054	0.027	0.0562	0.0340	800	3.18	7
	60	0.302	0.027	0.014	0.1542	0.0466	583	3.55	7
	90	0.201	0.018	0.009	0.2802	0.0563	483	3.73	7
Rectangular Metal Waveguide-Silver plated	15	2.58	1.580		0.0019	0.0049	5551	.55	8
	30	1.40	1.067		0.0066	0.0092	2956	.86	8
	60	0.669	0.376		0.0156	0.0104	2615	.79	8
	90	0.441	0.254		0.0300	0.0132	2060	.87	8

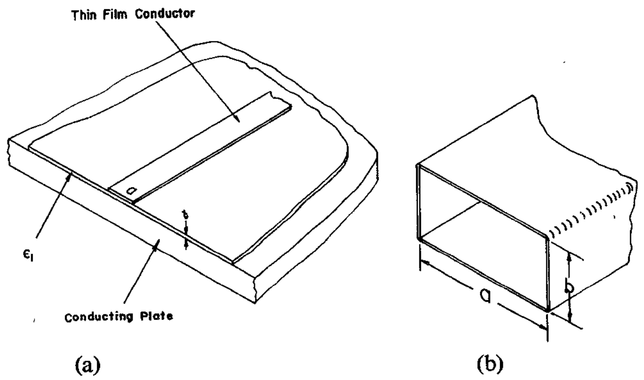

Fig. 2. (a) Microstrip transmission line used for MIC's. (b) Standard air-filled metal waveguide.

must be solved without adding significant loss to the waveguide and components. There are important achievements to be made in the further development of MDIC's as well, but they seem to be less basic in character and rapid progress in this endeavor is expected.

III. MIC COMPARISON

To provide a further comparison of the MDIC technique, the microwave microstrip integrated circuit transmission line will next be considered. While standard metal waveguide does not readily lend itself to planar circuit integration, some characteristics of this transmission line will also be provided for comparison. These transmission lines are shown in Fig. 2. Highest performance in the microstrip line is usually achieved with the lowest dielectric constant substrate material (ε_1). Alumina has been commonly used, but for high-frequency work, lower loss is achieved with fused quartz and this latter material will be used for the comparisons made here.[1] The numbers quoted for standard waveguide will assume silver plating on the interior walls.

In Table II are given theoretical attenuation factors in dB/cm and dB/λg at four frequencies for the three forms of transmission line. The corresponding unloaded Q of a resonator made from these transmission lines is also given. The Q_u of the insular guide is typically only 15 to 25 percent below that of silver-plated metal waveguide. The microstrip Q_u is 2.7 to 3.7 times lower than the insular Q_u and this ratio increases with frequency. This result demonstrates the fact that MDIC's become a more attractive choice as frequency increases.

Experimental results show that the ratio of insular Q to microstrip Q is somewhat higher than that given in Table II. Values of insular ring resonator unloaded Q of 5000 at 15 GHz and 3000 at 60 GHz have been measured.[2] By contrast, measured values of unloaded Q for fused quartz microstrip were typically 306 at 12 GHz [9] and 194 at 60 GHz [10]. These results lead to the conclusion that the alumina insular dielectric waveguide may be a full order of magnitude lower in attenuation than fused quartz microstrip.

The cross-sectional and guide-wavelength dimensions given in Table II allow a size comparison to be made. Both the guide width and guide wavelength are 2.7 to 3.5 times larger in metal waveguide than in alumina insular waveguide. When consideration is given to the space-saving potential of a planar configuration versus the three-dimensional configuration typical of standard waveguide, the possibility for space saving appears to be substantial. However, the requirements and complexity of any given system may not permit full realization of the potential circuit volume reduction.

The microstrip cross-sectional dimensions are smaller than those of insular waveguide. The guide wavelength, in contrast, is slightly larger for the fused quartz microstrip. Microstrip circuits will usually occupy less circuit area than insular circuits. Above 20 GHz, however, extreme miniaturization has a negative impact on many of the microstrip virtues. Not only are conductor losses increased, but the cost of holding tolerances in manufacture also is increased. In the range of frequencies from 20 to 110 GHz, alumina insular waveguide offers a reasonable compromise wherein size reduction compared to standard waveguide circuits is achieved without incurring extreme fabrication difficulties due to tolerance requirements.

[1] Lower loss yet is achieved in strip transmission lines which use air as the dielectric medium, such as the suspended substrate type. These lines are generally suspended in a machined channel for mode control, and for this reason do not appear to qualify as an inherently low-cost approach to MIC's.

[2] The unloaded Q was determined from the band-reject frequency response of a dielectric ring resonator loosely coupled to a dielectric transmission line.

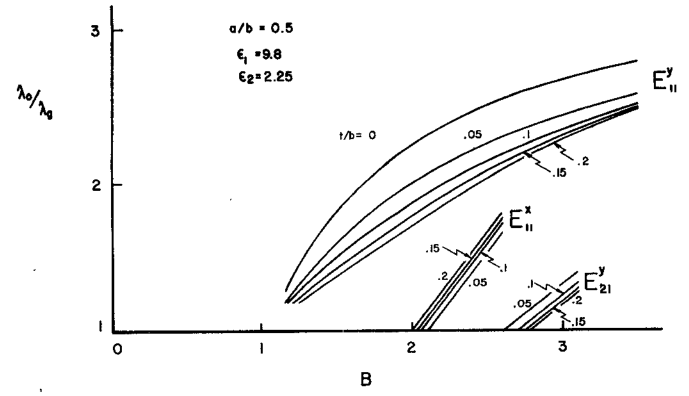

Fig. 3. Insular waveguide dispersion curves for $a/b = 0.5$.

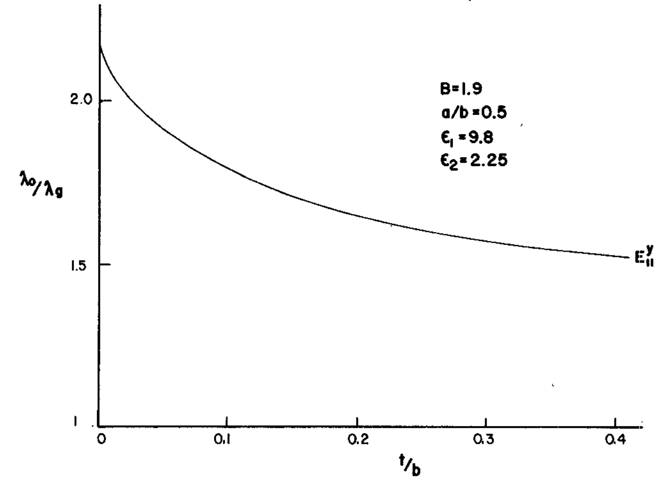

Fig. 4. Guide wavelength as a function of the t/b ratio.

IV. Development of MILIC

Planar integrated circuits for microwave and millimeter wavelengths which use the high-permittivity dielectric image waveguide were first introduced in 1970 [11]. Additional active and passive components have been developed since that time [12]. The loss mechanisms in the image waveguide, including conductor and dielectric attenuation [13] and radiation attenuation [14] from curved waveguide, have been characterized. In 1973 the insular waveguide was analyzed and applied in a 60-GHz communication receiver module [15], [16]. Other applications which have used the MILIC circuit technique include a *J*-band converter and a *K*-band aircraft data bus system [17], [18]. The image waveguide employing semiconductor materials has been used to demonstrate oscillators, modulators, and detectors wherein the active devices were mounted within the dielectric waveguide [19]–[22]. Dielectric waveguide phase shifters using p-i-n diodes have also been demonstrated [19], [23]. Some alternative dielectric waveguide configurations have recently been examined [24]. The first commercial products using the MILIC technique are balanced mixers for *Ka*-, *V*-, and *W*-band operation. Details of the transmission line properties, components and active devices, and some system applications are presented in the following.

V. Transmission Line Properties

A theoretical analysis of the propagation characteristics of the image waveguide was presented when the MDIC technique was initially described [11] and was later generalized to the insular transmission line configuration [15]. A typical set of dispersion curves giving the ratio of free-space wavelength λ_0 to the guide wavelength λ_g is shown in Fig. 3. The guide wavelength is dependent on the normalized guide dimension where

$$B = \frac{4b}{\lambda_0}\sqrt{\varepsilon_1 - 1}.$$

The guide wavelength in Fig. 3 has been determined for an alumina waveguide ($\varepsilon_1 = 9.8$) supported on polyethylene film ($\varepsilon_2 = 2.25$) having a cross section of $2a \times b$, where $a/b = 0.5$. This cross section, in which the guide width equals the guide height, is generally used with the insular configuration in order to obtain approximately the optimum bandwidth and suppression of higher order modes. In earlier work involving the image guide, an aspect ratio $2a/b = 1.0$ was used. This configuration is a good choice for image waveguide because it gives the maximum percent bandwidth for single-mode operation. The introduction of the insular film somewhat diminishes the image of the electromagnetic fields and therefore decreases the effective electrical height of the guide. The physical height (and therefore the electrical height) is increased by using a square waveguide. In Fig. 3 are also shown the two most probable modes that can limit the upper frequency of single-mode operation.

The fundamental mode is ${E_{11}}^y$ which has an electric-field polarization in the y (vertical) direction. The effect of even a small gap between the dielectric waveguide and the image plane is very great. A plot of the guide wavelength as a function of the t/b ratio for the square guide at a fixed frequency ($B = 1.9$) is shown in Fig. 4. The slope of this curve indicates the rate of change of guide wavelength with gap and is clearly largest for very small gaps. Experience with image waveguides has shown that, in practice, a zero gap is difficult to achieve and maintain uniformly throughout a circuit due to fabrication tolerances. The insular waveguide resolves this difficulty by introducing a uniform small gap. This is done by thermally bonding the dielectric waveguide to the ground plane using a low-loss low dielectric constant plastic film. This method also eliminates any other form of adhesive which may add significant dielectric loss to the image waveguide.

An important consideration in the use of the insular waveguide is control of the cutoff frequency of the ${E_{11}}^x$ mode. As the t/b ratio is increased, the ${E_{11}}^x$ mode cutoff is decreased in frequency as shown in Fig. 3. Thus a compromise choice for the t/b ratio in the range of 0.05–0.15 is usually made in order to obtain maximum single-mode bandwidth with minimum dependence of the guide wavelength on film thickness variation.

The attenuation constant of insular waveguide is shown in Fig. 5 [15]. Attenuation due to ohmic loss in the ground

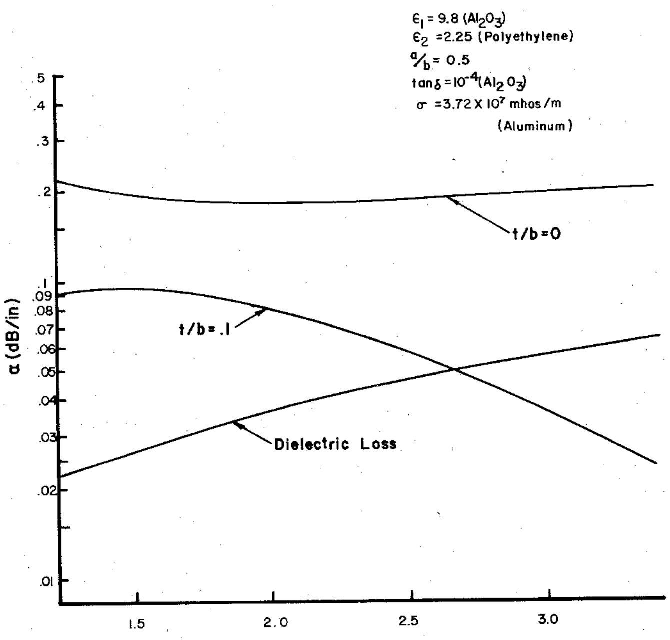

Fig. 5. Conductor and dielectric losses in insular waveguide.

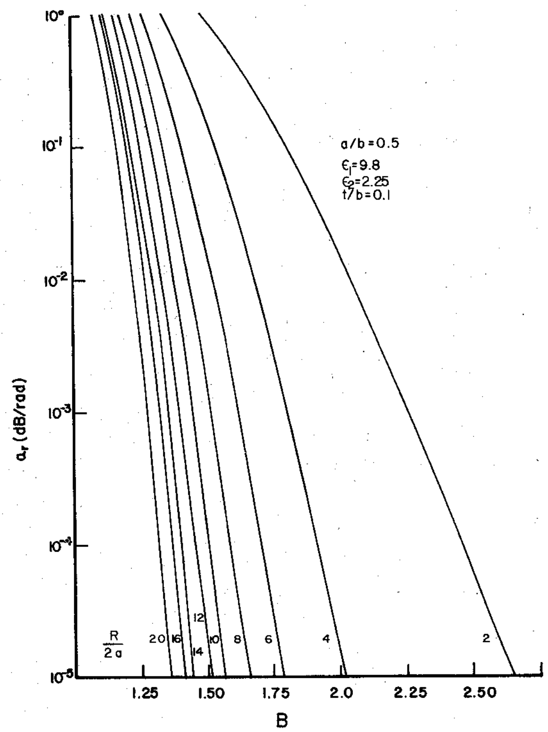

Fig. 6. Attenuation constant due to radiation from bends.

plane decreases with increasing frequency (B) because of greater field confinement to the high dielectric constant guide. The conductor loss of an insular guide having $t/b = 0.1$ is lower by a minimum factor of 2 than that of a guide having zero film thickness (image guide). The results of Fig. 5 neglect losses due to adhesives or conductor surface roughness which would increase overall image guide attenuation.

The use of high dielectric constant ratio ($\sqrt{\varepsilon_1/\varepsilon_2}$) has

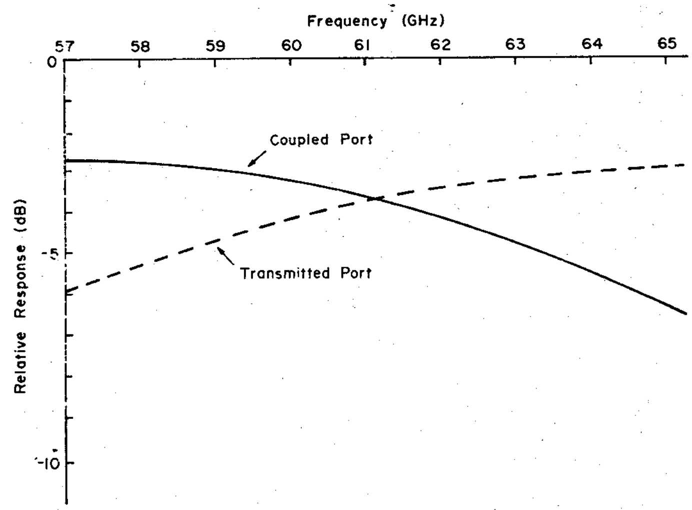

Fig. 7. Typical coupling characteristics of a 3-dB quadrature hybrid.

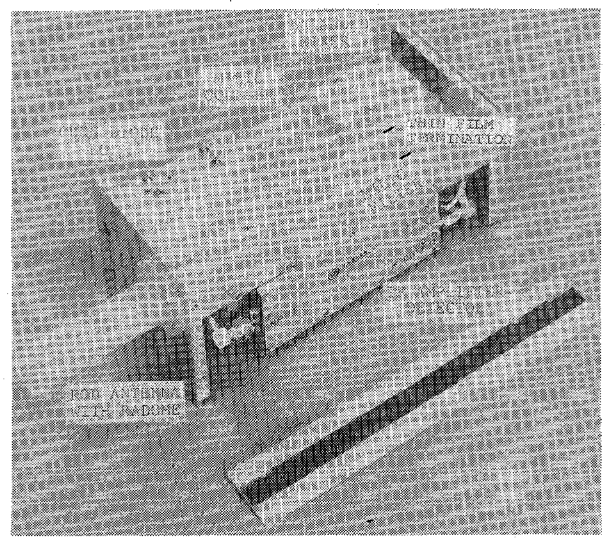

Fig. 8. V-band communications receiver [16].

a major impact on the allowable minimum radius of curvature which can be used without unacceptable radiation from bends. An analysis of radiation from curved microwave dielectric image waveguides was published earlier [14]. Radiation loss for a typical alumina insular guide is given in Fig. 6. Radiation loss can be limited to acceptable levels if a minimum operating frequency (B value) is observed for any specific waveguide cross-sectional dimension and minimum normalized bend radius ($R/2a$).

Another loss mechanism in dielectric guides is coupling of fundamental mode fields to those of radiation modes due to wall imperfections. This mechanism has been examined for optical guides [25] and microwave guides [21] but little quantitative data are available on the significance of this loss mechanism to microwave circuit performance. The fact that measured circuit Q's have been higher than theoretically predicted for adequately guided modes encourages the conclusion that no excess loss mechanism of any significance is present. However, further investigations to define the acceptable limits of surface tolerances would be of benefit in the manufacture of MDIC's for system applications.

VI. Passive Components

One of the first passive MDIC components which was subjected to analysis and experimentation was the parallel waveguide directional coupler [11], [12], [20]. Satisfactory agreement between analytical predictions and experimental couplers has been shown [12]. Couplers have been designed for several frequencies and used in a variety of applications [4], [15]–[17], [26]. The dielectric guide parallel line couplers tend to be narrow band because the coupling results from the interference of two waveguide modes which propagate at different velocities. A typical coupler response is shown in Fig. 7 of a coupler which was designed to operate as a 3-dB quadrature hybrid at 61.1 GHz in the V-band communications receiver module [16] described later (see Fig. 8). Such a coupler can be made less frequency dependent, and therefore usable over a wider band, by shortening the coupling region and decreasing the gap. Achieving small coupling factors (3 dB or less) is not difficult even in very short couplers if the waveguide cross-sectional dimensions are appropriately selected for the operating frequency. Couplers which are symmetrical about both planes of symmetry (parallel and normal to the waveguide direction of propagation) will always have a frequency-independent quadrature phase shift between transmitted and coupled waves.

Bandpass or band-reject filters having one or more resonators can be realized for MDIC circuits using ring resonators. The response of a single resonator bandpass filter for V-band operation is shown in Fig. 9. A disadvantage, for some applications, of this type of filter is the fact that multiple bandpass responses occur. The separation of the spurious responses from a desired response is a function of the diameter of the ring resonator. The increase of the separation of the spurs through diameter reduction is limited by the minimum radius-of-curvature considerations which were discussed earlier.

Analyses for single- and double-ring resonator filters have been developed [16]. Experimental verification of the single resonator theory has been demonstrated. It has been shown theoretically that if the frequency selectivity of the interstage couplers is utilized, the spurious responses of these filters can be substantially suppressed.

Fixed and variable attenuators have been demonstrated where lossy ferrite slabs or lossy thin films are introduced into the evanescent field region external to the high dielectric constant waveguide. One of the significant virtues of the dielectric refractive waveguide is that fields are accessible externally for convenient introduction of attenuating or phase-shifting media. These media must be introduced so that the fundamental mode is affected without causing coupling to higher order or radiating modes. The thin-film attenuators, such as are used as terminations in the V-band receiver (Fig. 8), introduce virtually no field perturbation but do achieve attenuation very effectively. Examples of diamond-shaped lossy ferrite attenuators, which do have a

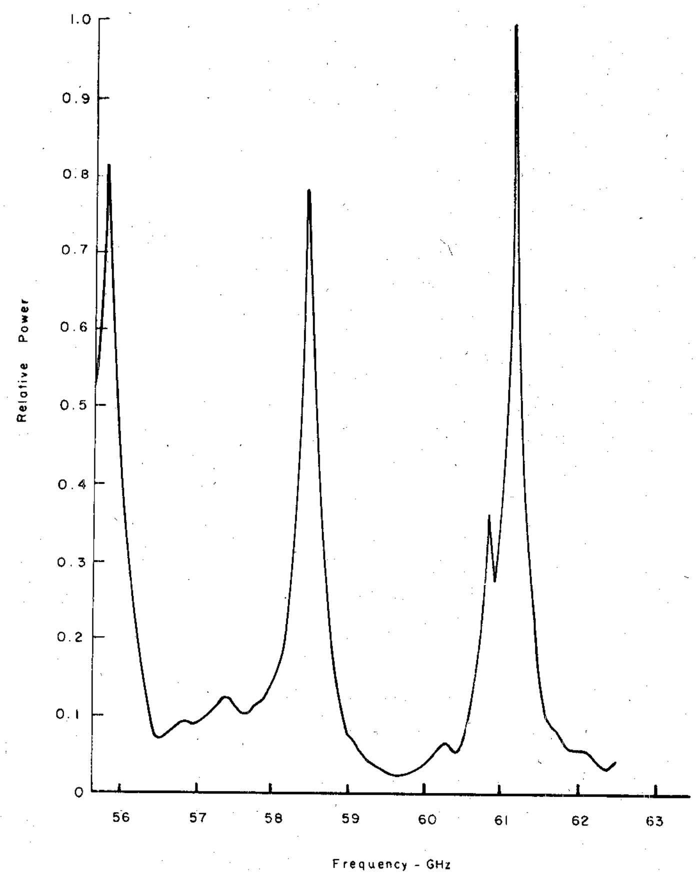

Fig. 9. Frequency response of ring preselector filter.

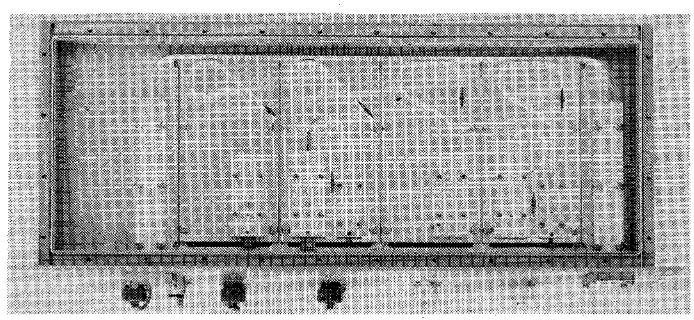

Fig. 10. View of a two-channel microwave data bus terminal having modular MILIC transmitters and receivers [17], [18].

higher VSWR than the thin-film type, are visible in the data bus terminal of Fig. 10, which is described in Section VIII.

Ferrite integrated components have also been under development for use in MDIC's. A V-band transmitter, also described later (Fig. 11), contains a field-displacement isolator [16]. A ferrite slab replaces a portion of the dielectric waveguide material along one side of the cross section. An absorbing film is placed at the outside edge of the ferrite slab and biasing magnets are located above and below the ferrite slab. Isolation ratios of 10 dB have been demonstrated with a loss of about 1 dB [16].

A Y-junction 3-port circulator using a ferrite post is a component which appears to have considerable promise for MDIC applications. A silicon image guide integrated ferrite circulator in which the ferrite material was placed

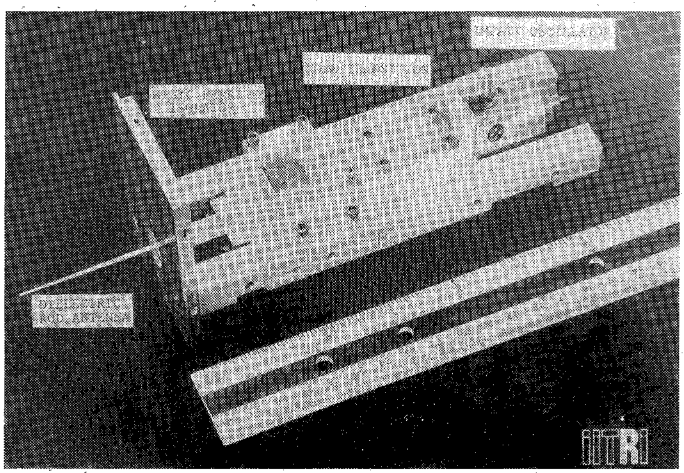

Fig. 11. *V*-band communications transmitter [16].

on top of a symmetrical silicon *Y* junction has been demonstrated [26]. While the insertion loss of this experimental model was 5 dB, isolation of 20 dB over a 1.5-GHz bandwidth near 62 GHz was achieved. Further investigation of the scattering loss mechanisms of the *Y* junction should permit design of an improved geometry with lower insertion loss.

Another significant advantage of MDIC's is the ability to directly incorporate radiating elements with the integrated circuit without the need for any form of launcher or transition. A suitably tapered dielectric guide will form an aperture having 10–15 dB of gain. An array of such radiators can form an even higher gain antenna. A single dielectric radiator was employed on the *V*-band transmitter and receiver units (Figs. 8 and 11). Gains of 15 dB were achieved with these antennas.

VII. Active Devices

A variety of active device configurations have been investigated for use in MDIC's. Two approaches to device mounting have been employed. Several devices and systems were fabricated using metal split-block mounts in which the active device is mounted in a rectangular air-filled waveguide which incorporates a mode converter from the E_{11}^y mode dielectric guide to the TE_{10} mode metal guide. This is an approach which utilizes proven device mounting techniques and yields performance comparable with that achieved in standard waveguide applications. A second approach, in which the active device is mounted directly in the dielectric waveguide, is more difficult to implement without causing conversion to higher order or radiation modes. The latter approach is more attractive from a production cost point of view. Descriptions of these various devices will be given in the following.

Examples of split-block metal mounts for oscillator and mixer diodes can be seen in Fig. 8. This photo shows a *V*-band communications receiver module. At lower left is a Gunn local oscillator in which the resonant element is a reduced-height metal waveguide which couples through a launcher to an insular dielectric waveguide. The balanced mixer consists of a dielectric waveguide quadrature hybrid and a split-block mount for a matched pair of Schottky-barrier diodes in pill packages. The split-block housing incorporates mode launchers for converting between the dielectric insular waveguide and the rectangular metal waveguide where the diodes are mounted. The IF outputs are taken through filters built into the base plate.

Direct mounting of semiconductor devices in a dielectric image waveguide has been demonstrated in a module consisting of an oscillator, modulator, and detector [20]–[21], [26]. The IMPATT oscillator consisted of a packaged diode connected to a radial ring resonator using a metal ribbon contact. The radial ring was a thin film deposited on the top surface of the silicon image waveguide and the packaged diode was mounted in a hole in the dielectric image guide. Bias was supplied through a filtered thin-film line also deposited on the top of the silicon image guide. Power output of the oscillator was 50 mW near 60 GHz. A packaged p-i-n modulator diode was incorporated within the silicon image waveguide in a similar fashion. A detector (or mixer) diode was mounted without packaging by allowing a whisker contact for a diode chip to extend vertically through a transverse hole in the image waveguide. Bias filtering in this case was incorporated into a metal structure above the dielectric waveguide.

These mounting techniques have been used to develop a single-ended mixer with integrated local oscillator having a 6.1-dB conversion loss at 60 GHz [20]–[22], [26]. A balanced mixer with external local oscillator which had a dielectric image waveguide hybrid achieved an 8.1-dB DSB noise figure at 60 GHz. A later version of the IMPATT oscillator gave a power output of 120 mW at 55 GHz.

Oscillators and oscillator mixers which also used radial disks in conjunction with packaged diodes within a silicon dielectric waveguide have also been demonstrated [19], [20]. These devices employed both Gunn and IMPATT oscillator diodes and tests were conducted at *Ku* and *V* band.

A breadboard self-oscillating mixer fabricated in silicon dielectric waveguide was tested using injection locking tests and showed an oscillator loaded *Q* of 350. Measurements of the device as a mixer indicated noise figures of 10 dB. The conversion loss ranged from -10 to $+10$ dB with conversion gain attributed to the negative resistance of the Gunn diode.

Gunn oscillators, self-oscillating mixers, and Schottky-barrier mixers for mounting in dielectric waveguide using a dielectric block are also under development.[3] Past efforts have demonstrated Gunn oscillators in *Ka* band and recent developments have been at 60 GHz. In this approach the resonator is a separate longitudinal block (of high thermal conductivity such as beryllium oxide), and the active device is attached to a metallized pattern on the transverse face of the block. The oscillator block is mounted to an external dielectric waveguide having similar cross section.

[3] Developed at the Minneapolis Honeywell Systems Research Center, Minneapolis, MN.

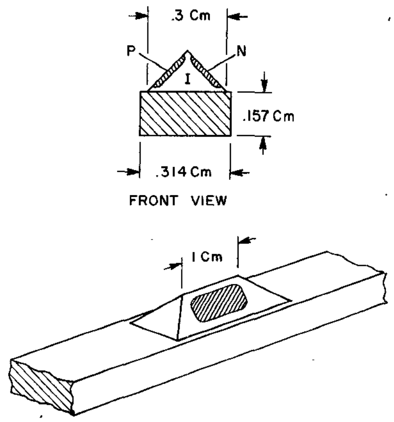

Fig. 12. P-I-N diode phase shifter for operation with a silicon dielectric waveguide at 70 GHz [19].

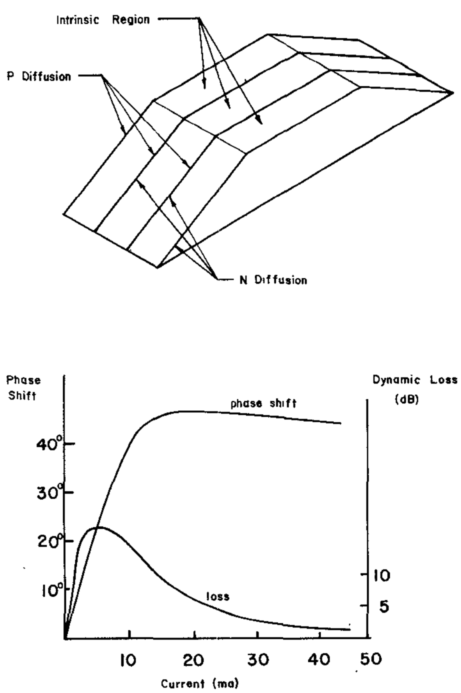

Fig. 13. Layered p-i-n diode phase shifter and measured performance at 70 GHz [23].

A unique active device for millimeter circuit applications is an electronically tuned p-i-n diode phase shifter [27]. This device has been applied to dielectric waveguides [19]. The structure of an experimental phase shifter for 70 GHz is shown in Fig. 12. A laminated p-i-n diode phase shifter, fabricated as shown in Fig. 13, operated somewhat more efficiently than the triangular device [23]. The measured phase shift for both structures was about the same, as shown in Fig. 13, but the triangular device operated at higher current. These devices require additional development to improve efficiency and reduce insertion loss. However, the possible system application involving an electronically steered phased array using low-cost MDIC modules having integrated oscillators, phase shifters, circulators, and radiators is very attractive and may justify further device and module development. The operation of the p-i-n phase shifter can be understood in terms of the insular waveguide dispersion curves of Figs. 3 and 4. The conductivity modulation of the p-i-n diode region is, in effect, changing the t/b ratio and thus the guide wavelength.

VIII. System Applications

The MILIC technique may be applied to a variety of system applications in the microwave and millimeter frequency ranges. As component development continues, the number of system types which can be covered will increase. At present, the technique is most appropriately applied to systems having modest operating bandwidth. This is not a severe limitation since many of the emerging millimeter system applications are of this type.

Radiometric receivers or transceivers for midcourse or terminal guidance of weapons are a logical system application for MILIC because of the potential for low cost in volume production. These systems require microwave sensors which are also very compact, light weight, and rugged. The low circuit loss of the dielectric waveguide means that MILIC subassemblies would provide performance comparable with waveguide counterparts.

Transmitters and receivers for covert communication applications (around 60 GHz) are another system application which can potentially benefit from the production cost savings of the MILIC technique. Many of the integrated module components described earlier were part of a complete FM voice and data communications receiver/transmitter pair as shown in Figs. 8 and 11 [4], [16]. While not all of the microwave components in these modules were integrated using the MILIC technique, several novel circuit components were demonstrated as described earlier. Future designs could be completely integrated and therefore achieve a greater potential cost reduction in production.

A variety of radar applications in the millimeter wavelength range can benefit from the combination of compact size and high performance of the MILIC technique. Airborne obstacle avoidance or navigation radars may operate at millimeter wavelengths to obtain high resolution with small antennas. Doppler-type radars are under consideration for use at millimeter wavelengths for such diverse applications as weapons fuzes, security alarms, and automotive braking systems. These are all potentially high-volume applications which require the low unit microwave subsystem cost which may be realizable with MILIC.

A K-band data bus system, for possible use with an aircraft flight control system, used the MILIC technique in each of three terminals [17], [18]. This demonstration system, which was satisfactorily flight tested, consisted of two channels operating on a single dielectric waveguide bus. An internal view of one of the terminals is shown in Fig. 10. Four drop-in modules can be seen in the photo. The transmitter and receiver of a low data rate digital channel (10 Mbit/s) are at the left and the transmitter and receiver of a high data rate FM analog channel (500 MHz) are at the right. The channel-dropping couplers for each module are of the noncontracting proximity type so that when the module is inserted in the terminal, RF coupling is established to the dielectric waveguide which forms the main bus within the terminal.

IX. Conclusions

A comparison of MIC's and ODIC's has been made. It has been shown that the MDIC technique was advanced through the development of a vareity of passive and active circuit components. The MDIC technique has been employed in various systems and can be applied to several emerging system applications with considerable advantage. The combination of high circuit performance, compact dimensions, and potentially low production cost makes the MDIC technique an attractive choice for use in the 20–110-GHz range.

Acknowledgment

The author wishes to thank Dr. P. P. Toulios (Epsilon Lambda Electronics), M. M. Chrepta and Dr. H. Jacobs (Army Electronics Command), G. R. Vanier (Martin Marietta Aerospace), Dr. G. E. Webber and S. Kofol (Honeywell Systems Research), Dr. Y. Chang (Hughes Electron Dynamics Divn.), and A. Kaurs (IIT Research Institute) for their contributions.

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