MICROWAVE INTEGRATED CIRCUITS

In this article a general overview and basic principles of operation of a class of highly integrated analog devices and circuits, used for applications in the microwave and millimeter-wave frequency range, are presented. Though there are subgroups of sister technologies that evolved over the years, having different acronyms such as MIC (microwave integrated circuits in hybrid form), MMIC (monolithic microwave integrated circuits), MIMIC (microwave and millimeter-wave monolithic integrated circuits), and MCMs (multichip modules), their basic principles of operation are similar, with their objectives and scopes rapidly overlapping. The discussions in this article may be directed to a broad class of such integrated circuits, referred to in general as microwave and millimeter-wave integrated circuits, with "MMIC" as a generic acronym. Essential building blocks of MMICs, such as the substrate material and parameters, transmission line geometries, passive and active devices, integrated antennas, integration architectures, and packaging concepts, are explained at a fundamental level for readers new to the subject. Fundamental design considerations and modern analytical and computer-aided design tools for the design of MMICs are introduced. Current trends and future directions of the technology are also discussed. More knowledgeable readers are referred to a selection of significant technical articles for further reading.

As indicated, microwave and millimeter-wave integrated circuits refer to a special group of highly integrated analog circuits, operating in the microwave and millimeter-wave frequency range. In this frequency range the various circuit functions that were usually implemented in the past using bulky metal waveguides and coaxial lines, can now be implemented using printed microstrip lines or other forms of planar transmission lines. These planar circuits can also be fabricated together with semiconductor active devices on a single chip, employing a technology similar to that used in microelectronic circuits. As a result, quite complex microwave and millimeter-wave circuits and systems have been realized in a compact, reliable, and cost-effective manner. In many ways, this class of modern integrated circuits has opened the promise and potential for microwave and millimeter-wave communication, much like what silicon digital integrated circuit technology has done for computers.

From a historical perspective, after the experimental demonstration of electromagnetic waves by Heinrich Hertz in 1888, and then the successful achievement of transatlantic communication by Guglielmo Marconi in 1901, signal distribution and circuit components in the microwave frequency range were implemented using rectangular metal waveguides. These waveguides were essentially hollow rectangular metal pipes capable of guiding microwave signals, and are sometimes referred to as "uniconductor waveguides." They are so named because the rectangular hollow waveguides use only one conductor, which is fundamentally different from conventional signal transmission in the very low-frequency range using two conductor transmission lines. Though the uniconductor waveguides had the advantages of low-loss propagation compared to two-conductor lines, due to their limited bandwidth of operation, dispersion and, above all, their bulky physical size, interest later shifted to "two-conductor lines," such as coaxial lines, for microwave circuits. However, due to the inconvenience of fabricating circuit components in coaxial form, flattened versions of coaxial lines were then introduced. Soon after, attempts were made to implement two-conductor lines by laminating metal strips on a hard dielectric surface in order to greatly simplify the fabrication process. The stripline and the microstrip line were the candidates of choice. The geometries of various waveguiding media used for microwave applications leading up to the printed microstrip line are shown in Fig. 1. A good discussion of the historical developments leading to MMICs is presented in Ref. 1.

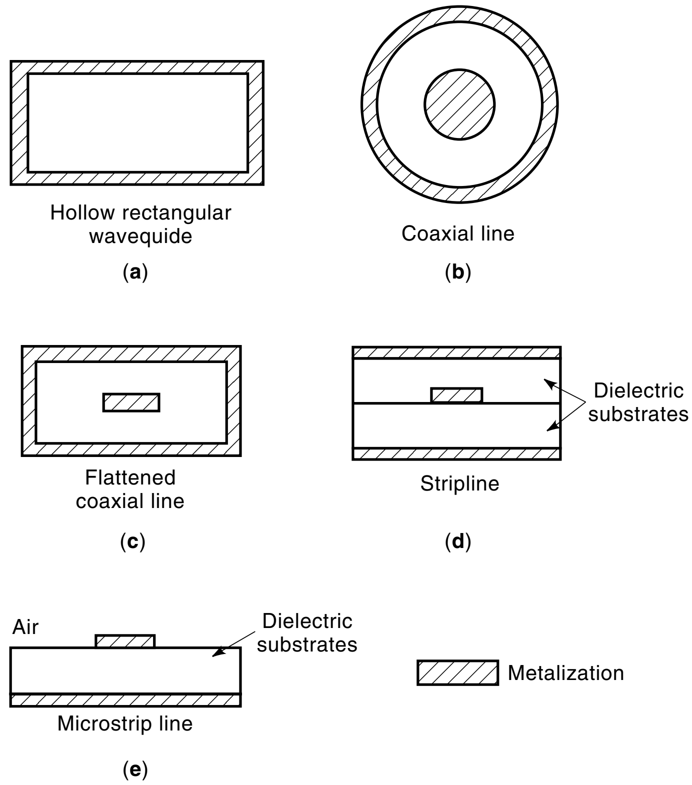

Figure 1. Evolution of waveguide geometries (cross-sections) used for microwave circuits, from (a) hollow (uniconductor) metal waveguide, to (b) coaxial line, to (c) flattened coaxial line, to (d) strip line, and currently to (e) microstrip line. Microstrip line is now the most commonly used transmission line for MMICs. Interest in other forms of transmission lines, such as slotline and coplanar waveguides, came later in order to meet specialized needs.

Sometime in the 1960s, the concept of microwave integrated circuits was introduced. Instead of building individual microwave components separately and then connecting them on a piece-by-piece basis, it was thought cost effective to laminate or print an entire circuit on a single dielectric substrate with individual components (such as filter, coupler, etc.), connected to each other in a continuous integrated fashion. Miniaturization of the circuit was possible by meandering the connecting microstrip lines. Also by using high dielectric-constant substrates, the same electrical size could be achieved while maintaining smaller physical dimensions. The transmission-line components were printed on a hard dielectric substrate by photolithographic processes, and they constituted a major portion of the circuit. Other passive components, such as chip capacitors or chip resistors, and any active components, such as diodes or transistors, were discretely mounted on the circuit board. In this sense the MICs are really "hybrid" integrated circuits. The substrate materials commonly used include alumina, sapphire, low-loss plastics (fiber reinforced), and ceramics. Though such MICs are much more cost effective and compact, compared with bulky waveguide circuits, the density of circuits that can be implemented is strictly limited by the precision required in the manual placement of discrete components. Small to moderately complex circuits are implemented in this manner. Complexities could be increased, however, by using double-sided or multilayered circuit boards.

It was natural then to try direct integration of microwave semiconductor devices together with the printed transmission line components on the same substrate (i.e., in a "monolithic fashion"), in order to implement active as well as passive circuit functions. This generation of integrated circuits was called MMIC (monolithic microwave integrated circuits) (2). The result was a dramatic reduction in size, allowed increased circuit complexity, and reduced cost. The substrate material needed for MMICs must be a semiconducting material, such as GaAs or Si, on which both active and passive components can be printed. As a result, the fabrication cost is increased, while allowing batch-processing of significantly more complex and compact circuits, compared to the hybrid MIC. A comprehensive discussion of monolithic microwave integrated circuits, specifically those based on GaAs material, is available in Refs. 3 and 4.

As the acronyms suggest, the MIC and MMIC are meant for applications in the microwave range. The basic concepts of the technology are similar for applications in the millimeter-wave range, except for the need to maintain tighter dimensional tolerance in the fabrication process due to smaller wavelengths at these frequencies. A more specialized category of monolithic integrated circuits was then developed specifically for applications in a broader frequency band covering the millimeter-wave range. Though MMICs may generically refer to the microwave as well as the millimeter-wave range, a different acronym, MIMIC (microwave and millimeter wave monolithic integrated circuits) is sometimes used to cover millimeter-wave applications.

MICs, MMICs, and MIMICs are now rapidly taking on new meanings and employing new materials, 3-D integration, integration of antennas, optical and optoelectronic components, high-speed digital circuits, and other specialized functions. Circuits and systems of greater complexity may be implemented on a single chip or module, consisting of multiple MMIC or MIMIC chips interconnected and packaged together in a hybrid MIC form [called a multichip module (MCM)] (1). The entire circuit or system may also be integrated through a batch process using multilevel processing technology. With the objective merging of these sister technologies, all related technologies for large-scale integration of circuits and systems operating in the microwave to millimeter-wave range are generally referred to as "microwave and millimeter-wave integrated circuits"—generically called by the common acronym MMIC. The applications may even cover the lower radio frequency (RF) range.

In the following sections the essential building blocks of MMIC, such as the substrate material and parameters, transmission line geometries, passive and active components, integrated antennas, integration architectures, and packaging concepts are discussed.

THE SUBSTRATE

The choice of a proper substrate for MMICs is conditioned by several factors, including dielectric constant, resistivity, thermal characteristics, mechanical strength, and fabricational tolerance. For hybrid MICs the required characteristics are low-loss, low-cost, and mechanically rigid insulating materials, such as alumina or soft-plastic substrates. Alumina is a ceramic-type material with relative dielectric constant, ϵ_r = 9.7. Teflon and similar types of soft-plastic materials can provide ϵ_r values ranging from 2 to 11. Usually the higher dielectric-constant substrates are preferred because they reduce the wavelength of propagation, which results in smaller-size circuits. However, for higher-frequency applications (20 GHz or higher), where the wavelength is already small and fabrication of very small-sized circuit components is a problem, a high dielectric-constant substrate may not be desirable. Substrates of lower dielectric constant may be more useful in this high-frequency range. This results in increased wavelength allowing the design of larger-size circuit components, so that inaccuracies in dimensions during the fabrication process can be better tolerated.

For monolithic microwave circuits, where active devices have to be fabricated together with passive components, the substrate will have to be a semiconductor. Si and GaAs are the most common types of substrate materials in use. Two factors become important in the selection of a semiconductor substrate for MMICs: (1) higher substrate resistivity, in order to achieve low propagation loss, and (2) higher carrier mobility, in order for the active devices to operate at higher frequencies. Si and GaAs, in their semiconducting states, cannot maintain high resistivity. Therefore, the base substrate must be in an insulating (or semiinsulating) state with higher resistivity levels, on which the passive microwave circuits can be printed. Then active devices are grown on the same base substrate in isolated regions, using ion implantation or epitaxial techniques. Table 1 lists the material parameters of various substrates pertinent to MMICs. It is seen that the electron mobility of GaAs is more than five times that of Si, and that the semiinsulating GaAs has a much higher (100 times or more) resistivity compared with that of Si, thus making GaAs a better choice for MMICs (3,4). However, compared with GaAs, Si fabrication technology is much more mature, owing to its extensive use in digital electronics. Also, as discussed earlier, in modern MMICs it is desirable to fabricate digital circuits for peripheral processing and control functions together with microwave circuits. The above situation makes it more compelling to try to use Si for MMICs. In this pursuit, the higher propagation loss due to lower values of resistivity of semiinsulating Si is a major hurdle. This problem is overcome by using silicon-on-sapphire (SOS) technology, where the base substrate is made out of low-loss sapphire, instead of the lossy semiinsulating Si. Even then, the SOS technology, due to lower carrier mobility of Si, usually finds application

Table 1. Properties of Semiconductors and Insulators Used in Microwave and Millimeter-Wave Integrated Circuits

Type of Substrate	Relative Dielectric Constant (ε_r)	Resistivity (ρ, Ω cm)	Electron Mobility μ_n, cm^2/V	Thermal Conductivity k, W/cm °K
Semiconductor				
Si	11.7	—	800[a]	1.45
Semiinsulating Si	11.7	10^3–10^5	—	1.45
GaAs	12.9	—	4300[a]	0.45
Semiinsulating GaAs	12.9	10^7–10^9	—	0.45
InP	12.6	—	—	—
Insulator				
Alumina	9.7	10^{11}–10^{14}	—	0.37
Sapphire	11.6	$>10^{14}$	—	0.46
Soft-plastic PTFE/glass	2–10	$>10^{13}$	—	0.002–0.004

[a] At $10^{17}/cm^3$ doping.

at lower frequencies (several gigahertz), leaving GaAs as the principal choice for the millimeter-wave range.

Assuming a printed microstrip line as the transmission line-of-choice for signal distribution in a MMIC, Fig. 2 shows the signal attenuation constant α for different substrates as a function of frequency. A set of parameters of practical interest to MMICs were chosen for these data, assuming copper to be the conducting medium. As seen in Fig. 2, the semiinsulating Si is the most lossy, SOS and GaAs are comparable in their loss performance, whereas alumina substrate provides the lowest loss. It turns out that for SOS, GaAs, and alumina substrates, the loss is dominated by the metal loss, not by loss in the substrate material. For semiinsulating Si, however, the loss in the substrate material contributes significantly to the total loss.

Besides material loss in the substrate, the substrate parameters influence the power lost to radiation in the form of "surface-waves" generated at various transmission-line junctions and circuits. The substrate thickness and the dielectric constant are the governing parameters. Figure 3 shows the effective dielectric constant, $\epsilon_e = (\lambda_0/\lambda)^2$, of the fundamental and the first higher-order surface-wave modes, where λ_0 is the wavelength in free space, and λ is the wavelength of the surface-wave mode (5). The fundamental mode propagates for all frequencies, whereas the higher-order mode has a cut-off frequency. In order to avoid excessive surface-wave loss, the cut-off thickness ($d = d_c$) of the substrate at which the second higher-order mode is excited is often used as a reference value for design of the substrate thickness. As a general rule, up to one-third of the critical value d_c can be safely used and will yield reasonable levels of surface-wave loss. This amounts to maximum practical thicknesses of about 725 μ at 10 GHz, and 244 μ at 30 GHz, for GaAs, and somewhat higher thicknesses for Si and alumina. These thicknesses do not usually pose a manufacturing problem for monolithic circuits, but can

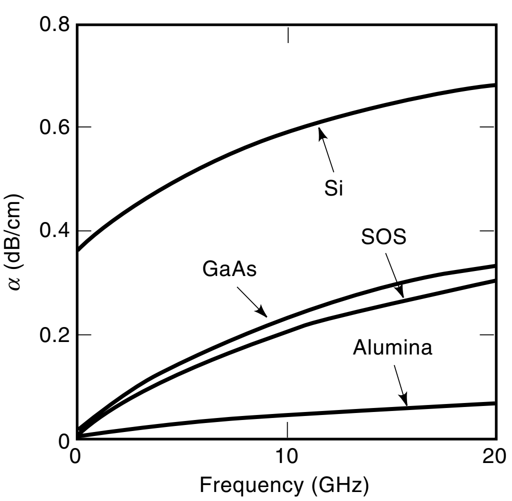

Figure 2. Attenuation (α) in a microstrip line with different substrate materials [semiinsulating Si and GaAs, indicated simply as Si and GaAs, SOS (silicon-on-sapphire), and alumina] as a function of frequency. All lines have approximately 50 Ω characteristic impedance. Alumina substrate thickness H = 500 μ (for hybrid circuits), and for all other substrates H = 100 μ. Resistivity of SOS = 10^{14} Ω cm; for semiinsulating GaAs = 10^7 Ω cm; for semiinsulating Si = 10^3 Ω cm; and for alumina = 10^{11} Ω cm. Line width W: SOS and semiinsulating Si, 80 μ; semiinsulating GaAs, 70 μ; alumina, 500 μ. Conducting medium is assumed to be copper.

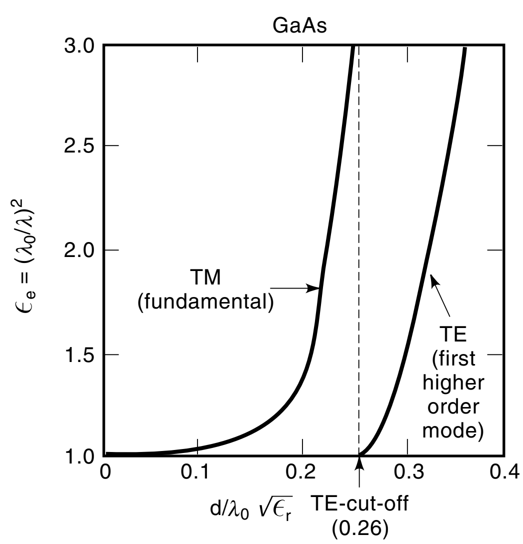

Figure 3. Dispersion characteristics for the fundamental (TM) and the first higher order (TE) mode of a GaAs substrate with a metalized ground plane on one side, used in MMICs. The cut-off value of $\sqrt{\epsilon_r}d/\lambda_0$ for the first higher order TE mode is 0.26. The dispersion characteristics for Si and alumina substrates are very similar to that of GaAs, with the corresponding cut-off numbers for the first TE modes equal to 0.261 and 0.264, respectively.

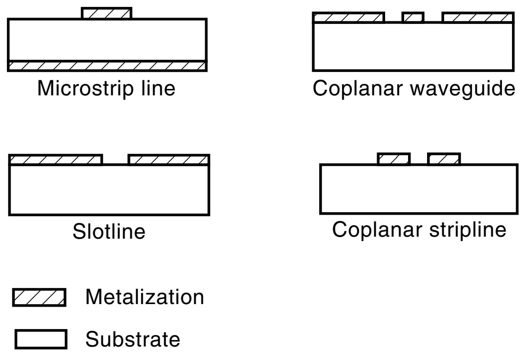

Figure 4. Different configurations of printed transmission lines (cross-sections) currently used in MMICs. The slotline and coplanar waveguides may sometimes use a conductor backing under the dielectric substrate for added mechanical support, but require careful design (8,9,30). Other variations of the above transmission lines with multilayer substrates are also useful.

be an important consideration for mechanical strength in hybrid MICs.

CHIP SIZE AND CIRCUIT COMPLEXITY

An estimate for the circuit complexity one can achieve in a MMIC of a certain size, at two selected frequencies—3 GHz for lower-frequency and 30 GHz for higher-frequency applications—is presented here. A Si substrate is assumed for calculations, but the estimates should be close for GaAs and alumina, since these materials have similar dielectric constants. At 3 GHz, a microstrip transmission line on Si has a guide wavelength $\lambda \simeq 4$ cm. The distributed “subcircuits” are assumed to be $\lambda/4 \times \lambda/4 \simeq 1$ cm $\times$ 1 cm in size (these are typical dimensions for distributed circuits) and therefore occupy most of the substrate area. If a mixture of 20% distributed functions and 80% lumped-circuit functions (of size 1 mm $\times$ 1 mm) are used, a 2 in. $\times$ 2 in. substrate can accommodate about 120 circuits or, equivalently, about 60 circuit functions if a factor of 2 is used to account for additional space required between components, to avoid intercomponent coupling. At 30 GHz, on the other hand, the distributed and lumped circuits are comparable in size, i.e., $\lambda/4 \times \lambda/4 \simeq 1$ mm $\times$ 1 mm. This will yield about 1300 circuit functions on a 2 in. $\times$ 2 in. substrate, taking into account a factor of 2 for additional intercomponent spacing. These figures are indicative of a low level of integration density in MMICs, compared with that achievable in digital integrated circuits. This fact strongly motivates the use of multilevel integration by stacking circuit layers with proper electrical isolation between layers. Though this stacked integration leads to other constraints, it can potentially increase the effective circuit density several times, while also allowing convenient integration as well of other functions (digital, optical, antennas, etc.) on independent layers.

TRANSMISSION MEDIA

Figure 4 shows various configurations of printed transmission lines that are used in MMICs (6,7). Other variations of these transmission lines with different arrangements of the dielectric substrates or metal planes are also useful. For example, the slotline or coplanar waveguide may be used with a conductor back plane for added mechanical support and increased signal isolation (8,9). Among the geometries in Fig. 4, the microstrip line is the most commonly used transmission line for MMICs. However, under certain situations other geometries may be more suitable. Table 2 compares the practical features of various transmission lines. Specific technical details of the transmission lines can be obtained for microstrip (10,11), coplanar waveguide (12,13), and slotline (14).

In the following, basic design data are provided, and important design considerations for MMICs are discussed, based on requirements for the transmission line used. Microstrip line is assumed as the transmission line of choice. Figures 5(a) to 5(e) present data for various useful transmission line characteristics for GaAs, Si, and alumina substrates.

Figure 5(a) shows variation of the characteristic impedance Z_c of a microstrip line as a function of W/H, while keeping the substrate thickness H fixed, for different substrate materials. Data are plotted for values of W/H around 1, where the characteristic impedance is nominally 50 Ω. The characteristic impedance reduces for larger values of W/H, owing to an increase in the effective capacitance between the line and the ground plane. Figure 5(b) shows the attenuation constant owing to material loss for the same parameters of Fig. 5(a). As can be seen from Fig. 5(b), the loss increases sharply for smaller values of W/H, making small values of W/H undesirable. In order to maintain compactness of integration the upper limit of W/H is restricted—a reasonable upper limit for W/H is four. The aforementioned constraints in W/H limit the range of Z_c values that can be practically attained to about 10 Ω to 100 Ω.

Figure 5(d) shows the variation of attenuation constant for different values of substrate thickness H, while maintaining a 50 Ω line (with properly adjusted line width W). These data show that material loss sharply increases as the substrate thickness is reduced. Therefore, the choice of substrate thickness H below a certain limit is not desirable. It may be recalled that the upper limit for H is restricted, in order to minimize excitation of substrate modes.

Table 2. Characteristic Features of Common Printed Transmission Lines

Type of Line	Z_C (Ω)	Loss	Dispersion	Connect Series Element	Connect Shunt Element	Discontinuity Radiation
Microstrip line	10–100	Low	Low	Easy	Difficult	Low
Coplanar waveguide (CPW)	20–150	Medium	Medium	Easy	Easy	Low
Coplanar stripline (CPS)	40–250	Medium	Medium	Easy	Easy	High
Slotline	60–250	High	High	Difficult	Easy	High

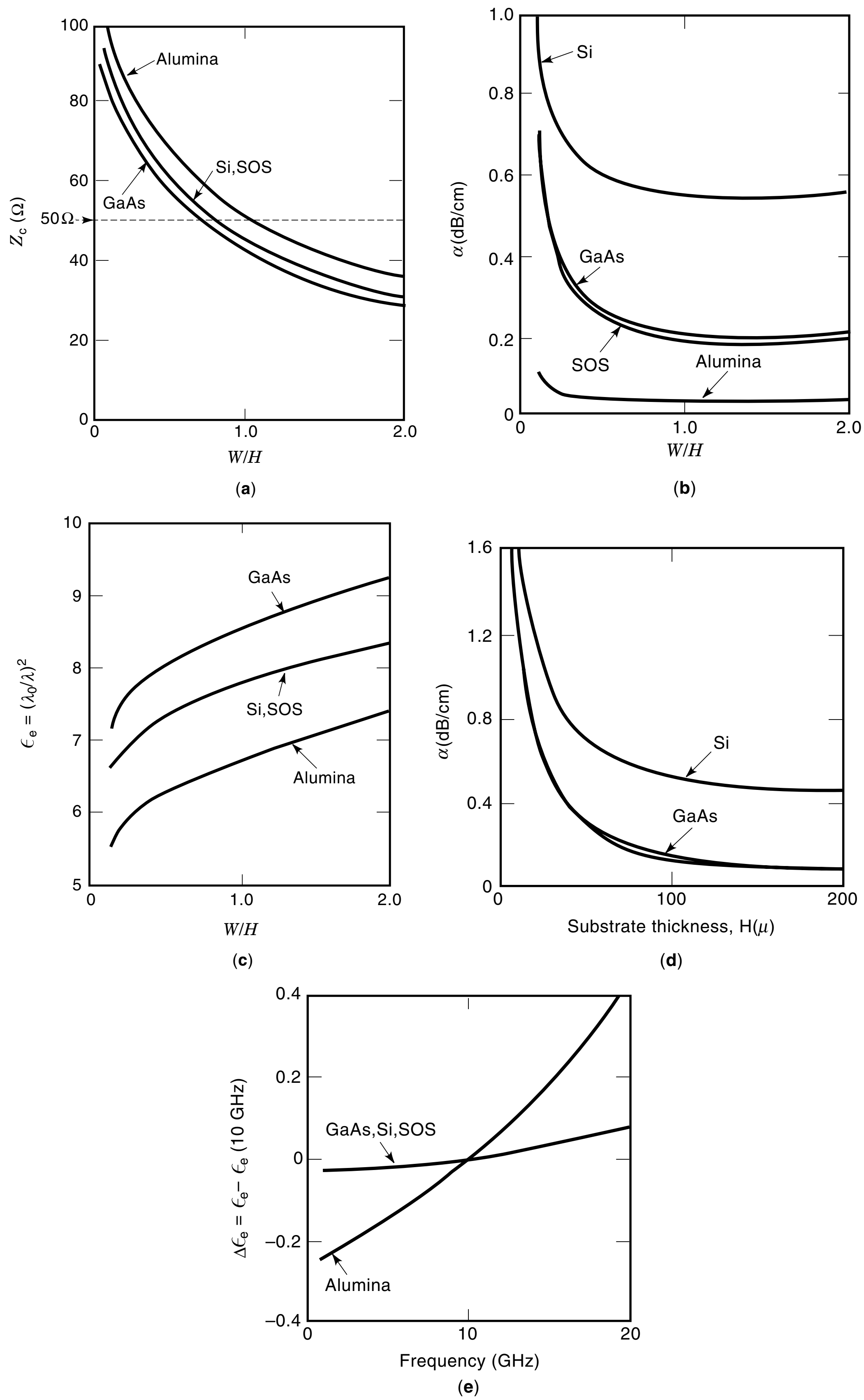

Figure 5. Variation of (a) characteristic impedance Z_c; (b) attenuation constant α; and (c) effective dielectric constant $\epsilon_e = (\lambda_0/\lambda)^2$, as a function of W/H for the substrates of Fig. 2, but with frequency = 10 GHz. Variation of α for semiinsulating Si and GaAs substrates (characteristics for SOS and alumina are close to that of GaAs) as a function of substrate thickness H (with W selected for different H to have Z_c = 50 Ω) at 10 GHz is plotted in (d). Frequency variation for the ϵ_e of (c) is plotted in (e), in order to show dispersion behavior.

The microstrip line, like other printed transmission lines used in MMICs, does not support the TEM (transverse electromagnetic) mode. This is so because the material medium around the transmission line is not uniform—it is partly air and partly the substrate material. As a result, the transmission line is dispersive. The effective dielectric constants, ϵ_e, of microstrip lines on different MMIC substrates are shown in Fig. 5(c). As should be expected, the effective dielectric constant lies between 1.0 and ϵ_r of the substrate material. The actual value depends on the electrical "filling factor" of the substrate. This filling factor increases with increased W/H. This is because as W/H increases, the fraction of the total electric field confined in the dielectric material increases, allowing only a small fraction to fringe out into the air medium. Figure 5(e) shows the dispersion behavior of ϵ_e for the same parameters of Fig. 5(c), but keeping the line width W fixed. Notice that the dispersion is stronger for the line on an alumina substrate. This is because the alumina substrate chosen for the data in Fig. 5(e) is much thicker than is the case for Si or GaAs. Dispersion worsens for thicker substrates. This is also a consideration that limits the substrate thickness to smaller values.

Besides the restriction on the line width and substrate thickness, it is important to consider the constraint on the spacing between two adjacent lines. The lower limit of the line-to-line separation determines the minimum level of isolation that can be maintained between nearby circuits. This consequently restricts the compactness of integration. Figure 6(a) plots the electric field of a 50 Ω transmission line on a GaAs substrate as a function of distance Δ (normalized with respect to the line width W) from the center of the transmission line in the transverse direction. The field rapidly drops beyond the region below the line. At a distance four times the line width W the field strength drops to about 3% of its peak value. In order to achieve this high level of isolation one must, therefore, maintain a center-to-center separation S between two lines of about eight times the line width W ($7W$ for edge-to-edge separation). For a 10% field isolation the corresponding value for center-to-center separation is about $4W$. Figure 6(b) illustrates how the above field coupling translates to coupling of signal power, as a function of edge-to-edge separation S between lines. For $S/W = 3$ one can achieve better than about 25 dB isolation, which can be increased to about 30 dB for $S/W = 4$. In most practical applications an S/W ratio greater than 3 provides reasonable isolation.

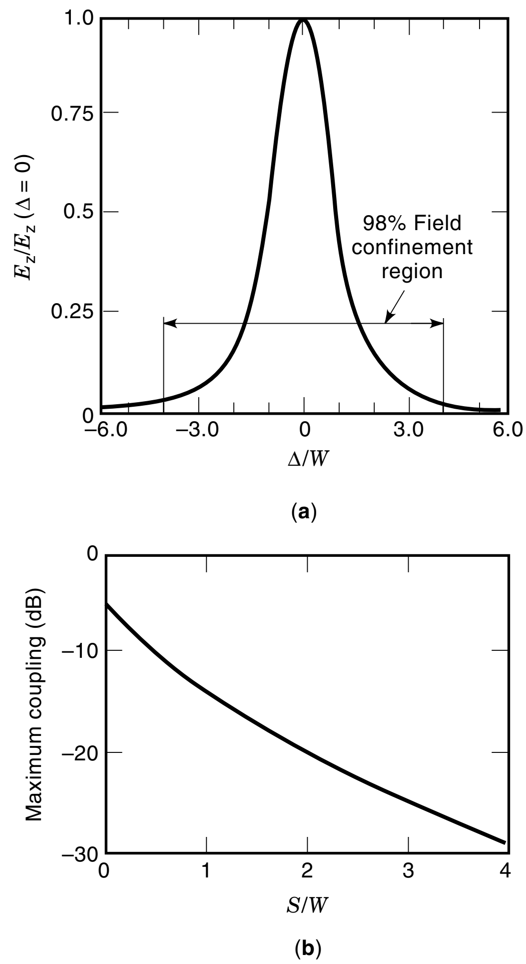

Figure 6. (a) Variation of the field strength of normal (to the substrate) component of electric field of a 50 Ω microstrip line on a 100 μ-thick GaAs substrate, sampled at the bottom ground plane, plotted as a function of the distance Δ from the center of the line. Width W of the line is 70 μ, and frequency = 10 GHz. (b) Level of power that can be coupled from a signal line to a nearby line as a function of edge-to-edge separation S between the lines. It is assumed here that the signal line is matched to the source and terminated by the characteristic impedance of the line. The coupled line is also match terminated at both ends. Here the maximum level of power that can be coupled between the lines, which occurs when the line lengths are odd multiples of λ/4, is plotted. Such characteristics also generally apply to other substrates and frequency, and are useful to determine the minimum separation one must maintain between lines in an MMIC in order to maintain a minimum level of isolation.

PASSIVE COMPONENTS

Some of the passive components commonly used in MMICs include (1) resistors, (2) capacitors, and (3) inductors. These components can be implemented in lumped form if their physical size can be maintained sufficiently small (< λ/10) compared to the operating wavelength λ. Otherwise, "distributed" behavior becomes more pronounced, and therefore the components no longer operate as normally expected. The lumped condition is more easily satisfied at lower microwave frequencies (where λ is larger), making the use of such lumped components more practical in this range. Except for resistances, the inductive and capacitive elements can also be realized in distributed form, using a transmission-line stub of a certain length. As a basic principle, however, the lengths of such distributed components are proportional to the operating λ. At a low operating frequency, where the operating wavelength may be too large, the required large length of the distributed components can make it difficult to implement in an MMIC. Therefore, the use of the distributed elements in MMICs is limited only to the higher-frequency range (where the wavelength is sufficiently small). In the intermediate frequency range (around 10 GHz to 20 GHz) a mixture of lumped and distributed components may prove useful.

Besides implementing simple inductances and capacitances in distributed form, a variety of other circuit functions, e.g., delay lines, couplers, resonators, and filters can only be implemented in distributed form. Transmission line segments

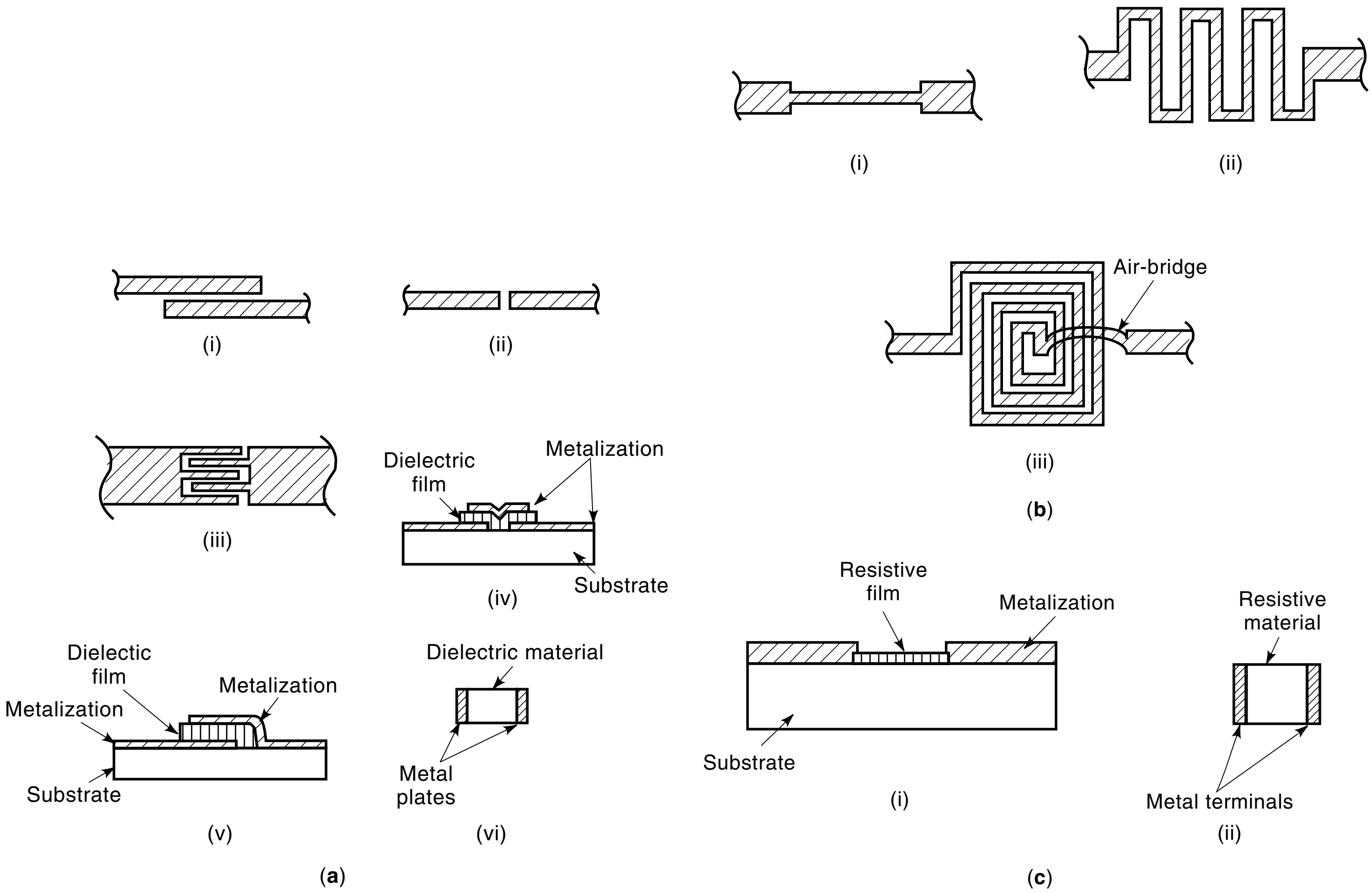

Figure 7. Various configurations of lumped passive components used in MMICs. (a) Capacitors in different forms: (i) edge coupled, (ii) end coupled, (iii) interdigitated, (iv) end overlay, (v) overlay, and (vi) chip capacitor. (i) to (iii) are planar forms showing the top view of the metalizations, whereas (iv) to (vi) are nonplanar components showing their side views. (b) Planar inductors in different forms: (i) using a straight section of a high-impedance transmission line, (ii) meander line-type, and (iii) spiral inductor with an overbridge connection. (c) Resistances in two forms: (i) film resistance and (ii) chip resistance.

are interconnected in a variety of arrangements to achieve circuit functions that are useful in many microwave applications. However, all such distributed circuit elements are essentially transmission line metallizations, which can be fabricated in a MMIC similar to other metal interconnections. The various lengths and widths of transmission line segments required can be designed using distributed circuit theory discussed in (15,16).

In the following only lumped circuit elements as used in MMICs will be discussed. Figure 7 shows various configurations of MMIC lumped components, some of which may be relevant to hybrid-type integration, and others to monolithic integration.

Capacitors

Figure 7(a) shows useful configurations of capacitance components used in MMICs: (1) edge-coupled, (2) end-coupled, (3) interdigitated, (4) end-coupled overlay, (5) overlay, and (6) chip capacitance. Of the above, (4) and (5) are relevant only to monolithic integration, (6) only to hybrid MIC configuration, and the others can be implemented in either monolithic or hybrid form. All capacitances shown in Fig. 7(a) are essentially series-type circuit elements, but a shunt-type capacitance can be realized by connecting a via-hole to one of the terminals. Up to about 1 pF capacitance can be achieved using an edge-coupled or end-coupled design, with some higher values possible from an interdigitated configuration. Capacitance values in the range of 10 pF to 30 pF can be realized by overlay-type designs, which are useful for RF-bypass or dc-blocking applications. Much higher values can be implemented only in discrete chip form, which can be used in hybrid MICs, but not in monolithic form.

The edge-coupled, end-coupled, and interdigitated capacitors are implemented in MMICs as two metallized lines with a suitable gap(s) maintained between them. No additional dielectric film is required. In all other designs in Fig. 7(a) an additional dielectric film is needed. In a monolithic fabrication process such film-capacitances are realized by controlled deposition of dielectric films of required thickness. Some important considerations for the dielectric films to be used include: (1) dielectric constant of the material (and hence the capacitance values that can be achieved per unit area), (2) compatibility with monolithic fabrication process, (3) microwave losses, and (4) breakdown field. The capacitance would exhibit some resistive behavior in the microwave frequencies, due to (1) losses in metal and dielectric film, and (2) radiation into the free-space and/or substrate medium. Q-factors of the order of 50 to 100 can be achievable in the X-band (10 GHz). Distributed effects are always present, to some extent, resulting in deviations from lumped behavior of the device. These effects may be taken into account through the use of computer-aided modeling and design.

Inductors

Figure 7(b) shows different configurations of MMIC inductors: (1) using a high-impedance line, (2) a meander-line type, and (3) a spiral-type, among which the spiral-type allows a higher range of inductance that can be achieved. All such inductors are implemented in a planar metallized form, and, thus, can be used in hybrid or monolithic integration. In the spiral-type inductor one would need an air-bridge to connect to the center of the spiral. This would require an additional fabrication step in monolithic form, or could be manually established in a hybrid MIC. The operation of all inductance elements is based on the production of strong magnetic stored energy in the vicinity of the device (equivalent to the operation of a coil in audio or RF circuits). The goal here is to achieve high inductance within a small physical space.

Unavoidable capacitive effects are also present in the planar inductor design, due to edge coupling between lines and the presence of the ground plane under the metal lines. This is in addition to resistive effects owing to material loss (metal and dielectric), as well as radiation. Therefore, the planar inductor does not behave like an ideal inductance, but needs to be treated as an R–L–C resonant circuit, with a dominant inductive effect in the operating frequency range. All the nonideal factors must be carefully accounted for, requiring the use of accurate computer-aided modeling tools. Inductance values on the order of 10 nH can be achieved using planar spiral inductors, with Q-factors on the order of 50 in the X-band. These values are useful for RF isolation/bypass purposes. The use of inductors requiring higher inductance values should be avoided in MMICs.

Resistors

Figure 7(c) shows two general classes of MMIC resistors: (1) the resistive film element, and (2) the chip resistor. Chip resistors find application only in hybrid circuits, while the film resistors are convenient to implement in monolithic circuits. The resistors are useful in resistive loading and match termination elements. Resistances requiring high power dissipation (e.g., in dc biasing) should be avoided in MMICs.

The resistive film used in a film-type resistor can be realized by the deposition of a lossy-metal film or a semiconductor film. A lossy-metal film of an appropriate material can be deposited in the MMIC fabrication process, in a manner similar to the fabrication of a film capacitance. Important considerations for the choice of the lossy-metal film are: (1) sheet resistivity (which determines the resistance per unit length), (2) thermal variation of resistivity, and (3) compatibility with MMIC fabrication. The resistive film may also be realized in an MMIC using a semiconductor process, similar to that used for active devices. The doping level in the semiconductor controls the resistance value, which can be realized using an epitaxial or implantation technique. The use of metal films for resistors is usually preferred over semiconductor films, owing to nonlinearity behavior of the latter at high current values and poor thermal stability. Nonideal effects common to both types of film resistors include additional capacitive effects between the film and the ground plane, inductive effects of the metal connection, and some radiative effects. This results in frequency dependence of the performance, which must be properly accounted for in the design process.

Other Passive Elements

Besides the aforementioned passive circuit components, other passive circuit configurations such as (1) junctions between transmission lines, (2) transmission line bends, (3) vias, and (4) open ends, which are frequently used in MMICs, need to be considered. These are generally called "discontinuity" elements, whose presence is not desirable but inevitable in MMICs. The discontinuity elements can be modeled as R–L–C equivalent circuits, using a computer simulation or some approximate theoretical approach. Whenever possible, their unwanted effects should be minimized by proper design of the discontinuity itself, or through compensation within the design of the rest of the circuit.

It is desirable to integrate antenna elements together with other microwave circuits in an MMIC. This approach is particularly attractive in large integrated phased-array radars, in order to avoid the complexity of fabricating the circuits and antenna elements separately and then manually connecting them. Although current applications of MMICs in the wireless communication industry are growing, large phased-array radars are still the major driving force behind MMIC technology. The microstrip antenna (17) is the most suitable candidate for such integration. This is mainly because of the planar nature of microstrip antennas, which can be fabricated with an MMIC process in a manner similar to other metallizations. The basic geometry of the metallization structure of a microstrip antenna, which can be connected to the rest of the MMIC by a microstrip line, is shown in Fig. 8(a). The radiation from this microstrip antenna is along the broadside direction (outward, perpendicular to the substrate). Sometimes it may be preferable to have the antenna element radiate along the endfire direction (along the substrate plane). Figure 8(b) shows one such printed antenna configuration, called a tapered-slot antenna (18). The tapered-slot antenna shown in Fig. 8(b) is fed by a slotline, and radiates to the right along the plane of the substrate.

One of the drawbacks of integrating antennas with MMICs is that it often occupies significant space on the valuable semiconductor substrate. Another problem is that since the MMIC substrate is normally optimized for circuit functions in order to minimize radiation from the circuit components, the same substrate cannot at the same time be optimal for antenna radiation. Certain techniques may sometimes be used to provide a compromise between both functions. In such a situation, a multilevel integration, as shown in Fig. 8(c) is desirable, where the antenna is fabricated on a cheaper dielectric substrate, independently optimized for antenna radiation, retaining the valuable semiconductor substrate only for circuit integration. The common metal plane between the antenna and circuit layers serves as the ground plane for both.

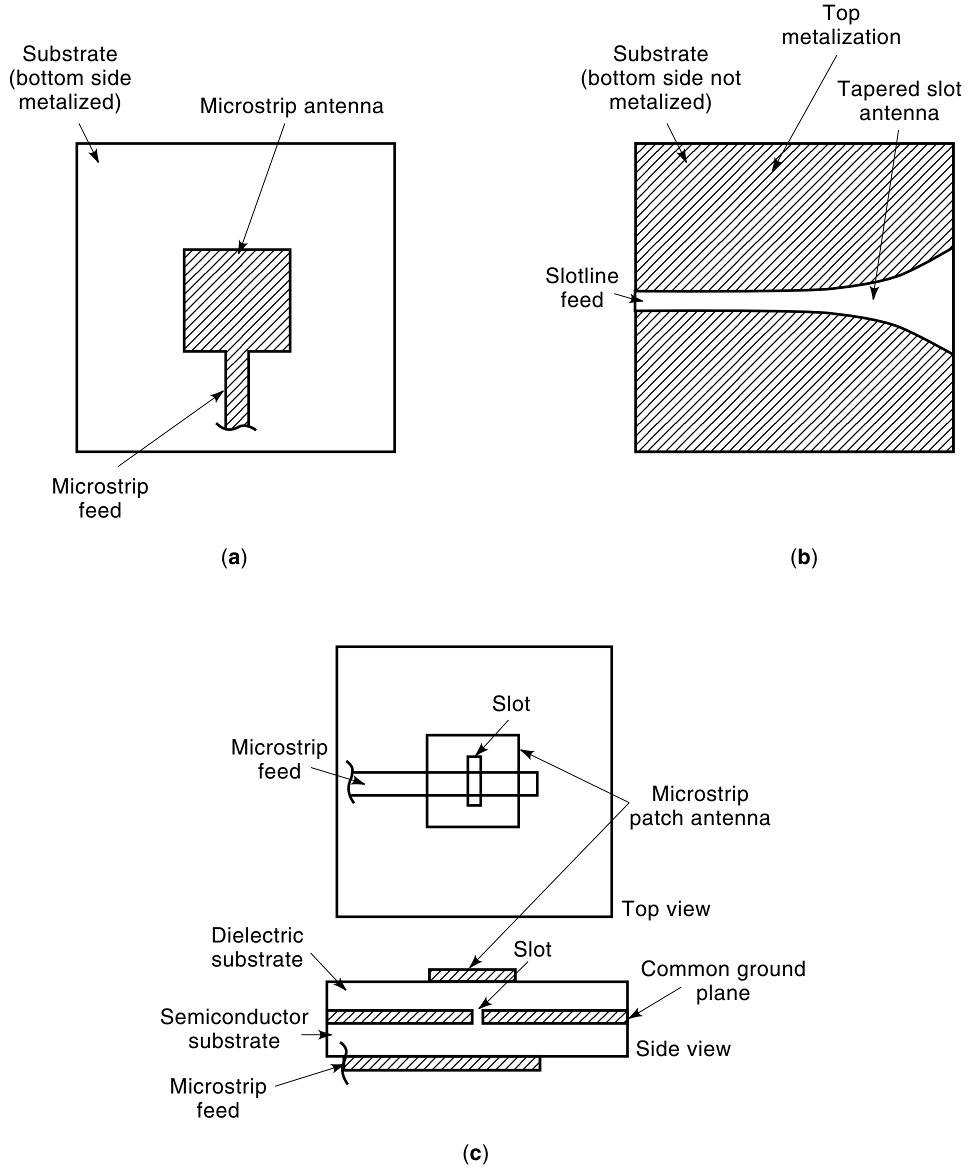

Figure 8. Geometries of printed antennas that can be integrated together with MMICs. (a) A microstrip line-fed printed antenna (shows top surface) for radiation normal to the substrate. (b) A coplanar stripline-fed printed tapered-slot antenna (shows top surface), which radiates along end-fire direction, (toward the right side along the substrate plane). In (a) and (b) the antenna and microwave circuitry are printed on the same substrate, whereas (c) shows an aperture-coupled microstrip antenna, where the antenna is printed on a different substrate layer, coupled to the microwave circuit layer through an aperture on a common ground plane.

It may be noticed in Fig. 8(c) that the antenna and circuit layers are electrically isolated from each other by the common ground plane, while they are "electromagnetically" connected between each other only through a small slot etched on the ground plane (19). This idea can be naturally extended to more layers, with possibly more than one antenna layer, or an additional dielectric layer for distributed feeding circuitry, thus reserving the bottom semiconductor layer mostly for active functions.

ACTIVE DEVICES AND PROCESSING

For hybrid-type integration there is flexibility gained in using heterogeneous active components such as bipolar or field-effect devices, and two or three terminal devices. However, uniformity must be maintained in the type of active devices one might use in monolithic integration. In the following the active device and fabrication process used in monolithic MMICs will be discussed. Some early forms of MMICs used two-terminal active devices, such as Schottky and Gunn diodes. Modern MMICs use MESFETs (MEtal Semiconductor Field Effect Transistor) as a versatile active component (20). MESFETs are convenient to fabricate in an MMIC process, and are known to provide good performance in implementing a large class of active circuits, including specialized amplifiers with low-noise, high-gain, and broadband features, as well as mixers, switches, oscillators, and phase shifters. The power levels that can be achieved from a single MESFET amplifier or oscillator are low to moderate. Power may be increased by use of on-chip power combiners. However, operation of MMICs should be limited to moderate power levels, to avoid problems associated with heat dissipation. Power outputs on the order of 10 W can be realized from a single chip using power-combining techniques. For a detailed theory of MESFETs one may refer to texts on semiconductor devices (20–22). Theoretical work and practical techniques for the design of microwave active circuits can be found in (15,23–25).

The MMIC fabrication process starts with a good quality substrate wafer, followed by more than 30 to 40 individual processing steps. For GaAs MMIC, the substrate material is semiinsulating GaAs, whereas in SOS (silicon-on-sapphire) MMIC the base material is sapphire. The specific processing steps for the two cases are different, though they more or less share a major set of common processing techniques. Only the major processing techniques will be briefly discussed. First, an active semiconducting layer, which is needed for active device fabrication, is formed on the substrate. There are two techniques commonly used in forming the active layer: (1) epitaxy and (2) ion implantation, which may be used independently or in combination. In the epitaxial technique, a doped single-crystal semiconducting layer can be deposited on top of a crystalline base substrate. An intermediate high-resistivity buffer layer is used in the epitaxy process, in order to screen out any diffusion of impurity atoms from the substrate into the active layer. There are different types of epitaxial growth processes: VPE (vapor phase epitaxy), MBE (molecular beam epitaxy), and LPE (liquid phase epitaxy), each having different basic advantages and drawbacks. In the ion implantation technique, on the other hand, the dopant atoms can be implanted directly onto a semiinsulating semiconductor substrate, using high-energy impurity ions. This process is quite versatile, and even selective doping profiles at different locations on the substrate may be possible. However, this process requires a base semiconductor substrate with a high state of purity. Therefore, if direct implantation is not practical, an epitaxially grown "buffer" layer on top of the primary substrate may be used as the implantation medium.

Once the active layers are formed using one or a combination of the above techniques, the active device areas are isolated from the surrounding regions, leaving "mesas." This is important for microwave circuits, in order to reduce parasitic coupling to the active components. Mesa isolation may be achieved by deep etching of the substrate around the active area. The mesa-etching process may be substituted by implantation of oxygen onto the epitaxial layer surrounding the active device region. The oxygen implantation creates the required high-resistivity barriers. This process is called isolation implant, which essentially uses the epitaxial deposition in combination with selective ion implantation.

Next, ohmic contacts to the active areas are made to provide source and drain contacts for the MESFET. The standard approach involves alloying of Au (gold) or AuGe (gold-germanium) onto the substrate. This results in a heavily doped region under the contact, which facilitates establishing the ohmic junction. The gate regions of the MESFET are then processed. The gates are Schottky-type contacts, which are formed by depositing Ti-Pt-Au (titanium-platinum-gold compound). Because the gate regions are usually small (1 μ or less), this calls for high alignment accuracy in the lithographic patterning process. Some form of lithography (optical or electron-beam) is needed here, as well as in other fabrication steps, for accurate definition of devices and the interconnection layout.

At this stage the active device processing is essentially completed. The active devices are now subjected to on-wafer dc and microwave tests. Wafers that do not meet process control specifications are rejected, in order to avoid any subsequent processing costs. Following this, the first layer of metallization is deposited for external contacts, transmission line interconnections, spiral inductors, and distributed circuits. Then, thin films of appropriate resistive or dielectric materials are deposited to form thin-film resistors and capacitors. Resistors may also be realized using semiconductor material in the initial epitaxial or implantation process. Then a second layer of metallization is deposited to connect thin-film capacitors, and to form cross-overs or other miscellaneous connections. The two-level metallization process allows topological flexibility in the circuit layout. Some of the functionalities of the first- and second-level metallizations may be interchanged as needed.

The final steps in the MMIC fabrication involve back-plating of the substrate, in order to provide the ground plane for the circuit. The thickness of the substrate is critical for maintaining correct values of characteristic impedance of the transmission-line components. Therefore, the back side of the wafer must be "thinned" in a controlled manner. The entire backside is then metallized. Ground connections from the bottom metal plane to the circuits on the top surface are provided through "via-holes". This is possible by the etching of through-holes at required locations and then metallizing the inner surface of the hole. Wet-chemical etching, reactive ion etching (RIE), or combinations thereof are used.

It may be mentioned that much of the technologies used for MMIC fabrication have been adapted from well-established techniques used in the silicon digital IC industry. Each processing step needs to be optimized for MMIC application, however—particularly for GaAs MMIC (4). Figure 9 shows photographs of two integrated circuits fabricated in hybrid and monolithic processes.

COMPUTER-AIDED DESIGN

It is virtually impossible to design complex MMICs through an experimental trial-and-error procedure. Except for a few simple MMIC components, analytical formulas are not available for accurate design. This is owing to the complexity of electromagnetic interactions in and between different MMIC components. Because of the nature of MMIC fabrication, any "tuning" after fabrication would also be quite difficult or impossible. From the above considerations, computer-aided simulation and design (26) play a critical role in the successful design of MMICs.

The computer-aided simulation tools for MMICs that are currently available may be classified into four broad categories: (1) purely circuit-based tools, (2) circuit-2D tools, (3) circuit-2.5D tools, and (4) full EM-based tools or 3D-EM tools. Purely circuit-based tools perform simulations employing simple circuit theory, which requires the user to provide an equivalent-circuit model for individual components, valid for the microwave frequency-range of operation. As a result of the relative simplicity of the circuit theory used in simulation, such tools are computationally fast (particularly for linear circuits), but electromagnetic interactions cannot be properly modeled. This approach has only limited use, because accurate equivalent-circuit models for MMIC components are often not available. On the other hand, purely EM-based tools can rigorously model all electromagnetic interactions in an MMIC, and can handle arbitrary geometries of components, package structures, and microstrip antennas. This is accomplished by treating the entire chip as a 3-D (3-dimensional) electromagnetic system and, therefore, such tools may be called "3-D-EM" tools. However, compared with purely cir-

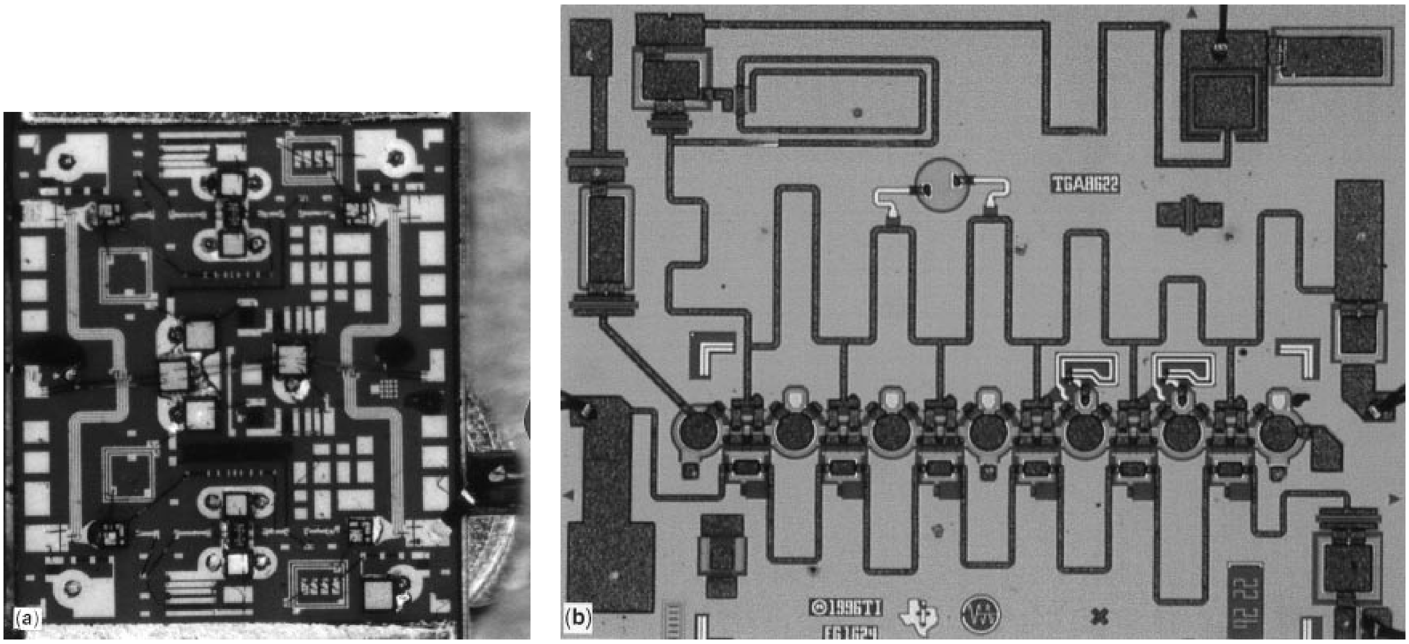

Figure 9. Photographs of commercially used hybrid and monolithic microwave/millimeter wave integrated circuits: (a) A balanced amplifier operating in the 2 GHz to 8 GHz frequency range, consisting of printed Lange coupler, FETs and associated power supply and biasing circuits (film/chip resistance, chip capacitance, and printed inductance) integrated in a hybrid MIC form. Actual size is $\frac{3}{8}$ in. $\times$ $\frac{1}{8}$ in. (Picture courtesy of Mini-Circuits, Brooklyn, NY.) (b) A GaAs traveling-wave MMIC amplifier (7 dB gain, 18 dBm output power level) operating over a broad bandwidth of 2 GHz to 18 GHz, consisting of six stages of GaAs FETs, printed transmission lines, biasing film resistance, capacitance and printed inductance, integrated in a monolithic MMIC form. Actual size 0.11 in. $\times$ 0.086 in. (Picture courtesy of MITEQ Inc., Hauppage, NY.)

cuit-based tools, the 3-D-EM tools are often computationally quite time consuming. A suitable compromise between the purely circuit-based and purely EM-based (or 3-D-EM) tools is provided by the circuit-2-D and circuit-2.5-D tools, which are based on hybrid circuit-EM models. Compromise between speed and rigor is also achieved, having subgroups among the 3-D-EM tools, depending on the level of rigor, type, and size of geometries the software tools can handle.

In the circuit-2-D tools the parameters of the transmission lines are calculated by treating them as infinite-length lines, which simplifies the problem to a 2-dimensional (2-D) structure. An approximate "quasistatic" or a more accurate "full-wave" approach may be used to this effect (6,15). Coupling between nearby transmission lines can also be incorporated via coupled-line analysis. However, electromagnetic effects of transmission line discontinuities, such as junctions, bends, and open/short circuits, coupling among lumped/distributed components, and the effect of the surrounding package structure, are ignored. The circuit-2.5-D tools, on the other hand, model the electromagnetic effects of the discontinuities, in addition to the transmission line parameters, but still fail to model the electromagnetic interactions among components and package. The term "2.5-D" in circuit-2.5-D tools appropriately suggests that the rigor of EM modeling used here lies somewhere between the circuit-2-D and 3-D-EM tools.

The various commercial CAD tools that are currently available mainly provide simulation capability, where the operator needs to manually iterate the simulation procedure to arrive at a final design. In addition to the simulation, limited design capability may also be available in some cases, where a final design with user-defined parameters can be reached, starting with an approximate design specified by the user. However, owing to the excessive computation needed in design algorithms, such design-oriented tools are mostly circuit-based, with very limited EM-modeling.

The EM-modeling required for different types of MMIC CAD tools can be performed using a variety of numerical techniques. The major techniques include (1) moment method (MM), (2) finite-element method (FEM), (3) transmission line matrix method (TLM), and (4) finite-difference method (FDM). The individual techniques have their own advantages and drawbacks, and have specific strength in being able to handle specific classes of problems. For example, the moment method may be suitable for planar geometries, whereas FEM can be useful for nonplanar components, such as film capacitors, via-holes, and so on. A comprehensive review of commercial EM-simulation tools currently available, their modeling techniques, and scope of application, is presented in (27). Major suppliers of product lines for MMIC CAD include Hewlett-Packard Co. (HP-EESOF), Westlake Village, CA; Ansoft Corporation, Pittsburg, PA; and Sonnet Software Inc., Liverpool, NY.

CURRENT TRENDS AND FUTURE DIRECTIONS

In current MMIC technology there is greater emphasis on advanced interconnects and packaging of MMICs in the form

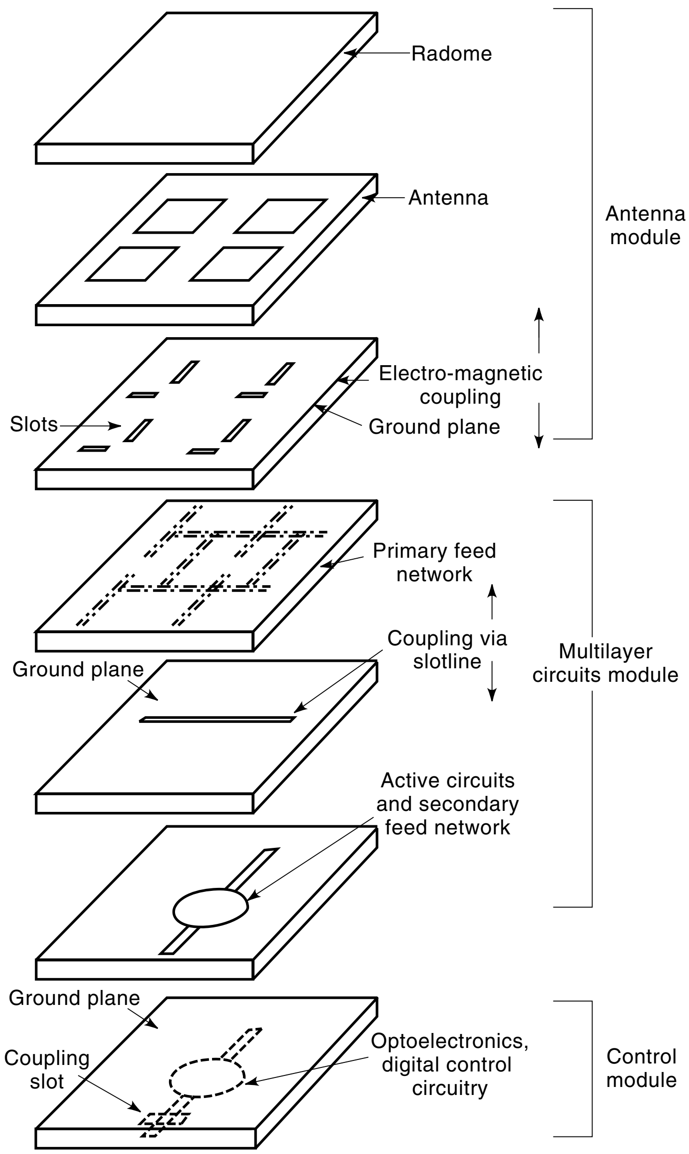

Figure 10. Conceptional sketch of a multifunctional MMIC configuration with microwave/millimeter wave active and passive circuits integrated together with printed antennas, optoelectronics, digital circuits, and possibly other specialized functions, in multiple levels. The next generations of MMICs may take such forms in order to realize high-density, reliable, and multifunctional integration on a single package.

of multichip modules (MCM). In addition to compact, highly integrated chips, future system applications will require greater packaging density and increased functionality at the MCM level. The effect of the packaging structure is recognized to have a critical role in the overall performance of MMICs. Packaging of multichip modules in a "tile" architecture, interconnected in multiple levels using layer-to-layer transitions, and between chip to substrate or chip to chip using "solderless" connections, is an attractive approach to achieve the high-density, low-cost, and multifunctionality demands of the future. A sketch of one such architecture is shown in Fig. 10. The multichip modules may be fabricated similarly to the chip itself on a larger substrate, using a common semiconductor processing technique. The functional and fabricational concepts of chips and MCM will therefore merge, expanding the scope of MMICs to also include digital, optoelectronic, and other functionalities. A review of current trends and future directions of MMIC research and technology can be found in (1).

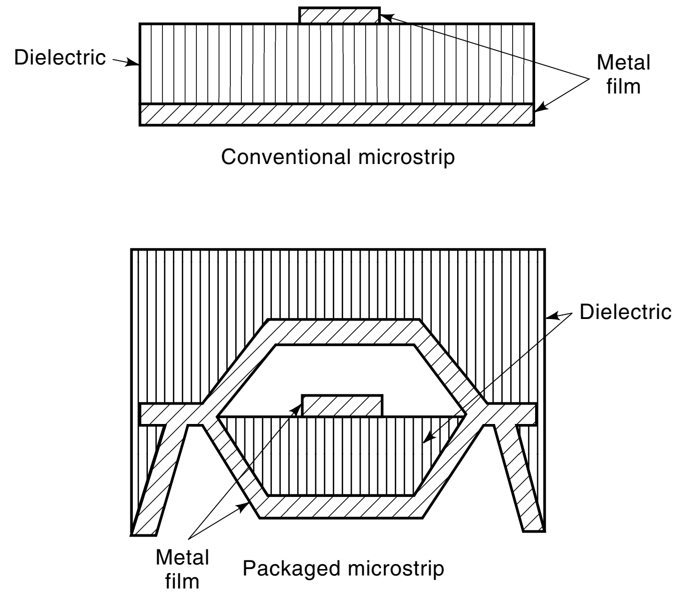

Figure 11. Geometry of a packaged microstrip line, in contrast to a conventional microstrip line, which can be useful for avoiding parasitic coupling between nearby components. Similar packaged configurations for other types of printed lines are also possible.

In a multilevel architecture, particularly for applications in higher frequencies, there may be fundamental problems owing to a nonconventional "power leakage" phenomenon. Under certain conditions power can leak or couple from the printed transmission lines to the surrounding substrate structure (28). This can cause attenuation of the signal along the transmission line, and also result in undesired coupling to the

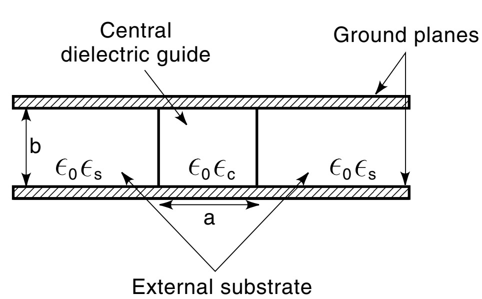

Figure 12. The geometry of a dielectric guide that exhibits low-loss characteristics, compared with metal lines for millimeter and submillimeter applications. The guide is not truly a dielectric guide, because it has metal planes on top and bottom [sometimes called NRD guide (31), H-Guide (32), or PPDW (33), operating in different preferred modes]. The metal planes are useful for isolation from top and bottom, permitting integration of circuits in multiple levels on top of one another. Most of the signal is contained in the dielectric medium between the metal planes, resulting in lower attenuation, compared with commonly used metal lines (e.g., microstrip line or coplanar waveguide).

Top layer Heat dissipation	Active devices and/or passive devices
PPDW layer Low-loss	Passive devices, power distribution, interconnects
Bottom layer Heat dissipation	Active devices and/or passive devices

Figure 13. Schematic of a hybrid-integration architecture in multiple levels, with parallel-plate dielectric waveguide (PPDW) in the middle level(s) for signal distribution, and printed metal lines in the top and bottom levels for connection to active components. Such architectures will be attractive for millimeter and submillimeter ranges for low-loss signal distribution. Conventional circuits with metal lines (e.g., microstrip line) will prove to be too lossy at high frequencies.

surrounding structure. Such problems should be carefully considered in advanced MMIC designs. The undesired effects can be minimized or eliminated by using shorting pins, properly designed multilayer substrate arrangement, or new types of transmission media (8).

Besides the nonconventional leakage problem, conventional parasitic coupling between various planar transmission line discontinuities may also be prohibitive at higher millimeter and submillimeter frequencies, requiring new techniques to achieve greater isolation between components. Approaches to minimizing the parasitic coupling, by placing components physically farther apart, will not be desirable due to space limitations. Lines fabricated in a "boxed" manner, with metal walls surrounding the central line (see Fig. 11) may be useful. This can be achieved in semiconductor processing using "micromachining" technology (29). Ironically, this concept is equivalent to a "flattened coaxial line," which in the past was rejected for use in MMICs because of perceived inconvenience in fabrication.

Another concern is the metallic loss experienced by printed lines at higher frequencies. This loss can be significantly reduced by using dielectric-type guides (see Fig. 12), where a significant fraction of the field is confined to a dielectric medium (which will have lower loss than metals). However, the dielectric waveguides will not be suitable for connecting to active devices that require metal connections for their operation. A hybrid architecture with combinations of metal lines and dielectric guides, as schematically shown in Fig. 13, can solve this problem. Designs combining the dielectric-waveguide concept, together with other ideas discussed above, may allow us to meet diverse and fundamental challenges.

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MICROWAVE INTEGRATED CIRCUITS.

See MONOLITHIC MICROWAVE INTEGRATED CIRCUITS.