MICROWAVE CIRCUITS

The term "microwave circuits" is used to identify the electrical circuits used at microwave frequencies for performing signal processing functions like amplification, frequency conversion, mixing, detection, phase shifting, filtering, and power dividing. By microwave frequencies, we refer to electromagnetic signals whose wavelength is in centimeters, roughly from 30 cm to 1 mm with the corresponding frequencies ranging from 1 GHz (GHz = 10^9 Hz) to 300 GHz. The frequency range from 30 GHz to 300 GHz is also known as the millimeter-wave band. Microwave frequencies present several interesting and unusual features not found in other portions of the electromagnetic frequency spectrum. These features make microwaves uniquely suitable for several useful applications in telecommunications, radar, industrial heating and sensors, and so on. The most common consumer application of microwaves is the domestic microwave oven used for food processing.

Microwave circuits differ from lower-frequency electronic circuits for several reasons. Active devices (transistors, diodes, etc.) used at microwave frequencies are special designs and in several cases operate on entirely different physical principles. Parasitic reactances associated with passive and active circuit elements used at lower frequencies become significant and can cause disastrous effects on performance of circuits at microwave frequencies. Dimensions of lumped elements used in low-frequency electronics can become comparable to the wavelengths at microwave frequencies and cause what are known as distributed circuit effects. Transmission lines (and other structures) used for transmission of signals from one location to another inside a circuit need to be designed differently from those at lower frequencies. All these features make the design, technology, and operation of microwave circuits significantly different from their lower-frequency counterparts.

TYPES OF MICROWAVE CIRCUITS

Types of microwave circuits may be classified in several different ways. Depending on the type of active devices used, there are vacuum tube circuits and solid-state circuits. Depending on the technology used, there are printed circuits, hybrid integrated circuits, monolithic circuits, and so on. Depending on the circuit functions, there are amplifier circuits, filter circuits, mixer circuits, power-divider circuits, and so on. Depending on the special performance features, there are low-noise circuits, high-power circuits, and so on. Depending on the transmission structures whose sections form the basic building blocks for circuit design, there are waveguide circuits, coaxial circuits, stripline circuits, microstrip circuits, coplanar waveguide (CPW) circuits, finline circuits, slotline circuits, dielectric waveguide circuits, and so on. Depending on the special material properties used, there are ferrite circuits, surface acoustic wave (SAW) circuits, and so on.

This article provides a brief overview of the important types of microwave circuits. Several specific types of microwave circuits are described in more detail in other articles in this encyclopedia. These include articles on frequency converters/mixers, microwave signal amplifiers, microwave couplers, microwave detectors, microwave filters and multiplexers, microwave oscillators, microwave phase shifters, microwave switches, power combiners/dividers, and stripline components.

LUMPED AND DISTRIBUTED CIRCUITS

All electronic circuits can be grouped into five classes depending on their physical dimensions compared to the wavelength at the frequency of operation. When all three physical dimensions of a component or a circuit are much smaller than the wavelength at the frequency of operation, we call it a lumped circuit. These are most extensively used components and circuits at lower frequencies. Lumped components are used at microwave frequencies also, but their dimensions have to be proportionately smaller. When one of the physical dimensions of a component is comparable to the wavelength (other two being still small), we refer to these as one-dimensional components, and the circuits using these components are called one-dimensional circuits. Circuits using sections of transmission lines as components, commonly known as transmission line circuits, are one-dimensional. Transmission line circuits are used extensively at microwave and millimeter-wave frequencies. Components and circuits with two of their dimensions comparable to the wavelength at the operating frequency are appropriately called two-dimensional components. Thin-film components, planar components and circuits fabricated on thin substrates, microstrip patch antennas, and reduced-height waveguide components belong to this class. These planar components are the important building blocks in microwave integrated circuits. The fourth class of electronic circuits have all three of their dimensions comparable to the wavelength at the operating frequency. These are known as three-dimensional components. Waveguides, hollow metallic cylindrical tubes used as transmission structures in place of conventional transmission lines, have both of their transverse dimensions comparable to the wavelength. Circuits using these waveguide sections and resonant cavities made out of these waveguides are examples of three-dimensional components and circuits used at microwave frequencies. Finally, the fifth class of electronic circuits (as classified by their size) have at least one of their dimensions much larger than the wavelength at the operating frequency. These are known as quasioptical circuits. The term "quasioptical" is derived from their likeness to optical circuits that are orders of magnitude larger than the submicron wavelengths at optical frequencies.

EVOLUTION OF MICROWAVE CIRCUITS

For a long time the term "microwave circuits" was synonymous with "waveguide circuits." A waveguide was recognized as a useful transmission structure for microwave frequencies in the early 1930s. The work of Southworth and others (1–3) at Bell Telephone Laboratories deserves mention in this respect. It was soon realized that a short length of waveguide, with suitable modifications, might function as a radiator and also as a reactive element. Resonant cavities and horn antennas are mentioned in a 1936 article by Southworth (1). Modern waveguide circuitry had its beginning in the efforts to obtain both a more efficient transfer of microwave power from a source to a waveguide transmission line, thereby providing the elements of a transmitter, and again in the efficient recovery of microwave power at the receiving end, thereby providing the elements of a receiver. These efforts led to the development of several components like traveling detectors, wavemeters, terminations, and so on. Some idea of the techniques used in 1934 can be obtained by recalling that optical benches were commonly used to set up microwave experiments (4). Several photographs of equipment of those days are available in an interesting article surveying the history of the progress of microwave arts published in the fiftieth anniversary issue of *Proceedings of the IRE* (4).

The principle of multiple reflections from discontinuities and the associated principle of cavity resonance played an important role in the development of microwave technology. In some cases, these principles were used to match a source of microwave power to a waveguide. In others, they served to match a waveguide to a receiver, such as a crystal detector. In still others, they served to pass freely a band of frequencies. Together, these principles formed the foundations of microwave circuits. One of the key features of microwave circuits has been the empirical adjustment or tuning of characteristics by screws and irises (and even by denting) in waveguides. In the beginning it was an art that was learned by trial and error. This came to be known as "plumbing" and had been for quite a long time a practical tool for microwave engineers.

Perhaps the greatest single contribution to the engineering analysis of microwave circuits was by Phillip H. Smith (5), who provided a graphical tool for solving otherwise complicated transmission line problems. Not only were laborious calculations avoided, but, while solving the problems on a Smith Chart, one could visualize the step-by-step processes underway. Few gadgets of microwave circuitry have been more useful than the Smith Chart. Rapid developments in microwave circuits took place during the Second World War when special laboratories were set up at the Massachusetts Institute of Technology and at Columbia University to apply microwave techniques to radar problems. Many significant developments in microwave circuits took place during these years, but were published later. A few of those deserve mention. Fox (6) developed devices by which phase could be added progressively to a waveguide. Another product was a hybrid tee (or magic tee) (7), and still another equally significant one was the first directional coupler (8). All these devices found practical uses immediately. Another direction of wartime evolution was the extension of filter techniques to higher frequencies, leading to transmission line filters. Simultaneously, analytical tools were also developed. The classical description of network performance in terms of voltages, currents, impedance, and admittance matrices was replaced by a description based on the transmitted and the reflected wave variables, leading to the concept of scattering matrix.

The scattering matrix formalism allows simpler representation of multiport microwave networks. At this stage in the development of microwave circuits, two basic transmission structures were employed frequently. These were the waveguide and the coaxial TEM mode line. Waveguides provided higher power capability and low loss that lead to high-Q resonant cavities. Coaxial lines provided inherently wider bandwidth because of the absence of dispersion effects. Also, the concept of impedance could be easily interpreted in the case of coaxial lines. This simplified the design of components. These two transmission structures (waveguides and coaxial lines) grew as important components for microwave circuits. Often their roles have been complementary; sometimes they appear in the same module. It was at this stage that a very useful microwave technique emerged from a special adaptation of two-conductor transmission line theory. Introduced by Barrett and Barnes (9) in 1951, this structure, as used presently, consists of a thin strip of conductor sandwiched between two dielectric plates metalized on the outside. This structure is known as a stripline. Early stripline work used razor blades and glue to cut the thin strips and paste them on dielectric sheets. With the availability of copper-clad laminates (first introduced for printed circuits) the stripline techniques have developed into a predictable and precise batch process technology. The first detailed account of stripline circuits was made available by the Sanders Tri-plate Manual (10), published in 1956. A comprehensive account of stripline circuits was made available in a book by Harlan Howe, Jr. (11). The most significant feature of a stripline transmission structure is that the characteristic impedance of the line is controlled by the width of the central strip which is fabricated by photoetching a copper-clad dielectric substrate. The two-dimensional nature of the stripline circuit configuration permits the interconnection of many components without the need to break the outer conductor shielding. This also allows the placement of the input and output ports with a high degree of flexibility. Striplines were found to be very convenient for use in parallel-line couplers because of the natural coupling between two strips placed close to each other. The principles of the coupled line directional coupler were introduced by Wheeler (12) in 1952. Even today a vast majority of directional couplers use a stripline configuration.

In the early 1950s, another type of transmission structure was conceived (13,14), consisting of a single dielectric laminate with a conducting strip on one side and a complete conducting coating on the other side. This structure is known as a microstrip line. Microstrip lines enjoyed a brief spell of popularity and intensive investigations in the 1950s, but were not readily accepted at that time for microwave use due to the high loss per unit length caused by radiation. This was largely a result of the low dielectric constant (about 2.5) of the substrate materials then in use. Further developments were prevented by the lack of availability of both the high-dielectric-constant, low-loss materials and suitable methods for processing and production.

Ever-increasing demands for miniaturized microwave circuitry for use in weapons, aerospace, and satellite applications led to renewed intense interest in microstrip circuits in the 1960s. An elegant analysis of microstrip structure based on conformal mapping transformation was presented by Wheeler (15,16). The technology of high-dielectric-constant, low-loss dielectric materials and that of deposition of metallic films were perfected (17) and became easily available in the late 1960s. This led to rapid developments in the use of microstrip lines in microwave circuits. Today, microstrip line is the most common transmission structure used in hybrid and monolithic microwave integrated circuits.

The availability of a planar microwave transmission line structure like microstrip line, coupled with the rapid developments in microwave semiconductor devices and the techniques of thin film deposition and photolithography, eventually resulted in the technology of microwave integrated circuits (18–21). Microwave integrated circuits (MICs) represent an extension of thin-film hybrid integrated circuit technology to microwave frequencies. These hybrid MICs consist mostly of passive components and circuits in the form of conducting patterns deposited on ceramic or dielectric substrates plus active devices mounted on these circuits in the form of chips or in specially designed packages. In addition to microstrip, other types of lines called slotline and coplanar lines (22,23) have been used in some MICs. Slotline consists of a slot in the conducting pattern on one side of a dielectric substrate. The other side of the substrate does not contain any metallization. Coplanar lines also involve a metallization pattern, but only on one side of the substrate.

Another trend in microwave circuits is the use of lumped elements. Previously, lumped elements could not be used because the size of available lumped elements was comparable to the wavelength at microwave frequencies. With the use of photolithography and thin-film techniques, the size of elements (capacitors, inductors, etc.) can be reduced so much that these elements can be used up to J-band (10 GHz to 20 GHz) frequencies (24,25). Use of lumped elements on dielectric substrates, along with semiconductor devices in chip form mounted thereon, is an attractive option for microwave integrated circuits. Cost reduction of the order of one-fiftieth or more has been predicted with the use of these types of circuits (24). Apart from reduction in size, there is another advantage of lumped elements: Circuit design and optimization techniques perfected at lower frequencies can now be directly used in the microwave frequency range. In addition to lumped elements and one-dimensional transmission line components, two-dimensional planar components have also been proposed for use in microwave circuits (26). These components are compatible with stripline and microstrip line and provide a useful alternative in microwave circuit design.

The current generation of MICs is monolithic microwave integrated circuits (MMICs) using semiconductor substrates (27,28). Semiconductor substrates used are high-resistivity gallium arsenide and, to a limited extent, high-resistivity silicon. Difficulties arise from the need to use a variety of microwave semiconductor devices which cannot be fabricated by a common process, as well as because of the requirement of large substrate areas when distributed elements (transmission line sections) are used for passive functions. GaAs technology (29) and GaAs metal semiconductor field-effect transistors (MESFETs) (30) play the key role in microwave monolithic integrated circuits.

Microwave integrated circuits (hybrid or monolithic) exhibit almost the same advantages as those available in the case of integrated circuits at lower frequencies (31), namely, (1) improved system reliability, (2) reduced volume and weight, (3) batch production and (4) eventual cost reduction when a large number of standardized items are required.

As in the case of low-frequency integrated circuits, the MICs are responsible for both the expansion of present markets and the opening of many new applications, including a host of nonmilitary uses.

There are some difficulties associated with the use of MICs (31). Before MICs became popular, the microwave circuit designers and users had the flexibility to incorporate tuners and adjustment screws in circuits in order to optimize the performance of the circuit after fabrication. MICs, especially if they have to meet high reliability standards, lack these trimming arrangements. Consequently, devices used in MICs need to be characterized precisely and the circuits have to be designed more accurately. Computer-aided design, simulation, and optimization (32,33) techniques have therefore become a necessity.

The current state of the art in microwave circuits is summarized in several recent books (34–36).

WAVEGUIDE CIRCUITS

As pointed out in the section entitled "Evolution of Microwave Circuits," hollow metallic single-conductor waveguides of rectangular and circular cross section were among the earliest forms of transmission structures used at microwave frequencies (see Fig. 1). A rectangular-shaped waveguide has been more popular and is still used today for many applications. A large variety of waveguide circuit components such as couplers, detectors, isolators, attenuators, and slotted lines are commercially available for various standard waveguide frequency bands ranging from 1 GHz to over 220 GHz (37,38,42). Because of the recent trend toward miniaturization and integration, more and more microwave circuits are currently fabricated using planar transmission lines (such as microstrip line and coplanar waveguides) discussed later in this article. However, there is still a need for waveguide circuits in many applications such as high-power systems, millimeter wave systems, and some precision test/measurement applications (38,42). Also waveguides can be combined with other kinds of transmission lines (39) for some special applications.

Modes in a Waveguide

Unlike most of the other transmission structures discussed later in this article, waveguides do not support the transverse

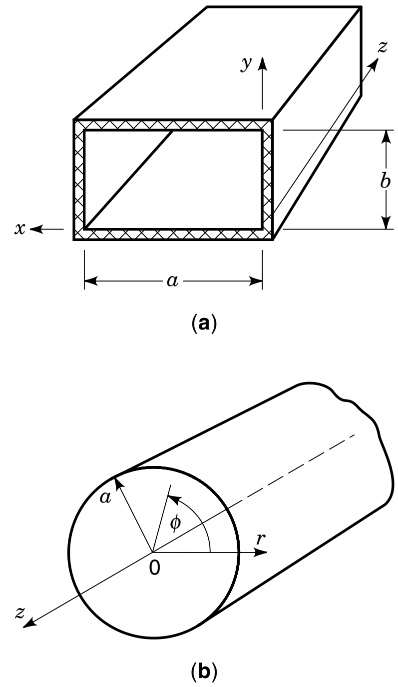


Figure 1. Hollow metallic single-conductor waveguides. (a) Rectangular waveguide. (b) Circular waveguide. Waveguides were the earliest form of transmission structures used at microwave frequencies and are still used today for special applications.

electromagnetic (TEM) mode of wave propagation. Waveguides support two other kinds of modes known as the transverse electric (TE) and transverse magnetic (TM) modes. TE modes have their electric field components only in a plane transverse to the direction of propagation along the waveguide, and for TM modes the magnetic field components are totally in the transverse plane. Both of these types of modes have cutoff frequencies below which wave propagation is not possible. For a rectangular waveguide the mode with the lowest cutoff frequency is the TE_{10} mode. Field patterns of the TE_{10} mode for a rectangular waveguide are shown in Fig. 2.

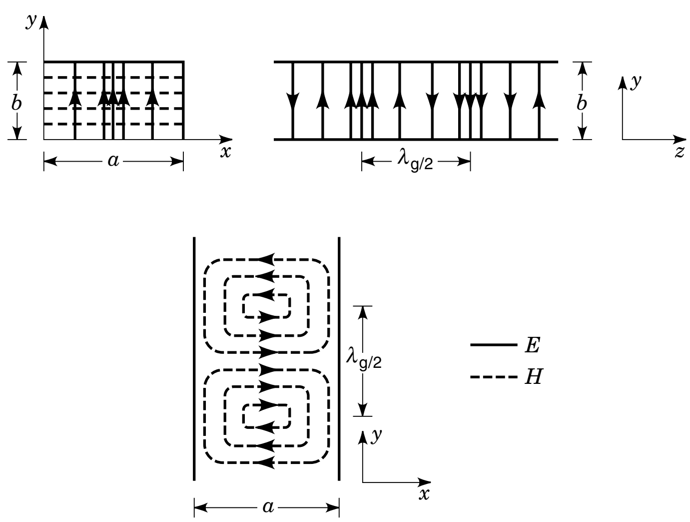


Figure 2. Field patterns of TE_{10} mode in a rectangular waveguide. Dashed lines show the H field, and solid lines show the E field. Note that there is no z-component of electric field.

Various field components for this mode can be expressed as (34, pp. 145–146)

$$\begin{aligned} E_y &= E_{y0}\sin(\pi x/a)e^{-j\beta z} \\ H_x &= H_{x0}\sin(\pi x/a)e^{-j\beta z} \\ H_z &= H_{z0}\cos(\pi x/a)e^{-j\beta z} \end{aligned} \quad (1)$$

where a is the waveguide width (in the x direction) and β is the phase constant of the wave along the z direction given by

$$\beta = \sqrt{\kappa^2 - \left(\frac{\pi}{a}\right)^2} \quad (2)$$

where κ is the wave number ($\kappa = \omega\sqrt{\mu\epsilon}$). The cutoff frequency for the dominant TE_{10} mode is given by

$$f_{c10} = \frac{1}{2a\sqrt{\mu\epsilon}} \quad (3)$$

Dispersion Characteristics. The fact that the propagation constant for individual waveguide modes is a nonlinear function of frequency, and that the different modes start to propagate at different frequencies, leads to wave dispersion in a waveguide (38, pp. 106–107).

Power-Handling Capability. The power-handling capability for a transmission medium needs to be characterized for high-power microwave circuits. Metallic waveguides can handle very high power due to their physical structure. In a rectangular waveguide operating in the fundamental mode, the maximum peak power that the waveguide can handle is given by (40)

$$P_{max} = 416(ab)(\text{kW/cm}^2) \quad (4)$$

where b is the waveguide dimension in the y direction.

Waveguide Circuit Components

Circuits for all kinds of signal processing functions have been designed using waveguides. A few of these are reviewed here.

Waveguide Phase Shifters. A phase shifter is a circuit that produces an adjustable shift in the phase angle of the wave transmitted through it. There are different types of waveguide phase shifters. Two of these, linear and rotary phase shifters, are described here.

Linear Phase Shifter. An example of linear phase shifters is the circuit consisting of three dielectric slabs placed in a rectangular waveguide (41) as shown in Fig. 3. The center slab is free to move longitudinally, and it is moved by a suitable drive mechanism to which it is keyed by means of a dielectric key that protrudes through a long centered slot cut in one broad face of the guide. Each end of the dielectric slab is cut stepwise to provide a broadband multisection quarter-wave transformer to match the partially filled guide to the empty and completely filled guide. If the center slab is displaced a distance x to the right, the effect is to lengthen lines 1 and 3 by an amount x and to shorten lines 2 and 4 by the same amount x. Therefore, the phase shifter change undergone by a wave propagating through the structure is

$$\Delta\phi = [(\beta_1 + \beta_3) - (\beta_2 + \beta_4)]x \quad (5)$$

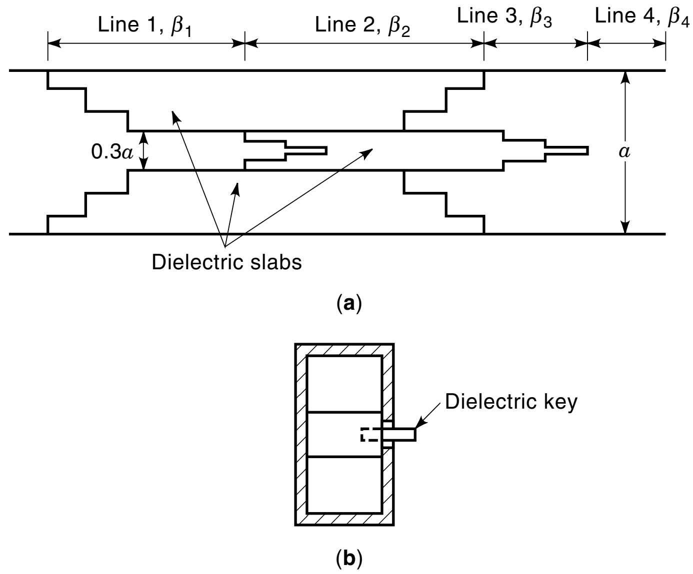


Figure 3. A linear phase shifter in a waveguide configuration. The dielectric key is used to move the central dielectric slab and thereby change the phase shift. [From Ref. (42), © Ellis Horwood Limited, reprinted with permission.]

The phase shift $\Delta\phi$ is proportional to the displacement x. The amount of phase shift increases if the dielectric constant of the slab is increased. If a material whose ϵ_r equal to 2.56 is used in a 3 cm waveguide of dimensions a = 2.25 cm, the phase shift obtained is about 0.4 rad/cm of displacement. About 16 cm of displacement gives a phase shift of more than 360°.

Rotary Phase Shifter. The rotary phase shifter (42, pp. 262–266) is a better precision instrument than the linear phase shifter. It consists of a half-wave plate and two quarter-wave plates (see Fig. 4). The quarter-wave plate on the left converts a linearly polarized TE_{11} mode into a circularly polarized mode, and the quarter-wave plate on the right produces a lin-

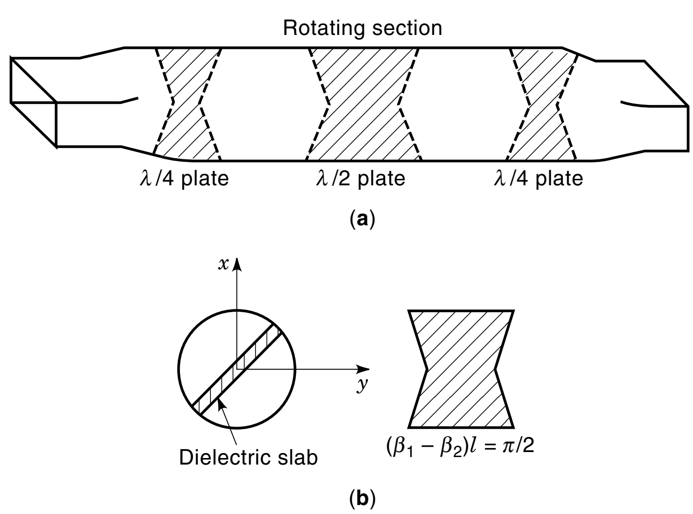


Figure 4. (a) A rotary phase shifter consists of a $\lambda/2$ plate and two $\lambda/4$ plates. Rotation of the $\lambda/2$ plate changes the phase. $\lambda/4$ plates convert circular polarization into linear and vice versa. (b) Details of the $\lambda/4$ plate. [From Ref. (53), © McGraw-Hill, 1992, reprinted with permission.]

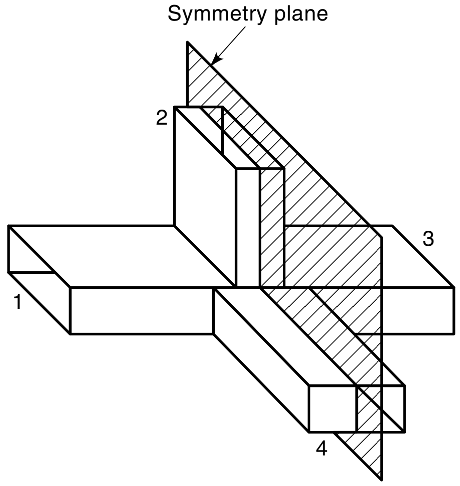


Figure 5. A microwave hybrid or magic tee in a rectangular waveguide configuration. The magic tee is a directional coupler with 3 dB coupling and is commonly used in balanced mixers.

early polarized wave when a circularly polarized wave is incident on it. Rotation of the half-wave plate through an angle θ changes the phase of the transmitted wave by an amount 2θ. This simple dependence of the phase change on mechanical rotation is the main feature of the rotary phase shifter.

Microwave Hybrid Junction. A rectangular waveguide hybrid, which is more popularly known as magic-tee, is shown in Fig. 5. If a wave in the dominant TE_{10} mode is incident at the port 4, the structure is symmetrical with respect to this wave, and hence equal powers are transmitted to port 1 and 3. If E_m^n represents the transmitted electric field in the nth port when the incident wave is in the mth port, then $E_4^1 = E_4^3$. Besides, it can be seen that no power is transmitted to port 2 from port 4, that is, $E_1^2 = 0$. On the other hand, if a TE_{10} wave is incident at port 2, the E field has an odd symmetry about the plane of symmetry and therefore excites fields in ports 1 and 3 which are 180° out of phase. Hence, $E_2^1 = -E_2^3$. Also, power incident at port 2 is not transmitted to port 4. Therefore, $E_2^4 = 0$. The power coupling factor may not be exactly one-half if ports 2 and 4 have reflections. To ensure a coupling of exactly one-half, which is desirable, the junction needs to be matched by irises or probes.

Directional Couplers. A directional coupler is a four-port circuit. An example is shown in Fig. 6. A portion of the wave

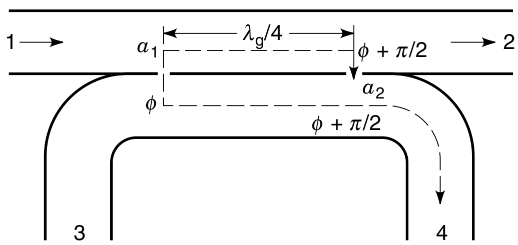


Figure 6. A waveguide directional coupler is a widely used circuit component used to sample the waves traveling in one particular direction (say 1 to 2) independent of the reflected wave traveling in the opposite direction (2 to 1).

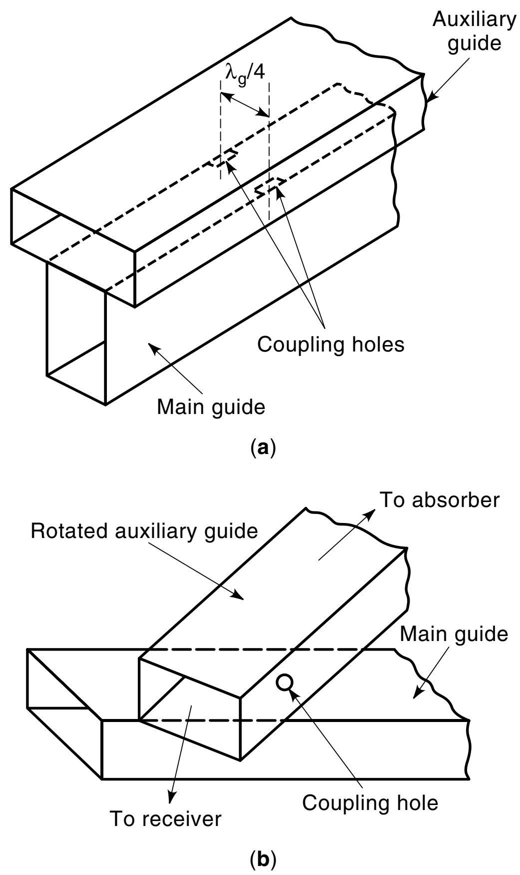


Figure 7. Two other designs of waveguide directional coupler circuits. In both of these cases, coupling takes place through holes in the common wall of the two waveguides.

incident at port 1 couples into the bent waveguide through the hole a_1. The remaining wave travels to the hole a_2 in the main waveguide (ports 1, 2), and a portion of it again couples into the bent waveguide. If the magnitudes of the energy coupled through holes a_1 and a_2 are equal, and if the distance between a_1 and a_2 is $\lambda_g/4$, then the two coupled signals are reinforced at port 4 because they arrive with equal phase. On the other hand, the two coupled signals cancel each other at port 3, because they are 180° out of phase. Similarly, a wave incident on the junction from port 2 travels to ports 1 and 3, but no signal travels to port 4. The ratios of signal flow between ports 1 and 4 and between ports 2 and 3 are known as the *coupling coefficient* of the directional coupler. In general, the leakage of energy through holes a_1 and a_2 is kept quite small. A directional coupler can be used as a standing-wave detector and forms an important component in microwave and millimeter-wave network analyzers. Some other designs (37, Sec. 7.2, 42, pp. 267–271) of typical waveguide directional couplers are shown in Fig. 7.

Waveguide Filters. Design procedures for filters using waveguides and other transmission structures have certain common features. These filters can be designed using the low-frequency prototype filter synthesis techniques. One such technique, called the *insertion-loss* method, begins with a complete specification of the attenuation characteristics of the filter and develops a basic prototype low-pass filter having the

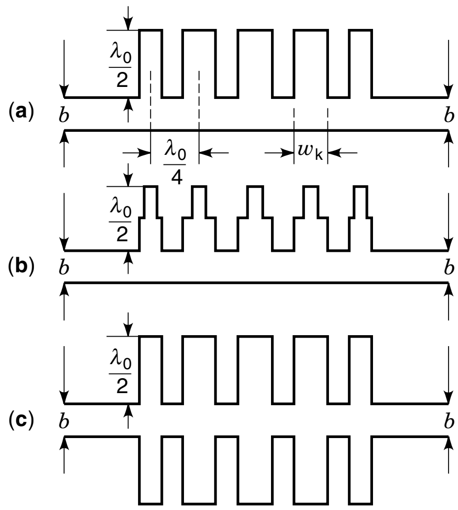


Figure 8. Waveguide stub filters. (a) Asymmetrical stubs without steps. (b) Asymmetrical stubs with steps. (c) Symmetrical stubs without steps. Both bandpass and bandstop characteristics can be designed in these circuits.

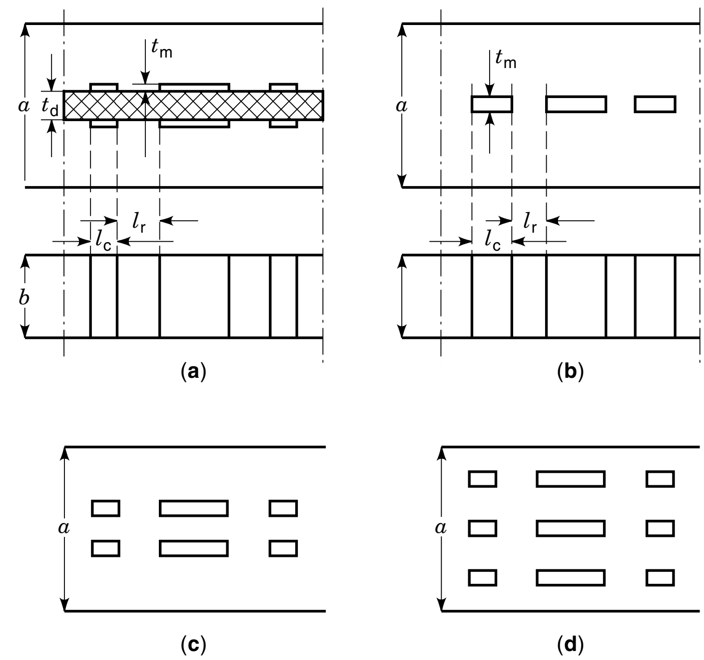


Figure 9. E-plane bandpass filters. (a) Large gap finline filter. (b) Single metal insert filter. (c) Double metal insert filter. (d) Triple metal insert filter. In these designs, fin dimensions and hence RF performance can be controlled accurately by photolithography techniques. [From Ref. (38), © Artech House, 1993, reprinted with permission.]

desired passband characteristics. Using suitable frequency transformations and element realizations, the required type of filter (low-pass, bandpass, high-pass, or bandstop filters) is derived. The lumped element values of these filters are then realized in terms of the distributed circuit elements. Special features for implementing filters in waveguide configuration are reviewed in this section.

Waveguide Stub Filters. One of the simplest realizations of waveguide bandpass (or bandstop) filters is a waveguide stub filter (38, pp. 185–190) shown in Fig. 8. For bandpass filters, the short-circuited E-plane stubs are half-wavelength long at the center frequency of the filter, and are connected in cascade with $\lambda/4$ separations. Band rejection filters use stubs that are an odd multiple of quarter-wavelength, also separated by $\lambda/4$ distance. The stubs can be asymmetrical or symmetrical along the main waveguide and with or without steps. The selection of the stub configuration depends on the required bandwidth and power-handling capability. Filters with stepped stubs can be designed to yield narrower bandwidth. Filters with stubs on both sides of the waveguide broadwall have large power-handling capability.

E-Plane Filters. E-plane filters have been developed as compatible filtering structures for integrated millimeter-wave circuits (43,44) and are most often realized in finline techniques or as all-metal structures. Their common feature is that the filter metalization pattern is obtained using photolithographic techniques. Thus, the geometry of the component is realized with very small manufacturing errors, which is very important at millimeter-wave frequencies. Four different configurations of E-plane waveguide filters are shown in Fig. 9. All of types are designed as bandpass filters (43,45,46). In Fig. 9, the shaded part is dielectric substrate to support the thin metallization structures; t_m is the thickness of the metal layer and t_d is the thickness of the dielectric substrate; and l_c is the length of the metal strip and l_r is the gap between metal strips.

Corrugated Waveguide Filters. Corrugated waveguide structures similar to that shown in Fig. 10 are used as lowpass filters in numerous antennas feed system to reject the spurious harmonics from transmitters (38, pp. 200–207, 49). They can also be designed as bandpass filters, with a wide or narrow passband response (47,48).

Evanescent-Mode Waveguide Filters. Evanescent-mode waveguide filters (Fig. 11) can be designed (50–52) to provide a very wide stopband with low passband insertion loss. Their size is compact, even when the passband is located in the lower microwave frequency region. For these reasons the evanescent-mode waveguide structures are often used as pseudo-low-pass filters, or as bandpass filters in a wide microwave spectrum. Due to the high skirt selectivity achievable in this filter type, they can also be used in diplexers and multiplexers.

Multiplexers

Muliplexer circuits are required for combination or separation of communication channels at different frequencies. The multiplexer for the antenna feed systems must provide separation of the receive and transmit bands and combination of the in-

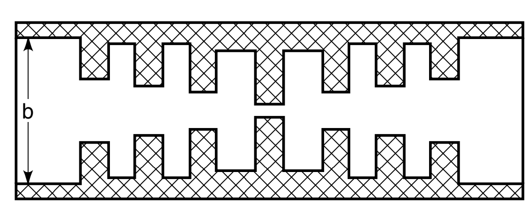


Figure 10. Longitudinal cross section of a corrugated waveguide filter.

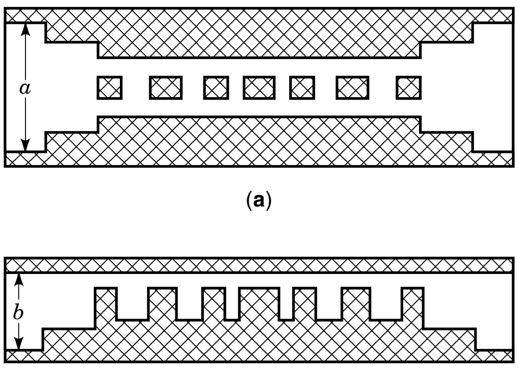


Figure 11. Ridged waveguide evanescent mode bandpass filter. (a) Top view. (b) Side view. These designs provide compact filters at lower microwave frequencies.

dividual transmission channels that cover only a small portion of the frequency band. There are four different multiplexing methods that are applied in feed systems (38, pp. 252–307). They are (1) the circulator/filter chain, (2) the directional filter approach, (3) the manifold multiplexing techniques, and (4) the branching filter concept. Each of these has its own particular properties and applications.

Waveguide Circuits Using Active Devices. Waveguide circuits using active devices can be designed for various applications, such as oscillator, mixer, detector, and so on (37, pp. 325–490). A waveguide cavity Gunn oscillator (53) is shown in Fig. 12 as an example. In this design the high impedance of the waveguide is transformed into low impedance at the location of the Gunn device by means of quarter-wave transformers. The cavity resonant frequency can be adjusted by changing the location of the short circuits. A tuning screw can be used for fine tuning of the cavity. More examples of active waveguide circuits can be found in Refs. 37 and 53.

Computer-Aided Design of Waveguide Circuits

Waveguide circuits require a different approach for computer-aided design (CAD) than that used for transmission line circuits at microwave frequencies. The traditional CAD methods for waveguide circuit are usually based on the network analysis, with various discontinuities in the waveguide modeled separately by a combination of equivalent reactances (54). This equivalent circuit approach has some drawbacks. The models are valid only for a specified geometry and only within a certain range of parameters. Another problem associated with using the equivalent circuit models is their inability to account for higher-order mode-coupling effects, which can occur if discontinuities are in close proximity. A field-theory-based approach (55) overcomes these limitations. Some features of this approach are: a very accurate prediction of frequency responses; higher-order mode effects taken into account; no restrictions on the wavelength (or frequency range); and straightforward extension in millimeter-wave bands. Several numerical methods are used for field analysis of waveguide circuits; the most popular are finite different time domain method (FDTD) (56) finite-element method (FEM) (57), transmission line matrix method (TLM) (58), mode-matching techniques (MMT) (59), and the method of integral equations (60). For automated design and yield analysis of waveguide circuits, modal analysis (61) has emerged as the most useful electromagnetic simulator, either in the generalized scattering matrix (GSM) formulation or in the generalized admittance matrix (GAM) form. It has been demonstrated (61) that for waveguide circuits the GAM approach requires only half the number of unknowns at the internal ports and hence is much more efficient than the GSM representation.

COAXIAL LINE CIRCUITS

Coaxial line is the most commonly used transmission structure over a very wide range of frequencies from very low frequencies through microwave frequencies and extending into millimeter-wave frequency range. However, because of the convenience of physical size, coaxial line circuits are popular only in the microwave frequency range. They are too bulky at lower frequencies and very difficult to fabricate (as well as very lossy) at millimeter-wave frequencies.

The geometry of a coaxial line is shown in Fig. 13. One can derive the expressions for electromagnetic fields in this line solving Laplace's equation for scalar potential. As shown in Fig. 13, the inner conductor is considered to be at V_0 volt po-

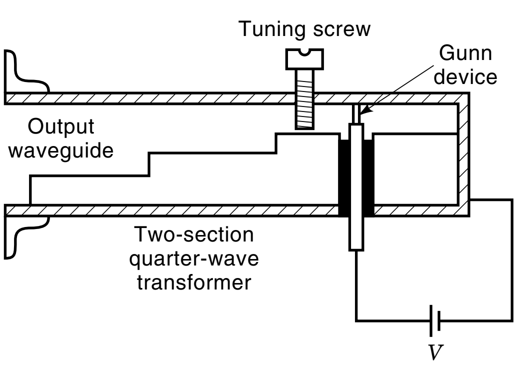


Figure 12. A Gunn oscillator waveguide circuit which uses a two quarter-wave sections to transform the high impedance of the waveguide to a low impedance at the Gunn device. [From Ref. (53), © McGraw-Hill, 1992, reprinted with permission.]

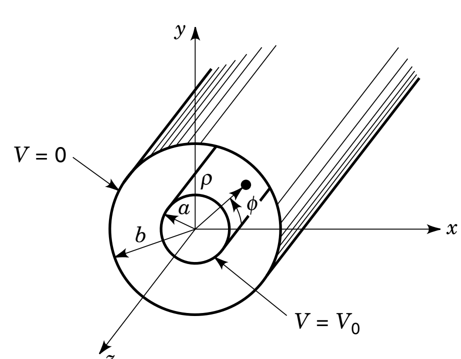


Figure 13. Geometry of a coaxial line. The ratio of the outer to inner conductor radii (b/a) determines the characteristic impedance Z_0 of the line.

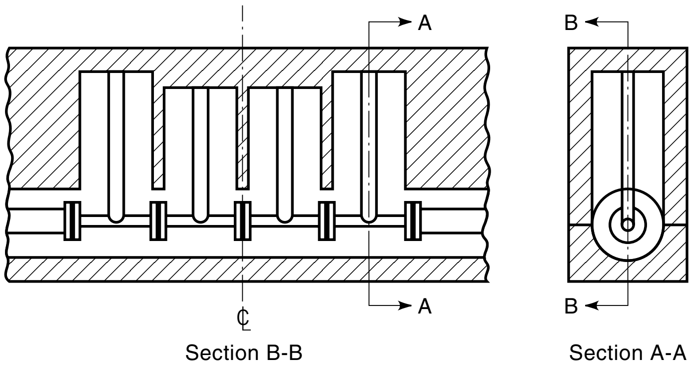


Figure 14. A high-pass filter constructed by coaxial lines. Lumped series capacitors and shunt inductors provide the filter operation. [From Ref. (62), © Artech House, 1980, reprinted with permission.]

tential and the outer conductor is at 0 V. The electric and magnetic field vectors can be derived as (34)

$$\overline{E}(\rho, \phi, z) = \frac{V_0 \hat{\rho} e^{-j\beta z}}{\rho \ln b/a} \tag{6}$$

$$\overline{H}(\rho, \phi, z) = \frac{V_0 \hat{\phi} e^{-j\beta z}}{\eta\rho \ln b/a} \tag{7}$$

where $\beta = \omega\sqrt{\mu\epsilon}$ and $\eta = \sqrt{\mu/\epsilon}$ are phase constant and the intrinsic impedance of the medium, respectively.

Coaxial lines possess general properties of TEM mode transmission lines. Characteristic impedance Z_0 of a coaxial line filled with a dielectric material of relative dielectric constant ϵ_r as shown in Fig. 13, is

$$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \frac{b}{a} \quad \Omega \tag{8}$$

In addition to TEM modes, coaxial lines can also support TE and TM waveguide modes. When coaxial line dimensions are selected appropriately for the operating frequency range; these modes are evanescent modes and they are excited only near discontinuities or sources. In practice, it is essential to know the cutoff frequencies of the lowest-order waveguide mode and use the coaxial line below this frequency. Various types of microwave circuits can be realized using coaxial lines (62,63). However, with the recent advances in planar circuit technology and because of their size and fabrication difficulties, they are not used commonly. In the past, coaxial lines have been widely used to design passive filter circuits. A common type of high-pass filters constructed by coaxial lines as shown in Fig. 14 has been described in the classic book by Matthaei et al. (62). In this configuration, coaxial stubs present shunt inductances, and disks spacers constitute series capacitors.

Another coaxial filter example described by Matthaei (62) is a series capacitance coupled half-wave resonator circuit shown in Fig. 15. This filter is realized by breaking the inner conductor at several locations. The gap spacing needed to produce a desired coupling can be found either experimentally or theoretically.

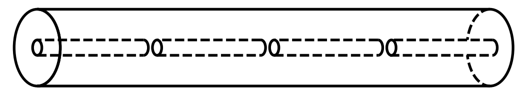


Figure 15. Series capacitance coupled half-wave resonators filter. Series coupling gaps are located in between cascaded straight resonator elements. The filter is realized by breaking the inner conductor at several locations.

Coaxial line components are also used extensively as coaxial probes connectors in between various circuit assemblies and for connecting circuits to instrumentation, and so on. Most of the coaxial lines that are used as cables and connectors have a 50 Ω characteristic impedance except for 75 Ω coaxial cable used for television systems. Coaxial connectors must have low standing wave ratio (SWR), no spurious higher-order modes, mechanical strength, and repeated usability. Some of the most common microwave coaxial connectors are popularly known as type N connector (originally named after P. Neill), (SMA) SubMiniature Amphenol connector, (SSMA) Scaled SubMiniature Amphenol connector, and (APC-7) Amphenol Precision Connector, 7mm connector. These connector types are shown in Fig. 16. The type N connector is a relatively large connector with an outer diameter

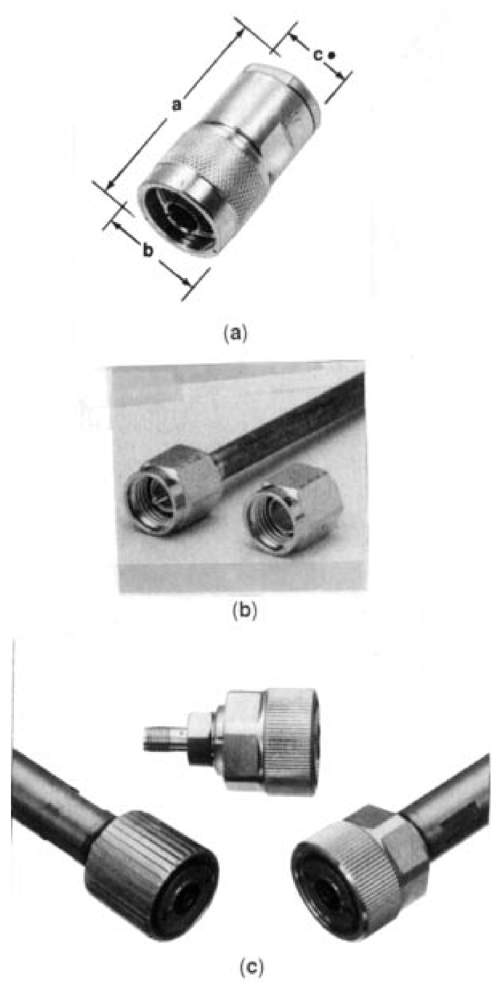


Figure 16. Some of the most common microwave coaxial connectors. (a) Type N connector. (b) SMA connector. (c) APC-7 connector.

of 0.625 in. The recommended upper operating frequency ranges from 11 GHz to 18 GHz. The SWR is typically less than 1.07. The SMA connector is small compared to the type N connector with an outer diameter of the female end of 0.210 in. and can be used up to 25 GHz. SMA connectors modified to work up to 40 GHz are known as K connectors. An SSMA connector is even smaller. The outer diameter of the female end is about 0.156 in. and the maximum operating frequency is about 38 GHz. The APC-7 connector is a precision connector which has an SWR less than 1.04 and an operating range of up to 18 GHz. Coaxial connectors are described in Refs. 34 (pp. 169–170) and 64.

STRIPLINE CIRCUITS

Striplines

A stripline (11,65) is a planar-type of transmission line that lends itself well to microwave integrated circuitry and package feedthroughs. The geometry of a stripline is shown in Fig. 17(a). A thin conducting strip of width W is centered between two wide conducting ground planes with a separation b. The entire region between the ground planes is filled with a dielectric.

Unlike microstrip lines and other open planar transmission lines described later in this article, a stripline can support a pure TEM mode because it has a homogeneous dielectric medium. The stripline, however, can also support higher-order TM and TE modes. These modes can be suppressed with shorting screws between the two ground planes and by restricting the ground planes spacing to less than one quarter wavelength. A sketch of the field lines for the TEM stripline mode is shown in Fig. 17(b).

Stripline Parameters

An exact solution of Laplace's equation of electromagnetic fields in a stripline can be obtained by the conformal mapping approach (66). However, closed-form expressions that give a good approximation of the exact results are used in circuit design (34).

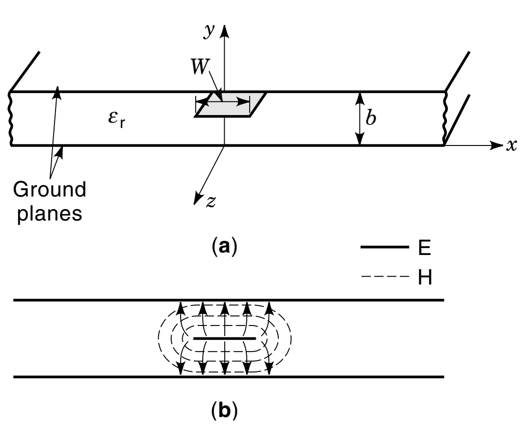


Figure 17. (a) Geometry of a stripline. A thin strip of width W is inserted in a dielectric with ground planes on the top and the bottom. (b) Electric and magnetic fields in a stripline. Striplines support a pure TEM mode.

The phase constant for a stripline is given (by the usual relation for homogeneously filled lines) as

$$\beta = \frac{\omega}{v_p} = \omega\sqrt{\mu_0\epsilon_0\epsilon_r} = \sqrt{\epsilon_r}k_0 \tag{9}$$

where ω is the angular frequency, v_p is the velocity of the wave along the line, μ_0 is the permeability of free space, ϵ_0 is the permittivity of free space, ϵ_r is the dielectric constant of the stripline dielectric, and k_0 is the phase constant of free space.

The characteristic impedance of a transmission line is given by

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{v_pC} \tag{10}$$

where L and C are inductance and capacitance per unit length of the line. An approximate expression for characteristic impedance (34) of striplines is

$$Z_0 = \frac{30\pi}{\sqrt{\epsilon_r}}\frac{b}{W_e + 0.441b} \tag{11}$$

where

$$\frac{W_e}{b} = \frac{W}{b} - \begin{cases} 0 & \text{for } W/b > 0.35 \\ (0.35 - W/b)^2 & \text{for } W/b < 0.35 \end{cases}$$

Since the stripline is a TEM-mode line, the attenuation due to the dielectric loss is obtained by the procedure commonly used for other TEM lines (67). The attenuation due to the conductor loss is approximated as

$$\alpha_c = \begin{cases} \dfrac{2.7\times 10^{-3}R_s\epsilon_r Z_0}{30\pi(b-t)}A & \text{for } \sqrt{\epsilon_r}Z_0 < 120 \quad \text{Np/m} \\ \dfrac{0.16R_s}{Z_0 b}B & \text{for } \sqrt{\epsilon_r}Z_0 > 120 \quad \text{Np/m} \end{cases} \tag{12}$$

with

$$A = 1 + \frac{2W}{b-t} + \frac{1}{\pi}\frac{b+t}{b-t}\ln\left(\frac{2b-t}{t}\right)$$
$$B = 1 + \frac{b}{0.5W + 0.7t}\left(0.5 + \frac{0.414t}{W} + \frac{1}{2\pi}\ln\frac{4\pi W}{t}\right)$$

where t is the thickness of the strip metallization.

Examples of Stripline Circuits

Design procedures for stripline circuits are identical to those for other TEM mode transmission line circuits. The main difficulty in transferring the design from one kind of transmission line (say coaxial line) to another (say stripline) arises from the fact that discontinuity and junction reactances are different for different kinds of transmission structures. Quite often, the first-order designs are carried out without considering the effect of discontinuity/junction reactances. Then the circuit performance is computed taking discontinuity/junction reactances into account, and designable parameters of the cir-

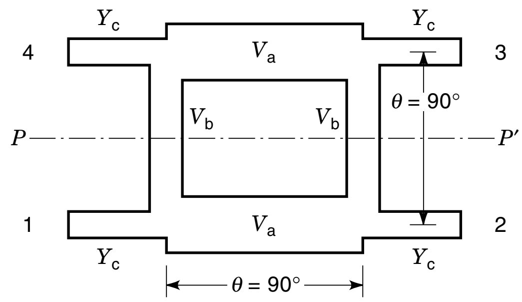


Figure 18. A branch-line coupler using striplines. Port 1 is the input port, ports 2 and 3 are output ports, and port 4 is the isolated port. Output signals at ports 2 and 3 are 90° out of phase.

cuit are optimized to compensate for discontinuity/junction effects. This design methodology is common to microwave circuit design using any kind of transmission structure.

Branch-Line Directional Couplers. These couplers, similar to the one shown in Fig. 18 (68), are essentially power division networks with two important features—namely, the two ports are mutually isolated (ports 1 and 4 in Fig. 18 when the input signal is connected to port 1), and the output signals at the other two ports (ports 2 and 3 in Fig. 18) are out of phase by 90°. These circuits form building blocks of several other circuits such as balanced mixers, variable attenuators, *pin* diode phase shifters, directional filters, diplexers, multiplexers, and transmit-receive (TR) switches. Branch-line couplers are also used extensively in antenna array feed networks in preference to Y-junction type of power dividers and as impedance transformers. In active circuits, they provide the advantage of direct-current (dc) coupling for biasing. Branch-line couplers are forward-wave couplers and hence can be cascaded without crossing lines.

Parallel Coupled-Line Directional Couplers. Parallel coupled-line directional couplers shown in Fig. 19 (69) offer much larger bandwidths as compared with the branch-line couplers. They are mostly backward-wave couplers, although forward-wave couplers are also possible using an inhomogeneous medium. The most commonly used parallel-coupled directional coupler is the TEM-mode single-section backward-wave coupler. As the term "backward-wave coupler" implies, the electric and magnetic field interaction between the parallel-

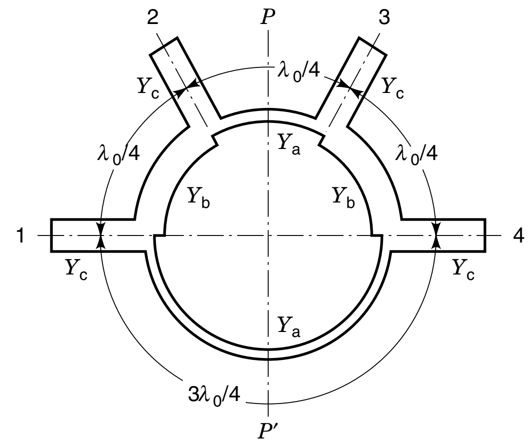


Figure 20. A stripline ring hybrid. The circumference is 3/2 wavelengths. When a signal is fed to port 1, output signals at ports 2 and 4 are 180° out of phase, and port 3 is isolated. For an input signal fed to port 3, output signals at ports 2 and 4 are in phase and port 1 is isolated.

coupled conductors causes the coupled signal to travel in a direction opposite to that of the input signal. Maximum coupling occurs when the length of the coupling region is equal to one-quarter wavelength (or an odd multiple of quarter wavelength). Analysis of the couplers is carried out in terms of two normal modes of propagation known as *even* and *odd* modes for symmetrical couplers. Even and odd modes exhibit even and odd symmetry of fields with respect to the plane of symmetry. These couplers offer a perfect match and infinite directivity at all frequencies because of the inherent property that the even- and odd-mode phase velocities are equal when the propagating mode is a pure TEM.

Hybrid Rings. The branch-line coupler as well as the coupled-line backward-wave coupler provides a phase difference of 90° between the two outputs. For hybrid ring couplers shown in Fig. 20 (70), the two output signals are either in-phase or 180° out-of-phase depending on the choice of the input port. The circumference of the ring is $3\lambda/2$, where λ is the wavelength in the stripline at midband frequency. For an input at port 1, outputs at ports 2 and 4 are 180° out-of-phase and the port 3 is isolated (with no output). When the input is at port 2, the two outputs at ports 1 and 3 are in-phase and the port 4 is isolated.

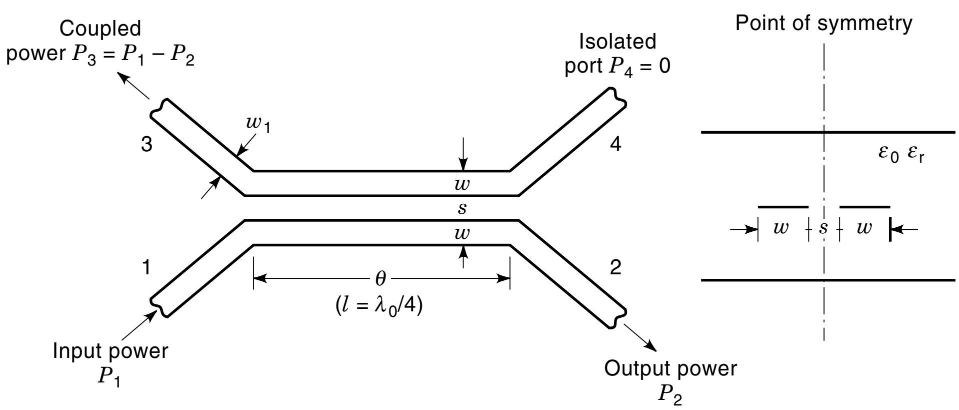


Figure 19. A parallel coupled-line coupler realized in stripline structure. Equal widths are used for two strips. When a signal enters into port 1, port 2 is the direct output and port 3 is the coupled point. No signal comes out of port 4, which is called the isolated port.

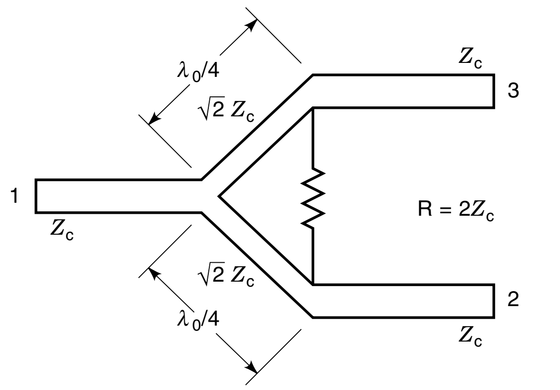


Figure 21. A matched stripline two-way power divider. Input power at port 1 splits equally into output ports 2 and 3. A resistor ($R = 2Z_c$) ensures that the circuit is matched at ports 2 and 3.

Power Dividers. In several microwave applications (as, for example, a feed for a phased array antenna) the input signal is required to be divided into several equiamplitude, equiphase output signals. A matched, symmetric n-way power divider has the advantage that it gives neither amplitude nor phase imbalance at any frequency. Such a power divider can also be used as an n-way power combiner by simply reversing the input and output ports. Using such combiners, output powers of a number of solid-state amplifiers and oscillators can be combined over a wide frequency range. A two-way power divider stripline circuit is shown in Fig. 21 (71). The resistor R between the output port ensures input match at ports 2 and 3 when the circuit is used as a power combiner.

Filters. Stripline filters generally make use of a cascade of distributed circuit elements in the form of coupled resonators, stubs, and so on. As pointed out in the discussion for waveguide filters, stripline filters are also designed using low frequency prototype filter synthesis techniques. A coupled-line bandpass filter is shown in Fig. 22 (72). This configuration is also commonly used for other filters using planar lines such as microstrip lines and coplanar waveguides.

***pin* Diode Switches.** A *pin* diode (which consists of an intrinsic layer sandwiched between p- and n-type layers) acts as an electronic switch when operated at the forward and reverse bias states (73). As a basic switching element, it is extensively used in the realization of multiple-throw switches, phase shifters, modulators, limiters, and duplexers. A single-pole single-throw switch using a *pin* diode is shown in Fig. 23 (65). With a variable forward bias, the forward bias resistance of the *pin* diode can be varied over a wide range. This property is used in realizing electronically variable attenuators. *pin* diode circuits can also be used as attenuators by varying the forward bias current of the diodes. *pin* diode attenuators with constant input impedance characteristic can be built by incorporating a circulator or a hybrid coupler in the circuit. Figure 24 shows a hybrid-coupled *pin* diode attenuator (65).

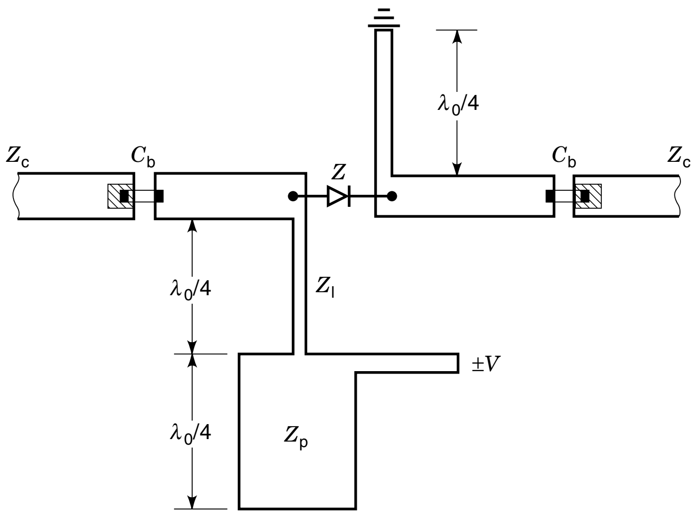


Figure 23. Layout of series SPST (single-pole single-throw) switch with the biasing circuit. dc blocking capacitors and dc return transmission inductor are used, and RF bypass transmission capacitor of a quarter-wavelength has low characteristic impedance ($Z_p < 25\ \Omega$). [From Ref. (65), © New Age Int. Ltd., 1989, reprinted with permission.]

Phase Shifters. Phase shifters can be built using *pin* diodes, varactors, or GaAs field-effect transistors (FETs). Of these three semiconductor devices, *pin* diodes are the most commonly used because of reproducibility of their characteristics

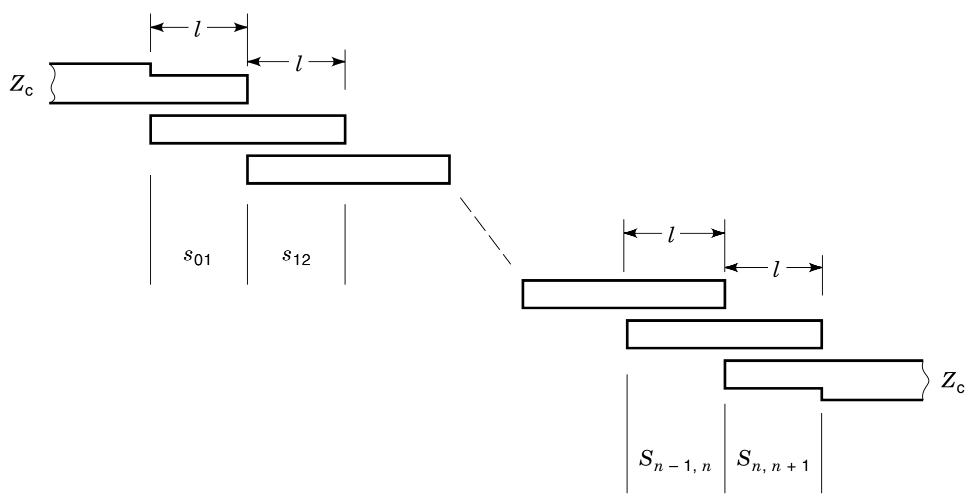


Figure 22. A stripline parallel-coupled bandpass filter. Each coupled section comprises one quarter-wavelength coupled lines ($l = \lambda/4$). Z_c is the characteristic impedance of input/output ports.

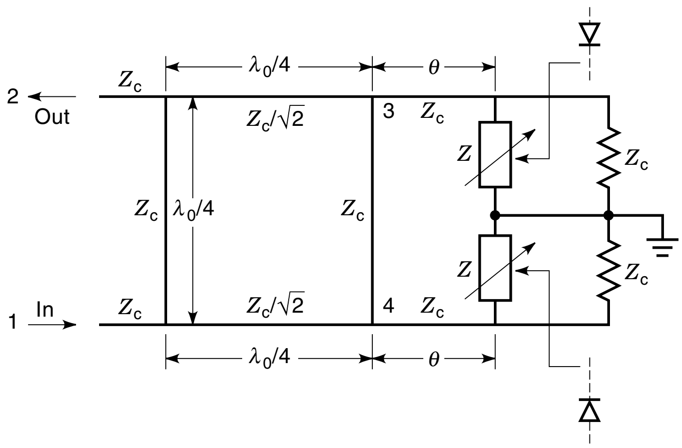


Figure 24. A hybrid-coupled *pin* diode attenuator. The attenuation is controlled by varying the forward bias current of the diodes. Two identical diodes are mounted symmetrically in the two output arms of the 3 dB, 90° hybrid coupler and are shunted by matched loads. [From Ref. (65), © New Age Int. Ltd., 1989, reprinted with permission.]

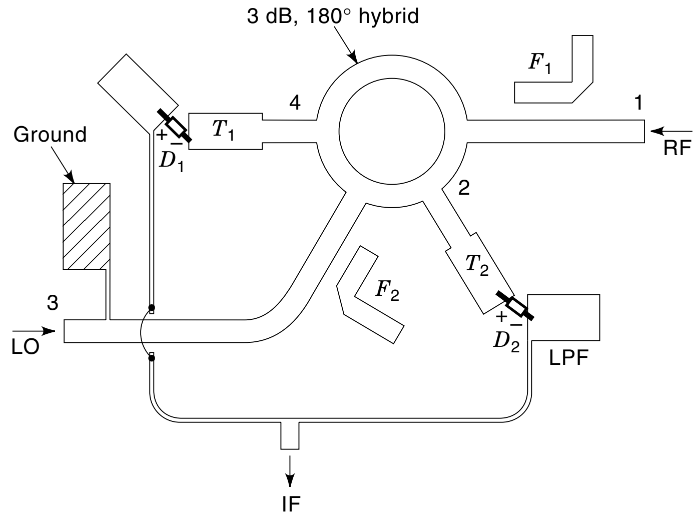


Figure 26. A hybrid ring balanced mixer where D_1, D_2 are mixer diodes; F_1, F_2 are image reject filters; and T_1, T_2 are matching transformers. The RF power fed to port 1 and the LO power fed to port 3 are split equally between the output ports 2 and 4. At the two mixer diodes, the RF signals appears 180° out of phase with each other whereas the LO signals appear in phase. [From Ref. (65), © New Age Int. Ltd., 1989, reprinted with permission.]

and high power-handling capability. Digital phase shifters are extensively employed in phased arrays to electronically scan the radiated beam. These phase shifters can be broadly classified as either the reflection type or the transmission type. The reflection-type phase shifters can be realized using a circulator or a hybrid coupler. Some common designs for transmission-type phase shifters are the switched line, the loaded line, and the low-pass high-pass. For phased array applications, several of these circuits are cascaded to form multibit phase shifters.

Microwave phase shifters can be designed using various different kinds of transmission lines. Figure 25 shows a switched line phase shifter with series-mounted diodes (74).

Mixers. A mixer circuit is an essential component of almost all receivers used in communication, radar, and radioastronomy applications. Microwave mixers make use of nonlinear semiconductor devices, usually Schottky barrier diodes for mixing operation. A typical mixer consists of a nonlinear mixer diode together with coupling networks for feeding the signal [radio frequency (RF)] and local oscillator (LO) power and for extracting the (IF) signal. Practical mixer configurations can be broadly divided into three categories: single-ended mixers, balanced mixers, and double-balanced mixers. Of the various types of mixers, the balanced mixer employing Schottky barrier diodes is the most commonly used configuration in practical application. Figure 26 shows a hybrid ring balanced mixer (65).

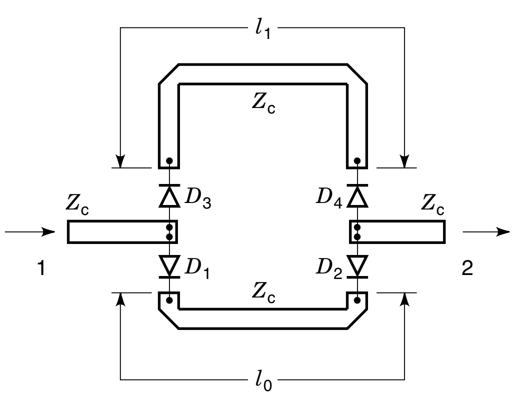


Figure 25. A switched line phase shifter with series mounted diode to switch between two fixed transmission line paths. The differential phase shift is $\beta(l_1 - l_0)$.

Several other types of stripline circuits have been reported in literature (11,34,65). Microwave circuits described in this section can also be realized in microstrip configuration, described in the next section.

MICROSTRIP CIRCUITS

Microstrip line is the most frequently used planar transmission structure and forms the basic building block for almost all hybrid microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs). The physical geometry of a microstrip line is shown in Fig. 27(a), and the approximate field distribution is depicted in Fig. 27(b). Microstrip line consists of a single dielectric substrate with a complete conducting coating (ground plane) on one side and a conductor strip on the other side of the substrate. In contrast to a stripline, top surface of the microstrip circuitry is open. Because of the nonhomogeneous dielectric medium surrounding the conductor strip (the substrate and the air above), the microstrip line cannot support a pure TEM mode. However, a quasi-TEM mode approximation is used for analysis of microstrip lines and is adequate for design of microstrip circuits (23).

Popularity of microstrip circuits is due to an increasing trend in miniaturization of, and cost considerations for, microwave circuits. Compared to waveguides, and coaxial lines, and striplines, it is easier to fabricate microstrip circuits and

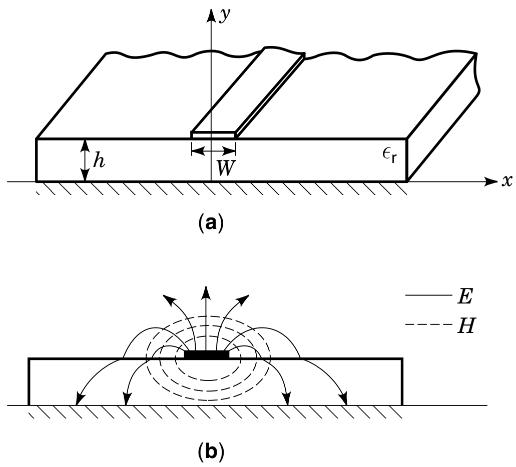


Figure 27. Geometry of a microstrip line. (a) Geometry (h is substrate height, W is the width of the conducting strip, and ϵ_r is relative dielectric constant) (b) Electric and magnetic field distribution in a microstrip line quasi-TEM mode.

integrate them with other active and passive microwave devices. The open nature of the microstrip lines allows easy access to circuitry to mount active devices and lumped element components such as resistors, capacitors and inductors. However, microstrip line circuits have some disadvantages such as higher loss, radiation, dispersion, and spurious coupling among components when compared to coaxial line circuits.

Design Formulas for Microstrip Lines

Analysis and design considerations for microstrip lines are very well documented in the literature (16,23,75,76).

Effective Dielectric Constant (ϵ_{eff}). Because of the nonhomogeneous dielectric structure of microstrip lines, the concept of effective dielectric constant has been introduced (16) and is commonly used for calculating line wavelength and phase velocity as needed in microstrip circuit design. A formula that is commonly used for calculation of ϵ_{eff} is (75)

$$\epsilon_{\mathrm{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}(1 + 10h/W)^{-1/2} \tag{13}$$

where h is height of the dielectric substrate, W is the width of the conducting strip, and ϵ_r is the dielectric constant of the substrate.

Characteristic Impedance (Z_0). As for any other transmission line, the characteristic impedance for the quasi-TEM mode is the most important parameter in microstrip circuit design. Given the dimensions h and W and the value of ϵ_r, the characteristic impedance of a microstrip line can be found by using the following formulas (35, pp. 52–53):

For narrow strips ($W/h < 3.3$),

$$Z_0 = \frac{119.9}{\sqrt{2(\epsilon_r + 1)}}\left[\ln\left(4\frac{h}{W} + \sqrt{16(h/W)^2 + 2}\right) - \frac{1}{2}\left(\frac{\epsilon_r - 1}{\epsilon_r + 1}\right)\left(\ln\frac{\pi}{2} + \frac{1}{\epsilon_r}\ln\frac{4}{\pi}\right)\right] \tag{14}$$

For wide strips ($W/h > 3.3$),

$$Z_0 = \frac{119.9\pi}{2\sqrt{\epsilon_r}}\left[\frac{W}{2h} + \frac{\ln 4}{\pi} + \frac{\ln(e\pi^2/16)}{2\pi}\left(\frac{\epsilon_r - 1}{\epsilon_r^2}\right) + \frac{\epsilon_r + 1}{2\pi\epsilon_r}\left(\ln\frac{\pi e}{2} + \ln\left(\frac{W}{2h} + 0.94\right)\right)\right]^{-1} \tag{15}$$

where e is the exponential base; $e = 2.71828$. For given values of characteristic impedance and ϵ_r, the W/h ratio can be found by using the following expressions:

For narrow strips (when $Z_0 > \{44 - 2\epsilon_r\}$ Ω),

$$\frac{W}{h} = \left\{\frac{e^A}{8} - \frac{1}{4e^A}\right\}^{-1} \tag{16}$$

where

$$A = \frac{Z_0\sqrt{2(\epsilon_r + 1)}}{119.9} + \frac{1}{2}\left(\frac{\epsilon_r - 1}{\epsilon_r + 1}\right)\left(\ln\frac{\pi}{2} + \frac{1}{\epsilon_r}\ln\frac{4}{\pi}\right)$$

For wide strips (when $Z_0 < \{44 - 2\epsilon_r\}$ Ω),

$$\frac{W}{h} = \left(\frac{2}{\pi}\right)\{(B - 1) - \ln(2B - 1)\} + \frac{\epsilon_r - 1}{\pi\epsilon_r}\left\{\ln(B - 1) + 0.293 - \frac{0.517}{\epsilon_r}\right\} \tag{17}$$

where $B = 59.95\pi^2/(Z_0\sqrt{\epsilon_r})$.

Microstrip Discontinuities

Microstrip circuits, like other types of microwave circuits, contain transmission line discontinuities such as bends, width changes, gaps, and junctions. These discontinuities introduce parasitic reactances and cause a degradation in circuit performance. Various types of microstrip discontinuities which are encountered in microwave circuits are shown in Fig. 28. This figure also includes approximate lumped element models for these discontinuities. At higher microwave frequencies, these discontinuity reactances become significant and need to be taken into account. Closed-form relations for discontinuity model elements and their values form a key part of any microwave circuit computer-aided design (CAD) software. However, equivalent lumped circuit models are not available for all types of discontinuities and substrate types. Another difficulty is that the accuracy for discontinuity models degrades at higher frequencies. Lack of accurate discontinuity models at millimeter-wave frequencies is still the main bottleneck in the CAD for millimeter-wave circuits (77).

In order to compensate for the discontinuity effects, one can construct the equivalent circuit for the discontinuity and take it into account in the design process. The second approach is to minimize the discontinuity effect by modifying the geometry of the discontinuity, such as chamfering or mitering the strip conductor in case of microstrip right-angle bends. Compensation techniques for microstrip discontinuities have been reported in the literature (35, pp. 140–165).

Passive Microstrip Circuits

Some commonly used microstrip passive circuits are couplers, power dividers, impedance matching circuits, and filters. De-

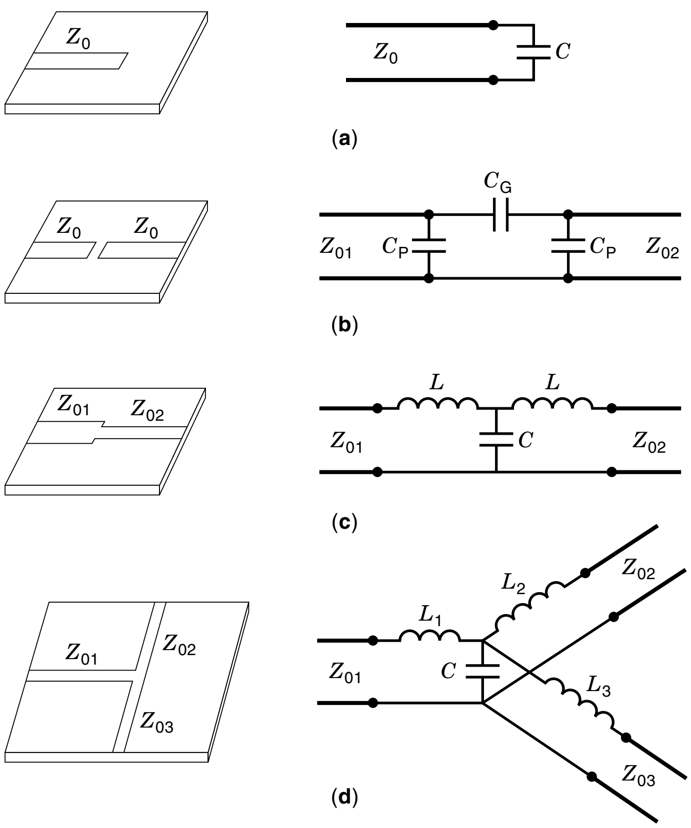


Figure 28. Some common types of microstrip discontinuities and their equivalent lumped element models. (a) Open-ended microstrip. (b) Gap in microstrip. (c) Change in width. (d) T junction.

sign process for these circuits is similar to that for stripline circuits.

Couplers. As in case of stripline circuits, the two common types of microstrip line couplers are also coupled line directional couplers and branch-line directional couplers. Layouts of these couplers are similar to stripline couplers. Even and odd mode analysis technique is applied in the design of microstrip couplers also. For coupled line couplers in microstrip configuration, the phase velocities for even and odd modes are not equal. This factor limits the directivity of these couplers. Design of these couplers is well explained in Refs. 34 and 35.

Branch line couplers are also similar to corresponding circuits in stripline configurations. They can be designed for different values of the coupling factor and may have more than two branches (34,35) in order to increase the circuit bandwidth.

Filters. Various types of filters (34,35) can be realized by using microstrip lines. Again, their design methodology is similar to stripline filters. Low-pass filters can be formed with cascaded sections of microstrip lines. One first designs the prototype filter using lumped elements and then substitutes these elements with their microstrip line equivalents. A short ($<\lambda_g/4$) length of a high impedance line behaves like a series inductance. Also a very short ($\ll\lambda_g/4$) length of low impedance line behaves like a shunt capacitance. An example of a low-

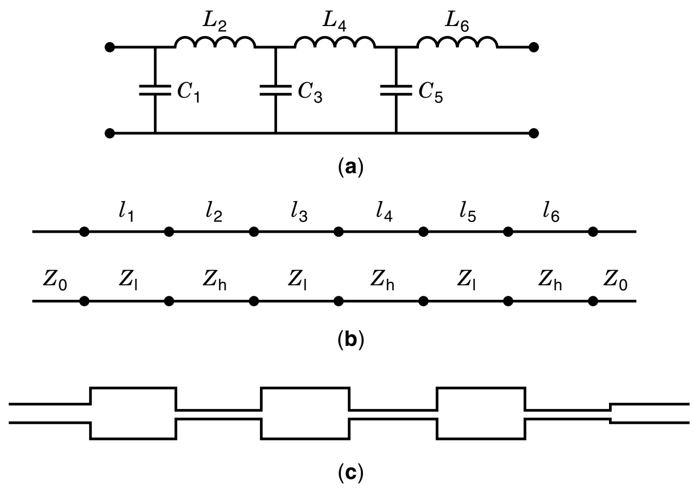


Figure 29. Filter design example. (a) Low-pass filter prototype circuit using lumped elements. (b) Stepped-impedance implementation. (c) Microstrip layout of final filter. High-impedance lines (narrow lines) behave like inductances and low-impedance lines (wide lines) behave like capacitances.

pass filter constructed by microstrip line elements is shown in Fig. 29.

Microstrip bandpass and bandstop filters can also be realized by using coupled sections of microstrip lines. Two popular types of microstrip bandpass filters are end-coupled and parallel (edge)-coupled bandpass filters. Figure 30 shows a general layout for an end-coupled microstrip bandpass filter. In this circuit, coupling gaps are located in between and couple the cascaded microstrip resonator elements. The gap width is usually much smaller than the substrate height to ensure the required coupling between the two adjacent resonators. Parallel-coupled bandpass microstrip filters are similar to the stripline filter shown in Fig. 22. Bandpass and bandstop filters (34,35) can also be realized using quarter-wave open-circuited or short-circuited microstrip line resonators.

Active Microstrip Circuits

Microstrip lines have been used in practically all possible types of active circuits used at microwave frequencies.

Microstrip Amplifiers. Microstrip lines are extensively used in various types of microwave amplifier circuits (34,78,79). All microwave amplifier circuits require some type of matching circuits both at the input and output sides in order to obtain specified gain characteristics over a desired frequency range. Microstrip lines are used for realizing matching networks as well as for biasing networks for microwave amplifiers. Micro-

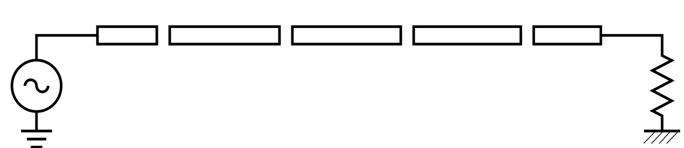


Figure 30. General microstrip layout for an end-coupled bandpass filter (series coupling gaps are located in between cascaded straight resonator elements).

strip lines are also used in distributed amplifiers with multi-octave bandwidths (78,79). Various types of microstrip matching networks are: single-stub matching network, double stub matching network, quarter-wave transformer, multisection transformer and tapered line. Microstrip amplifier circuit design examples including matching and biasing network design considerations are available in Refs. 34, 78, and 79.

Microstrip Oscillators. There are numerous types of oscillator circuits. One of the most common types of microstrip oscillator circuits is the "dielectric resonator oscillator" (DRO). Layout of a microstrip DRO oscillator (35,80) is shown in Fig. 31. In this circuit, the dielectric resonator is coupled to two microstrip lines used to provide a feedback path from the drain to the gate of the MESFET. A microstrip single stub matching circuit is used for the output matching.

Active Microwave Filters. Active microwave tunable filters have been reported in the literature (35,81). Figure 32 shows a layout of a varactor-tuned, multipole active microwave bandpass filter described in Ref. 81.

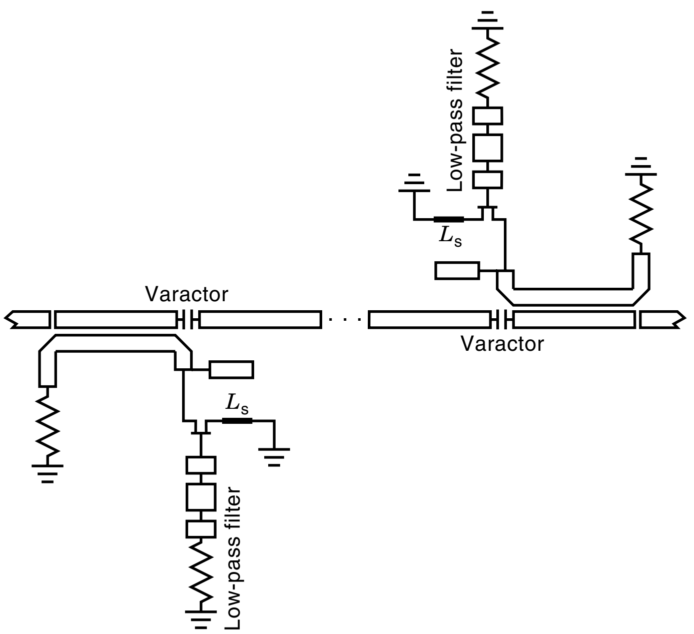


Figure 32. The multipole active tunable filter. The negative resistance is realized by the MESFET circuit. [From Ref. (81), © IEEE, 1990, reprinted with permission.]

Microstrip Circuits for High-Speed Digital Circuits. Microstrip lines are also used in ECL high-speed circuits or GaAs integrated circuits (ICs) for interconnection among the components and/or device chips. These microstrip lines are formed by the conductors of integrated circuits printed on a circuit board. At high frequencies or high speeds, it is essential to minimize reflection at the interconnections. Also, crosstalk between two parallel interconnects can become significant. Various design techniques for microstrip interconnections in high-speed digital circuits are described in the literature (35,82).

Monolithic Microstrip Circuits

Monolithic microwave integrated circuits (MMICs) are microwave circuits in which all circuit components (active and passive) are fabricated on the same semiconductor substrate (83). MMIC circuits are used in many areas of microwave circuits with an increasing popularity because of their significant advantages over hybrid MICs in terms of lower cost, smaller size, better performance, and higher reliability. In the lower microwave frequency range, lumped elements are used for realizing microwave matching networks. However, in the higher frequency range (over 20 GHz), lumped elements become lossy and difficult to design, and distributed elements such as microstrip and coplanar waveguides are used.

Monolithic microwave circuits are described in a separate article in this encyclopedia.

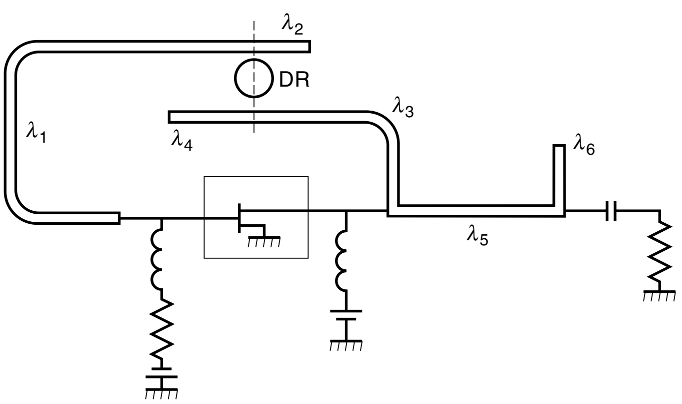


Figure 31. Microstrip implementation of the parallel feedback DRO. A dielectric resonator is coupled to two microstrip lines used to provide a feedback path from the drain to the gate of a MESFET. [Ref. (80)]

COPLANAR WAVEGUIDE CIRCUITS

Coplanar Waveguides

Unlike microstrip lines, the ground plane in a coplanar waveguide (CPW) (84–86) is located on the same side of the substrate that contains the strip conductor. CPWs, coplanar strips, and slotlines are categorized as coplanar lines or uniplanar lines (85) because all the metalization is contained in a single layer. CPW configurations have been widely utilized to realize a variety of microwave circuits including capacitors, inductors, magic tees, mixers, filters, oscillators, resonators, distributed amplifiers, and so on. Configurations of coplanar strips, CPW, and slotlines are shown in Fig. 33.

Field Distribution in Coplanar Lines. Knowledge of field distribution in transmission lines is useful to microwave circuit designers because it helps in configuring location and orientation of lumped active and passive elements in transmission line circuits. Approximate electric field and magnetic field distributions in three coplanar transmission structures are shown in Fig. 34. The field distributions are different from those in a microstrip line, and they lead to some advantages these lines exhibit compared to microstrip lines.

Advantages of CPW Circuits

One of the advantages of CPW circuits over microstrip circuits arises from the fact that mounting of lumped compo-

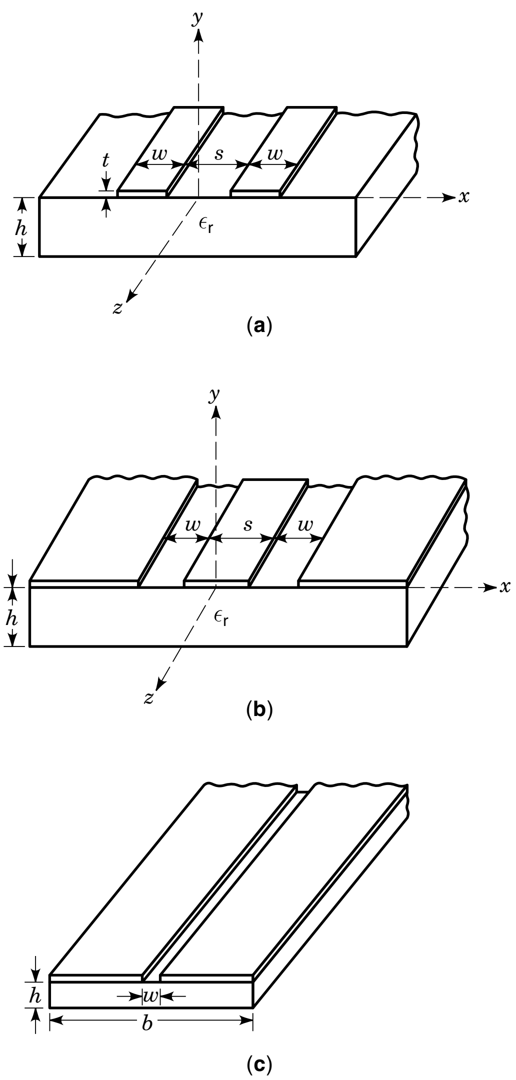


Figure 33. Various types of coplanar lines. (a) Coplanar strip. (b) Coplanar waveguide. (c) Slotline.

nents in shunt connection is easier in a CPW. In this case, drilling of holes through the substrate is not needed to reach the ground plane. Also, transition from a CPW to a slotline is easier to fabricate. This allows a great flexibility in the use of mixed transmission media.

CPW circuit configurations can be designed to exhibit a lower sensitivity to substrate thickness, less dispersion effect, and lower losses than the corresponding microstrip circuits. Implementation of circuits in CPW configurations allows thick substrates to be used, thus avoiding the need to use fragile thin substrates at higher microwave and millimeter-wave frequencies, as occurs for microstrip circuits. Since active components can easily be inserted in CPW circuits also, CPW configurations are used increasingly in monolithic microwave and millimeter-wave integrated circuits. As strip width and gap dimensions in CPW can be reduced without changing the CPW characteristic impedance, CPW circuits can be designed to radiate much less energy than the corresponding microstrip circuits. In addition, dispersive effects in the CPW can be reduced by choosing smaller transverse dimensions.

The CPW configurations, however, have some disadvantages such as possible excitation of the slot mode, lower power-handling capability, and field nonconfinement. Slot mode is an alternative mode possible in a CPW when two ground planes are not at the same potential and E-fields in two slots are oriented in the same direction. This mode can be excited by a non-symmetrical excitation (such as caused by a tee-junction discontinuity). Air bridges are needed to suppress excitation of the slot mode. The fields in a CPW are less confined than those in microstrip lines and therefore they make the CPW circuits more sensitive to packaging covers or shields placed above the circuit.

CPW Circuit Design Considerations

The main difference in the design of CPW circuits as compared to microstrip circuits is the different characteristics of discontinuities occurring in CPW circuits. As the density of active and passive devices in CPW circuits increases, the population of discontinuities also increases. Thus, the slot mode can be excited more frequently because of asymmetrical structure. When MMICs are composed of more than one kind of transmission lines, there is the need for appropriate transitions such as CPW to slotline or CPW to microstrip line. In

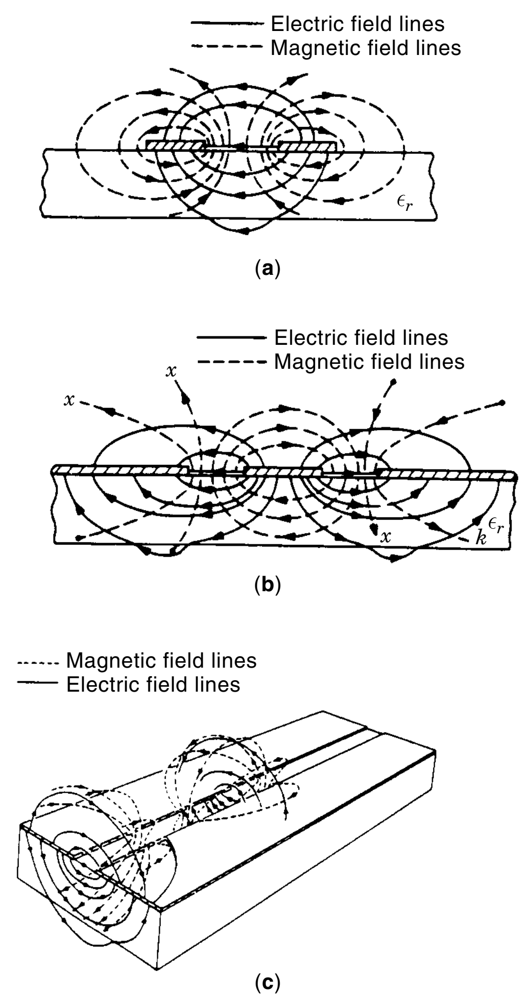


Figure 34. Electrical and magnetic field distributions in (a) coplanar strips, (b) a coplanar waveguide, and (c) a slotline.

the design of CPW circuits, characterization of these discontinuities and transitions needs to be taken into account for obtaining the desired performance. For the analysis and modeling of CPW discontinuities, several numerical methods like mode matching method (87), finite difference method (88), spectral domain analysis (89), transmission line method (90), integral equation method (91), method of lines (92), and so on, have been used.

In addition to discontinuities, other factors such as dispersion, metalization thickness, dielectric loss, conductor loss, radiation, and surface wave loss also affect the performance of CPW circuits. All these factors need to be taken into account in the design of CPW circuits.

Examples of CPW Circuits

Most of microwave circuits developed using microstrip lines and other transmission lines can be realized in CPW configurations also. Some examples of CPW circuits are reviewed in this section.

Capacitors and Inductors. CPW circuits need the basic reactive elements, namely capacitors and inductors, to be realized in CPW configurations. Due to the flexibility provided by CPW configurations to accommodate lumped elements both in series and the shunt connections, capacitors and inductors may be implemented in many ways. Series or shunt circuits for capacitors or inductors are possible using CPW or CPW-slotline transitions, and some of these are shown in Fig. 35 (23).

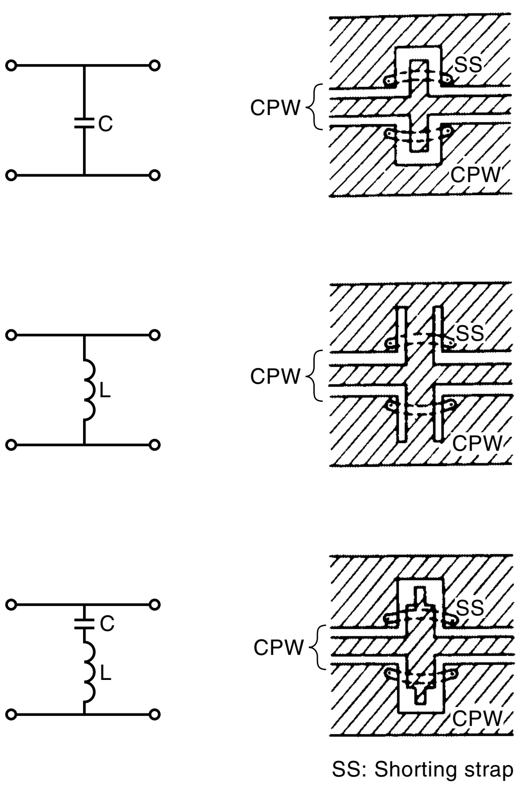


Figure 35. Capacitor and inductor elements realized in a CPW configuration. *C* represents a capacitor and *L* represents an inductor.

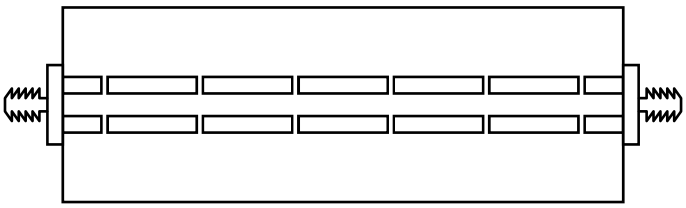


Figure 36. Layout of an inductively coupled multiresonator bandpass filter realized in a CPW configuration.

Filters. Parallel coupled line filters and end-coupled bandpass filters can be realized in CPW configurations also (93,94). Usually, the implementations of these filters utilize a single-layer configuration that is much easier to fabricate. Sometimes a double-layer geometry is used for a wide bandwidth (95). Inductively coupled bandpass filters can also be realized using CPW. These filter configurations eliminate the need for via holes to the ground. The layout of an inductively end-coupled bandpass filter in a CPW configuration is shown in Fig. 36.

Hybrid Ring Couplers and Ring Resonators. The hybrid ring coupler can be realized in a CPW-slotline configuration (96) as shown in Fig. 37(a). This circuit makes use of the properties of a slotline T junction and a CPW-slotline T junction together with the usual operation of a rat-race hybrid ring (97). The circumference of the slot ring is one wavelength divided equally into four quarter-wave sections.

Ring resonators can also be realized using CPW or slotline feed as shown in Fig. 37(b) (98). The resonator can be easily integrated with shunt and series active devices and used for several applications (99,100). The CPW-fed slotline ring resonators show characteristics similar to those of microstrip-fed slotline ring resonators.

Mixers. Most of the microwave mixers use Schottky barrier diodes for mixing operation. A typical mixer circuit consists of a mixer diode together with coupling networks for feeding the RF signal and local oscillator (LO) power and for extracting the IF signal. One of the commonly used mixers is the balanced mixer.

Balanced mixers realized in a CPW configuration (101) use a balanced local oscillator input and an unbalanced signal input. One of the mixer configurations is shown in Fig. 38. Local oscillator voltage is applied via the slotline, and the signal is fed through the coaxial line. Connection to the slotline is made by a small copper coaxial cable (not shown) at right angles to the slot, while a coaxial line connection to the CPW is made directly along as shown. The IF connecting wires are brought through holes in the substrate to mixer diodes.

Oscillators. A three-port MESFET oscillator designed in a CPW configuration (102) is shown in Fig. 39. The gate of the device is self-biased in order to minimize the number of bias points. The source and the drain are connected to 50 Ω CPW transmission lines.

Distributed Amplifiers. A low-noise distributed CPW amplifier (103) is shown in Fig. 40. The distributed amplifier topology offers not only typically greater than octave bandwidth,

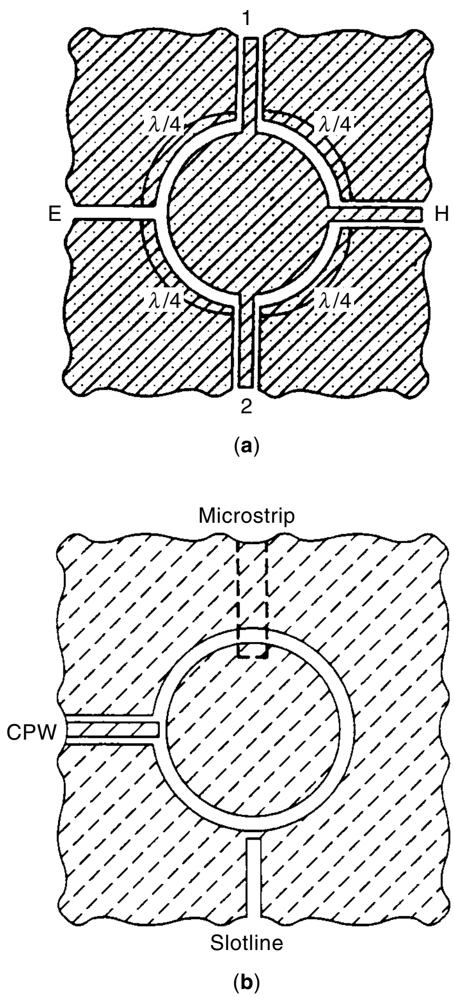


Figure 37. (a) Layout of a hybrid ring coupler in a CPW configuration where the slot ring is one wavelength (λ) and divided equally into four quarter-wave sections. (b) Circuit configuration of a slotline ring resonator with different coupling schemes such as CPW, slotline, or microstrip line.

but also an excellent phase linearity due to the transmission line characteristics inherent in its topology. A distributed amplifier is made up of a set of cascaded devices, which act as shunt capacitances, connected together by high-impedance transmission lines that simulate inductances. The CPW configurations offer simplified fabrication processing and hence lower cost compared to similar microstrip amplifiers.

Various CPW circuit examples mentioned above provide a sampling of microwave circuits that can be designed in CPW configurations. Several other CPW circuit examples have been reported in the literature (104–107).

LUMPED-ELEMENT CIRCUITS

Circuits employing lumped elements, such as inductors and capacitors, are used extensively at lower frequencies. Lumped elements, by definition, are much smaller than the wavelength ($< \lambda/10$) at the operating frequency and exhibit small phase shift across any physical dimension. Thus, the frequency limit for lumped elements is dependent on the size of the element. With improving technology and with the development of monolithic microwave circuits, miniaturization of electronic elements becomes a possibility, and lumped element circuits are used up to about 20 GHz. In millimeter wave monolithic circuits, lumped resistors and MIM capacitors are commonly used. Spiral inductors can be designed with self-resonance frequencies up to 40 GHz. There are several advantages of lumped-element circuits compared to distributed element transmission-line circuits (108, p. 118). First, lumped elements have smaller frequency-dependence and are therefore good for wide-band circuits. Second, the use

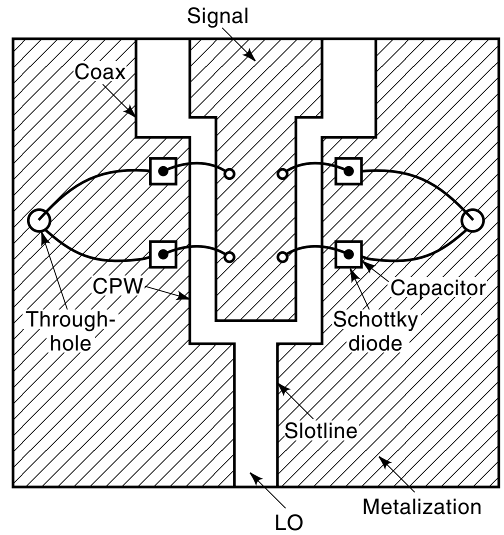


Figure 38. A circuit arrangement for a double balanced mixer using CPW where RF signal is fed through the coaxial line, LO voltage is applied via the slotline, and IF signal is brought out from the through-holes. [Based on Ref. (101).]

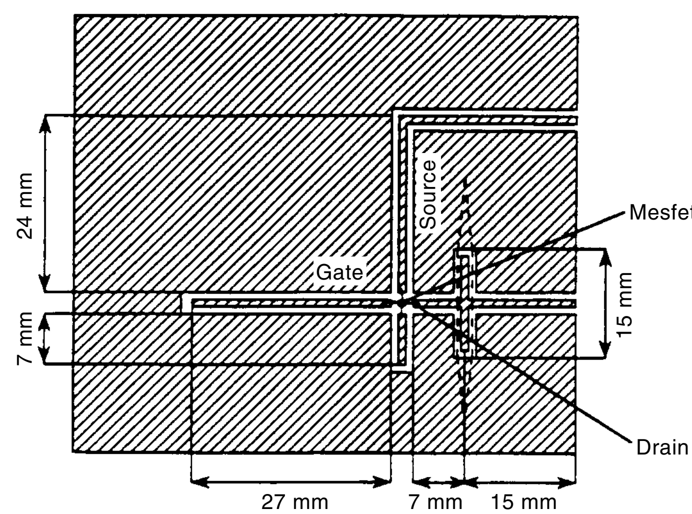


Figure 39. The circuit layout of an oscillator using CPW configurations where the gate of the MESFET is self-biased and is connected to a resonant section of open-circuited transmission line. The dashed line shows the possible position of optical waveguides in a Mach–Zehnde modulator. All CPW lines were designed to have an impedance of 50 Ω. [From Ref. (102), © IEEE, 1993, reprinted with permission.]

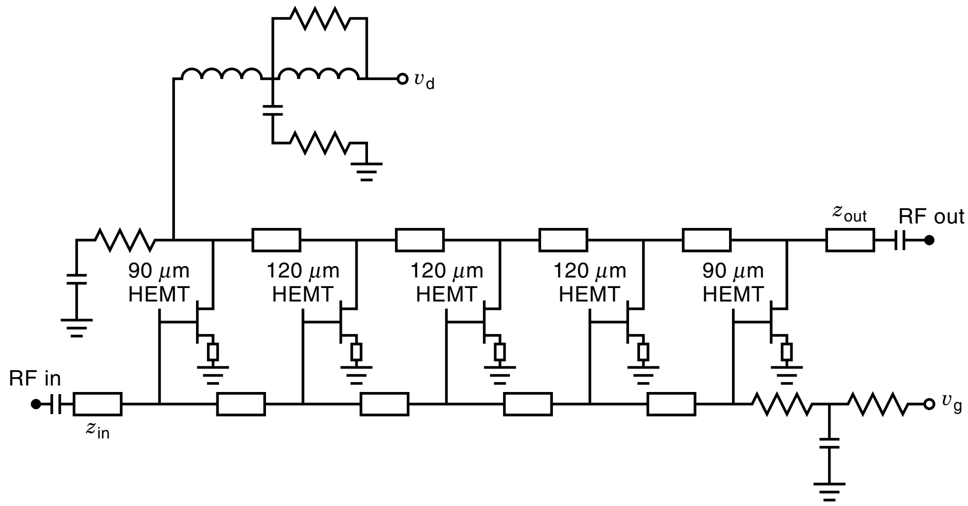


Figure 40. The circuit schematic of a 2 GHz to 20 GHz CPW distributed amplifier using high electron mobility transistors (HEMTs) and CPW lines. [From Ref. (103), © IEEE, 1993, reprinted with permission.]

of lumped elements affords a considerable size reduction (a factor of 10 in area) compared with distributed element circuits in microwave integrated circuits. Third, since the substrate area required is smaller and many lumped-element MICs can be processed simultaneously, the lumped elements are less costly.

Lumped-Element Components

Inductors. Depending on the value of the inductance required, lumped inductors can be realized either as straight narrow strips (ribbon inductors), as single-loop inductors, or as multiturn spiral inductors.

Ribbon Inductors. A microstrip ribbon inductor and its equivalent circuit are shown in Fig. 41. For short lengths ($< \lambda_g/4$) the inductance L and shunt capacitances C at the two ends can be calculated (35):

$$L = \frac{Z_0}{2\pi f} \sin\left(\frac{2\pi l}{\lambda_g}\right) \tag{18}$$

and

$$C = \frac{1}{2\pi f Z_0} \tan\left(\frac{\pi l}{\lambda_g}\right) \tag{19}$$

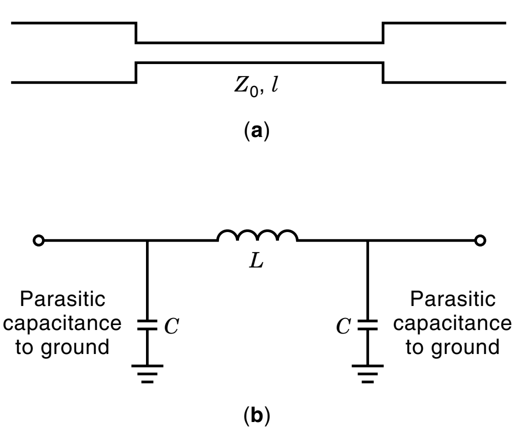


Figure 41. The ribbon inductor consisting of a high-impedance transmission line section. (a) Physical layout. (b) Equivalent circuit.

A narrow strip with high Z_0 is needed to achieve a high inductance value with low parasitic capacitance. However, in practice the choice of the strip width is determined by fabrication limits, by the direct-current-carrying capacity, and by the high resistance of very narrow strips. The strip length is limited simply by the need to ensure a realistic and economical chip size. The ribbon inductor is thus limited to values of less than 1 nH, but is a relatively "pure" inductor with low parasitic capacitances.

Loop Inductors. An example of a single-loop inductor is shown in Fig. 42. Because of their inefficient use of the chip area, loop inductors have been used very little in MMICs. However, design information can be found in a number of references (109–111).

Spiral Inductors. Spiral inductors with multiple turns are essential for inductance values above approximately 1 nH. There are two kinds of spiral inductors: circular spiral and square spiral (see Fig. 43). Circular (approximately) spirals have a slightly better quality factor at the cost of layout complexity and have a less convenient shape for integration with other components. So the square spirals are used more often in MMICs. Design equations can be found in Refs. 112–115. The drawback of the spiral inductors is that the need to connect the center turn back to the outside circuit dictates that either air-bridge or dielectric crossovers must be used. There are a number of different solutions for this connection problem, and these are illustrated in Fig. 44.

Stacked Spirals. Stacked spiral inductors (83) comprise a pair of interwound spirals placed on separate metal layers. The major advantage is that the turns are much more tightly packed than what normal photolithography and metal patterning would allow for a single-layer spiral. Since the turns

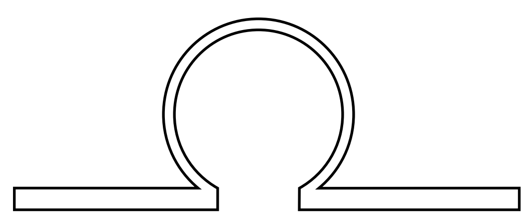


Figure 42. Layout of a single-loop inductor (not used much because of inefficient use of substrate area).

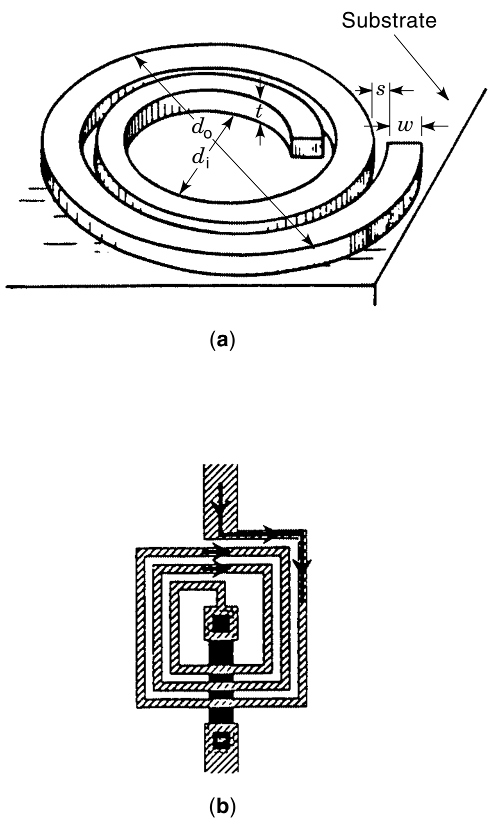


Figure 43. Spiral inductors. (a) Circular spiral. (b) Square spiral. Square spirals allow a more compact layout of components in MMICs.

are separated vertically, there is less capacitance between adjacent turns than there would normally be with such small gaps. However, since the lower metal thickness is limited to 1 μm or less, stacked spirals have higher series resistances. They are generally used at frequencies below 5 GHz or so.

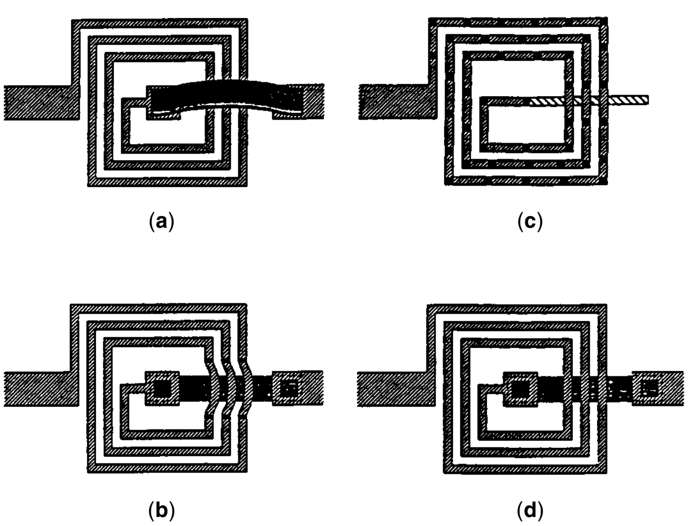


Figure 44. Different interconnection schemes for spiral inductors. (a) Single air-bridge. (b) Air-bridges over an underpass. (c) Formed entirely of air-bridges. (d) Using two metal levels for an underpass. [From Ref. (83), © IEE, 1995, reprinted with permission.]

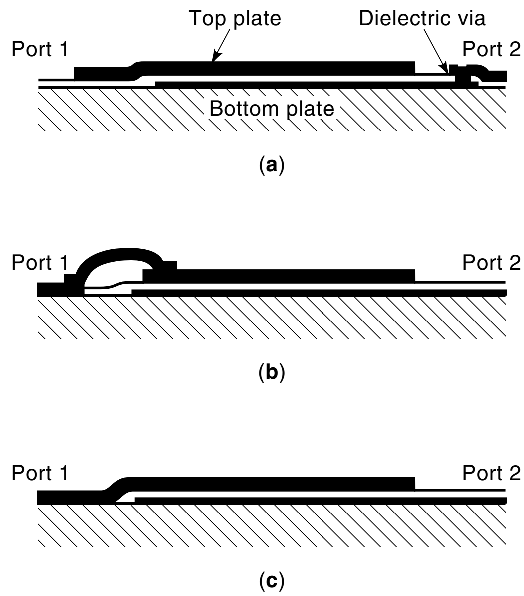
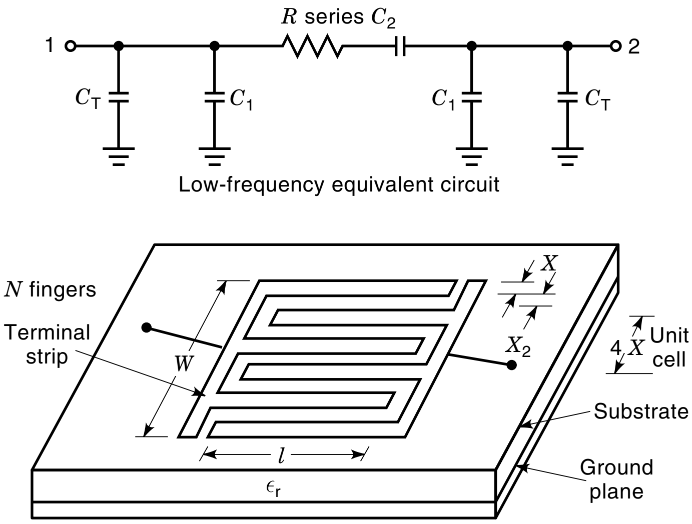


Figure 45. Overlay capacitors. (a) Using a dielectric via. (b) With an air-bridge. (c) Without an air-bridge or spacer dielectric.

Capacitors. Both overlay metal–insulator–metal (MIM) capacitors and interdigital capacitors are used in microwave circuits. Interdigital capacitors can be used for values up to approximately 1 pF, above which their size and the resulting distributed effects prevent their use. Overlay capacitors are therefore needed for most of applications, such as direct-current blocking and decoupling, where large capacitor values are required.

Overlay Capacitors. These consist of an MIM, with the most common insulators being silicon nitride, silicon dioxide, and polyimide. Silicon nitride is popular since it has a fairly higher ϵ_r compared to silicon dioxide and polyimide. The type of connection used from the capacitors to the rest of the circuit depends on whether an air-bridge or a polyimide-based two-metal level process is used. Three types of overlay capacitors with connections are shown in Fig. 45. Design equations for C and capacitor quality factor Q can be found in Ref. 108, pp. 161–165.

Interdigital Capacitors. A capacitor, simpler than the MIM capacitors, is the single-layer interdigital capacitor. The interdigital capacitor consists of a number of interleaved microstrip fingers coupled together and is fabricated in a single-layer structure. Its structure and equivalent circuit are shown in Fig. 46. The maximum value of capacitance of an interdigital capacitor is limited by its physical size. It can be fabricated with values of 0.1 pF to 15 pF in a reasonable size. Because of the long length of gap between lines, large capacitors resonate at low frequency. Therefore only small value capacitors (less than 2 pF) are practical at higher frequencies. Since interdigital capacitors do not use a dielectric film, their capacitance tolerance is very good and is limited only by the accuracy of the metal pattern definition. Hence, they are ideal as tuning, coupling, and matching elements where small capacitor values are required but precise values are necessary. Design equations for these capacitors are available in Refs. 116 and 117.



$R = \frac{4}{3}\frac{l}{XN}R_S$ $\quad Q = \frac{1}{\omega C_2 R}$

Figure 46. Interdigital capacitor layout and equivalent circuit. N is the number of fingers, $4X$ is the width of a unit cell. [From Ref. (116), © IEEE, 1970, reprinted with permission.]

Resistors. Because of the signal loss associated with resistances, the resistors are not used as much at microwave frequencies as in the low-frequency circuits. They are, however, irreplaceable in many cases such as for reflectionless terminations, for suppressing undesirable signals, for damping elements providing the isolation of circuits from each other, or for reducing the power level. Resistors can either use doped semiconductor layers (mesa resistors or implanted planar resistors) or sputtered thin-film resistive layers. Figure 47 shows the two resistor examples. In either case, since the layer or film thickness is fixed, it is very convenient to quote resistivity in terms of an ohm-per-square figure. Hence, the value of the resistor is chosen by selecting a suitable aspect ratio. A practical limit is imposed by the higher parasitic capacitance of large pads and the resistors physical size.

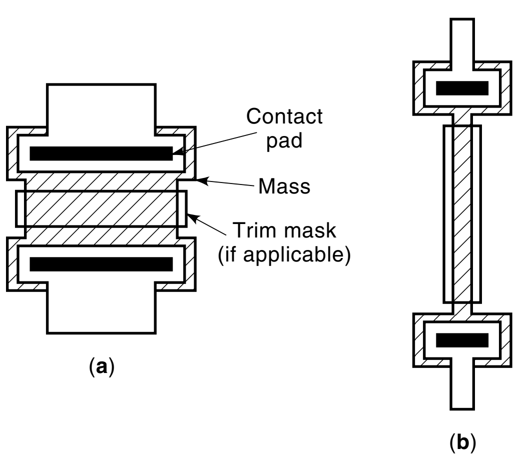


Figure 47. Lumped resistor examples. (a) Small value (= 50 Ω). (b) Large value (= 3000 Ω). [From Ref. (83), © IEE, 1995, reprinted with permission.]

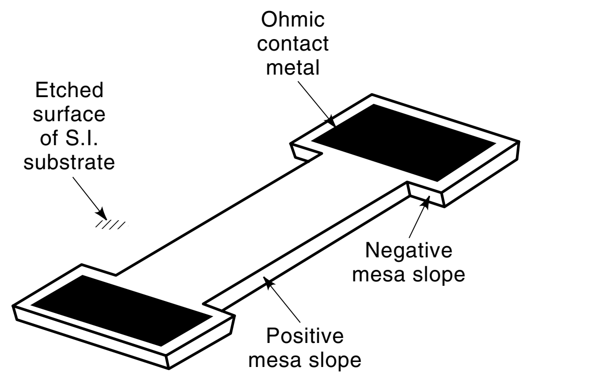


Figure 48. Mesa resistor view showing positive and negative mesa edges.

GaAs Mesa Resistors. The term "mesa" refers to the configuration where the whole wafer is doped and subsequently etched selectively so that active regions remain only where required. Figure 48 shows the details of a mesa resistor with passive and negative mesa edges (83, pp. 77–78). The GaAs resistor relies on the linearity of the semiconductor's current-field characteristic at low electric field values. Hence it is important to consider how much current is to be passed through the resistor. The maximum electric field allowed in the resistor is normally given as a "volts-per-unit-length" value for a certain permissible percentage deviation from perfect linearity.

Thin Film Resistors. Sputtered thin-film resistors offer improved linearity and lower temperature coefficients compared with the mesa types. In addition, the ohm-per-square figure can be optimized for the circuit designer without any limitations imposed by the requirements of the active devices. The most commonly used materials are tantalum nitride, cermet, and nickel chrome. Their temperature coefficients of resistance are less than one-tenth that of GaAs, and ohm-per-square figures of 50 Ω can be produced, which is convenient for the circuit designers (118, pp. 158–159).

Examples of Lumped-Element Circuits

Planar Spiral Transformers. A lumped element transformer with spiral inductors offers direct-current (dc) blocking, matching, and dc bias injection functions in a very small size (120,121). A planar spiral transformer, whose layout and equivalent circuit are shown in Fig. 49, is used as a lumped transformer up to 4 GHz or so (83, p. 73). The two-coupled inductors have self-inductance and mutual inductance. There are series resistances in the conductors, interturn capacitance, and shunt capacitance to ground. The most serious parasitic is usually the capacitance between the two spirals since this makes the transformer resonant as the capacitive coupling becomes dominant at higher frequencies. To minimize this parasitic capacitance while achieving a high mutual inductance, the turns need to be very narrow and close together. Typically a transformer would have 5 μm conductor widths and 5 μm gaps.

Lumped-Element Matching Circuits for MMIC Amplifiers. A lumped-element amplifier circuit (83, p. 19) is shown in Fig. 50. Lumped-element matching networks (using spiral inductors and overlay capacitors) provide an appropriate arrange-

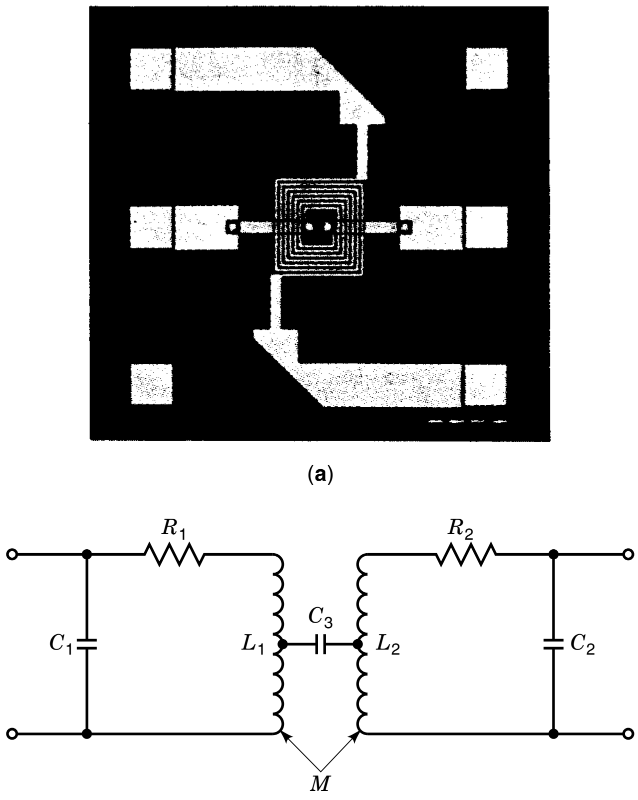


Figure 49. A lumped element spiral transformer. (a) Layout. (b) Equivalent circuits. [From Ref. (83), © IEE, 1995, reprinted with permission.]

ment at frequencies below 20 GHz. The chip is a 1 GHz to 2 GHz single-stage amplifier. When operation frequency is higher than 20 GHz, the performance of spiral inductors degrades because of their self-resonances.

Lumped-Element Resonators. Series and parallel lumped-element resonators using interdigital capacitors are shown in Fig. 51 (117). These kinds of resonators can be used at frequencies of 7 GHz and higher. A 0.3 pF capacitor with a 20 μm gap had a capacitance tolerance of less than 25% from sample to sample. These resonators are fabricated on one side of alumina or quartz substrate.

Filters. Figure 52 depicts a lumped element filter with bandstop loss of 30 dB at 9 GHz (117). The equivalent circuit is also shown. Interdigital capacitors are of practical use and allow the attainment of the few picofarad capacitor values required for the design of these filters at the higher microwave frequencies. Several other types of lumped element microwave circuits have been reported in the literature (83,118,119,121).

MULTILAYER MICROWAVE CIRCUITS

Multilayer Configurations

Portable microwave systems require circuits to be fabricated in smaller sizes and volumes. Multilayer configurations have begun to be adapted for microwave circuits to meet these size requirements (122–125). Also, multilayer designs exhibit more flexibility and, in several cases, yield better performance than the corresponding designs in single-layer configurations (126). A tight coupling is an outstanding characteristic that multilayer circuits can provide. Since a physical geometry with very narrow spacing is necessary to produce a tight coupling in single-layer directional couplers, directional couplers realized in two layers are well suitable for providing a tight coupling and high directivity (127). This tight coupling also makes it possible to obtain wide bandwidth in filter circuits (123). In addition, the circuits designed using symmetrical planar structures in traditional single-layer configurations can now be implemented in asymmetrical geometry. This asymmetry produces more design flexibility, leading to conveniently realizable physical geometries.

Multilayer configurations have also been utilized to integrate a number of passive components and active devices into a module to reduce the size and the volume of the whole system. This kind of use of multilayer structures has resulted in the development of multichip module (MCM) technology at microwave frequency (128,129). However, multilayer config-

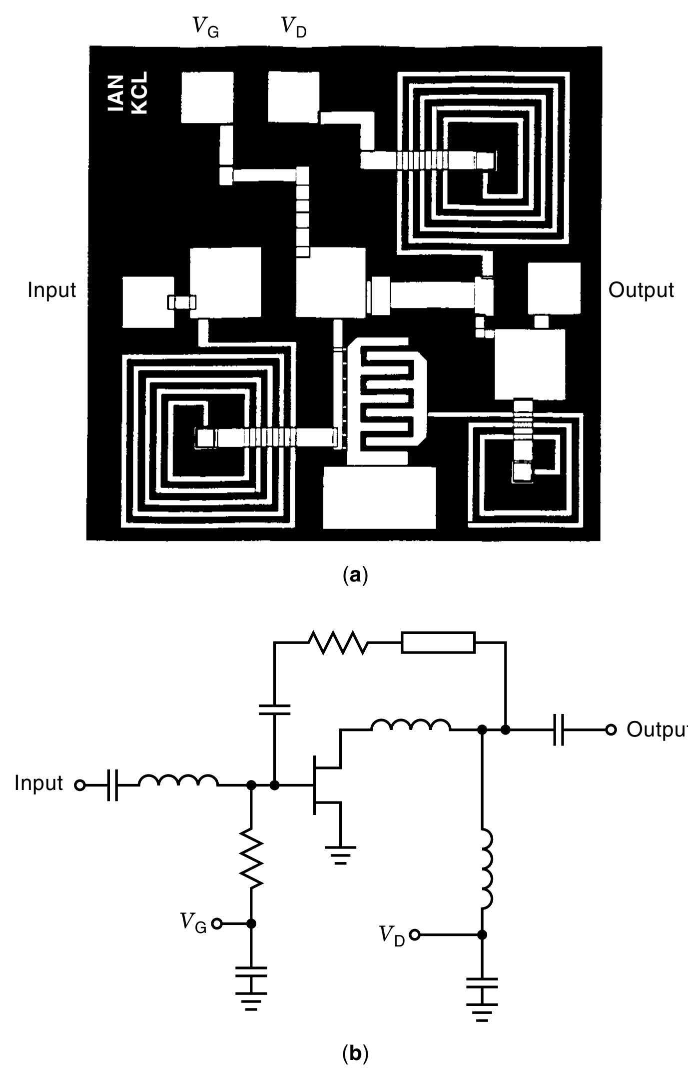


Figure 50. A lumped-element 1 GHz to 2 GHz MMIC amplifier. (a) Layout. (b) Circuit diagram. [From Ref. (83), © IEE, 1995, reprinted with permission.]

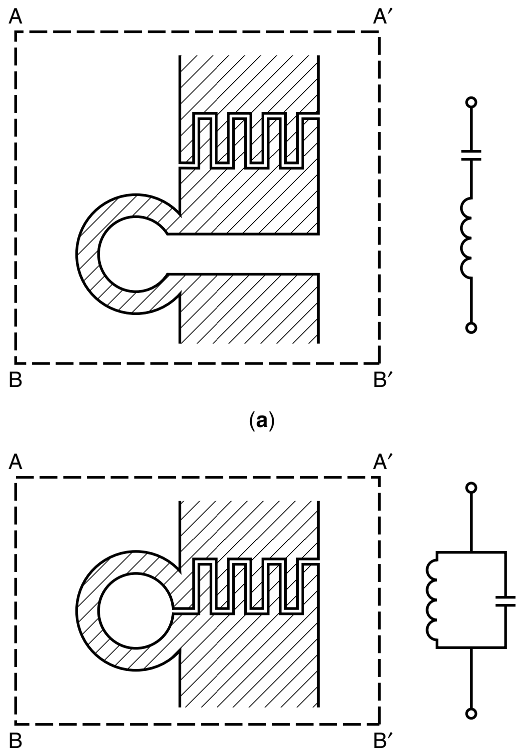


Figure 51. Series and parallel lumped-element resonator networks using interdigital capacitors. (a) Series *LC*. (b) Parallel *LC*. The size *AA′BB′* fits across a standard coaxial connector. [From Ref. (117), © IEEE, 1971, reprinted with permission.]

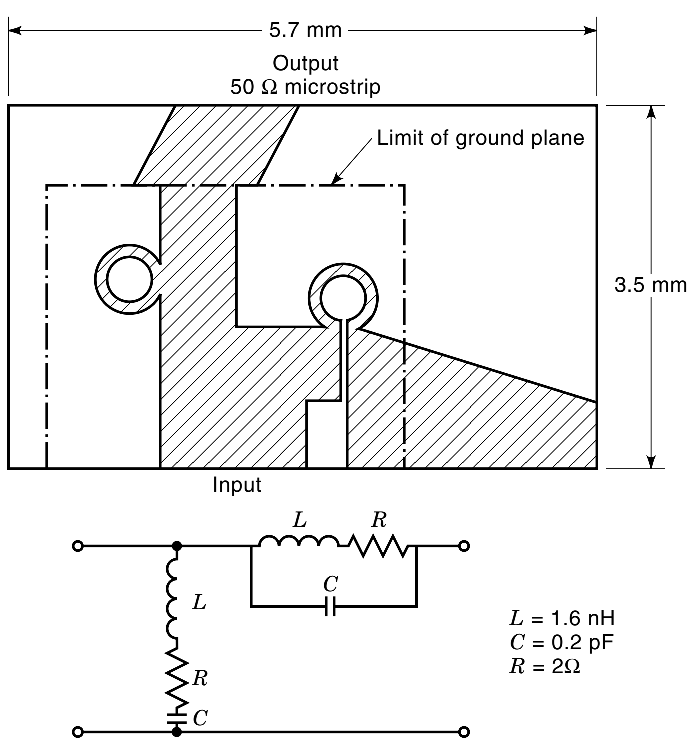


Figure 52. Bandstop filter and equivalent circuit. Bandstop loss at 9 GHz was 30 dB. [From Ref. (117), © IEEE, 1971, reprinted with permission.]

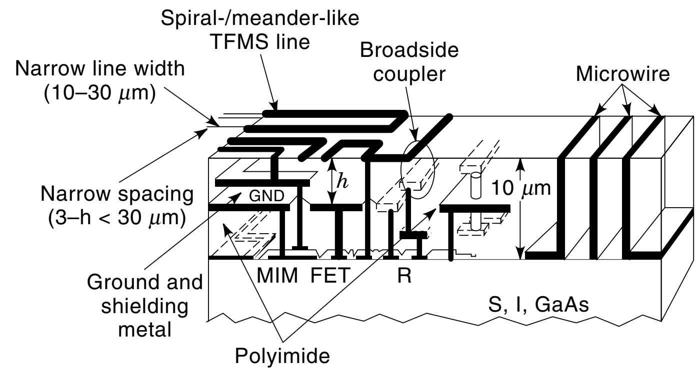


Figure 53. Structure of the three-dimensional multilayer MMIC fabricated on a GaAs substrate. Active devices and an MIM capacitor are placed on the surface of a wafer, thin polyimide films and conductors are stacked on the wafer, and thin-film microstrip (TFMS) lines and ground layers are connected through via-holes. [From Ref. (131), © IEEE, 1996, reprinted with permission.]

urations inherently require vertical interconnections between adjacent layers. Also, there is a possibility of air gap and misalignment between different dielectric layers, and these can affect the circuit performance.

Multilayer Microwave Circuit Technologies

Multilayer MMICs. Multilayer MMICs (130–132) are constructed using multilayer passive circuits integrated with active devices on the semiconductor substrate. Active devices, resistors, and MIM capacitors are formed on the surface of a semiconductor wafer. Dielectric films and conductors are stacked on the wafer, and transmission lines and the ground layers are connected through via-holes. This structure allows transmission lines with reduced line widths, vertical interconnections with short signal delays, and miniaturized connections in a small area. In addition, this provides miniature but low-loss transmission lines and increased design flexibility.

For examples using this multilayer structure, several miniature passive circuits such as directional couplers, Wilkinson power dividers, transmission lines, and planar baluns have been designed and fabricated. Active circuits such as mixers, amplifiers, phase shifters, and upconverters are integrated with passive circuits in planar forms. Figure 53 (131) shows the typical configuration of a multilayer MMIC. In Fig. 53, a three-dimensional MMIC fabricated on a GaAs substrate integrates active devices, resistors, and MIM capacitors on the surface of a semiconductor wafer. A thin-film microstrip (TFMS) line offers a compact meander-line configuration while thin polyimide films and conductors are stacked on the wafer and ground metal is inserted between layers.

Multichip Modules. A multichip module (MCM) (129) is defined as multilayer sandwiches of dielectric and conducting layers, on which integrated circuits and passive components (if any) are mounted directly on (or inside of) the sandwich structure, without separate packaging for each of the active components. That is, the chips are mounted bare onto the MCMs, which then provide the required power and ground, as well as all the signal interconnect and the electrical interface to the external environment. The entire MCM, including chips and passive components, may be placed in a hermetic

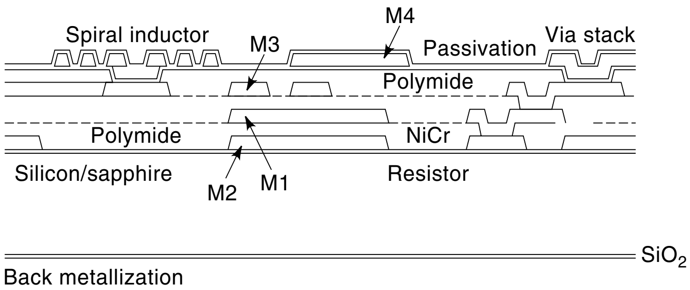


Figure 54. Multichip module (MCM-D) technology used for RF integration. Polyimide dielectrics are deposited onto a silicon sapphire substrate; then the chips are installed on the upper surface, and transmission lines and vias are fabricated.

package much like a large single-chip carrier, or it may be directly covered with a sealant material (such as epoxy or a glass passivation coating) to protect the components from physical damage.

Three general categories of MCMs are MCM-C (ceramic), MCM-L (laminate), and MCM-D (deposited). MCM-Cs are manufactured by stacking unfired layers of ceramic dielectric, onto which liquid metal lines are "silk-screened" using a metal ink process. The individual inked layers are then aligned, pressed together, and cofired into a solid planar structure, onto which integrated circuits can be installed. MCM-Ls are manufactured through the lamination of sheet layers of organic dielectric, and they are very similar to traditional printed circuit-board technology. MCM-Ds are manufactured through the deposition of organic or inorganic dielectrics onto a silicon or alumina support substrate. After each dielectric layer is deposited, one of several technique is used to pattern metal lines as well as metal vias. The chips are then installed on the upper surface.

MCM-D technology can provide a versatile platform for the integration of GaAs MMICs and silicon devices for microwave circuits where performance, size, and weight are critical factors. Multilayer circuits such as spiral inductors, baluns, directional couplers, Lange couplers, transmission line transformers, filters, amplifiers, and voltage-controlled oscillators have been realized using this technology (129). Figure 54 shows a typical configuration that can be fabricated by MCM-D technology suitable for design of multilayer microwave circuits.

Design of Multilayer Circuits

Multilayer microwave circuits can be divided into two groups, the first of which consists of planar components employing multilayer transmission structures, while in the second group, one integrates various circuits into a single multilayer module.

Multilayer couplers, filters, baluns, inductors, and so on, belong to the first group because these employ multilayer transmission structures to overcome difficulties occurring in single-layer designs. It is well known (62) that coupled lines realized in single-layer structures produce a weak coupling. Thus, when a tight coupling is required, coupled lines can be implemented in multilayer configurations because overlapping geometry between coupled lines is possible. Coupled-line couplers requiring a tight coupling and those requiring high

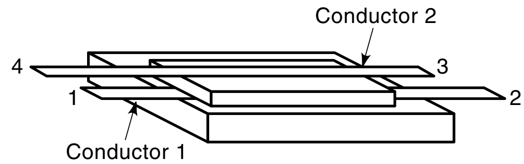


Figure 55. Two-layer coupled-line coupler. Conductors are placed on different levels. A tight coupling can be obtained.

directivity are designed (127) using this advantage. For the design of parallel coupled-line filters and end-coupled filters, a wide bandwidth is frequently required. For this purpose, multilayer structures used in coupled-line filters (133) and end-coupled filters (95) allow overlapping geometry in the design, which leads to a wide bandwidth and flexibility in selection of physical dimensions. Baluns using multilayer coupled lines (134) can also be designed for wideband operation and with compact dimensions because a tight coupling can easily be obtained in multilayer configurations. Apertures in the ground plane can be employed to achieve interconnection between different layers in multilayer circuits (135) such as aperture-coupled couplers and magic tees.

For the multilayer circuits in the second group, passive components and/or active devices are integrated into a single module for miniaturization and cost-effective production (131). When these are integrated, vertical vias between different layers and apertures in the ground plane are placed appropriately considering miniaturization, crosstalk, and productivity.

Examples of Multilayer Circuits

Some examples of multilayer microwave circuits are discussed in this section.

Couplers. Since single-layer structure is not convenient for couplers requiring a tight coupling, multilayer configuration has been explored to overcome this difficulty. As a result, coupled-line directional couplers in two layers (136) and reentrant type couplers (137) designed for a tight coupling have been reported. Figure 55 shows a two-layer coupler (136). Two conductors with unequal widths are placed on different layers to yield a tight coupling. Different port impedances can be used at the four external ports.

Figure 56 shows a reentrant-type coupler where two identical conductors placed on the top layer with a wider conductor on the bottom layer produce a tight coupling. The spacing

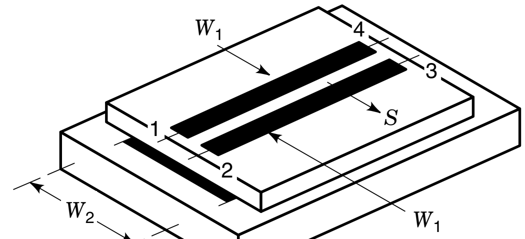


Figure 56. Reentrant-type coupler. Two identical conductors are placed on top layer with a wide spacing, a wide conductor is placed on the bottom layer. This coupler provides a tight coupling.

Figure 57. Multilayer parallel coupled-line filter. Various conductors can be placed on different levels; each coupled section produces tight coupling, leading to broad bandwidth for the filter.

between the two conductors on the top layer is wide, not leading to tight tolerance requirement of a narrow gap in fabrication.

Filters. Multilayer configurations have been used for wideband parallel coupled-line filters (138) and end-coupled bandpass filters (95) because filters in single-layer configurations cannot yield a wide bandwidth. Aside from the wide bandwidth, enhanced freedom in circuit layout in multilayer designs makes multilayer configurations more attractive. Parallel coupled-line filters and end-coupled bandpass filters have been developed in multilayer structure and also in multilayer coplanar waveguide structure. Examples of these filter circuits are shown in Figs. 57 and 58.

In Fig. 57, coupled lines, which can be placed on different layers, constitute a bandpass filter where each coupled line can have nonsymmetrical geometry leading to flexibility in design. Due to these coupled lines offering tight coupling, multilayer coupled-line bandpass filters provide wide bandwidths which are not achievable in single-layer configurations. In Fig. 58, gap-coupled sections constitute a bandpass filter in two-layer configuration. Since this structure allows overlapping conductors in each gap-coupled section, this can also be used for obtaining a wide bandwidth.

Baluns. Due to the requirement for a wide bandwidth and compact design, planar Marchand baluns have been developed (134) using coupled lines in two-layer configurations. These baluns provide wide bandwidth (more than one octave) and compaction of physical dimensions. Figure 59 shows one such circuit reported in the literature. In Fig. 59, two kinds of coupled-line sections in two layers constitute a planar Machand balun. An unbalanced signal entering port 1 is transformed into a balanced signal coming out of ports 2 and 3.

Three-line baluns using three-coupled lines have also been designed (139) in a two-layer structure, leading to compact design and good performance. Figure 60 shows one of such balun designs. In this design, one of the conductors is placed

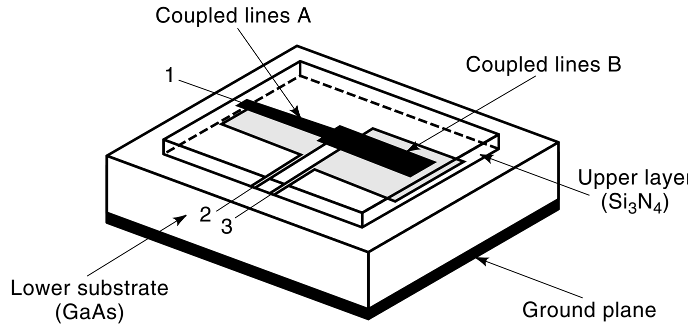


Figure 59. Planar Marchand balun. Two kinds of coupled lines constitute a balun transforming an unbalanced signal entering into port 1 to a balanced signal coming out of ports 2 and 3. [From Ref. (134), © IEEE, 1990, reprinted with permission.]

on one layer while two other conductors are placed on the second layer. With appropriate terminations at the ports, this balun transforms an unbalanced signal at port 1 to a balanced signal at ports 2 and 3.

Hybrids. Branch-line couplers (140) and magic tees (135) have been developed using multilayer configurations to produce better performance than what can be obtained in single-layer configurations. Figure 61 (140) shows a multilayer branch-line coupler where the two output ports are mutually isolated, and the signals at these two ports are out of phase by 90°. The distance between two microstrips or slotlines is one quarter-wavelength. It is possible to make 3 dB branch-line couplers by suitably choosing the values of Z_m and Z_s.

Figure 62 shows (135) a multilayer magic tee where the microstrip line (difference arm) on the lower substrate is coupled to a slot-aperture and is terminated on the same layer by an open-circuit stub. The other three magic tee ports are located at the top layer. With the excitation at port 1 (difference port), signals at ports 2 and 3 are equal in magnitude and out of phase by 180°. When the sum port (port 4) is fed, signals at ports 2 and 3 are in phase and equal in magnitude. In addition to the circuits described above, there are many other multilayer circuits like transmission line transformers (141), aperture-coupled multilayer circuits (142), and aperture-fed and microstrip patch antennas (143).

DESIGN OF MICROWAVE CIRCUITS

As is true also for design processes in other domains of engineering, the computer-aided design (CAD) approach (144–

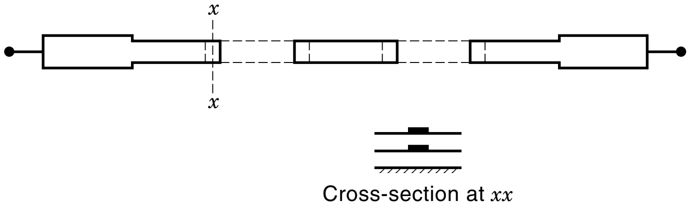


Figure 58. Two-layer end-coupled bandpass filter. Half-wave resonators shown in dotted lines are at lower layer. Each gap-coupled section can have overlapping geometry for tight coupling and therefore broad bandwidth of the filter.

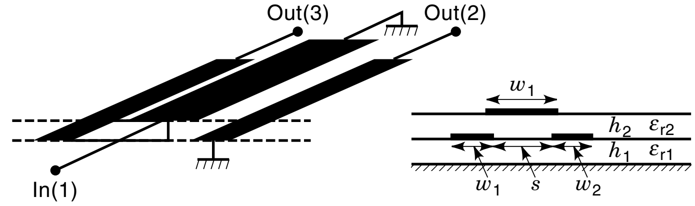


Figure 60. Two-layer three-line balun. One conductor is placed on one layer while two other conductors are placed on the other layer. With appropriate terminations at different ports, this circuit works as a balun.

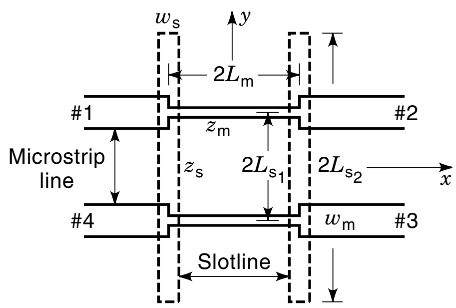


Figure 61. A branch-line coupler in a two-layer structure. Slotlines are placed on the lower layer while two microstrip lines are located on the upper layer, and two outputs are (at ports 2 and 3) 90° out of phase and equal in magnitude. [From Ref. (140), © IEEE, 1995, reprinted with permission.]

146) is being used extensively for the design of microwave circuits and is also being refined further. In order to appreciate the CAD methodology, it is necessary to review the conventional design process that designers used before the CAD methods and software were developed.

Conventional Design Procedure

A flow diagram depicting the conventional design procedure is shown in Fig. 63. One starts with the desired circuit specifications and arrives at an initial circuit configuration. Available design data and previous experience are helpful in selecting this initial configuration. Analysis and synthesis procedures are used for deciding values of various parameters of the circuit. A laboratory model is constructed for the initial design, and measurements are carried out for evaluating its characteristics. Performance achieved is compared with the desired specifications; if the given specifications are not met, the circuit is modified. Adjustment, tuning, and trimming mechanisms incorporated in the circuit are used for carrying out these modifications. Measurements are carried out again and the results are compared with the desired specifications. The sequence of modifications, measurements, and comparison is carried out iteratively until the desired specifications are achieved. At times the specifications are compromised in view of the practically feasible performance of the circuit. The final circuit configuration thus obtained is sent for prototype fabrication.

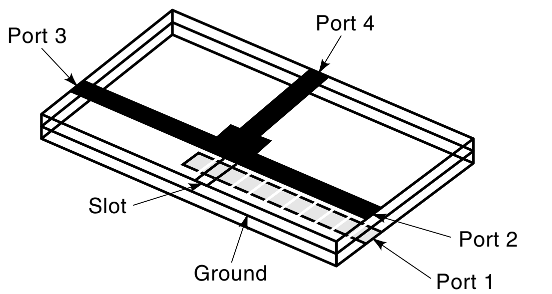


Figure 62. A two-layer microstrip magic-tee junction (ports 2, 3, and 4) coupled through a slot in the ground to a microstrip line (port 1) on the backside. [From Ref. (135), © IEEE, 1997, reprinted with permission.]

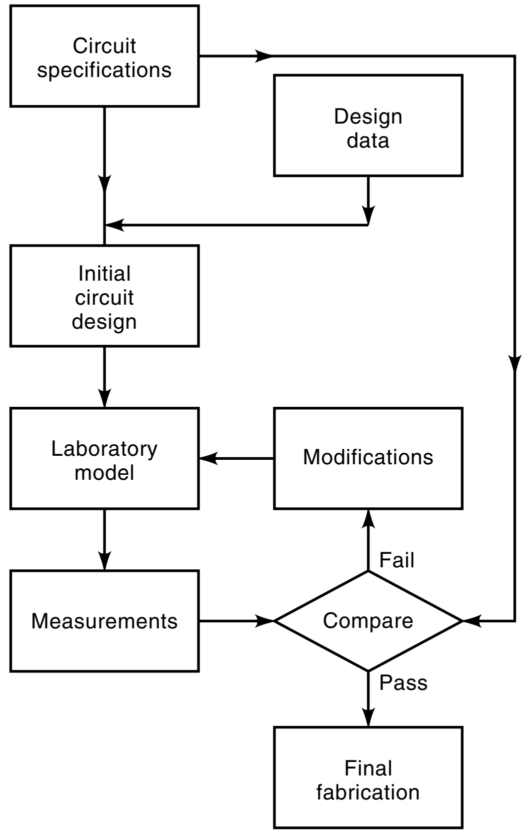


Figure 63. The conventional design procedure that was used for microwave circuits before CAD methods were developed.

The above procedure had been used for the design of microwave circuits for quite some time. However, it became increasingly difficult to use this iterative experimental method successfully because of the following considerations:

1. Increased complexity of modern systems demands more precise and accurate design of circuits and subsystems. Consequently, the effect of tolerances in the circuit design becomes increasingly important.
2. A larger variety of active and passive components, as described in previous sections, are now available for achieving a given circuit function. The choice of the appropriate device or transmission structure becomes difficult if the iterative experimental approach is used.
3. It is very difficult to incorporate any modifications in the circuits fabricated by MIC technology.

The method developed for dealing with this situation is known as "computer-aided design (CAD)." Computer-aided design in its strict interpretation may be taken to mean any design process where the computer is used as a tool. However, usually the term CAD implies that without the computer as a tool, that particular design process would have been impossible or much more difficult, more expensive, more time-consuming, and less reliable and more than likely would have resulted in an inferior product.

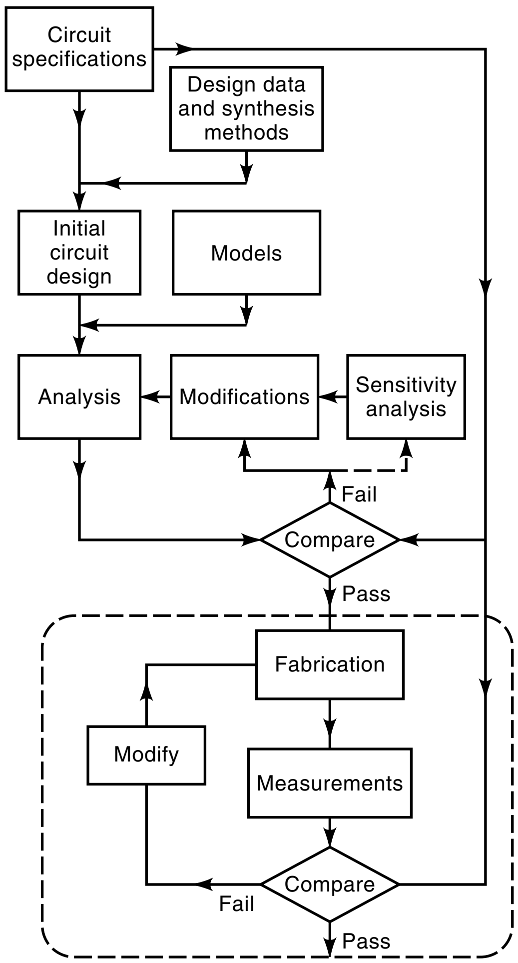


Figure 64. Computer-aided design methodology used for microwave circuits. Recent developments have brought microwave CAD tools to a level of maturity.

CAD of Microwave Circuits

A typical flow diagram for the CAD procedure is shown in Fig. 64. As before, one starts with a given set of specifications. Synthesis methods and available design data (at times prestored in computer memory) help to arrive at the initial circuit design. The performance of this initial circuit is evaluated by a computer-aided circuit analysis. Numerical models for various components (passive and active) used in the circuit are needed for the analysis. These are called from the library of subroutines developed for this purpose. Circuit characteristics obtained as results of the analysis are compared with the given specifications. If the results fail to satisfy the desired specifications, the designable parameters of the circuit are altered in a systematic manner. This constitutes the key step in the optimization. Several optimization strategies include sensitivity analysis of the circuit for calculating changes in the circuit parameters. The sequence of circuit analysis, comparison with the desired performance, and parameter modification is performed iteratively until the specifications are met or the optimum performance of the circuit (within the given constraints) is achieved. The circuit is now fabricated and the experimental measurements are carried out. Some modifications may still be required if the modeling and/or analysis are not accurate enough. However, these modifications, hopefully, are very small, and the aim of the CAD method is to minimize the experimental iterations as far as practicable.

The process of CAD, as outlined above, consists of three important segments, namely:

1. Modeling
2. Analysis and
3. Optimization

Modeling involves characterization of various active and passive components to the extent of providing a numerical model that can be handled by the computer. In the case of microwave circuits, one comes across a variety of active and passive elements. Semiconductor devices used include bipolar and MESFET transistors, point contact and Schottky barrier detectors, varactor and *pin* diodes, and transferred electron and avalanche devices. Passive elements used in microwave circuits include sections of various transmission structures, lumped components, YIG and dielectric resonators, nonreciprocal components, and planar (two-dimensional) circuit elements. Transmission structures could be coaxial line, waveguide, stripline, microstrip line, coplanar line, slotline, or a combination of these. As mentioned earlier in this article, not only do these transmission structures need to be characterized fully for impedance, phase velocity, and so on, it also becomes necessary to model the parasitic reactances caused by geometrical discontinuities in these densely packed transmission lines.

Modeling of components in microwave circuits had been the main difficulty in successful implementation of CAD techniques at microwave frequency. However, the development of electromagnetic (EM) simulation techniques developed over the last decade has helped to construct adequate models and bring microwave hybrid and monolithic circuit CAD software to a level of maturity. Modeling still remains the major bottleneck for CAD of certain classes of microwave circuits [such as coplanar waveguide (CPW) circuits, multilayered circuits, and integrated circuit-antenna modules] and most of the millimeter-wave (above about 40 GHz) circuits. Current research in efficient use of EM simulation techniques and in use of artificial neural network models (77) will lead to further improvement in CAD tools for microwave and millimeter-wave circuits.

EMERGING TRENDS IN MICROWAVE CIRCUITS

Even after going through developments over almost a century, the field of microwave circuits continues to see developments in full swing even today; particularly in the areas of multilayered circuits, integrated circuit-antenna modules, quasioptical circuits and systems, and exotic methodologies for CAD.

Multilayered Circuits

Microwave multilayered circuits were described earlier in the section entitled "Multilayer Microwave Circuits." Multilayered circuit technology is responsible for two novel innovations in monolithic microwave circuits. The first one of these is the development of three-dimensional passive circuit technology (147) as an evolution from the two-dimensional planar microwave circuit technology which has been the cornerstone of integrated microwave circuit technology so far. Three-dimensional microwave circuits make use of multilayered configurations combined with vertical wall-like microwave structures. This technology can reduce the sizes of inductors and transmission lines to one-third or one-fourth of the size of two-dimensional configurations.

Another novel concept that has emerged from the application of multilayer circuit technique is that of master slice MMIC (148). The basic idea is similar to that of gate arrays used for semiconductor application-specific integrated circuits (ASICs). In an MMIC master slice, many units that contain transistors, resistors, and lower electrodes for MIM capacitors are located repeatedly (nearly 6 units/mm^2) on a GaAs or Si wafer to form a master array. Additional upper layers provide custom design interconnects and top conductor for capacitors to yield semi-custom-designed circuits.

Integrated Circuit-Antenna Modules

Another very interesting trend in microwave and millimeter-wave design is the integration of conventional circuit and antenna functions in single components. This integration has been made possible by common fabrication technology used for planar circuits and printed antennas. Various design approaches applicable to integrated circuit-antenna modules have been developed (149). Quasioptical systems (150) designed to generate high power at millimeter-wave frequencies by employing a grid array of sources are important examples of integrated circuit-antenna modules.

Knowledge-Aided Design (KAD)

Emerging innovations in design techniques (77) for microwave circuits include use of artificial neural networks and development of knowledge-based design tools.

Artificial neural networks (ANNs) are neuroscience-inspired computational tools that learn from experience (training), generalize from previous examples to new ones, and abstract essential characteristics from inputs containing noise or irrelevant data. A significant application of ANN computing to microwave design has been for development of component models (151). These models are as accurate as results for EM simulators used for training them but are as efficient as network models. ANNs are expected to play a significant role in microwave design in areas of modeling and optimization and possibly as a means of embedding knowledge in design tools.

Any design process involves several steps starting from problem identification and going through specification generation, concept generation, initial analysis and evaluation, and initial design to a detailed optimized design. It is for the last of these steps (from initial design to detailed optimized design) that the current microwave CAD tools have been developed. The earlier steps in the design process are not at all trivial. We need a technology to aid the earlier stages of design where designers make important and expensive decisions. Knowledge-based system seems to be the most appropriate technology for this purpose.

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MICROWAVE COMPONENTS.

See Stripline components.