1

INTRODUCTION

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In modern information and communication techniques, planar integrated microwave circuits play an important role. Such planar microwave circuits were used for the first time in the 1950s. They are produced with thin-film metallic strip lines on a plastic or ceramic substrate material, are cost-effective, and need reduced space as compared to, for example, waveguide circuits. Moreover, active elements like diodes and transistors can be easily integrated into the metallic planar waveguide structures. During the first 40 years of planar circuit development the so-called microstrip line that had been developed by ITT [1] was used primarily in planar microwave integrated circuit design. Active semiconductor elements as well as thin-film and thick-film capacitors and resistors have been integrated into the circuits using hybrid technologies.

With the development of modern microwave transistors like field effect transistors (MESFETs: metal-semiconductor field effect transistors) and heterostructure field effect transistors (HEMTs: high electron mobility transistors) on GaAs or InP materials, the application of hybrid and also of monolithic microwave integrated circuits has grown intensively over the last 25 years. Today, a broad class of analog and function block circuits is available to the microwave engineer in a frequency range from 0 to about 150 GHz. A wide range of literature has been published in international conference proceedings, in leading international journals, and in specialized books on the subject, such as references 2–6.

Coplanar Microwave Integrated Circuits, by Ingo Wolff.
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Monolithic microwave integrated circuits (MMIC) offer the advantage of a cost-effective mass production, improved electrical parameters, smaller size and weight as well as improved reliability compared to the hybrid integrated circuits. The disadvantage of monolithic integrated circuits compared to the hybrid integrated ones is that a tuning, as it is possible for hybrid integrated circuits, is almost impossible after production. The design costs are normally very high, and the additional technology through-run that might be needed due to design errors is highly expensive. Therefore, accurate design tools are needed for an optimal "first shot" design result.

Looking closely to the technologies, which have been applied for the microwave integrated circuit design and production so far, a large part of all realized circuits (including possibly lumped elements) use a microstrip-based technology. Figures 1.1a to 1.1d show the most common forms of the microstrip line that have been used. Figure 1.1a shows the conventional microstrip line, which consists of a strip of width w and metalization thickness t on top of a substrate material of height h, which may be a dielectric material (plastic-based or ceramic) or a semi insulating semiconductor material (e.g., GaAs, InP). The backside of the substrate is completely covered by a metalization layer. The fundamental mode of the microstrip line is a quasi-TEM mode that has a dispersive behavior because at higher frequencies the electromagnetic field is more and more concentrated into the dielectric carrier material.

Figure 1.1b shows the so-called strip line where the strip of width w is inserted within a homogeneous dielectric material of relative permittivity ε_r shielded by two large conducting planes on top and bottom of the substrate material. The fundamental mode on this line is a true dispersion less TEM

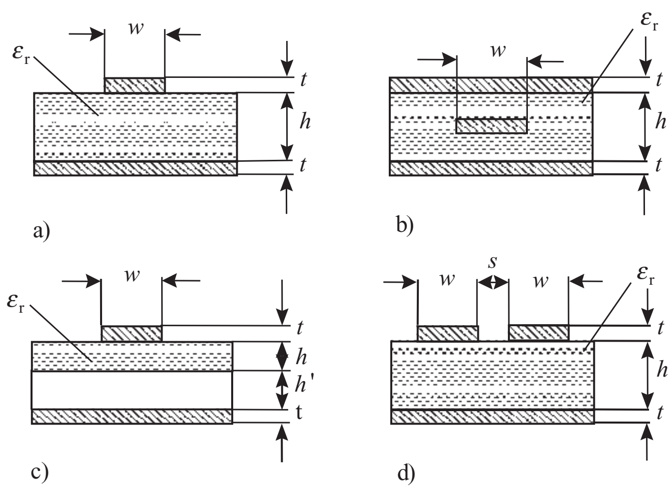


Fig. 1.1. Fundamental microstrip waveguides as they are used in microwave integrated circuits: (a) The conventional microstrip line, (b) the strip line, (c) the suspended microstrip line, and (d) the coupled microstrip lines.

mode, but this line is used only for special applications, such as in high-quality filter structures. This line is not commonly used for hybrid or monolithic integrated circuit applications because the implementation of active semiconductor elements cannot be easily realized.

The suspended microstrip line, which has a substrate material of reduced thickness separated from the ground metalization by an air region (Fig. 1.1c), is also normally only used for filter applications and only very seldom for circuit applications. The reduced substrate thickness leads to lower dielectric losses, which makes this line attractive for low-loss filters. Also, because of the small substrate height, the dispersion of this line is smaller than that in the case of the conventional microstrip line (Fig. 1.1a).

The coupled microstrip lines, shown in Fig. 1.1d, are often used in microwave integrated circuits, when couplers or filters are to be realized within the circuitry. The two lines can carry two fundamental quasi-TEM modes, the even and the odd mode, which have different effective dielectric constants (i.e., different phase velocities of their waves) and different dispersion properties because of the different field structures of the modes. This line structure often appears within a circuit if the circuit is not designed carefully enough and if two single microstrip lines come too close to each other. This leads to an unwanted parasitic coupling within microstrip circuits, which can be avoided only by leaving enough space between the two lines so that the coupling coefficient is reduced to an acceptable low value. This is one reason why microstrip-based circuits often need large space for their proper realization.

Figures 1.2a to 1.2d show an alternative line for the design of microwave integrated circuits—that is, coplanar waveguide structures. The coplanar strips

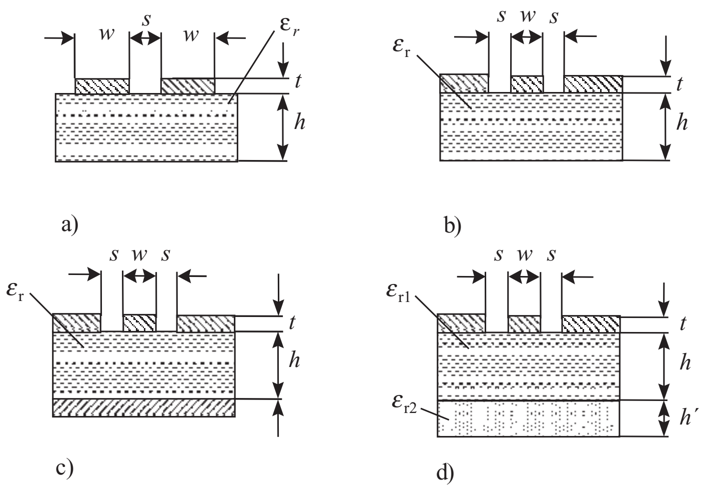


Fig. 1.2. Coplanar waveguides for microwave integrated circuit applications: (a) The coplanar strips, (b) the coplanar waveguide, (c) the conductor-backed coplanar waveguide, and (d) the dielectric-material-backed coplanar waveguide.

shown in Fig. 1.2a are normally used only in low radio-frequency (rf) circuits in conjunction with hybrid and/or lumped planar elements. For higher microwave frequencies, this line is not used in circuit design because it has a large stray field and does not define a solid common ground plane condition.

A true alternative to the microstrip line especially for applications in modern microwave integrated circuit design is the coplanar waveguide shown in Fig. 1.2b, which is the subject of this book. Alternative forms like the conductor-backed coplanar waveguide or the dielectric-material-supported coplanar waveguide are shown in Figs. 1.2c and 1.2d, respectively. Their properties are discussed in Chapter 2. The coplanar waveguide has the "hot" strip and the ground planes both on top of the dielectric carrier material and therefore forms a *real planar waveguide*. Because, in principle, it is a three-conductor line, it can carry two fundamental modes with zero cutoff frequency: (a) the so-called "even mode," which has equal potentials of the ground planes, and (b) the so-called "odd mode," which has ground potentials of different signs but equal magnitude.

Figure 1.3 shows the electric and the magnetic field distribution of (a) the even mode (coplanar waveguide mode) and (b) the odd mode (slotline mode). The even mode is a quasi-TEM mode with even symmetry with respect to the symmetry plane, its dispersion is very low (see also Chapter 2), and it is normally used for application in circuit design. The electric field lines begin (or end) at the center conductor and they end (or begin) on the two surrounding ground planes. The magnetic field lines enclose the center conductor. If current is transported on the center conductor (e.g., with direction into the paper plane as shown in Fig. 1.3a), the current densities in the ground planes have the

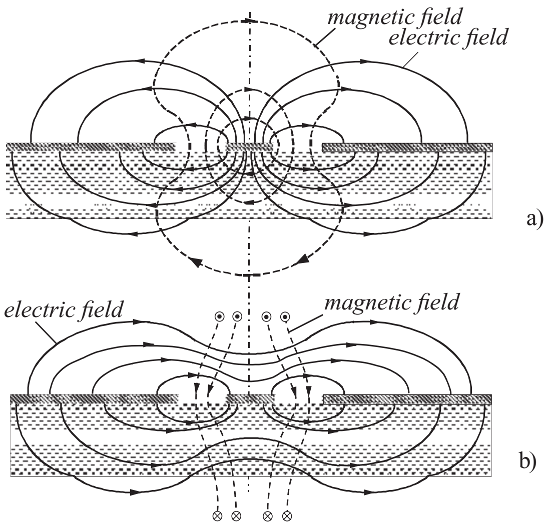


Fig. 1.3. Electric and magnetic field distribution of (a) the even mode and (b) the odd mode on a coplanar waveguide.

opposite direction. Because of the low dispersion of the fundamental "even mode," very broadband applications are possible, making this mode propagation applicable in microwave integrated circuits.

The electric field lines of the odd mode start on one ground plane and end on the other ground plane, which means that the potentials of the two ground planes have opposite signs. Not all of the electric field lines touch the center conductor. In the case of infinitely wide ground planes the odd mode, like a slot-line mode, is a hybrid mode and has magnetic field components in longitudinal direction and its dispersion can be considered large. If the ground plane width is finite, the magnetic field lines may be closed in the cross section enclosing the ground planes.

Despite its promising properties, the coplanar waveguide, up to now, has been used only seldom in commercial microwave integrated circuits. This is astonishing because in 1969 Wen [7] proposed the coplanar line as a possible microwave waveguide and in 1976 and 1977 Houdart [8, 9] demonstrated the big advantages of this waveguide in microwave circuit applications.

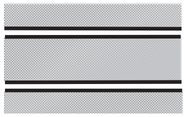
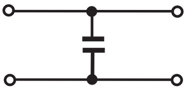
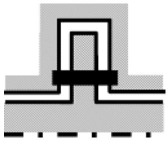
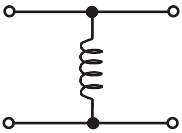
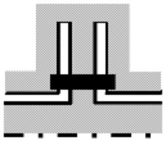
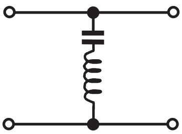
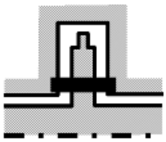
Tables 1.1 and 1.2 show two tables published in similar form by Houdart [8] in 1976. The tables show that he really recognized already at that time the broad application range of coplanar lines and components. He showed that the coplanar circuit approach is especially interesting for the realization of hybrid and monolithic microwave integrated circuits because it has several advantages compared to the microstrip line technique. An application of coplanar technologies to circuit design has been first described by Simon [10].

These advantages, as they are seen today (and as they already had been seen by Houdart 30 years ago), are as follows:

TABLE 1.1. Properties of Various Microwave Microcircuit Techniques as First Shown by Houdart [8]

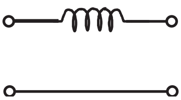
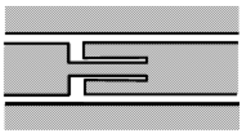
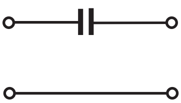
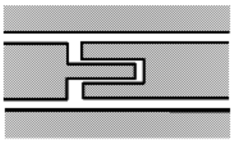
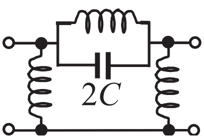
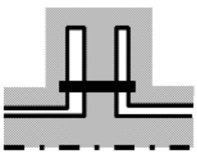
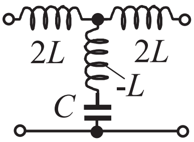
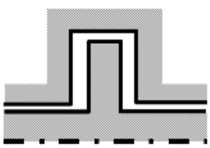
	Microstrip Line	Suspended Strip Line	Slotline	Coplanar Waveguide
Characteristic impedance	25–95 Ω	40–130 Ω	40–130 Ω	30–140 Ω
Effective dielectric constant for $\varepsilon_r = 9.8$	≈6	≈2.4	≈5	≈5
Spurious modes	Low	High	Non-TEM propagation	Low
Integration level	High	Low	—	High
Technological difficulties	Ceramic holes edge plating	—	Double-side etching	—
Parallel components	Poor	Difficult	Easy	Easy
Series components	Easy (except distributed lines)	Easy (except distributed lines)	Difficult	Easy

TABLE 1.2a. Fundamental Lumped Elements and Filter Elements Realized in Coplanar Waveguide Technology

Circuit Element	Equivalent Circuit	Application
		Transmission line
		Stop-band filter
		Pass-band filter
		Stop-band elliptic filter

Source: After Houdart [8].

TABLE 1.2b. Fundamental Lumped Elements and Filter Elements Realized in Coplanar Waveguide Technology

Circuit Element	Equivalent Circuit	Application
		Stop-band filter
		Pass-band filter
		High-pass filter
		All-pass filter

Source: After Houdart [8].

- The available range of characteristic impedances is larger for the coplanar line (30–140 Ω) than for the microstrip line (25–95 Ω), for example.
- The coplanar-based microwave integrated circuit is a real planar circuit because the "hot" lines as well as the ground planes are located on the upper surface of the carrier material. This enables series and parallel implementation of active and passive lumped elements into the circuit without any via hole connections through the substrate material. Good ground contacts can be realized anywhere in the circuit, and the space saved from the elimination of via holes leads to a more condensed circuit design.
- No backside preparation and no substrate thinning are needed because the coplanar circuit in principle can work with arbitrarily thick substrate materials. Heat transfer problems can be solved using a flip chip technology when mounting the circuits into a housing. Together with the above-mentioned advantage of avoiding the via-holes, it means that three essential technology drawbacks, which might reduce the yield of the circuit production and which increase the costs, can be avoided.

  The coplanar technology provides the possibility to design highly condensed microwave integrated circuits, especially if additional use is made of a lumped element technique. Very small circuit layouts can be made up to highest frequencies. Because the fundamental coplanar waveguide does not use a conducting ground plane on the backside of the substrate material, the parasitic capacitances of the lumped circuit components like spiral inductors or interdigital capacitors are small compared to the microstrip case. This results in a much higher first resonant frequency of these components so that even at millimeter-wave frequencies (e.g., 40–60 GHz) a lumped element technique can be used in coplanar monolithic integrated circuits.
- The fundamental even mode of the coplanar waveguide is less dispersive than the fundamental mode of the microstrip line. This is especially true if the coplanar waveguides are carefully designed—that is, if small gap widths s are used. So, broadband circuits from low rf frequencies up into the millimeter-wave range can be realized. Because the coplanar waveguide has two geometrical design parameters for optimizing the waveguide with respect to the circuit requirements (line width w and gap width s), it has one more degree of freedom for the circuit designer than does the microstrip line.
- Finally, simple coplanar-based on-wafer measurement techniques are available for testing the coplanar circuits. On-wafer measurement results may be directly interpreted and transferred to the component or circuit properties, something that is not always true in the case of a microstrip-technology-based circuit or component.

For a long time, several disadvantages were claimed regarding the application of coplanar waveguides in integrated circuits. They shall be discussed here briefly:

- First it was claimed that the coplanar waveguide has higher losses compared to the microstrip line. As already mentioned above, there is one more geometrical parameter available for the design of a coplanar waveguide compared to the microstrip line so that, for instance, a 50-Ω line may be realized in many ways using different *w* and *s* values. Moreover, the losses of a 50-Ω line can be changed by, say, using a waveguide with a large center strip width. Therefore, by applying this technique, the losses of the coplanar waveguides can always be kept in the same order as those of the microstrip line.
- The second argument against coplanar circuits has been that a large part of the expensive semiconductor substrate (e.g., GaAs) is covered by the ground planes, and therefore coplanar circuits are not cost-effective. As will be shown in this book, coplanar circuits can be designed smaller in size than microstrip-based integrated circuits because additional ground planes on top of the substrate can reduce the coupling between adjacent lines. In fact, space reduction in the order of 30–50% is possible if coplanar circuits are used instead of microstrip-based circuits.

One of the disadvantages of the coplanar waveguide, which has already been mentioned above, is the fact that two fundamental modes can propagate on the line with zero cutoff frequency if the two ground planes are not held at the same potential. In this book it will be shown that different air-bridge techniques, which are able to sufficiently suppress the unwanted "odd mode" of the coplanar guide and which also do not incur an additional technology cost in the production of the circuits, have been developed for application in coplanar MMICs. In coplanar hybrid integrated circuits, this problem is a little bit more difficult because using (for example) bond wires as air bridges is not always easy, since a production of the bonded bridges with an accuracy and reproducibility required for high-quality circuits is difficult.

Finally, there is one main reason that, as the author of this book feels, kept the coplanar technique from being applied intensively: No accurate and flexible design basis was available for a long time. All available commercial circuit design software tools were specialized on the design of microstrip circuits, so the practicing engineer did not really dare to use the coplanar concept for his/her circuit design. Parallel to this book, the author and his research group have developed a software basis that can be implemented into the most common circuit design programs and that contains models for nearly all line structures, discontinuities, and lumped elements needed in a coplanar environment for circuit design. These design tools that have been intensively evaluated up to frequencies of 70 GHz should help the microwave engineer to realize that circuit design on the basis of coplanar waveguides can be much easier than in the microstrip case. At the end he will really enjoy the advantages and possibilities, which lie behind coplanar technology.

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