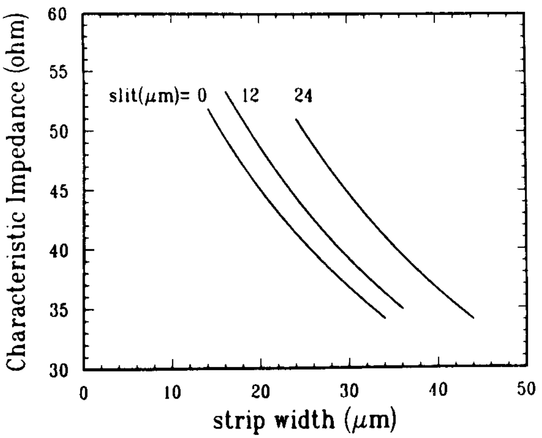


Figure 2.31 Calculated value of the characteristic impedance of a valley microstrip line as a function of the strip width for slit widths = 0, 12 μm, and 24 μm. The dielectric film thickness, H, is 10 μm, and the valley taper, θ, is 35° (from [92], © 1992 IEEE. Reprinted with permission.).

especially suitable for monolithic MICs and for broadband hybrid MICs where real-estate requirements are of prime importance. Impedance transformations on the order of 20:1 can be easily accomplished using the lumped-element approach. Therefore, high-power devices that have very low impedance values can easily be tuned with large impedance transformers using lumped elements. Consequently, lumped elements find applications in high-power oscillators, power amplifiers, and broadband circuits.

With the advent of new photolithographic techniques, the fabrication of lumped elements that was limited to X-band frequencies can now be extended to about 60 GHz. The three basic building blocks for circuit design—inductors, capacitors, and resistors—are available in lumped form. Computer-aided design of circuits using lumped elements requires a complete and accurate characterization of lumped elements at microwave frequencies. This necessitates the development of comprehensive mathematical models that take into account the presence, for example, of ground planes, proximity effect, fringing fields, and parasitics. In this section we describe briefly the design of inductors, capacitors, and resistors [95–98].

Design of Inductors

Inductors are used as RF chokes, matching elements, and reactive terminations; and they can also be found in filters, couplers, dividers and combiners, and resonant circuits. A lumped inductor may be realized using a high-impedance microstrip section or a spiral conductor as shown in Figure 2.32a. Inductors in MICs are

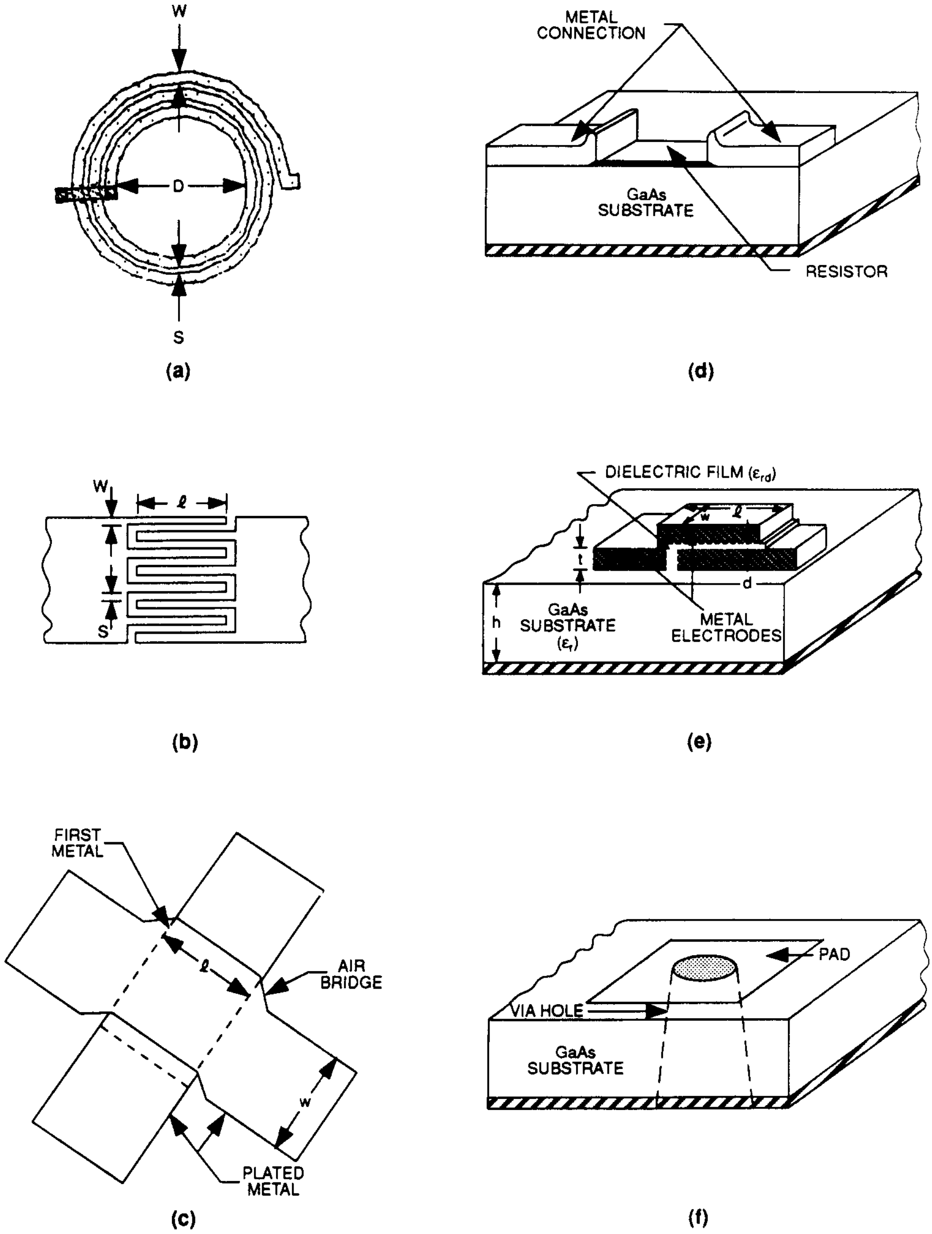


Figure 2.32 MMIC circuits use passive lumped elements: (a) spiral inductor; (b) interdigital capacitor; (c) airbridge crossover; (d) thin film resistor; (e) MIM capacitor; and (f) via hole.

fabricated using a standard IC process with no additional process steps. The innermost turn of the spiral inductor is connected to other circuitry through a conductor that passes under airbridges in MMICs, whereas a wire bond connection is made in hybrid MICs. The width and thickness of the conductor under the airbridges determine the current-carrying capacity of the inductor. Typically the thickness is 0.5 μm to 1.0 μm and the airbridge separates it from the upper conductors by 1.5 μm to 3.0 μm. Typical inductance values for monolithic microwave circuits operating above L-band fall in the range of 0.5 nH to 10 nH. In order to realize high Q inductors, the conductor thickness must be greater than 4 times the skin depth at the operating frequency. Silver-plated inductors have much higher Q than gold plated inductors.

Straight sections of microstrip are used for low inductance values typically up to 2 nH to 3 nH. Spiral inductors (circular or rectangular) have higher Q and can provide higher inductance values. These inductors are commonly used for high-density circuits. The presence of a ground plane also affects the inductance value, which decreases as the ground plane is brought nearer. This decrease can be taken into account by means of a correction factor K_g. With this correction, the effective inductance L may be written as

$$L = K_g L_0 \tag{2.146}$$

where L_0 is the free-space inductance value. A closed-form expression for K_g for a ribbon is given by [96]

$$K_g = 0.57 - 0.145\,\ell n\frac{W}{h}, \qquad \frac{W}{h} > 0.05 \tag{2.147}$$

where W is the conductor width and h is the substrate thickness. To a first-order approximation, the above expression can also be used with other types of inductors.

Table 2.7 gives approximate expressions for inductances and resistances of various types of inductors. In the case of spirals n is the number of turns and S is the spacing between the turns, R_s is the sheet resistance of the conductor per square, ℓ is the length of the conductor, and K is a correction factor that takes into account the crowding of the current at the corners of the conductor. Expressions for K for various structures are

$$K = 1.4 + 0.217\,\ell n\left(\frac{W}{5t}\right) \qquad 5 < \frac{W}{t} < 100 \qquad \text{for a ribbon} \tag{2.148a}$$

$$K = 1 + 0.333\left(1 + \frac{S}{W}\right) \qquad \text{for a spiral} \tag{2.148b}$$

Table 2.7
Expressions for Lumped Inductors

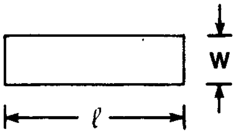
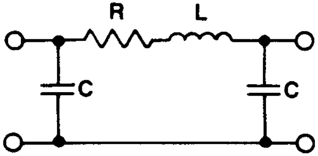
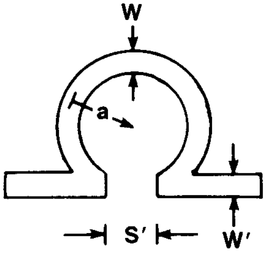
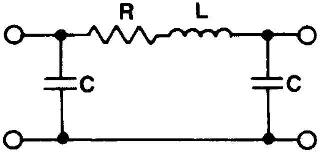
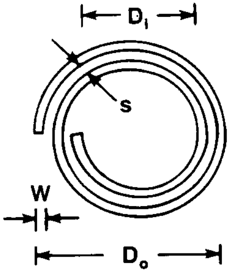
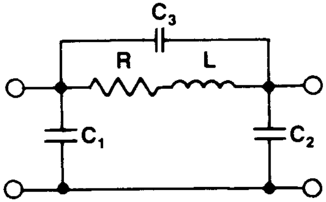
Inductors	*Equivalent Circuit*	*Expressions*
Strip 		$L(\text{nH}) = 2 \times 10^{-4}\ell\left[\ell\text{n}\left(\frac{\ell}{W+t}\right) + 1.193 + 0.2235\frac{W+t}{\ell}\right] \cdot K_g$ $R\ (\Omega) = \frac{KR_s\ell}{2(W+t)}$
Loop 		$L(\text{nH}) = 1.257 \times 10^{-3}a\left[\ell\text{n}\left(\frac{a}{W+t}\right) + 0.078\right] \cdot K_g$ $R\ (\Omega) = \frac{KR_s}{W+t}\pi a$

Table 2.7 (continued)
Expressions for Lumped Inductors

Inductors	*Equivalent Circuit*	*Expressions*
Spiral  	 	$L(\text{nH}) = 0.03937\frac{a^2n^2}{8a + 11c} \cdot K_g$ $a = \frac{D_0 + D_i}{4}, \quad c = \frac{D_0 - D_i}{2}$ $R\ (\Omega) = \frac{K\pi anR_s}{W}$ $C_3\ (\text{pF}) = 3.5 \times 10^{-5}D_0 + 0.06$

where t is the thickness of the conductors. The unloaded Q of an inductor may be calculated from

$$Q = \frac{\omega L}{R} \tag{2.149}$$

More accurate models for MMIC spiral inductors with 1.5, 2.5, and 3.5 turns have been published in the literature [98].

Design of Capacitors

Lumped-element capacitors are commonly used in matching circuits, filters, dividers, and couplers and for RF by-passing and dc blocking. Bascially there are two types of passive capacitors generally used in microwave and millimeter wave circuits: interdigital, shown in Figure 2.32b, and *metal-insulator-metal* (MIM), depicted in Figure 2.32e. The choice between the interdigital and MIM capacitors depends on the capacitance value to be realized, the processing technology available, size requirements, and the frequency of operation. Usually for values less than 1 pF interdigital capacitors can be used, while for higher values MIM techniques are generally used to minimize the overall size.

The analysis of interdigital capacitors has been reported by Alley [95]. These capacitors can be fabricated employing an interdigital microstrip conductor pattern, by the technique used in the fabrication of MICs, and do not require any additional processing step. The series capacitance is a strong function of the number of fingers and the gap between the fingers and increases with the length of the fingers. An approximate closed-form expression for circuit elements is given in Table 2.8. Here n is the number of fingers, ϵ_{re} is the effective dielectric constant of microstrip line of width W, h is the substrate thickness, and R_s is the surface resistance of the microstrip conductors. All dimensions are in microns. The elliptic functions $K(k)$ and $K'(k)$ are defined in Section 7.2.1. Unfortunately, this model has limitations as it does not accurately represent the capacitor's characteristics. Table 2.9 provides more accurate interdigital capacitor equivalent circuit model values extracted from accurately measured "on-wafer" S-parameters [98].

MIM capacitors are constructed by using a thin layer of a low-loss dielectric between two metal plates. In MMICs, the bottom plate of the capacitor uses first metal, a thin unplated metal, and typically the dielectric material is silicon nitride (Si_3N_4). The top plate uses a thick plated conductor to reduce the loss in the capacitor. Typically the bottom plate and the top plate have sheet resistances of 0.06 Ω/sq and 0.01 Ω/sq, respectively, and a typical dielectric thickness is 0.2 μm. The dielectric constant of silicon nitride is about 6.8, which yields a capacitance of about 300 pF/mm^2. The top plate is generally connected to other circuitry by using an air bridge that provides higher breakdown voltages.