RF and Microwave Wireless Systems. Kai Chang
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CHAPTER FOUR

Various Components and Their System Parameters

4.1 INTRODUCTION AND HISTORY

An RF and microwave system consists of many different components connected by transmission lines. In general, the components are classified as passive components and active (or solid-state) components. The passive components include resistors, capacitors, inductors, connectors, transitions, transformers, tapers, tuners, matching networks, couplers, hybrids, power dividers/combiners, baluns, resonators, filters, multiplexers, isolators, circulators, delay lines, and antennas. The solid-state devices include detectors, mixers, switches, phase shifters, modulators, oscillators, and amplifiers. Strictly speaking, active components are devices that have negative resistance capable of generating RF power from the DC biases. But a more general definition includes all solid-state devices.

Historically, wires, waveguides, and tubes were commonly used before 1950. After 1950, solid-state devices and integrated circuits began emerging. Today, monolithic integrated circuits (or chips) are widely used for many commercial and military systems. Figure 4.1 shows a brief history of microwave technologies. The commonly used solid-state devices are MESFETs (metal–semiconductor field-effect transistors), HEMTs (high-electron-mobility transistors), and HBTs (heterojunction bipolar transistors). Gallium–arsenide semiconductor materials are commonly used to fabricate these devices and the MMICs, since the electron mobility in GaAs is higher than that in silicon. Higher electron mobility means that the device can operate at higher frequencies or higher speeds. Below 2 GHz, silicon technology is dominant because of its lower cost and higher yield. The solid-state devices used in RF are mainly silicon transistors, metal–oxide–semiconductor FETs (MOSFETs), and complementary MOS (CMOS) devices. High-level monolithic integration in chips is widely used for RF and low microwave frequencies.

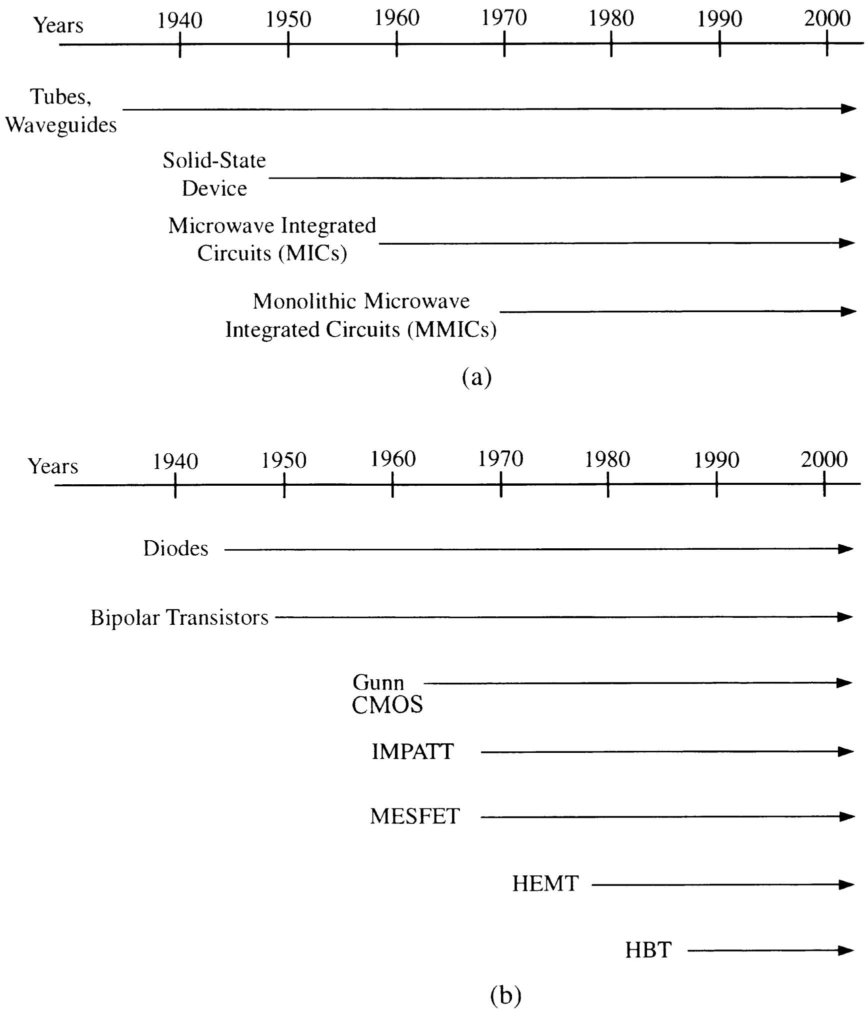
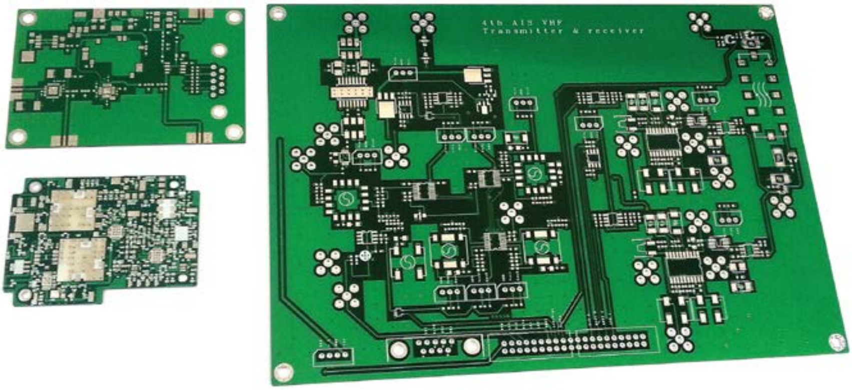


FIGURE 4.1 History of microwave techniques: (*a*) technology advancements; (*b*) solid-state devices.

In this chapter, various components and their system parameters will be discussed. These components can be represented by the symbols shown in Fig. 4.2. The design and detailed operating theory will not be covered here and can be found in many other books [1–4]. Some components (e.g., antennas, lumped *R*, *L*, *C* elements, and matching circuits) have been described in Chapters 2 and 3 and will not be repeated here. Modulators will be discussed in Chapter 9.

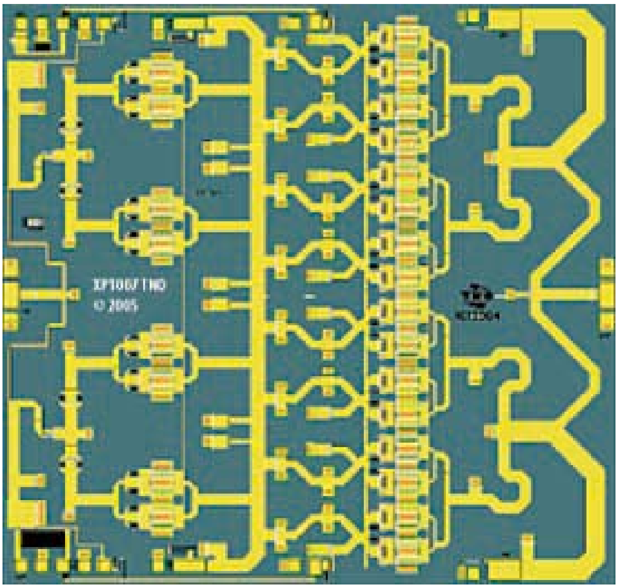
MIC (microwave integrated circuit)

- 여러 개의 단품 마이크로파 소자를 회로보드에 compact 하게 구성하여 회로모듈을 구현한 것



MMIC (monolithic microwave integrated circuit)

- 여러 개의 단품 마이크로파 소자를 단일 반도체 IC 칩으로 구성하여 회로모듈을 구성한 것.



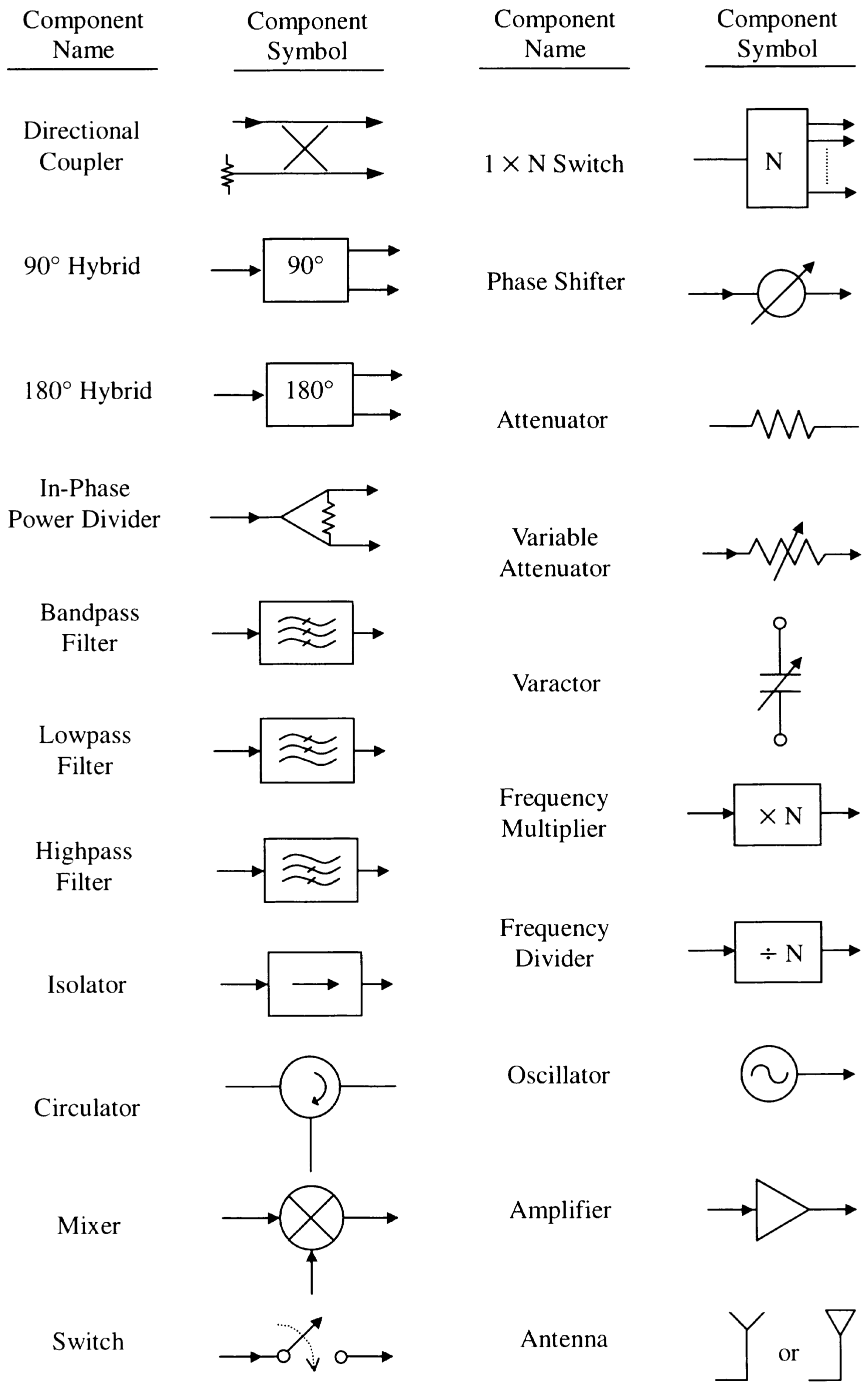


FIGURE 4.2 Symbols for various components.

4.2 COUPLERS, HYBRIDS, AND POWER DIVIDERS/COMBINERS

Couplers and hybrids are components used in systems to combine or divide signals. They are commonly used in antenna feeds, frequency discriminators, balanced mixers, modulators, balanced amplifiers, phase shifters, monopulse comparators, automatic signal level control, signal monitoring, and many other applications. A good coupler or hybrid should have a good VSWR, low insertion loss, good isolation and directivity, and constant coupling over a wide bandwidth.

A directional coupler is a four-port device with the property that a wave incident in port 1 couples power into ports 2 and 3 but not into 4, as shown in Fig. 4.3 [5]. The structure has four ports: input, direct (through), coupled, and isolated. The power P_1 is fed into port 1, which is matched to the generator impedance; P_2, P_3, and P_4 are the power levels available at ports 2, 3, and 4, respectively. The three important parameters describing the performance of the coupler are coupling factor, directivity, and isolation, defined by

$$\text{Coupling factor (in dB): } C = 10 \log \frac{P_1}{P_3} \tag{4.1}$$

$$\text{Directivity (in dB): } D = 10 \log \frac{P_3}{P_4} \tag{4.2}$$

$$\begin{aligned} \text{Isolation (in dB): } I &= 10 \log \frac{P_1}{P_4} \\ &= 10 \log \frac{P_1}{P_3}\frac{P_3}{P_4} = 10 \log \frac{P_1}{P_3} + 10 \log \frac{P_3}{P_4} \\ &= C + D \end{aligned} \tag{4.3}$$

In general, the performance of the coupler is specified by its coupling factor, directivity, and terminating impedance. The isolated port is usually terminated by a matched load. Low insertion loss and high directivity are desired features of the coupler. Multisection designs are normally used to increase the bandwidth.

Example 4.1 A 10-dB directional coupler has a directivity of 40 dB. If the input power $P_1 = 10$ mW, what are the power outputs at ports 2, 3, and 4? Assume that the coupler (a) is lossless and (b) has an insertion of 0.5 dB.

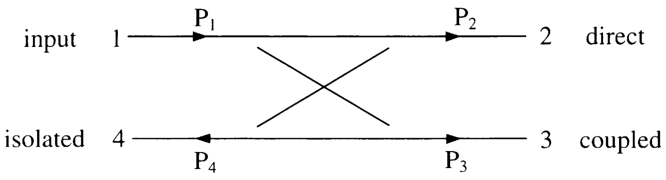


FIGURE 4.3 Directional coupler.

Solution (a) For a lossless case, C (dB) = 10 dB = 10 log(P_1/P_3) = P_1 (dB) − P_3 (dB):

$$P_1 = 10 \text{ mW} = 10 \text{ dBm}$$
$$P_3 = P_1 - C = 10 \text{ dBm} - 10 \text{ dB} = 0 \text{ dBm} = 1 \text{ mW}$$
$$D \text{ (dB)} = 40 \text{ dB} = 10 \log \frac{P_3}{P_4} = P_3 \text{ (dB)} - P_4 \text{ (dB)}$$
$$P_4 = P_3 \text{ (dB)} - D \text{ (dB)} = 0 \text{ dBm} - 40 \text{ dB} = -40 \text{ dBm}$$
$$= 0.0001 \text{ mW}$$
$$P_2 = P_1 - P_3 - P_4 \approx 9 \text{ mW or } 9.5 \text{ dBm}$$

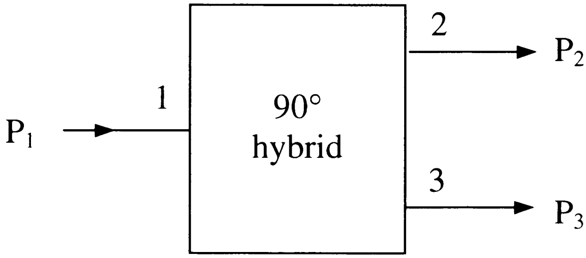
(b) For the insertion loss of 0.5 dB, let us assume that this insertion loss is equal for all three ports:

$$\text{Insertion loss} = \text{IL} = \alpha_L = 0.5 \text{ dB}$$
$$P_3 = 0 \text{ dBm} - 0.5 \text{ dB} = -0.5 \text{ dBm} = 0.89 \text{ mW}$$
$$P_4 = -40 \text{ dBm} - 0.5 \text{ dB} = -40.5 \text{ dBm} = 0.000089 \text{ mW}$$
$$P_2 = 9.5 \text{ dBm} - 0.5 \text{ dB} = 9 \text{ dBm} = 7.9 \text{ mW}$$

■

Hybrids or hybrid couplers are commonly used as 3-dB couplers, although some other coupling factors can also be achieved. Figure 4.4 shows a 90° hybrid. For the 3-dB hybrid, the input signal at port 1 is split equally into two output signals at ports 2 and 3. Ports 1 and 4 are isolated from each other. The two output signals are 90° out of phase. In a microstrip circuit, the hybrid can be realized in a branch-line type of circuit as shown in Fig. 4.4. Each arm is $\frac{1}{4}\lambda_g$ long. For a 3-dB coupling, the characteristic impedances of the shunt and series arms are: $Z_p = Z_0$ and $Z_s = Z_0/\sqrt{2}$, respectively, for optimum performance of the coupler [2, 3, 5]. The characteristic impedance of the input and output ports, Z_0, is normally equal to 50 Ω for a microstrip line. The impedances of the shunt and series arms can be designed to other values for different coupling factors [5]. It should be mentioned that port 4 can also be used as the input port; then port 1 becomes the isolated port due to the symmetry of the circuit. The signal from port 4 is split into two output signals at ports 2 and 3.

The 180° hybrid has characteristics similar to the 90° hybrid except that the two output signals are 180° out of phase. As shown in Fig. 4.5, a hybrid ring or rat-race circuit can be used as a 180° hybrid. For a 3-dB hybrid, the signal input at port 1 is split into ports 2 and 3 equally but 180° out of phase. Ports 1 and 4 are isolated. Similarly, ports 2 and 3 are isolated. The input signal at port 4 is split into ports 2 and 3 equally, but in phase. The characteristic impedance of the ring $Z_R = \sqrt{2}Z_0$ for a 3-dB hybrid [2, 3, 5], where Z_0 is the characteristic impedance of the input and output ports. A waveguide version of the hybrid ring called a magic-T is shown in Fig. 4.6.



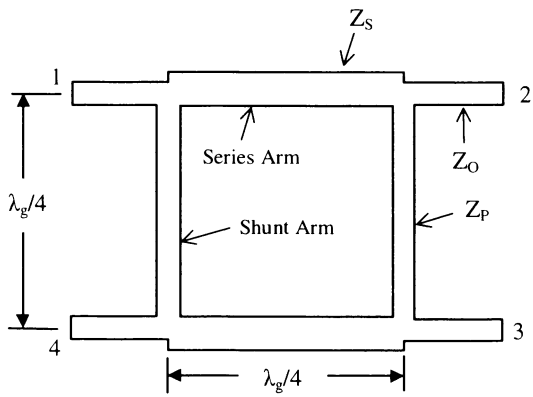
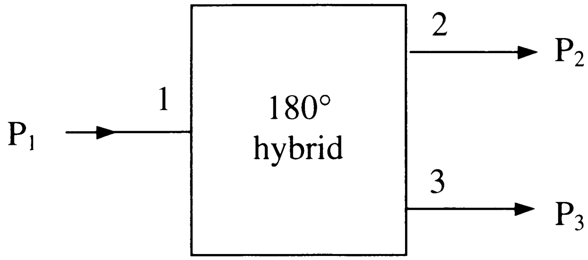


FIGURE 4.4 A 90° hybrid coupler. For a 3-dB hybrid, $Z_s = Z_0/\sqrt{2}$ and $Z_p = Z_0$.

A Wilkinson coupler is a two-way power divider or combiner. It offers broadband and equal-phase characteristics at each of its output ports. Figure 4.7 shows the one-section Wilkinson coupler, which consists of two quarter-wavelength sections. For a 3-dB coupler, the input at port 1 is split equally into two signals at ports 2 and 3. Ports 2 and 3 are isolated. A resistor of $2Z_0$ is connected between the two output ports to ensure the isolation [2, 3, 5]. For broadband operation, a multisection can be used. Unequal power splitting can be accomplished by designing different characteristic impedances for the quarter-wavelength sections and the resistor values [5]. The couplers can be cascaded to increase the number of output ports. Figure 4.8 shows a three-level one-to-eight power divider. Figure 4.9 shows the typical performance of a microstrip 3-dB Wilkinson coupler. Over the bandwidth of 1.8–2.25 GHz, the couplings at ports 2 and 3 are about 3.4 dB ($S_{21} \approx S_{31} \approx -3.4$ dB in Fig. 4.9). For the lossless case, $S_{21} = S_{31} = -3$ dB. Therefore, the insertion loss is about 0.4 dB. The isolation between ports 2 and 3 is over 20 dB.



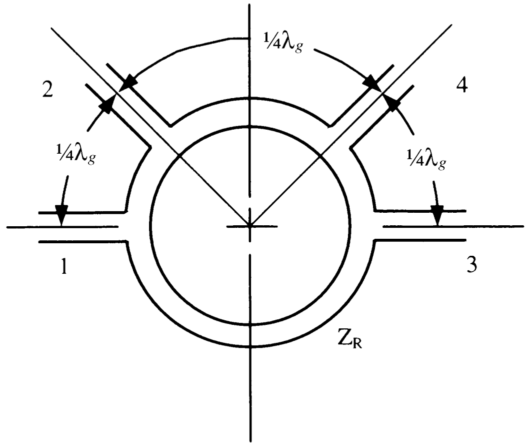


FIGURE 4.5 An 180° hybrid coupler. For a 3-dB hybrid, $Z_R = \sqrt{2}Z_0$.

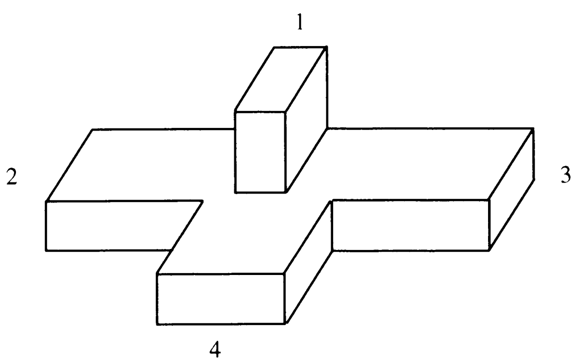
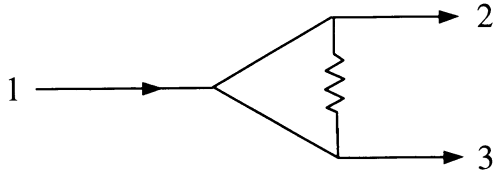


FIGURE 4.6 Waveguide magic-T circuit.



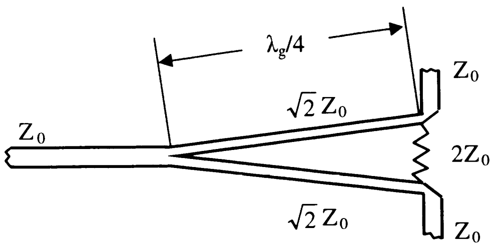


FIGURE 4.7 A 3-dB Wilkinson coupler.

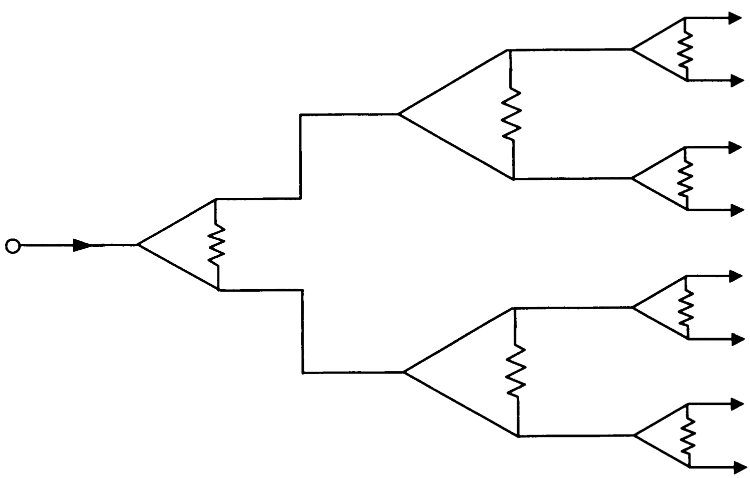


FIGURE 4.8 A 1×8 power divider.

4.3 RESONATORS, FILTERS, AND MULTIPLEXERS

Resonators and cavities are important components since they typically form filter networks. They are also used in controlling or stabilizing the frequency for oscillators, wave meters for frequency measurements, frequency discriminators, antennas, and measurement systems.

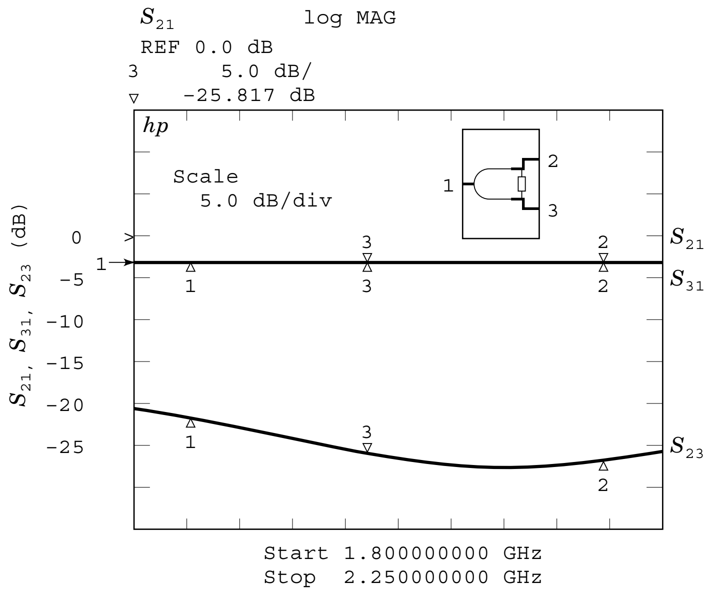


FIGURE 4.9 Performance of a microstrip 3-dB Wilkinson power divider.

Combinations of L and C elements form resonators. Figure 4.10 shows four types of combinations, and their equivalent circuits at the resonant frequencies are given in Fig. 4.11. At resonance, $Z = 0$, equivalent to a short circuit, and $Y' = 0$, equivalent to an open circuit. The resonant frequency is given by

$$\omega_0^2 = \frac{1}{LC} \tag{4.4}$$

or

$$f = f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4.5}$$

In reality, there are losses (R and G elements) associated with the resonators. Figures 4.10*a* and *c* are redrawn to include these losses, as shown in Fig. 4.12. A quality factor Q is used to specify the frequency selectivity and energy loss. The unloaded Q is defined as

$$Q_0 = \frac{\omega_0(\text{time-averaged energy stored})}{\text{energy loss per second}} \tag{4.6a}$$

For a parallel resonator, we have

$$Q_0 = \frac{\omega_0(1/2)VV^*C}{(1/2)GVV^*} = \frac{\omega_0 C}{G} = \frac{R}{\omega_0 L} \tag{4.6b}$$

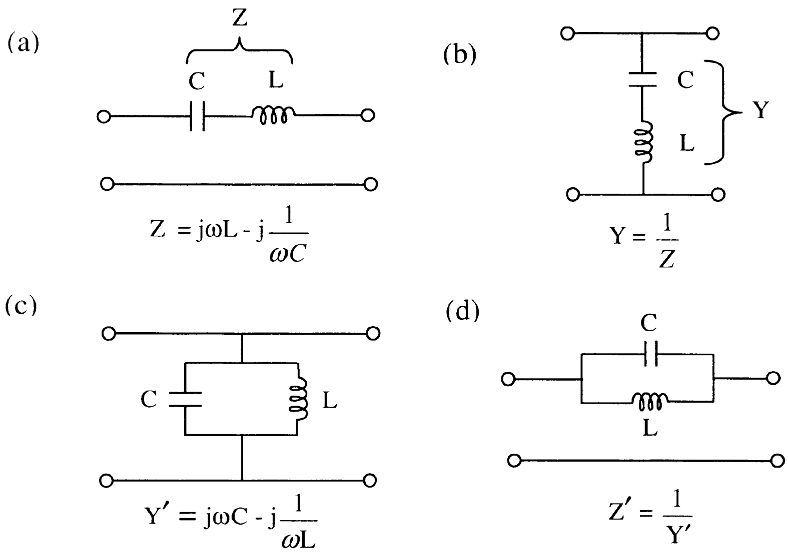


FIGURE 4.10 Four different basic resonant circuits.

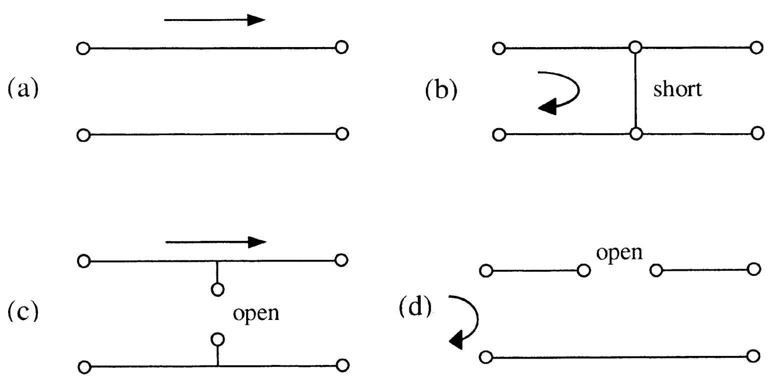


FIGURE 4.11 Equivalent circuits at resonance for the four resonant circuits shown in Fig. 4.10.

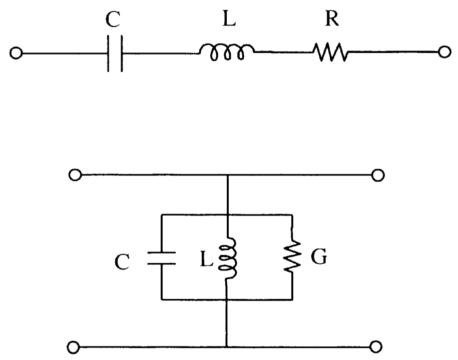


FIGURE 4.12 Resonators with lossy elements R and G.

For a series resonator, we have

$$Q_0 = \frac{\omega_0 (1/2) II^* L}{(1/2) R II^*} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R} \tag{4.6c}$$

In circuit applications, the resonator is always coupled to the external circuit load. The loading effect will change the net resistance and consequently the quality factor [5]. A loaded Q is defined as

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} \tag{4.7}$$

where Q_{ext} is the external quality factor due to the effects of external coupling. The loaded Q can be measured from the resonator frequency response [6]. Figure 4.13 shows a typical resonance response. The loaded Q of the resonator is

$$Q_L = \frac{f_0}{f_1 - f_2} \tag{4.8}$$

where f_0 is the resonant frequency and $f_1 - f_2$ is the 3-dB (half-power) bandwidth. The unloaded Q can be found from the loaded Q and the insertion loss IL (in decibels) at the resonance by the following equation [6]:

$$Q_0 = \frac{Q_L}{1 - 10^{-IL/20}} \tag{4.9}$$

The higher the Q value, the narrower the resonance response and the lower the circuit loss. A typical Q value for a microstrip resonator is less than 200, for a waveguide cavity is several thousand, for a dielectric resonator is around 1000, and for a crystal is over 5000. A superconductor can be used to lower the metallic loss and to increase the Q.

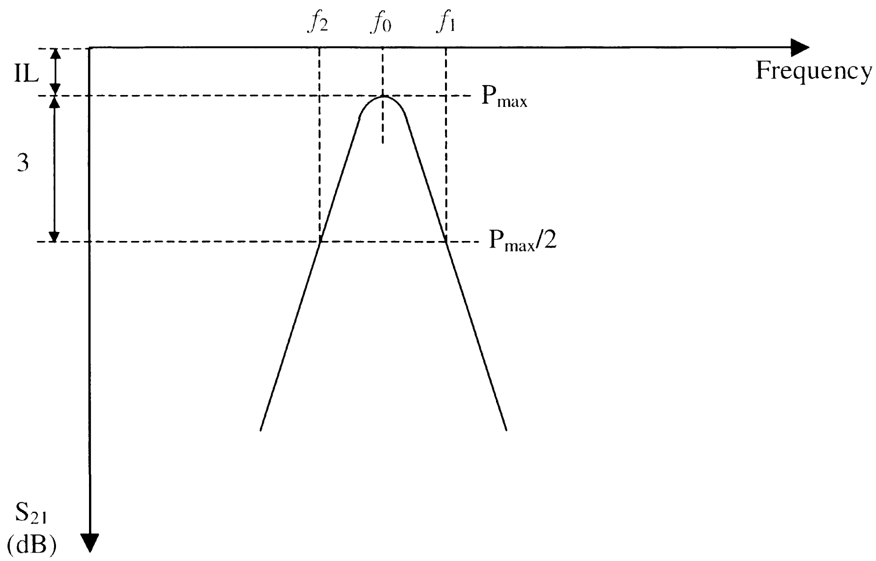


FIGURE 4.13 Resonator frequency response.

Commonly used resonators for microstrip circuits are open-end resonators, stub resonators, dielectric resonators, and ring resonators, as shown in Fig. 4.14. The boundary conditions force the circuits to have resonances at certain frequencies. For example, in the open-end resonator and stub resonator shown in Fig. 4.14, the voltage wave is maximum at the open edges. Therefore, the resonances occur for the open-end resonator when

$$l = n(\tfrac{1}{2}\lambda_g) \qquad n = 1, 2, 3, \ldots \tag{4.10}$$

For the open stub, the resonances occur when

$$l = n(\tfrac{1}{4}\lambda_g) \qquad n = 1, 2, 3, \ldots \tag{4.11}$$

For the ring circuit, resonances occur when

$$2\pi r = n\lambda_g \qquad n = 1, 2, 3, \ldots \tag{4.12}$$

The voltage (or E-field) for the first resonant mode ($n = 1$) for these circuits is shown in Fig. 4.15. From Eqs. (4.10)–(4.12), one can find the resonant frequencies by using the relation

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} = \frac{c}{f\sqrt{\varepsilon_{\text{eff}}}} \tag{4.13}$$

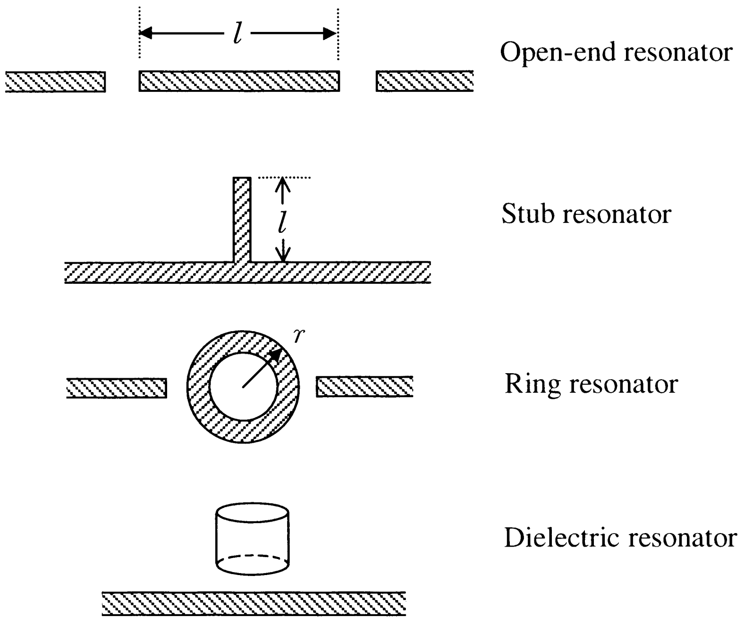


FIGURE 4.14 Commonly used resonators for microstrip circuits.

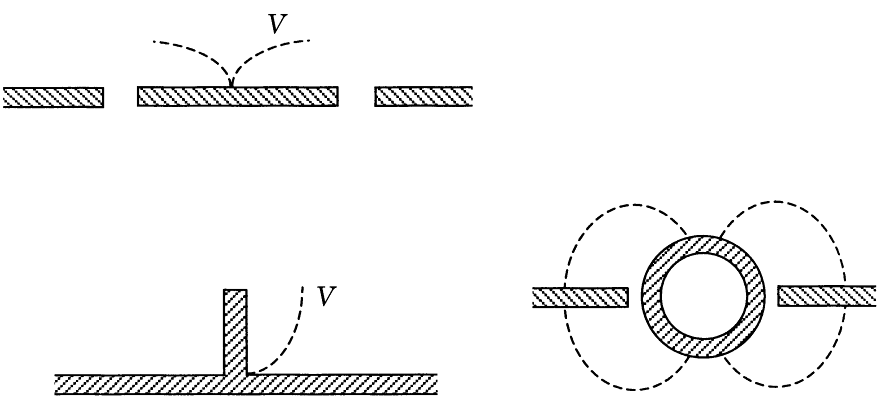


FIGURE 4.15 Voltage distribution for the first resonator mode.

Figure 4.16 shows the typical results for a loosely coupled ring resonator. Three resonances are shown for $n = 1, 2, 3$. The insertion loss is high because of the loose coupling [6].

One major application of the resonators is to build filters. There are four types of filters: the low-pass filter (LPF), bandpass filter (BPF), high-pass filter (HPF), and bandstop filter (BSF). Their frequency responses are shown in Fig. 4.17 [5]. An ideal

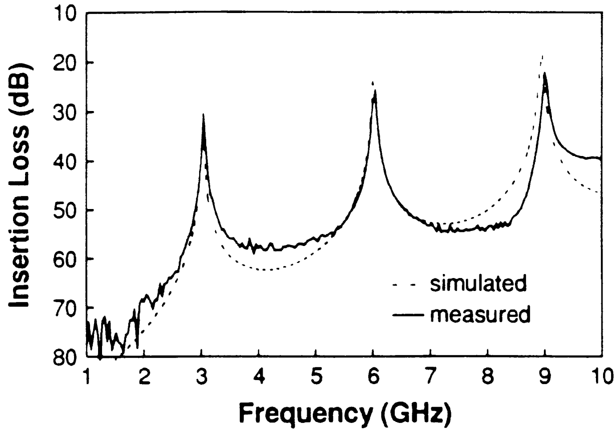


FIGURE 4.16 Microstrip ring resonator and its resonances.

filter would have perfect impedance matching, zero insertion loss in the passbands, and infinite rejection (attenuation or insertion loss) everywhere else. In reality, there is insertion loss in the passbands and finite rejection everywhere else. The two most common design characteristics for the passband are the maximum flat (Butterworth) response and equal-ripple (Chebyshev) response, as shown in Fig. 4.18, where A is the maximum attenuation allowed in the passband.

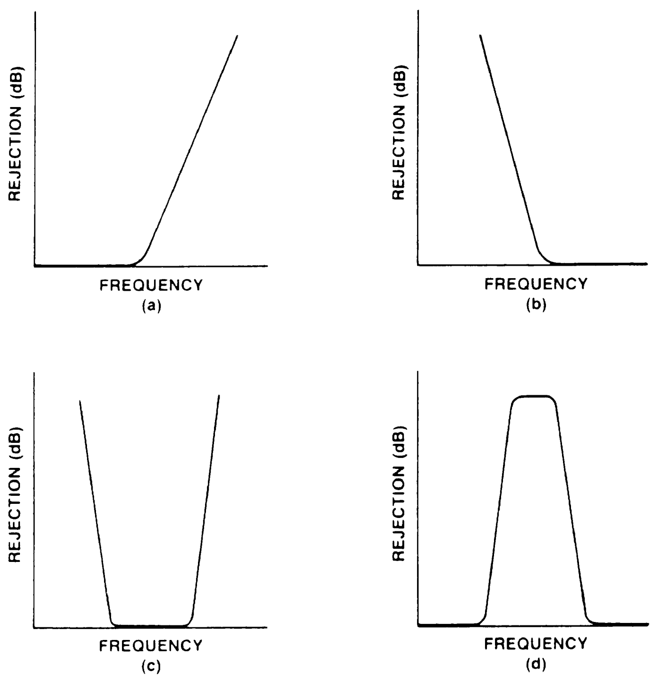


FIGURE 4.17 Basic types of filters: (*a*) low pass; (*b*) high pass; (*c*) bandpass; (*d*) bandstop.

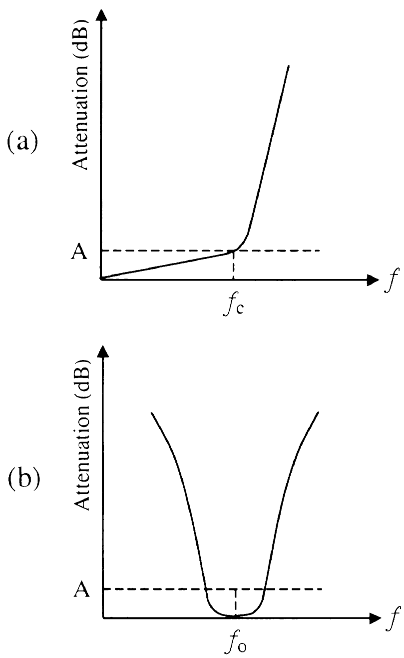


FIGURE 4.18 Filter response: (*a*) maximally flat LPF; (*b*) Chebyshev LPF; (*c*) maximally flat BPF; (*d*) Chebyshev BPF.

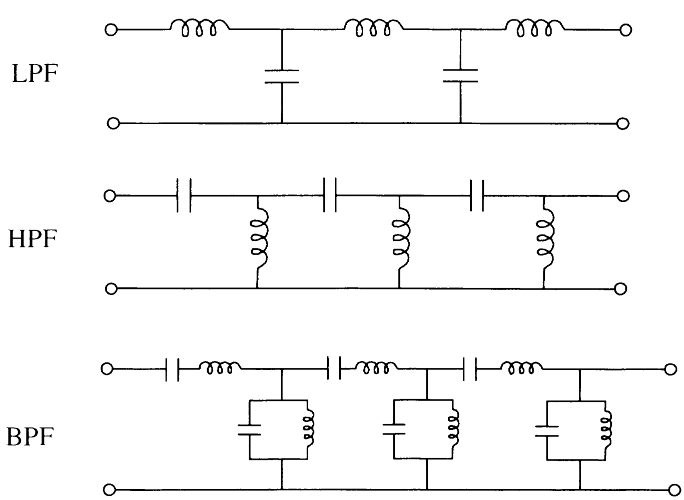


FIGURE 4.19 Prototype circuits for filters.

The prototype circuits for filters are shown in Fig. 4.19. In low frequencies, these circuits can be realized using lumped *L* and *C* elements. In microwave frequencies, different types of resonators and cavities are used to achieve the filter characteristics. Figure 4.20 shows some commonly used microstrip filter structures. The step impedance filter has low-pass characteristics; all others have bandpass characteristics. Figure 4.21 shows a parallel-coupled microstrip filter and its performance. The insertion loss (IL) in the passband around 5 GHz is about 2 dB, and the return loss (RL) is greater than 20 dB. The rejection at 4 GHz is over 20 dB and at 3 GHz is over 35 dB. The simulation can be done using a commercially available circuit simulator

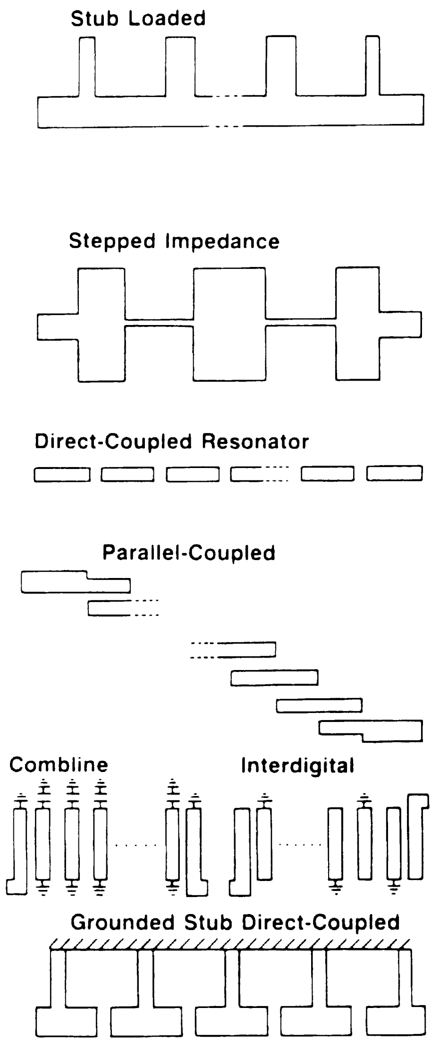
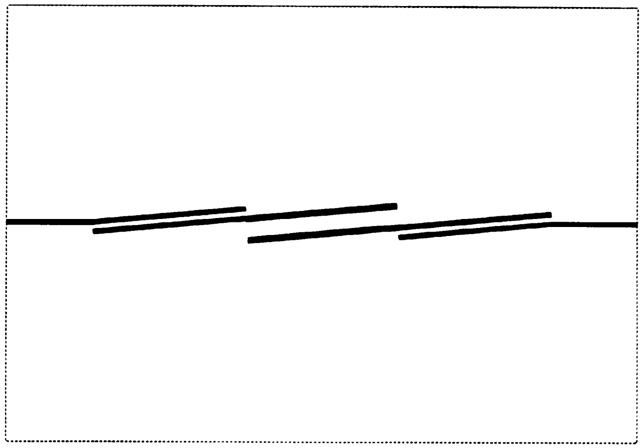


FIGURE 4.20 Commonly used microstrip filter structures [5].

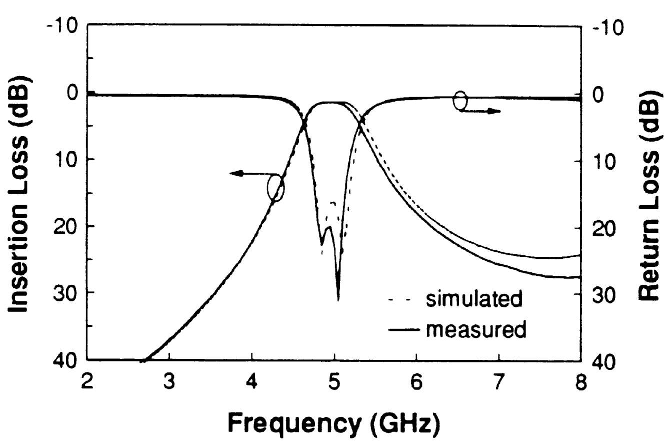
or an electromagnetic simulator. For very narrow passband filters, surface acoustic wave (SAW) devices and dielectric resonators can be used.

The filter can be made electronically tunable by incorporating varactors into the filter circuits [1]. In this case, the passband frequency is tuned by varying the varactor bias voltages and thus the varactor capacitances. Active filters can be built by using active devices such as MESFETs in microwave frequencies and CMOS in RF. The active devices provide negative resistance and compensate for the losses of the filters. Active filters could have gains instead of losses.

A frequency multiplexer is a component that separates or combines signals in different frequency bands (Fig. 4.22*a*). It is used in frequency division multiple



(a)



(b)

FIGURE 4.21 Microstrip bandpass filter and its performance: (*a*) circuit layout; (*b*) simulated and measured results.

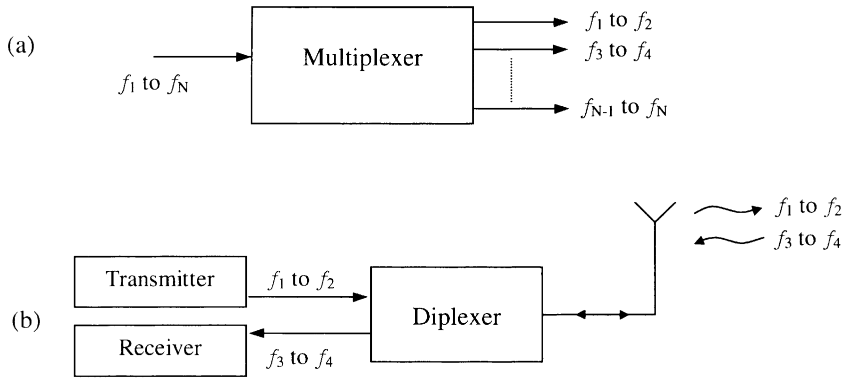


FIGURE 4.22 Multiplexer and diplexer: (*a*) a multiplexer is used to separate many different frequency bands: (*b*) a diplexer is used to separate the transmitting and receiving signals in a communication system.

access (FDMA) to divide a frequency band into many channels or users in a communication system. Guard bands are normally required between the adjacent channels to prevent interference. A filter bank that consists of many filters in parallel can be used to accomplish the frequency separation. A diplexer is a component used to separate two frequency bands. It is commonly used as a duplexer in a transceiver (transmitter and receiver) to separate the transmitting and receiving frequency bands. Figure 4.22*b* shows a diplexer used for this function.

4.4 ISOLATORS AND CIRCULATORS

Isolators and circulators are nonreciprocal devices. In many cases, they are made with ferrite materials. The nonreciprocal electrical properties cause that the transmission coefficients passing through the device are not the same for different directions of propagation [2]. In an isolator, almost unattenuated transmission from port 1 to port 2 is allowed, but very high attenuation exists in the reverse direction from port 2 to port 1, as shown in Fig. 4.23. The isolator is often used to couple a microwave signal source (oscillator) to the external load. It allows the available power to be delivered to the load but prevents the reflection from the load transmitted back to the source. Consequently, the source always sees a matched load, and the effects of the load on the source (such as frequency pulling or output power variation) are minimized. A practical isolator will introduce an insertion loss for the power transmitted from port 1 to port 2 and a big but finite isolation (rejection) for the power transmitted from port 2 to port 1. Isolation can be increased by cascading two isolators in series. However, the insertion loss is also increased.

Example 4.2 The isolator shown in Fig. 4.23*a* has an insertion loss α_L of 1 dB and an isolation α_I of 30 dB over the operation bandwidth. (a) What is the output power

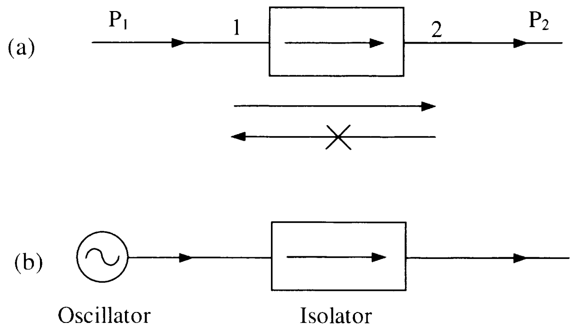


FIGURE 4.23 Isolator and its applications: (*a*) isolator allows power to flow in one direction only; (*b*) isolator is used to protect an oscillator.

P_2 at port 2 if the input power at port 1 is $P_1 = 10$ mW? (b) What is the output power P_1 at port 1 if the input power at port 2 is $P_2 = 10$ mW?

Solution

(a)
$$P_2 = P_1 - \alpha_L = 10 \text{ dBm} - 1 \text{ dB} = 9 \text{ dBm}$$
$$= 7.94 \text{ mW}$$

(b)
$$P_1 = P_2 - \alpha_I = 10 \text{ dBm} - 30 \text{ dB} = -20 \text{ dBm}$$
$$= 0.01 \text{ mW}$$

■

A circulator is a multiport device for signal routing. Figure 4.24 shows a three-port circulator. A signal incident in port 1 is coupled into port 2 only, a signal incident in port 2 is coupled into port 3 only, and a signal incident in port 3 is coupled into port 1 only. The signal traveling in the reverse direction is the leakage determined by the isolation of the circulator. A circulator is a useful component for signal routing or separation, and some applications are shown in Fig. 4.25. A terminated circulator can be used as an isolator (Fig. 4.25*a*). The reflection from port 2 is dissipated in the termination at port 3 and will not be coupled into port 1. Figure 4.25*b* shows that a circulator can be used as a duplexer in a transceiver to separate the transmitted and received signals. The transmitted and received signals can have the same or different frequencies. This arrangement is quite popular for radar applications. The circuit shown in Fig. 4.25*c* is a fixed or a variable phase shifter. By adjusting the length l of a transmission line in port 2, one can introduce a phase shift of $2\beta l$ between ports 1 and 3. The length l can be adjusted by using a sliding (tunable) short. A circulator can be used to build an injection locked or a stable amplifier using a two-terminal solid-state active device such as an IMPATT diode or a Gunn device [1]. The circulator is used to separate the input and output ports in this case, as shown in Fig. 4.25*d*.

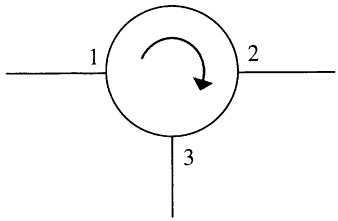


FIGURE 4.24 Three-port circulator.

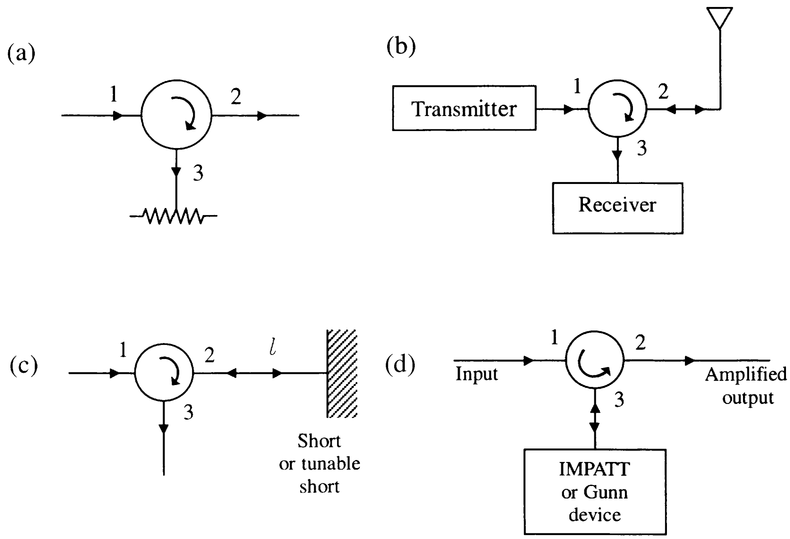


FIGURE 4.25 Some applications of circulators: (*a*) as an isolator; (*b*) as a duplexer; (*c*) as a phase shifter; (*d*) as an amplifier circuit.

4.5 DETECTORS AND MIXERS

A detector is a device that converts an RF/microwave signal into a DC voltage or that demodulates a modulated RF/microwave signal to recover a modulating low-frequency information-bearing signal. Detection is accomplished by using a nonlinear I–V device. A p–n junction or a Schottky-barrier junction (metal–semiconductor junction) has a nonlinear I–V characteristic, as shown in Fig. 4.26. The characteristic can be given by [1]

$$i = a_1 v + a_2 v^2 + a_3 v^3 + \cdots \tag{4.14}$$

If a continuous wave is incident to the detector diode, as shown in Fig. 4.27a, we have

$$v = A \cos \omega_{\rm RF} t \quad \text{or } v = A \sin \omega_{\rm RF} t \tag{4.15}$$

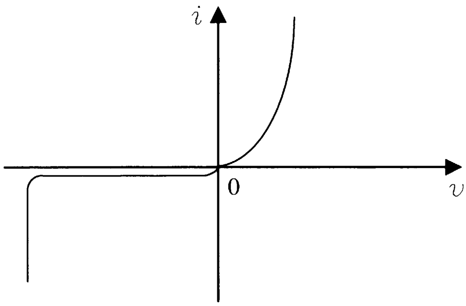


FIGURE 4.26 Nonlinear I–V characteristics.

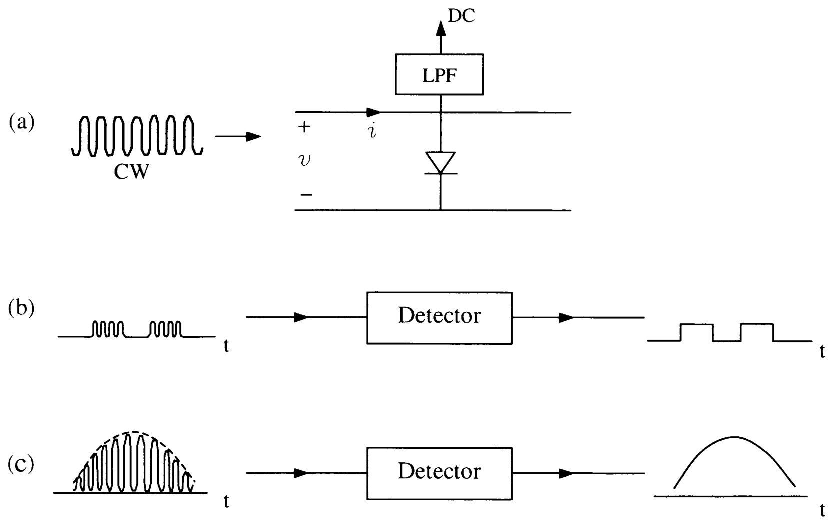


FIGURE 4.27 Detectors are used to (*a*) convert a CW RF signal to DC output, (*b*) demonodulate a pulse-modulated RF carrier, and (*c*) demodulate an analog-modulated RF carrier.

The first two terms will give

$$\begin{aligned} i &= a_1 A \cos \omega_{\text{RF}} t + a_2 A^2 \cos^2 \omega_{\text{RF}} t \\ &= a_1 A \cos \omega_{\text{RF}} t + \tfrac{1}{2} a_2 A^2 + \tfrac{1}{2} a_2 A^2 \cos 2\omega_{\text{RF}} t \end{aligned} \tag{4.16}$$

A DC current appears at the output of a low-pass filter:

$$i_{\text{DC}} = \tfrac{1}{2} a_2 A^2 \propto A^2 \tag{4.17}$$

The detector is normally operating in the square-law region with the DC current proportional to the square of the incident RF signal [7]. If the incident RF signal is pulse modulated, as shown in Fig. 4.27*b*, then DC currents appear only when there are carrier waves. The output is the demodulated signal (modulating signal) of the pulse-modulated carrier signal. Similarly, the detector's output for an analog-modulated signal is the modulating low-frequency signal bearing the analog information.

The performance of a detector is judged by its high sensitivity, good VSWR, high dynamic range, low loss, and wide operating bandwidth. The current sensitivity of a detector is defined as

$$\beta_i = \frac{i_{\mathrm{DC}}}{p_{\mathrm{in}}} \tag{4.18}$$

where P_{in} is the incident RF power and i_{DC} is the detector output DC current.

Since the baseband modulating signal usually contains frequencies of less than 1 MHz, the detector suffers from $1/f$ noise (flicker noise). The sensitivity of the RF/microwave receiver can be greatly improved by using the heterodyne principle to avoid the $1/f$ noise. In heterodyne systems, the initial baseband frequency is converted up to a higher transmitted carrier frequency, and then the process is reversed at the receiver. The frequency conversions are done by mixers (upconverters and downconverters). In the downconverter, as shown in Fig. 4.28, the high-frequency received signal (RF) is mixed with a local oscillator (LO) signal to generate a difference signal, which is called the intermediate-frequency (IF) signal. The IF signal can be amplified and detected/demodulated. It can also be further downconverted to a lower frequency IF before detection or demodulation. The upconverter is used to generate a high-frequency RF signal for transmission from a low-frequency information-bearing IF signal. The upconverter is used in a transmitter and the downconverter in a receiver.

The input voltage to the downconverter is given by

$$v = A \sin \omega_{\mathrm{RF}} t + B \sin \omega_{\mathrm{LO}} t \tag{4.19}$$

Substituting this into Eq. (4.14) gives

$$\begin{aligned} i = {} & a_1(A \sin \omega_{\mathrm{RF}} t + B \sin \omega_{\mathrm{LO}} t) \\ & + a_2(A^2 \sin^2 \omega_{\mathrm{RF}} t + 2AB \sin \omega_{\mathrm{RF}} t \sin \omega_{\mathrm{LO}} t + B^2 \sin^2 \omega_{\mathrm{LO}} t) \\ & + a_3(A^3 \sin^3 \omega_{\mathrm{RF}} t + 3A^2 B \sin^2 \omega_{\mathrm{RF}} t \sin \omega_{\mathrm{LO}} t \\ & + 3AB^2 \sin \omega_{\mathrm{RF}} t \sin^2 \omega_{\mathrm{LO}} t + B^3 \sin^3 \omega_{\mathrm{LO}} t) + \cdots \end{aligned} \tag{4.20}$$

Because the term $2AB \sin \omega_{\mathrm{RF}} t \sin \omega_{\mathrm{LO}} t$ is just the multiplication of the two input signals, the mixer is often referred as a multiplier for two signals, as shown in Fig. 4.29.

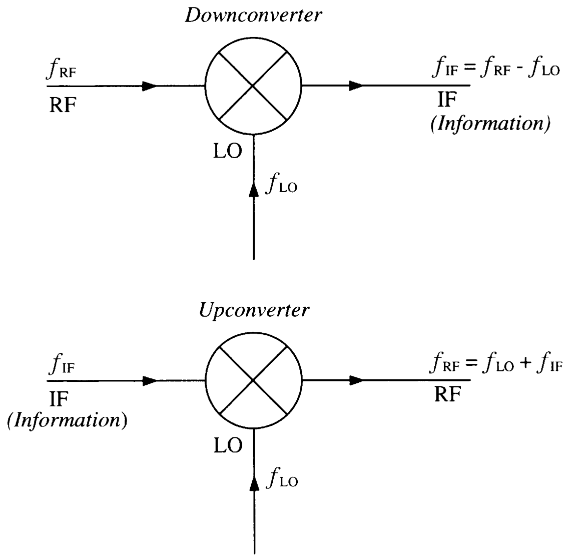


FIGURE 4.28 Downconverter and upconverter.

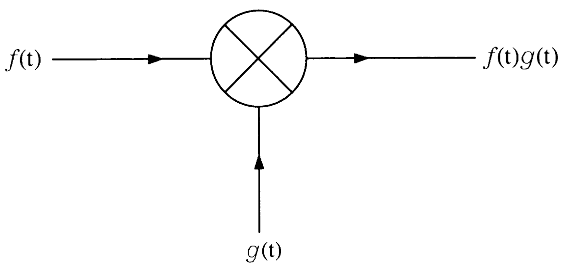


FIGURE 4.29 Multiplication of two input signals by a mixer.

Using the trigonometric identities, the following frequency components result from (4.20):

$$\begin{aligned}
a_1 v &\rightarrow \omega_{RF}, \omega_{LO} \\
a_2 v^2 &\rightarrow 2\omega_{RF}, \omega_{RF} \pm \omega_{LO}, 2\omega_{LO} \\
a_3 v^3 &\rightarrow 3\omega_{RF}, 2\omega_{RF} \pm \omega_{LO}, 2\omega_{LO} \pm \omega_{RF}, 3\omega_{LO}, \omega_{RF}, \omega_{LO} \\
&\vdots
\end{aligned}$$

For the downconverter, a low-pass filter is used in the mixer to extract the IF signal ($\omega_{RF} - \omega_{LO}$ or $\omega_{LO} - \omega_{RF}$). All other frequency components are trapped and eventually converted to the IF signal or dissipated as heat. For the upconverter, a bandpass filter is used to pass $\omega_{IF} + \omega_{LO}$.

The conversion loss for a downconverter is defined as

$$L_c \text{ (in dB)} = 10 \log \frac{P_{\mathrm{RF}}}{P_{\mathrm{IF}}} \tag{4.21}$$

where P_{RF} is the input RF signal power to the mixer and P_{IF} is the output IF signal power.

A good mixer requires low conversion loss, a low noise figure, low VSWRs for the RF, IF, and LO ports, good isolation between any two of the RF, IF, and LO ports, good dynamic range, a high 1-dB compression point, a high third-order intercept point, and low intermodulation. Definitions of dynamic range, third-order intercept point, 1-dB compression point, and intermodulation will be given in Chapter 5. As an example of mixer performance, a 4–40-GHz block downconverter from Miteq has the following typical specifications [8]:

RF frequency range	4–40 GHz
LO frequency range	4–42 GHz
IF frequency range	0.5–20 GHz
RF VSWR	2.5
IF VSWR	2.5
LO VSWR	2.0
LO-to-RF isolation	20 dB
LO-to-IF isolation	25 dB
RF-to-IF isolation	30 dB
Conversion loss	10 dB
Single-sideband noise figure (at 25°C)	10.5 dB
Input power at 1 dB compression	+5 dBm
Input power at third-order intercept point	+15 dBm
LO power requirement	+10 to +13 dBm

Note that the noise figure is approximately equal to the conversion loss for a lossy element (as described in Chapter 5). The mixer normally consists of one or more nonlinear devices and associated filtering circuits. The circuits can be realized by using a microstrip line or waveguide [1]. The same *p–n* junction or Schottky-barrier junction diodes employed for detectors can be used for mixers. The use of transistors (e.g., MESFET, HEMT) as the nonlinear devices has the advantage of providing conversion gain instead of conversion loss.

4.6 SWITCHES, PHASE SHIFTERS, AND ATTENUATORS

Switches, phase shifters, and attenuators are control devices that provide electronic control of the phase and amplitude of RF/microwave signals. The control devices can be built by using ferrites or solid-state devices ($p-i-n$ diodes or FETs) [1, 7]. Phase shifting and switching with ferrites are usually accomplished by changing the magnetic permeability, which occurs with the application of a magnetic biasing field. Ferrite control devices are heavy, slow, and expensive. Solid-state control devices, on the other hand, are small, fast, and inexpensive. The ferrite devices do have some advantages such as higher power handling and lower loss. Table 4.1 gives the comparison between ferrite and $p-i-n$ diode control devices [1]. It should be mentioned that the use of FETs or transistors as control devices could provide gain instead of loss.

Switches are widely used in communication systems for time multiplexing, time division multiple access (see Chapter 10), pulse modulation, channel switch in the channelized receiver, transmit/receive (T/R) switch for a transceiver, and so on. Figure 4.30 illustrates these applications. A switch can be classified as single pole, single throw (SPST), single pole, double throw (SPDT), single pole, triple throw (SP3T), and so on, as shown in Fig. 4.31. Ideally, if the switch is turned on, all signal power will pass through without any attenuation. When the switch is off, all power will be rejected and no power leaks through. In reality, there is some insertion loss when the switch is on and some leakage when the switch is off. From Fig. 4.32 the insertion loss and the isolation are given by

When the switch is on,

$$\text{Insertion loss} = \alpha_L = 10 \log \frac{P_{\text{in}}}{P_{\text{out}}} \tag{4.22}$$

When the switch is off,

$$\text{Isolation} = \alpha_I = 10 \log \frac{P_{\text{in}}}{P_{\text{out}}} \tag{4.23}$$

A good switch should have low insertion loss and high isolation. Other desired features depending on applications are fast switching speed, low switching current, high power-handling capability, small size, and low cost. For a solid-state switch, the switching is accomplished by the two device impedance states obtained from two

TABLE 4.1 Comparison between Ferrite and *p–i–n* Diode Control Devices

Parameter	Ferrite	$p-i-n$
Speed	Low (msec)	High (μsec)
Loss	Low (0.2 dB)	High (0.5 dB/diode)
Cost	High	Low
Weight	Heavy	Light
Driver	Complicated	Simple
Size	Large	Small
Power handling	High	Low

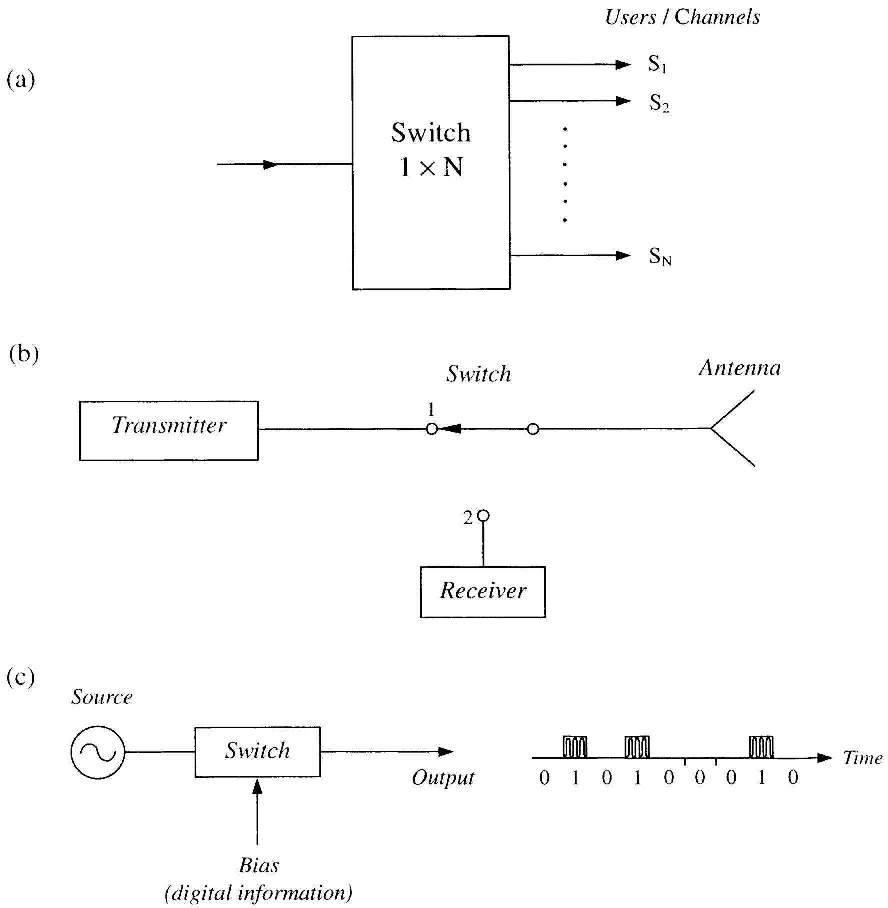


FIGURE 4.30 Applications of switches: (*a*) channel switch or time multiplexing; (*b*) T/R switch or duplexer; (*c*) pulse modulator.

different bias states [1]. For one state, the device acts as a short circuit, and for the other, as an open circuit.

One major application of switches is to build phase shifters. Figure 4.33 shows a switched-line phase shifter and its realization using p–i–n diodes [1]. When the bias is positive, the signal flows through the upper line with a path length l_1. If the bias is negative, the signal flows through the lower line with a path length l_2. The phase difference between the two bias states is called a differential phase shift, given by

$$\Delta\phi = \frac{2\pi}{\lambda_g}(l_1 - l_2) \tag{4.24}$$

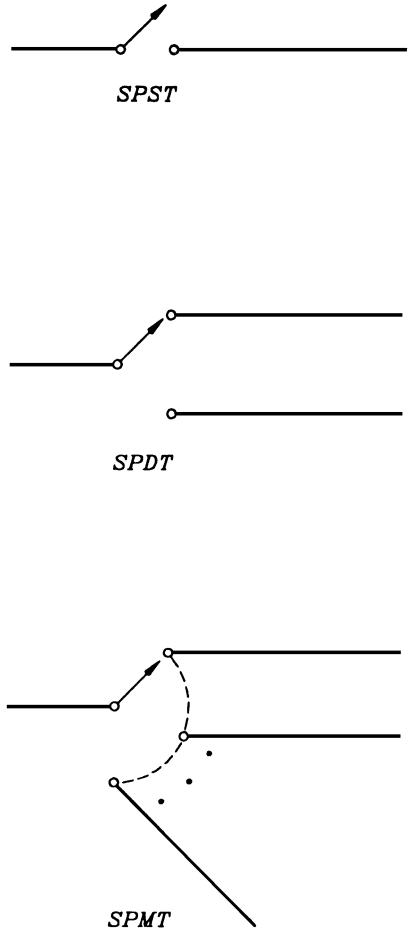


FIGURE 4.31 Switches and their output ports.

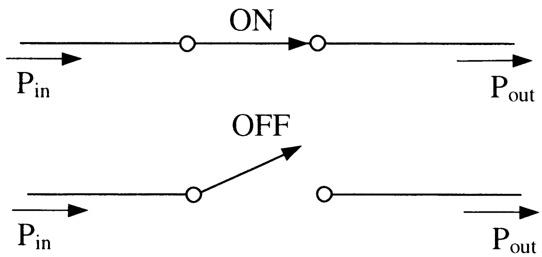


FIGURE 4.32 Switch in on and off positions.

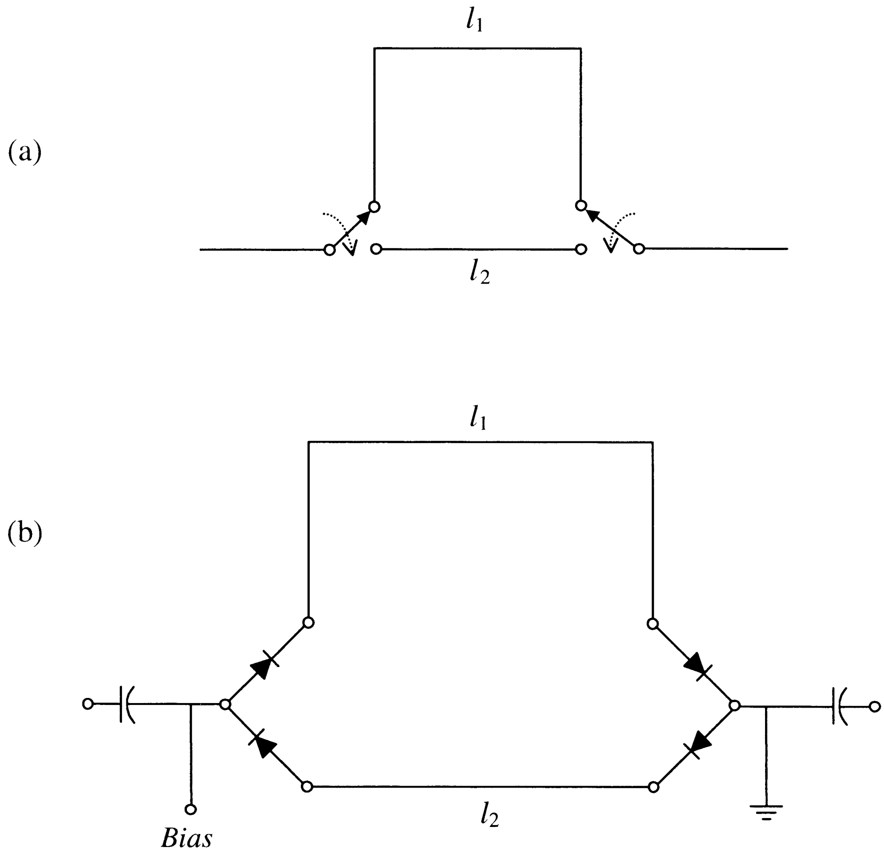


FIGURE 4.33 Switch-line phase shifter: (*a*) schematic diagram; (*b*) construction using $p{-}i{-}n$ diodes.

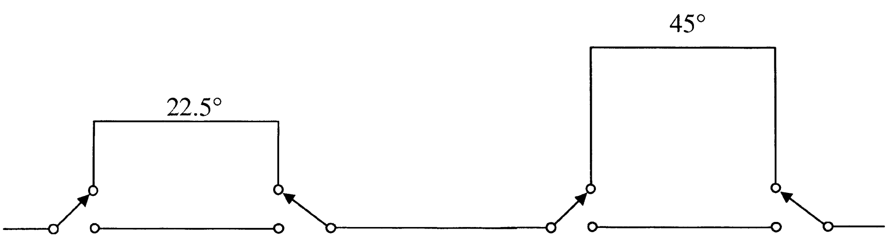


FIGURE 4.34 Two-bit phase shifter.

This phase shifter provides two phase states and is a 1-bit phase shifter. For more states, one can cascade two or more 1-bit phase shifters. Figure 4.34 illustrates an example of a 2-bit phase shifter. Four differential phase states result from switching the four SPDT switches. These phases are 0° (reference), 22.5°, 45°, and 67.5°. One major application of phase shifters is in phased-array antennas.

Instead of operating in two states, on and off as in a switch, one can vary the bias continuously. The device impedance is then varied continuously and the attenuation (insertion loss) is changed continuously. The component becomes a variable attenuator or electronically tunable attenuator. One application of the variable attenuator is automatic gain control used in many receiver systems.

4.7 OSCILLATORS AND AMPLIFIERS

Oscillators and amplifiers are active components. The component consists of a solid-state device (transistor, FET, IMPATT, Gunn, etc.) that generates a negative resistance when it is properly biased. A positive resistance dissipates RF power and introduces losses. In contrast, a negative resistance generates RF power from the DC bias supplied to the active solid-state device. Figure 4.35 shows a general oscillator circuit, where Z_D is the solid-state device impedance and Z_C is the circuit impedance looking at the device terminals (driving point) [1]. The impedance transformer network includes the device package and embedding circuit. The circuit impedance seen by the device is

$$Z_c(f) = R_c(f) + jX_c(f) \tag{4.25}$$

For the oscillation to occur, two conditions need to be satisfied,

$$\mathrm{Im}(Z_D) = -\mathrm{Im}(Z_C) \tag{4.26}$$

$$|\mathrm{Re}(Z_D)| \geq \mathrm{Re}(Z_C) \tag{4.27}$$

where Im and Re mean imaginary and real parts, respectively. The real part of Z_D is negative for a negative resistance. The circuit impedance is only a function of

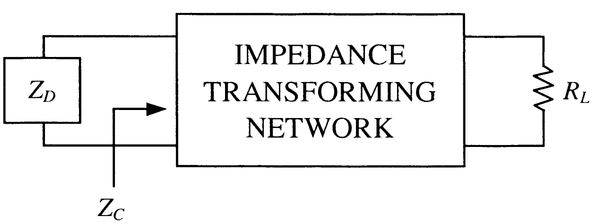


FIGURE 4.35 General oscillator circuit.

frequency. The device impedance is generally a function of frequency, bias current, RF current, and temperature. Thus at the oscillating frequency f_0 , we have

$$R_C(f_0) \le |R_D(f_0, I_0, I_{RF}, T)| \tag{4.28}$$

$$X_C(f_0) + X_D(f_0, I_0, I_{RF}, T) = 0 \tag{4.29}$$

Equation (4.28) states that the magnitude of the negative device resistance is greater than the circuit resistance. Therefore, there is a net negative resistance in the overall circuit. Equation (4.29) indicates that the oscillating frequency is the circuit resonant frequency since the total reactance (or admittance) equals zero at resonance. For a transistor or any three-terminal solid-state device, Z_D is replaced by the transistor and a termination, as shown in Fig. 4.36. The same oscillation conditions given by Eqs. (4.28) and (4.29) are required.

Oscillators are used as sources in transmitters and as local oscillators in upconverters and downconverters. System parameters of interest include power output, DC-to-RF efficiency, noise, stability, frequency tuning range, spurious signals, frequency pulling, and frequency pushing. These parameters will be discussed in detail in Chapter 6.

An amplifier is a component that provides power gain to the input signal to the amplifier. As shown in Fig. 4.37, P_{in} is the input power and P_{out} is the output power. The power gain is defined as

$$G = \frac{P_{out}}{P_{in}} \tag{4.30}$$

or

$$G \text{ (in dB)} = 10 \log \frac{P_{out}}{P_{in}} \tag{4.31}$$

Amplifiers can be cascaded to provide higher gain. For example, for two amplifiers with gain G_1 and G_2 in cascade, the total gain equals $G_1 G_2$. The amplifier used in

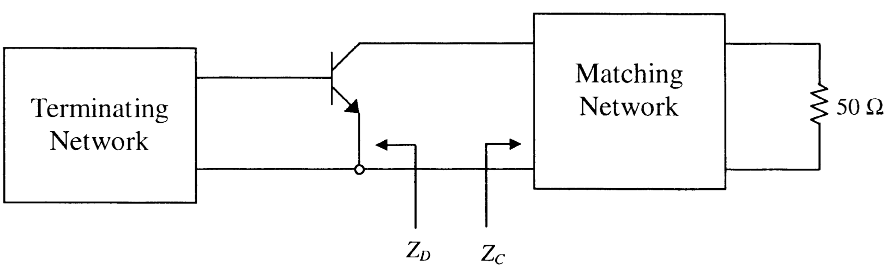


FIGURE 4.36 Transistor oscillator.

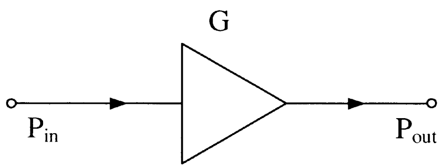


FIGURE 4.37 Amplifier with power gain G.

the last stage of a transmitter provides high power output and is generally called a power amplifier (PA). The amplifier used in the receiver normally has a low noise figure and is called a low-noise amplifier (LNA). An amplifier can be constructed by designing the input and output matching network to match an active solid-state device. Figure 4.38 shows a transistor amplifier circuit [1]. The important design considerations for an amplifier are gain, noise, bandwidth, stability, and bias arrangement. An amplifier should not oscillate in the operating bandwidth. The stability of an amplifier is its resistance to oscillation. An unconditionally stable amplifier will not oscillate under any passive termination of the input and output circuits.

For a power amplifier, desired system parameters are high power output, high 1-dB compression point, high third-order intercept point, large dynamic range, low intermodulation, and good linearity. Most of these parameters will be defined and discussed in Chapters 5 and 6. For battery operating systems, high power added efficiency (PAE) is also important. The PAE is defined as

$$\mathrm{PAE} = \frac{P_{\mathrm{out}} - P_{\mathrm{in}}}{P_{\mathrm{DC}}} \times 100\% \tag{4.32}$$

where P_{DC} is the DC bias power. Power added efficiencies of over 50% are routinely achievable for transistor amplifiers.

Table 4.2 gives the typical performance of a Miteq amplifier [8].

Example 4.3 In the system shown in Fig. 4.39, calculate the output power in milliwatts when (a) the switch is on and (b) the switch is off. The switch has an insertion loss of 1 dB and an isolation of 30 dB.

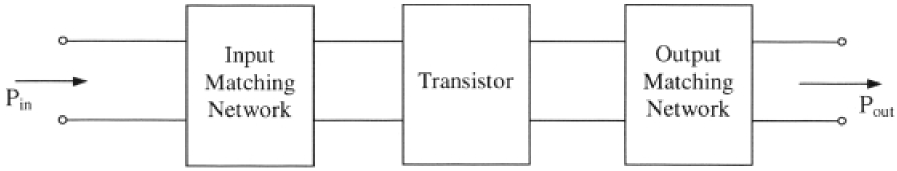


FIGURE 4.38 Transistor amplifier circuit.

TABLE 4.2 Performance of Miteq Amplifier Model MPN2-01000200-28P

Operating frequency	1–2 GHz
Gain	27 dB minimum
Gain flatness	±1.5 dB maximum
Noise figure	1.5 dB maximum
VSWR	2.0 maximum
Output 1 dB compression point	+28 dBm
Output third-order intercept point	+40 dBm

Solution

$$P_{\text{in}} = 0.001 \text{ mW} = -30 \text{ dBm}$$

For the switch, $\alpha_L = 1$ dB, $\alpha_I = 30$ dB:

(a) When the switch is ON, we have

$$\begin{aligned} P_{\text{out}} &= P_{\text{in}} - L - L_c - \alpha_L + G_1 + G_2 \\ &= -30 \text{ dBm} - 1 \text{ dB} - 4 \text{ dB} - 1 \text{ dB} + 10 \text{ dB} + 30 \text{ dB} \\ &= +4 \text{ dBm} = 2.51 \text{ mW} \end{aligned}$$

(b) When the switch is OFF, we have

$$\begin{aligned} P_{\text{out}} &= P_{\text{in}} - L - L_c - \alpha_1 + G_1 + G_2 \\ &= -30 \text{ dBm} - 1 \text{ dB} - 4 \text{ dB} - 30 \text{ dB} + 10 \text{ dB} + 30 \text{ dB} \\ &= -25 \text{ dBm} = 0.00316 \text{ mW} \end{aligned}$$

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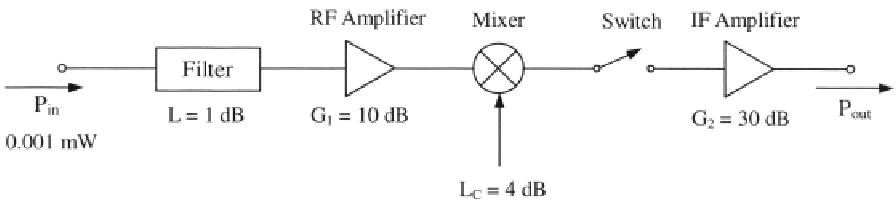

FIGURE 4.39 Receiver system.

4.8 FREQUENCY MULTIPLIERS AND DIVIDERS

A frequency multiplier is used to generate the output signal with a frequency that is a multiple of the input signal frequency, as shown in Fig. 4.40. If the input frequency is f_0, the output frequency is nf_0, and n could be any of 2, 3, 4, ... When $n = 2$, it is a $\times 2$ multiplier, or a doubler. When $n = 3$, it is a $\times 3$ multiplier, or a tripler. The multiplier consists of a low-pass filter, a nonlinear device such as a step recovery diode or a varactor, and input- and output-matching networks. Figure 4.41 shows a block diagram [1]. The low-pass filter, located in the input side, passes the fundamental signal and rejects all higher harmonics. The varactor is the nonlinear device that produces harmonics. The bandpass or high-pass filter at the output side

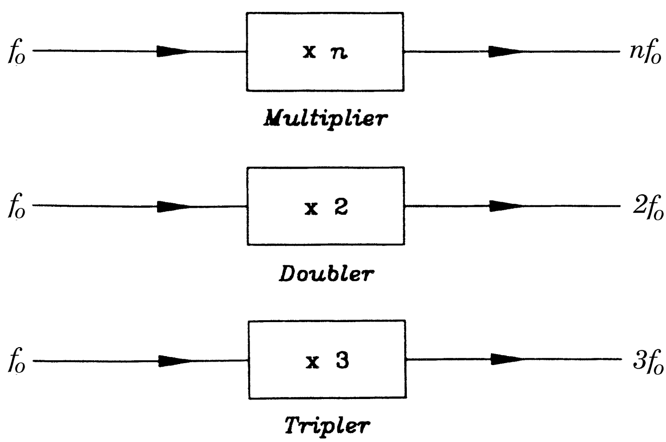

FIGURE 4.40 Frequency multipliers.

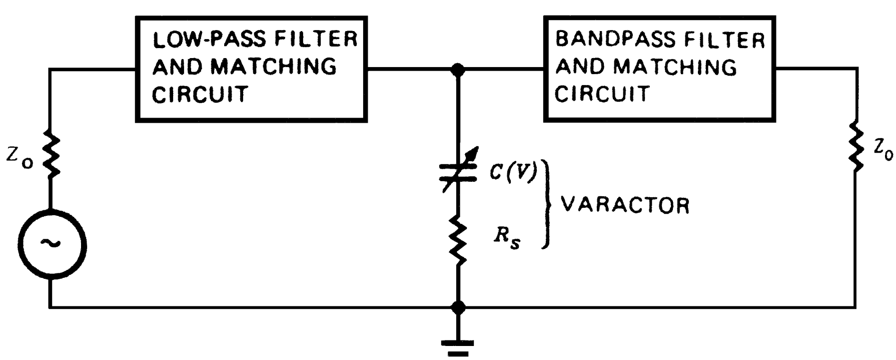

FIGURE 4.41 Multiplier circuit schematic: Z_0 = load impedance or characteristic impedance of transmission line; $C(V)$, R_s = variable capacitance and series resistance of varactor.

passes only the desired harmonic and rejects all other signals. The conversion efficiency (η) and conversion loss (L_c) are defined as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \tag{4.33}$$

$$L_c \text{ (in dB)} = 10 \log \frac{P_{\text{in}}}{P_{\text{out}}} \tag{4.34}$$

where P_{in} is the input power of the fundamental frequency and P_{out} is the output power of the desired harmonic. Frequency multipliers have been built up to millimeter-wave and submillimeter-wave frequencies [7].

Frequency dividers are commonly used in phase-locked loops (PLLs) and frequency synthesizers (Chapter 6). A frequency divider generates a signal with a frequency that is $1/N$ of the input signal frequency, where $N = 2, 3, 4, \ldots$. Figure 4.42 shows a symbol of a frequency divider and its input and output frequencies. Frequency division may be achieved in many ways. One example is to use the mixer-with-feedback method shown in Fig. 4.43. This is also called a regenerative divider. The mixer output frequency is

$$f_0 - f_0\left(\frac{N-1}{N}\right) = \frac{f_0}{N} \tag{4.35}$$

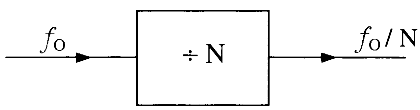

FIGURE 4.42 Frequency divider.

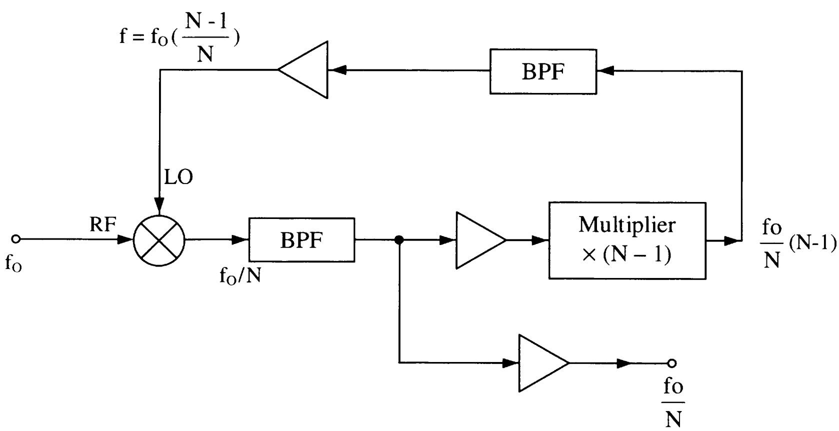

FIGURE 4.43 Regenerative frequency divider.

The maximum division ratio depends on the selectivity of the bandpass filter following the mixer. The amplifiers used in Fig. 4.43 are to boost the signal levels.

PROBLEMS

4.1 A 6-dB microstrip directional coupler is shown in Fig. P4.1. The coupling is 6 dB, and the directivity is 30 dB. If the input power is 10 mW, calculate the output power at ports 2, 3, and 4. Assume that the coupler is lossless.

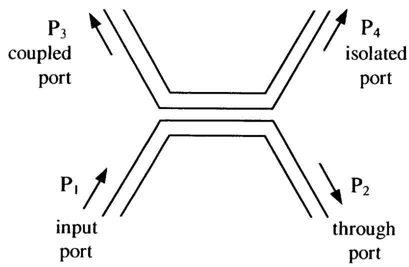

FIGURE P4.1

4.2 A three-way power divider has an insertion loss of 0.5 dB. If the input power is 0 dBm, what is the output power in dBm and milliwatts at any one of the output ports?

4.3 A bandpass filter (maximum flat characteristics) has the following specifications:

Passband from 9 to 10 GHz

Insertion loss 0.5 dB maximum

Off-band rejection:

At 8 GHz	IL = 30 dB
At 8.5 GHz	IL = 20 dB
At 10.5 GHz	IL = 15 dB
At 11 GHz	IL = 25 dB

(a) Plot the characteristics in log-scale (i.e., decibels vs. frequency).

(b) Plot the characteristics in regular scale (i.e., magnitude vs. frequency).

4.4 A downconverter has a conversion loss of 4.17 dB and RF and LO isolation of 20 dB. If the RF input power is 0 dBm, what are the IF output power and the RF power leaked into the LO port?

4.5 A switch has an insertion loss of 0.4 dB and isolation of 25 dB. If the input power is 1 mW, what are the output power levels when the switch is on and off?

4.6 In the system shown in Fig. P4.6, assume that all components are matched to the transmission lines. Calculate the power levels P_A, P_B, and P_C in milliwatts (P_A, P_B, and P_C are shown in the figure).

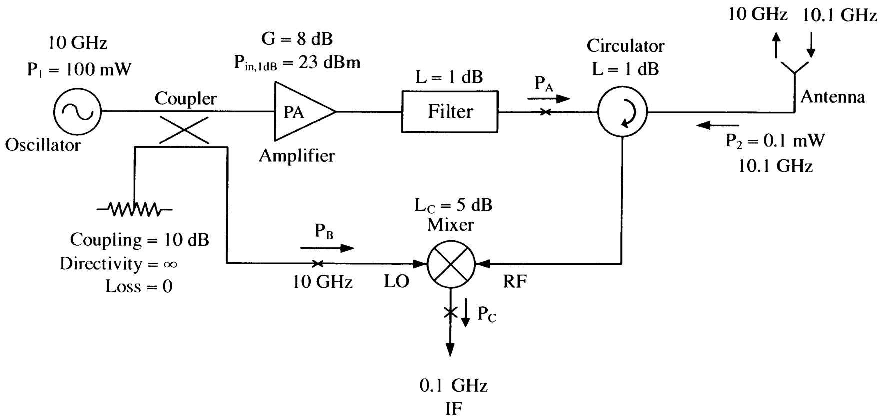

FIGURE P4.6

4.7 A transmitter is connected through a switch and a cable to an antenna (Fig. P4.7). If the switch has an insertion loss of 1 dB and an isolation of 20 dB, calculate the power radiated when the switch is in the on and off positions. The cable has an insertion loss of 2 dB. The antenna has an input VSWR of 2 and 90% radiating efficiency.

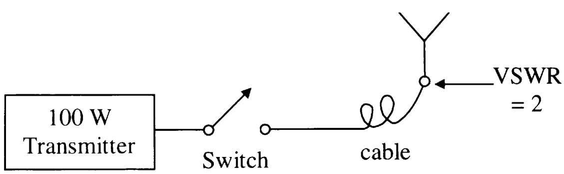

FIGURE P4.7

4.8 A transceiver is shown in Fig. P4.8. In the transmitting mode, the transmitter transmits a signal of 1 W at 10 GHz. In the receiving mode, the antenna receives a signal P_2 of 1 mW at 12 GHz. A switch is used as a duplexer. The switch has an insertion loss of 2 dB and isolation of 40 dB. The bandpass filter (BPF) has an insertion loss of 2 dB at 12 GHz and a rejection of 30 dB at 10 GHz. Calculate (a) the transmitted power P_1 at the antenna input, (b) the 10-GHz leakage power at the receiver input, (c) the 12-GHz received power at the receiver input.

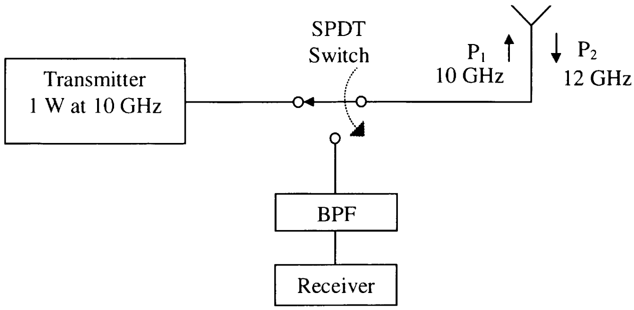

FIGURE P4.8

4.9 A system is shown in Fig. P4.9. The switch is connected to position 1 when the system is transmitting and to position 2 when the system is receiving. Calculate (a) the transmitting power P_t in milliwats and (b) the receiver output power P_{out} in milliwatts. Note that $P_r = 0.001$ mW, and the switch has an insertion loss of 1 dB.

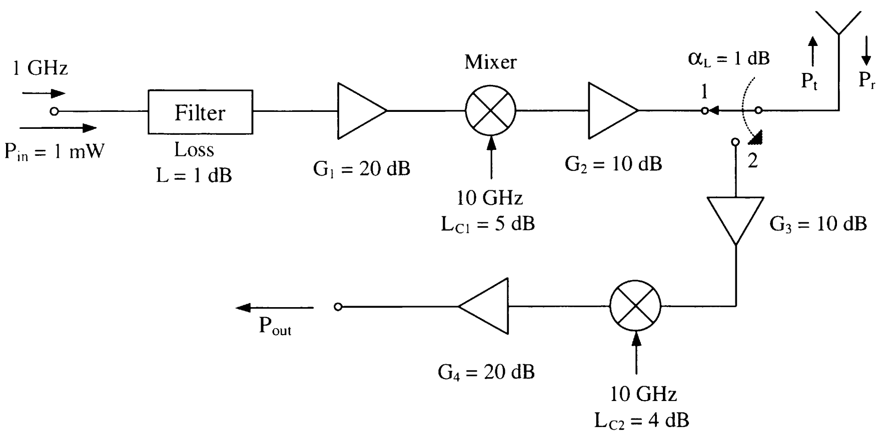

FIGURE P4.9

4.10 In the system shown in Fig. P4.10, calculate the power levels P_A, P_B, P_C, and P_D in milliwatts. Assume that all components are matched to the transmission lines.

4.11 List all states of phase shifts available in the circuit shown in Fig. P4.11.

4.12 Redraw Fig. 4.43 for a regenerative frequency divider for $N = 2$. What is the output power for this divider if the input power is 1 mW? Assume that the mixer conversion loss is 10 dB, the bandpass filter insertion loss is 4 dB, and the amplifier gain is 18 dB.

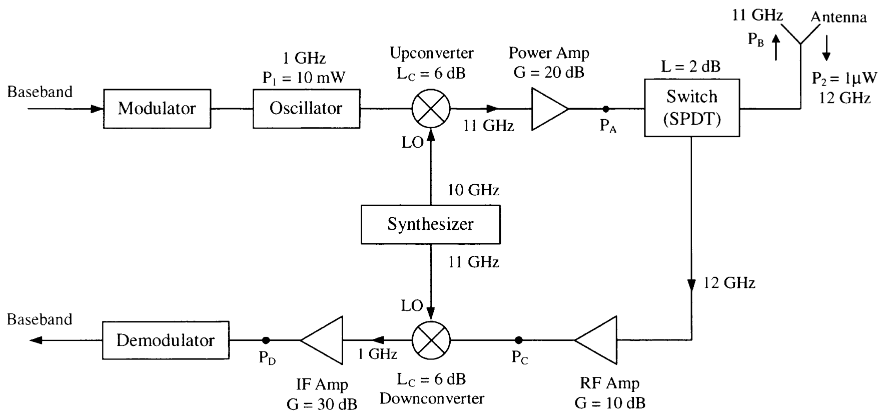

FIGURE P4.10

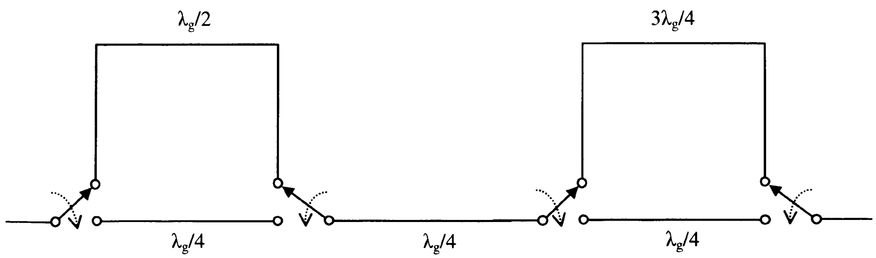

FIGURE P4.11

REFERENCES

1. K. Chang, *Microwave Solid-State Circuits and Applications*, John Wiley & Sons, New York, 1994.
2. R. E. Collin, *Foundation for Microwave Engineering*, 2nd ed., McGraw-Hill, New York, 1992.
3. D. M. Pozar, *Microwave Engineering*, 2nd ed., John Wiley & Sons, New York, 1998.
4. S. Y. Liao, *Microwave Devices and Circuits*, 3rd ed., Prentice-Hall, Englewood Cliffs, NJ, 1990.
5. K. Chang, Ed., *Handbook of Microwave and Optical Components*, Vol. 1, *Microwave Passive and Antenna Components*, John Wiley & Sons, New York, 1989.
6. K. Chang, *Microwave Ring Circuits and Antennas*, John Wiley & Sons, New York, 1996, Ch. 6.
7. K. Chang, Ed., *Handbook of Microwave and Optical Components*, Vol. 2, *Microwave Solid-State Components*, John Wiley & Sons, New York, 1990.
8. *Miteq Catalog*, Miteq, Hauppauge, NY.