and

$$q_c = \tanh\left[1.043 + 0.121\left(\frac{b-S}{S}\right) - 1.164\left(\frac{S}{b-S}\right)\right]$$

$$\epsilon_{ree} = \left[1 + \frac{S}{b}\left(a_1 - b_1 \ln\left(\frac{W}{b}\right)\right)\left(\sqrt{\epsilon_r} - 1\right)\right]^2 \qquad (3.104)$$

where

$$a_1 = [0.8145 - 0.05824 \ln(S/b)]^8$$
$$b_1 = [0.7581 - 0.07143 \ln(S/b)]^8$$

The above equations offer an accuracy of about 1% for $\epsilon_r \leq 16$, $S/b \leq 0.4$, and $W/b \leq 1.2$. These conditions are usually met in practice. The even- and odd-mode characteristic impedances of coupled suspended microstrip lines are shown in Figure 3.34(a) for $\epsilon_r = 2.32$. For the same parameters, the effective dielectric constants are shown in Figure 3.34(b).

3.7.3 Broadside-Coupled Offset Striplines

Broadside-coupled offset striplines are shown in Figure 3.35. This structure is more general than the broadside-coupled striplines configuration discussed in section 3.7.1 or the edge-coupled stripline configuration shown in Figure 3.11. Shelton [39] has given closed-form expressions for the analysis and synthesis of broadside-coupled offset lines. Here, we present the synthesis equations only as they are more frequently used. Two sets of equations are given, one for tightly coupled lines and the other for loosely coupled lines. The conditions for tight and loose coupling are defined by

Tight coupling case: $$\frac{w'}{1-s'} \geq 0.35$$
$$\frac{w'_c}{s'} \geq 0.7 \qquad (3.105)$$

Loose coupling case: $$\frac{w'}{1-s'} \geq 0.35$$
$$\frac{2w'_o}{1+s'} \geq 0.85 \qquad (3.106)$$

In the above equations, $s' = S/b$, $w' = W/b$, $w'_c = W_c/b$, and $w'_o = W_o/b$ denote the normalized values. The coupling between TEM lines can be expressed

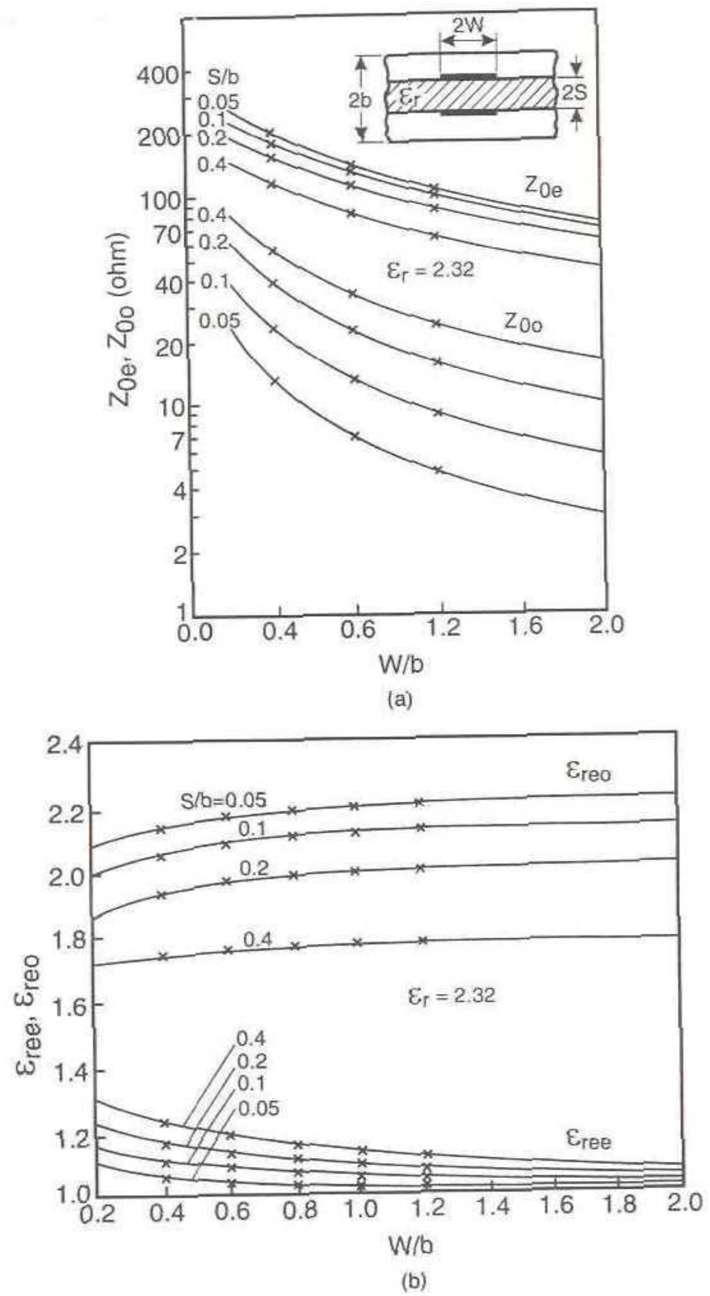

Figure 3.34 (a) Characteristic impedance and (b) effective dielectric constants of coupled broadside coupled suspended microstrip lines. $\epsilon_r = 2.32$. (From [38], ©1988 IEEE. Reprinted with permission.)

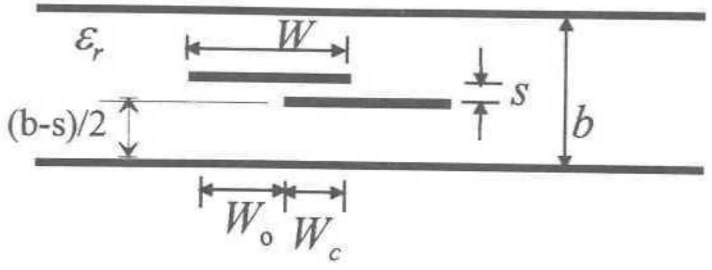

Figure 3.35 Broadside coupled off-set striplines.

in terms of even- and odd-mode characteristic impedances. For a TEM coupler that is matched at all its ports:

$$\frac{Z_{0e}}{Z_0} = \frac{Z_0}{Z_{0o}} \tag{3.107}$$

Defining ρ as

$$\sqrt{\rho} = \frac{Z_{0e}}{Z_0} = \frac{Z_0}{Z_{0o}} \tag{3.108}$$

we obtain the synthesis equations given below:

Tight coupling case: $$A = \exp\left[\frac{60\pi^2}{\sqrt{\epsilon_r}Z_0}\left(\frac{1-\rho s'}{\sqrt{\rho}}\right)\right]$$

$$B = \frac{A - 2 + \sqrt{A^2 - 4A}}{2}$$

$$p = \frac{(B-1)\left(\frac{1+s'}{2}\right) + \sqrt{(B-1)^2\left(\frac{1+s'}{2}\right)^2 + 4s'B}}{2}$$

$$r = \frac{s'B}{p}$$

$$C_{fo} = \frac{1}{\pi}\left[-\frac{2}{1-s'}\ln s' + \frac{1}{s'}\ln\left(\frac{pr}{(p+s')(1+p)(r-s')(1-r)}\right)\right]$$

$$C_o = \frac{120\pi\sqrt{\rho}}{\sqrt{\epsilon_r}Z_0}$$

$$w' = \frac{s'(1-s')}{2}(C_o - C_{fo})$$

$$w'_o = \frac{1}{2\pi}\left[(1+s')\ln\frac{p}{r} + (1-s')\ln\left(\frac{(1+p)(r-s')}{(s'+p)(1-r)}\right)\right]$$

Loose coupling case: $$C_o = \frac{120\pi\sqrt{\rho}}{\sqrt{\epsilon_r}Z_0} \tag{3.109}$$

$$\Delta C = \frac{120\pi}{\sqrt{\epsilon_r}Z_0}\frac{(\rho-1)}{\sqrt{\rho}}$$

$$K = \frac{1}{\exp(\frac{\pi\Delta C}{2}) - 1}$$

$$a = \sqrt{\left(\frac{(s'-K)}{(s'+1)}\right)^2 + K} - \frac{(s'-K)}{(s'+1)}$$

$$q = \frac{K}{a}$$

$$C_{fo} = \frac{2}{\pi}\left[\frac{1}{1+s'}\ln\frac{1+a}{a(1-q)} - \frac{1}{1-s'}\ln q\right]$$

$$w'_c = \frac{1}{\pi}\left[(s'\ln\frac{q}{a} + (1-s')\ln\left(\frac{1-q}{1+a}\right)\right]$$

$$C_f(a=\infty) = -\frac{2}{\pi}\left[\frac{1}{1+s'}\ln\left(\frac{1-s'}{2}\right) + \frac{1}{1-s'}\ln\left(\frac{1+s'}{2}\right)\right]$$

$$w' = \frac{1-s'^2}{4}\left[C_o - C_{fo} - C_f(a=\infty)\right]$$

3.8 Slot-Coupled Microstrip Lines

Slot-coupled microstrip lines are shown in Figure 3.36. This configuration is useful for realizing coupling in multilayer MICs. Directional couplers realized using