Computer-Aided Design Models for Broadside-Coupled Striplines and Millimeter-Wave Suspended Substrate Microstrip Lines

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Abstract —This paper presents computer-aided design models for broadside-coupled striplines and suspended substrate microstrip lines. The models have been obtained from the results of conformal transformation on homogeneous stripline, the equivalence of the odd-mode with the quasi-TEM mode of covered microstrip line, and logarithmic regression of spectral-domain results. The models can take the effects of finite strip thickness into account. The present models will be vital to the CAD of microwave and millimeter-wave filters, couplers, dc blocks, and various other circuits.

I. Introduction

Coupled lines are extensively used as basic building blocks for passive and active components, such as directional couplers, filters, baluns, and digital phase shifter networks. Coupled lines in a homogeneous medium have equal even- and odd-mode phase velocities. But velocities are different if the medium happens to be inhomogeneous. A broadside-coupled stripline has a homogeneous configuration, (See Fig. 1, $\epsilon_1 = \epsilon_2 = \epsilon_r$), whereas broadside-coupled suspended microstrip (See Fig. 1, $\epsilon_2 = 1$, $\epsilon_1 = \epsilon_r \geqslant 1$) and inverted microstrip (See Fig. 1, $\epsilon_1 = 1$, $\epsilon_2 = \epsilon_r \geqslant 1$) have inhomogeneous configuration. As a result, the even- and odd-mode phase velocities are different.

Broadside-coupled stripline has been analyzed by Cohn [1] using conformal transformation of the geometry of the structure. Cohn's procedure requires the solution of a transcendental equation, and explicit design formulas are obtained using Gunderson and Guida's [2] relationships for the even- and odd-mode fringe capacitances together with Cohn's analysis, when $W/b \geqslant 0.35$.

There have been numerous methods for the solution of multiple boundary value problems involving more than one dielectric medium in planar transmission lines. Examples are the conformal mapping method [3], the integral equation method [4], [5], the relaxation method [6], the variational method [7], [8], [19] and the method of moments [9]. An excellent account of the relative merits and demerits of the methods has been presented in the article on the discrete variational conformal technique by Diaz [10].

Although the above methods are rigorous and adequately accurate, each of them requires considerable analytical effort and leads to complicated computer programming. Therefore, from the standpoint of fast and cost-effective computer-aided design of planar integrated circuits there remains a strong need for simple but accurate models for the electrical characteristics of broadside-coupled striplines and microstrip lines.

In the present work we have developed such models using the results of conformal transformation of homogeneous broadside-coupled lines, the analogy of the odd-mode configuration with a shielded microstrip line, and the logarithmic regression of spectral-domain results.

II. Theory

A. Broadside-Coupled Stripline

Fig. 1(a) and (b) shows the even- and the odd-mode field distributions, respectively, of a broadside-coupled planar transmission line having two different substrate layers. For $\epsilon_1 = \epsilon_2 = \epsilon_r$, the structure reduces to a strip transmission line. According to Cohn [1] the characteristic impedances Z_{0e} and Z_{0o} of the even mode and the odd mode of the structure are given by

$$Z_{0e} = \frac{60\pi}{\sqrt{\epsilon_r}} \frac{K(k')}{K(k)} \tag{1a}$$

and

$$Z_{0o} = \frac{293.9 S/b}{\sqrt{\epsilon_r}\tanh^{-1}(k)} \tag{1b}$$

where k is the solution of the following transcendental equation:

$$W/b = \frac{1}{\pi}\left\{\ln\left(\frac{1+R}{1-R}\right) - \frac{S}{b}\ln\left(\frac{1+R/k}{1-R/k}\right)\right\} \tag{2a}$$

and K is the complete elliptic function of the first kind,

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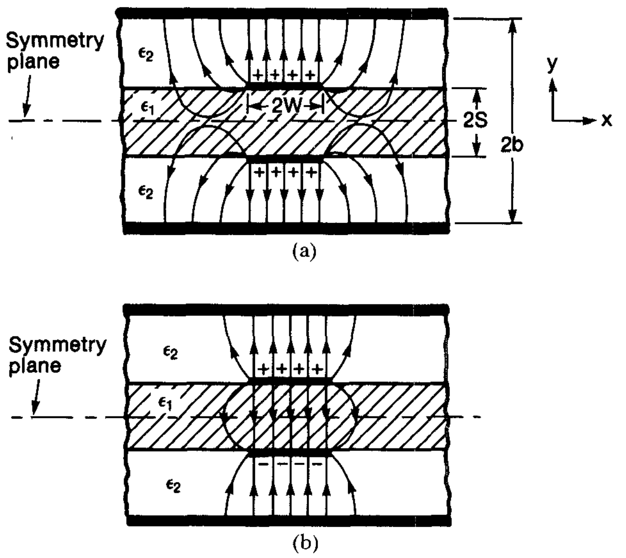

Fig. 1. General structure of broadside-coupled microstrip line. (a) Even-mode field distribution. (b) Odd-mode field distribution.

$k' = \sqrt{1-k^2}$, with

$$R = \sqrt{\left(k\frac{S}{b}-1\right)\Big/\left(\frac{1}{k}\frac{b}{S}-1\right)}. \tag{2b}$$

The results given by the above equations are claimed to be virtually exact for $W/S \geqslant 0.35$. However, an explicit solution of (1) can be obtained as follows:

The odd-mode field distribution (Fig. 1(b)) has the same field distribution as in a shielded microstrip line. Therefore, suitably modifying the equations in [11], we can write

$$Z_{0o}\sqrt{\epsilon_{eo}} = Z^a_{0\infty} - \Delta Z^a_{0\infty} \tag{3}$$

where, ϵ_{eo} is the odd-mode effective dielectric constant, and

$$Z^a_{0\infty} = \frac{\eta_0}{2\pi}\ln\left\{\frac{3S}{W}+\sqrt{\left(\frac{S}{W}\right)^2+1}\right\}$$

$$\eta_0 = 120\pi\Omega$$

$$\Delta Z^a_{0\infty} = \begin{cases} P & \text{for } \dfrac{W}{S} \leqslant \dfrac{1}{2} \\ P.Q. & \text{for } W/S \geqslant 1/2 \end{cases}$$

$$P = 270\left\{1-\tanh\left(0.28+1.2\sqrt{\frac{b-S}{S}}\right)\right\}$$

and

$$Q = 1-\tanh^{-1}\left\{\frac{0.48\sqrt{\dfrac{2W}{S}-1}}{\left(1+\dfrac{b-S}{S}\right)^2}\right\}. \tag{4}$$

Once $Z_{0o}\sqrt{\epsilon_{eo}}$ has been obtained, combining (2b) and (3) gives

$$k = \tanh\left\{\frac{293.9S/b}{Z_{0o}\sqrt{\epsilon_r}}\right\}. \tag{5}$$

Using (5) in (1a), we obtain Z_{0e}.

Hillberg's [12] accurate approximation gives

$$\frac{K(k)}{K(k')} = \frac{1}{\pi}\ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right), \qquad 0.5 \leqslant k^2 \leqslant 1 \tag{6a}$$

$$= \frac{\pi}{\ln\left(2\dfrac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)}, \qquad 0 \leqslant k^2 \leqslant 0.5. \tag{6b}$$

The above equations are valid also for $W/b \leqslant 0.35$, and offer an accuracy within 1 percent of spectral-domain results,

B. Broadside-Coupled Suspended Microstrip line ($\epsilon_1 = \epsilon_r \geqslant 1$, $\epsilon_2 = 1$)

The even- and the odd-mode characteristic impedances of broadside-coupled suspended microstrip lines are given by

$$Z^s_{0e} = Z^a_{0e}/\sqrt{\epsilon^s_{ee}} \tag{7a}$$

and

$$Z^s_{0o} = Z^a_{0o}/\sqrt{\epsilon^s_{eo}}. \tag{7b}$$

Z^a_{0e} and Z^a_{0o} are the even- and odd-mode characteristic impedance of the corresponding air-filled homogeneous broadside-coupled striplines, and ϵ^s_{ee} and ϵ^s_{0o} are the even- and the odd-mode effective dielectric constant of the inhomogeneous broadside-coupled line. Z^a_{0e} and Z^a_{0o} are obtained from (1a) and (3) respectively.

From the analogy of the odd-mode field distribution with that in a covered microstrip line, we obtain the odd-mode effective dielectric constant by appropriately modifying March's [11] and Hammerstad's [13] expressions as

$$\epsilon^s_{eo} = \frac{1}{2}(\epsilon_r+1)+q(\epsilon_r-1)/2 \tag{8}$$

where the filling factor q is given by

$$q = q_\infty q_c \tag{9a}$$

$$q_\infty = \left(1+\frac{5S}{W}\right)^{-a(U)b(\epsilon_r)} \tag{9b}$$

$$a(U) = 1+\frac{1}{49}\ln\left\{\frac{U^4+(U/52)^2}{U^4+.432}\right\} + \frac{1}{18.7}\ln\left\{1+\left(\frac{U}{18.1}\right)^3\right\} \tag{9c}$$

$$U = 2W/S \tag{9d}$$

$$b(\epsilon_r) = 0.564\left\{\frac{\epsilon_r-0.9}{\epsilon_r+3}\right\}^{0.053} \tag{9e}$$

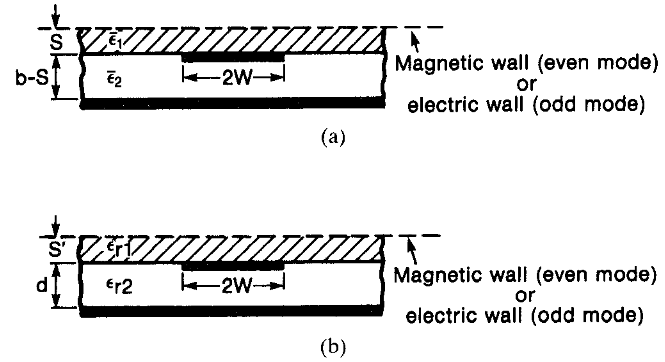

Fig. 2. Derived configuration of broadside-coupled striplines for (a) anisotropic case and (b) isotropic case.

and

$$q_c = \tanh\left\{1.043 + 0.121\left(\frac{b-S}{S}\right) - 1.164\left(\frac{S}{b-S}\right)\right\}. \tag{9f}$$

The even-mode effective dielectric constant is obtained from the logarithmic regression of spectral-domain results as

$$\epsilon_{ee}^{s} = \left\{1 + \frac{S}{b}\left(a_1 - b_1 \ln\left(\frac{W}{b}\right)\right)\left(\sqrt{\epsilon_r} - 1\right)\right\}^2 \tag{10}$$

where

$$a_1 = \{0.8145 - 0.05824 \ln(S/b)\}^8 \tag{11}$$

$$b_1 = \{0.7581 - 0.07143 \ln(S/b)\}^8. \tag{12}$$

The above equations offer an accuracy of 1 percent when compared with results from the variational method in the Fourier transform domain [19] for $\epsilon_r \leqslant 16$, $S/b \leqslant 0.4$, and $W/b \leqslant 1.2$. These conditions are mostly met in practice.

C. Broadside-Coupled Suspended Microstrip on Anisotropic Substrate.

Some anisotropic substrate materials, such as random fiber PTFE, pyrolytic boron nitride, sapphire, and epsilam 10, show certain advantages over ceramics, which include lower losses, higher homogeneity, and lower variation of electrical properties from batch to batch. Such anisotropic materials are often used in designing suspended microstrip broadside couplers. The relative permittivity tensor for such a material can be written as

$$\bar{\epsilon}_i = \begin{bmatrix} \epsilon_{xxi} & \epsilon_{xyi} & 0 \\ \epsilon_{xyi} & \epsilon_{yyi} & 0 \\ 0 & 0 & \epsilon_{zzi} \end{bmatrix}. \tag{13}$$

Fig. 2(a) shows the configuration of a broadside-coupled suspended microstrip, on an anisotropic substrate, with electric and magnetic walls at the line of symmetry. Using Szentkuti's [15] transformation gives the corresponding equivalent isotropic structure as shown in Fig. 2(b). Here

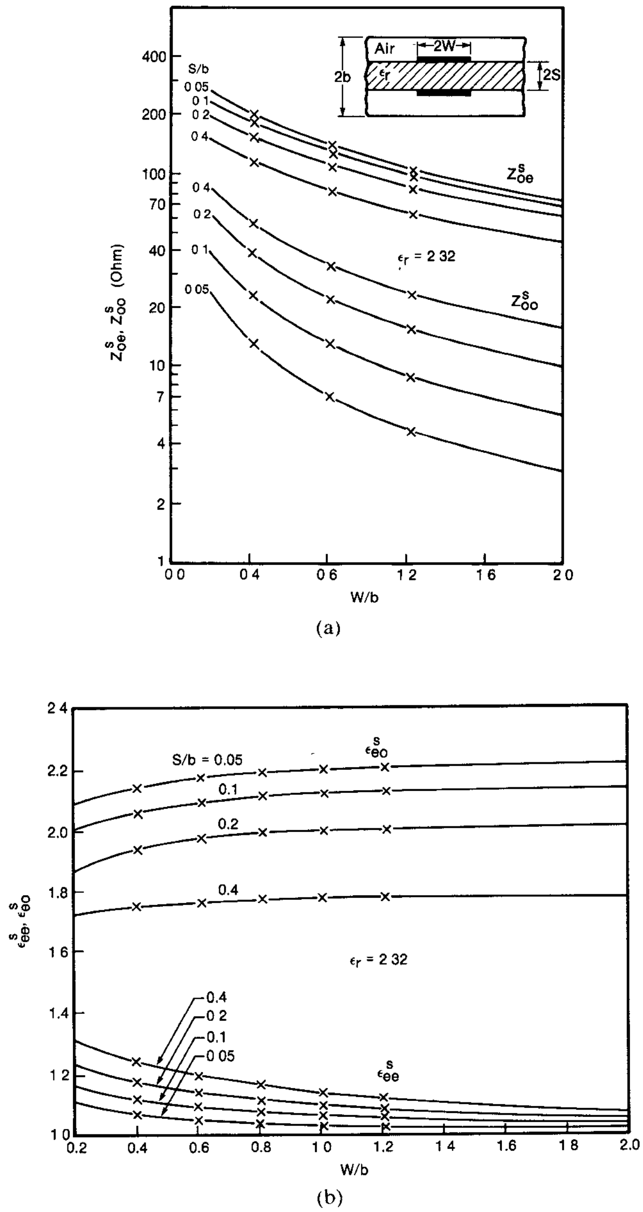

Fig. 3. Comparison with spectral-domain results. ——— [19]; × × × present models. (a) Characteristic impedance. (b) Effective dielectric constants $\epsilon_r = 2.32$.

$$S' = S\sqrt{\frac{\epsilon_{xx1}}{\epsilon_{yy1}} - \left(\frac{\epsilon_{xy1}}{\epsilon_{yy1}}\right)^2} \tag{14a}$$

$$d = (b-S)\sqrt{\frac{\epsilon_{xx2}}{\epsilon_{yy2}} - \left(\frac{\epsilon_{xy2}}{\epsilon_{yy2}}\right)^2} \tag{14b}$$

and

$$\epsilon_{r1} = \sqrt{\epsilon_{xx1}\epsilon_{yy1} - \epsilon_{xy1}^2} \tag{14c}$$

$$\epsilon_{r2} = \sqrt{\epsilon_{xx2}\epsilon_{yy2} - \epsilon_{xy2}^2}. \tag{14d}$$

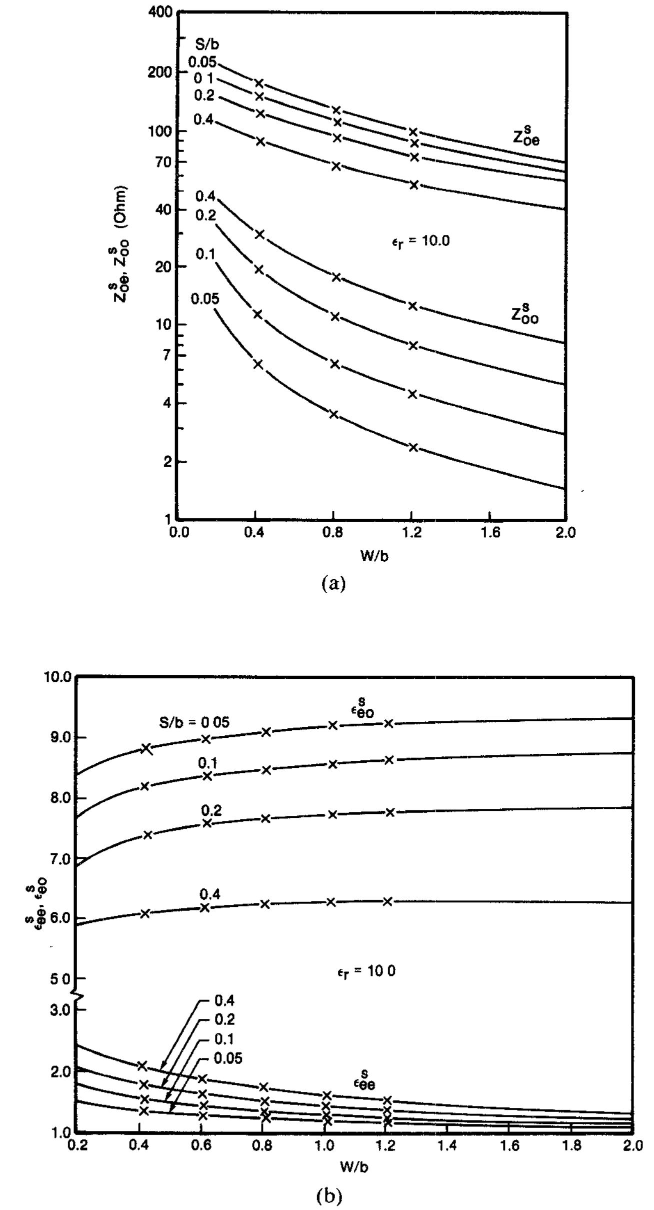

Fig. 4. Comparison with spectral-domain results. ——— [19]; × × × present models. (a) Characteristic impedance. (b) Effective dielectric constant $\epsilon_r = 10.00$.

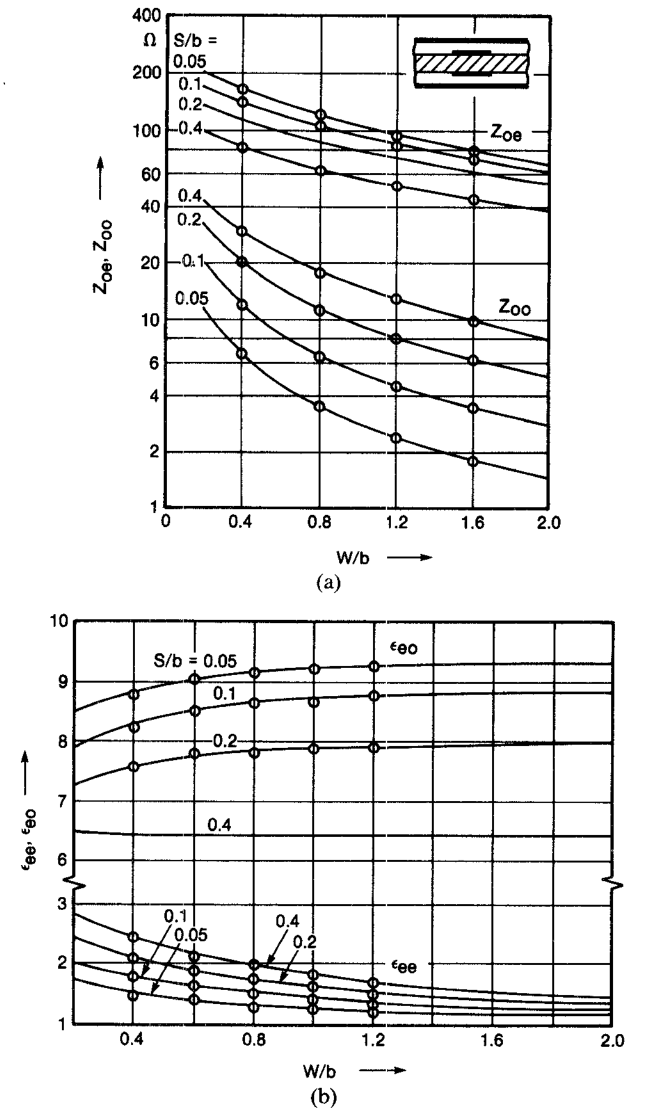

Fig. 5. Comparison with spectral domain results. ——— [16]; ○○○ present models. (a) Characteristic impedance. (b) Effective dielectric constant epsilam 10 substrate ($\epsilon_{xx} = \epsilon_{zz} = 15$, $\epsilon_{yy} = 10$, $\epsilon_{xy} = \epsilon_{yx} = \epsilon_{zx} = \epsilon_{xy} = 0$).

Once the equivalent isotropic structure has been obtained, (1) through (13) can be used to compute the effective dielectric constant and the characteristic impedance of the anisotropic line within 1 percent of the variational method in Fourier transform domain results [16] as long as $d \geqslant S'$.

III. Computed Results

Pictorial representations of the models presented in this article are given in Figs. 3, 4, and 5 for the three most commonly used commercially available substrates, polyolefin ($\epsilon_r \cong 2.32$), alumina ($\epsilon_r \cong 10$), and epsilam 10 ($\epsilon_{xx} = \epsilon_{zz} = 15$, $\epsilon_{yy} = 10$, $\epsilon_{xy} = \epsilon_{yx} \simeq 0$). These are included as an immediate design aid and as a reference for the installation of the formulas on a computer. A better appreciation of the above models can be obtained from Table I.

TABLE I

	$\epsilon_r = 2.32$, $\frac{S}{b} = 0.1$					
	REF [14]		Present Models		REF [8]	
$\frac{W}{b}$	Z^s_{oe}	Z^s_{oo}	Z^s_{oe}	Z^s_{oo}	Z^s_{oe}	Z^s_{oo}
0.1	274.00	63.30	273.20	63.80	280	64.5
0.2	232.70	40.50	232.20	40.90	235	41.5
0.4	182.20	24.00	181.06	23.93	180	24.4
0.6	152.50	17.00	150.00	16.95	150	16.8
0.8	130.10	13.50	128.00	13.62	128	13.2
1.0	-	-	112.99	10.70	-	-

IV. Effects of Finite Strip Thickness

The derivations of the above models assume a zero strip thinkness. Such an assumption is valid for many practical applications of broadside-coupled striplines and microstrip lines. However, in many other applications, a finite strip thickness has to be taken into consideration. Qualitatively speaking, the effect of finite strip thickness t on the effective dielectric constant is roughly within ± 0.8 percent for all substrate materials used for millimeter-wave applications [19], i.e., Duroid or fused quartz, and $t/b \leq 0.02$, although this upper bound on t/b is rarely encountered in practice. But for $\epsilon_r \simeq 10$, the effect of finite strip thickness can be as high as 1.5 percent on the even-mode effective dielectric constant and 0.75 percent on the odd-mode effective dielectric constant [19]. On the other hand, the error in the odd-mode characteristic impedance can be on the order of 4 percent and the error in even-mode impedance, 2 percent [19]. Based on these observations the following corrections are proposed.

1) Correction for the Effective Dielectric Constant in Odd Mode: Replace q_∞ by $(q_\infty - q_t)$ in (9b) and compute the correct ϵ_{eo}^{st}, where

$$q_t = (2/\pi)(t/S)/\sqrt{2W/S}. \tag{15}$$

2) Correction for the Even-Mode Effective Dielectric Constant: The correct even-mode effective dielectric constant with finite strip thickness is given by

$$\epsilon_{ee}^{st} = \epsilon_{ee}^{s}\left(1 + 2\frac{\epsilon_{eo}^{st} - \tau\epsilon_{eo}^{s}}{\epsilon_{eo}^{s}}\right). \tag{16}$$

The odd-mode characteristic impedance Z_{0o}^{at} of the air-filled broadside-coupled line with finite strip thickness can be written as [18]

$$Z_{0o}^{at} = \frac{\eta_0}{C_{p1} + C_{p2} + C_{f1} + C_{f2}} \tag{17}$$

$$\eta_0 = 120\pi\,\Omega.$$

For $2W/(b-t) \geq 0.35$,

$$C_{p1} \equiv \frac{4W/(b-\delta)}{1 - \dfrac{t}{(b-\delta)}} \tag{18a}$$

$$C_{p2} = \frac{4W/(b+\delta)}{1 - \dfrac{t}{(b+\delta)}}, \qquad \delta = b/2 - S \tag{18b}$$

$$C_{f1} = \frac{1}{\pi}\left\{\frac{2}{1-t/(b-\delta)}\ln\left(\frac{1}{1-t/(b-\delta)}+1\right) - \left(\frac{1}{1-t/(b-\delta)}-1\right)\ln\left(\frac{1}{(1-t/(b-\delta))^2}-1\right)\right\} \tag{18c}$$

$$C_{f2} = \frac{1}{\pi}\left\{\frac{2}{1-t(b+\delta)}\ln\left(\frac{1}{1-t/(b+\delta)}+1\right) - \left(\frac{1}{1-t/(b+\delta)}-1\right)\ln\left(\frac{1}{(1-t/(b+\delta))^2}-1\right)\right\}. \tag{18d}$$

For $0.1 \leq 2W/(b-t) \leq 0.35$, replace W/b in the above expressions by [18]

$$\frac{W_n}{b} = \frac{(0.07(1-t/b)+2W/b)}{2.4}. \tag{19}$$

The odd-mode characteristic impedance of broadside-coupled suspended microstrip is given by

$$Z_{0o}^{st} = Z_{0o}^{at}/\sqrt{\epsilon_{eo}^{st}}. \tag{20}$$

The even-mode characteristic impedance with finite strip thickness is given by

$$Z_{0e}^{st} = Z_{0e}^{s}\left\{1 - \frac{1}{2}\frac{Z_{0o}^{s} - Z_{0o}^{st}}{Z_{0o}^{s}}\right\}. \tag{21}$$

V. Conclusions

Simple expressions have been reported for the even- and odd-mode effective dielectric constants and characteristic impedances of broadside-coupled striplines and suspended substrate microstrip lines. The equations have been derived from the conformal mapping results of homogeneous striplines, the equivalence of the odd-mode with the covered microstrip mode, and the logarithmic regression of spectral-domain results. Effects of finite strip thickness have been taken into account. The models represent a considerable improvement in the broadside-coupled stripline and microstrip line filter and coupler designs and are fully compatible with the needs and trends of computer-aided and programmable-calculator-aided microwave and millimeter-wave integrated circuit design.

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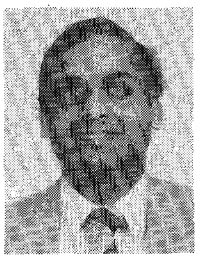
References

[1] S. B. Cohn, "Characteristics of broadside coupled strip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 633–367, June 1960.
[2] L. C. Gunderson and A. Guida, "Stripline coupler design," Microwave J., vol. 8, no. 6, pp. 97–101, June 1956.
[3] H. A. Wheeler, "Transmission line properties of parallel strips separated by a dielectric sheet," *IEEE Trans.* vol. MTT-13, pp. 172–185, Mar. 1965.
[4] T. G. Bryant and J. A. Weiss, "Parameters of microstrip lines and coupled pair of microstrip lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 1021–1027, Dec. 1968.
[5] E. Yamashita aned K. Atsuki, "Analysis of thick-strip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 120–122, Feb. 1971.
[6] J. S. Hornsby and A. Gopinath, "Numerical analysis of dielectric loaded waveguide with microstrip line—Finite difference method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 684–690, Sept. 1969.
[7] E. Yamashita and R. Mittra, "Variational method for analysis of Microstrip lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 251–256, Apr. 1968.
[8] J. I. Allen and M. F. Estes, "Broadside coupled strips in a layered dielectric medium," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 662–669, Oct. 1972.

[9] D. W. Kammler, "Calculation of characteristic admittances and coupling coefficients for strip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 925–927, Nov. 1968.
[10] R. E. Diaz, "The discrete variational conformal technique for the calculation of strip transmission line parameters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 714–715, June 1986.
[11] S. L. March, "Empirical Formulas for the impedance and effective dielectric constant of covered microstrip for use in the Computer aided design of microwave circuits," in *Proc. 11th European Microwave Conf.*, 1981, pp. 671–676.
[12] W. Hilberg, "From approximations to exact relations for characteristic impedances," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 259–265, 1969.
[13] E. Hammerstad and O. Jensen, "Accurate models for microstrip computer aided design," in *IEEE MTT-S Symp. Dig.*, 1980, pp. 407–409.
[14] I. J. Bahl and P. Bhartia, "Analysis of broadside coupled microstrip lines," *Arch. Elek. Übertragung.*, vol. 34, pp. 223–226 May 1980.
[15] B. T. Szentkuti, "Simple analysis of anisotropic microstrip lines by a transform method," *Electron. Lett.*, vol. 12, pp. 672–673, 1976.
[16] I. J. Bahl and P. Bhartia, "Analysis of inhomogeneous broadside coupled striplines employing anisotropic substrates," *Arch. Elek. Übertragung.*, vol. 34, no. 12, pp. 492–495, 1981.
[17] I. J. Bahl and P. Bhartia, "The design of broadside coupled stripline circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 165–168, Feb. 1981.
[18] H. Howe, *Stripline Circuit Design*. Dedham, MA: Artech House, 1974, pp. 38–39.
[19] I. J. Bahl and P. Bhartia, "Characteristics of inhomogeneous broadside-coupled striplines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 529–535, June 1980.
[20] D. L. Gish and O. Graham, "Characteristic impedance and phase velocity of a dielectric supported air strip transmission line with side walls," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 131–148, Mar. 1970.



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