Network Analysis and Synthesis of Multislot Back-to-Back Microstrip Directional Couplers

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***Abstract*—This paper develops a method to analyze and synthesize multislot back-to-back microstrip directional couplers. The analysis is based on an equivalent four-port network of the coupler, where the slot is represented by a lumped reactance connected in series with the microstrip lines through ideal transformers. The reactance and turn-ratio values are computed by network analysis, taking into account the structure parameters of the slot, such as its length, inclination angle, and offset distance. The characteristics of the directional coupler are calculated by using even- and odd-mode analysis. After deriving synthesis equations for uniform multislot couplers, an approximation scheme is devised for nonuniform directional couplers by combining the loose coupling theory with an optimization process. Several different uniform and nonuniform couplers are then explored, and their results are shown as accurate.**

***Index Terms*—CAD, microstrip couplers, multilayer, network analysis, slot coupling.**

I. Introduction

THE increasing complexity of microwave systems has demonstrated a need for high-density interconnects in MICs (microwave integrated circuits) and MMICs (monolithic microwave integrated circuits) [1], [2]. Multilayer microstrip circuits coupled with each other through slots cut in a common ground plane have become an attractive way to design these applications [3]–[6], where the direction of the slot is either longitudinal or transverse to the microstrip lines.

A double-sided directional coupler with a longitudinal slot was investigated by Tanaka *et al.* [5], who came up with a tight coupler as well as a loose one in a more compact size than their predecessors had [7]. However, its unequal even- and odd-mode characteristic impedances and phase velocities resulted in poor directivity. Another type of multilayer directional coupler, using transverse slots placed discretely, has also been reported [6], [8]. In contrast to the first coupler, this one has the same characteristic impedances and phase velocities for even and odd modes, which produces high directivity. However, the measurement data were not as good as the simulation results.

There have been a few attempts to analyze and synthesize the multislot back-to-back microstrip directional coupler. The spectral-domain moment method with an optimization process was described in a noticeable recent paper [9]. While this numerical scheme demonstrates versatility and accuracy, it suffers from two drawbacks: it requires extensive computer time, and any change in the geometry requires the development of a new solution.

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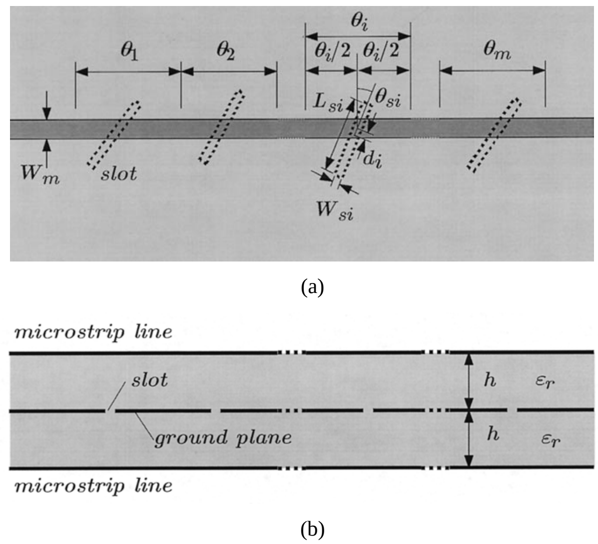

Fig. 1. Top and side views of a multislot back-to-back microstrip directional coupler.

This paper develops an efficient analysis and synthesis method for multislot back-to-back microstrip directional couplers, which can accommodate inclined and off-center slots. Section II defines the nature of the directional coupler and analyzes it by using the equivalent-network model [10] and the even- and odd-mode analysis [11], [12]. Based on the results of this analysis, synthesis methods for uniform and nonuniform directional couplers are detailed in Section III. Various design alternatives are discussed in Section IV, which also examines the characteristics of some uniform multislot directional couplers. In addition, the result of designing a broad-band directional coupler with nonuniform multislots is considered. Section V contains conclusions.

II. Analysis

Fig. 1 shows the general structure of a multislot back-to-back microstrip directional coupler. Two identical microstrip lines of width W_m are coupled to each other via multislots cut in the common ground plane. The ith coupling element of the directional coupler has a slot at the center of a line of electrical length θ_i [see Fig. 1(a)]. Here, L_{si}, W_{si}, θ_{si}, and d_i denote the length, width, inclination angle, and offset distance, respectively, of the slot. The substrate of the microstrip line has a dielectric constant of ϵ_r and a thickness of h, as shown in Fig. 1(b).

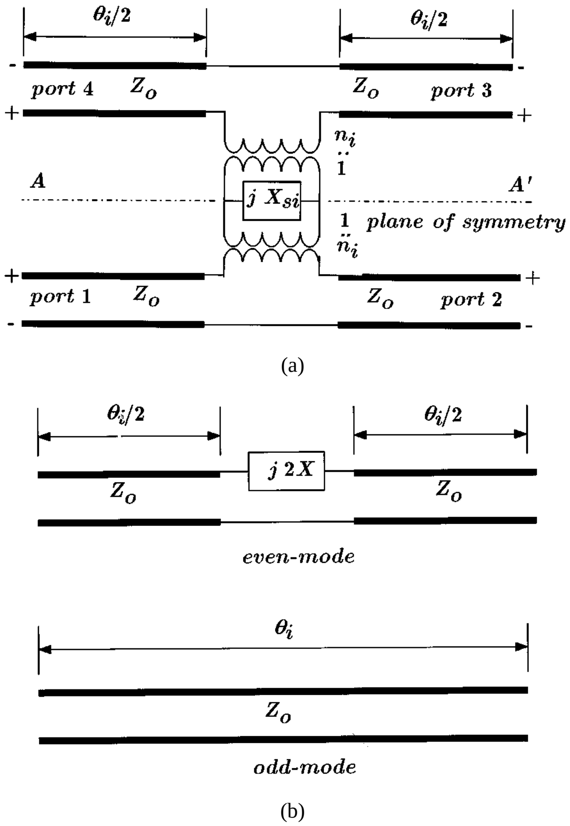

Fig. 2. Equivalent-network representation of the ith element. (a) Equivalent network. (b) Even- and odd-mode representation.

An equivalent network of the ith element can be developed, as shown in Fig. 2(a), by network analysis [10], where Z_o is the characteristic impedance of the microstrip line and n_i is the turn ratio of the ideal transformer. The reactance of the slot at the microstrip-slot junction X_{si} is given as

$$X_{si} = Z_{si}\big[\cot \beta_{si}(L_{si}/2 + d_i + \Delta L_{si}) + \cot \beta_{si}(L_{si}/2 - d_i + \Delta L_{si})\big]^{-1} \quad (1)$$

where Z_{si} and β_{si} are the characteristic impedance and phase constant of the corresponding slotline, respectively, and ΔL_{si} denotes the extended length of the slotline due to the nonzero reactance at the end. The slotline parameters, such as Z_{si}, β_{si}, and ΔL_{si}, can be obtained by various analysis methods [13], and n_i can be efficiently computed through the network analysis [10] for various configurations.

Since the developed four-port network is symmetric across the midplane of A–A', it can be analyzed by using even- and odd-mode analysis. Fig. 2(b) shows these even- and odd-mode circuit representations, where X_i is given as

$$X_i = {n_i}^2 X_{si}. \quad (2)$$

Some algebraic manipulation produces the following even- and odd-mode $ABCD$ parameters:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^i_{\text{even}} = \begin{bmatrix} p_i & jZ_o q_i \\ jr_i/Z_o & p_i \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^i_{\text{odd}} = \begin{bmatrix} \cos\theta_i & jZ_o \sin\theta_i \\ j\sin\theta_i/Z_o & \cos\theta_i \end{bmatrix} \quad (4)$$

respectively, where

$$\begin{cases} p_i = \cos\theta_i - \hat{X}_i \sin\theta_i \\ q_i = \sin\theta_i + \hat{X}_i(1+\cos\theta_i) \\ r_i = \sin\theta_i - \hat{X}_i(1-\cos\theta_i) \end{cases} \quad (5)$$

with $\hat{X}_i = X_i/Z_o$.

Multiplying the transmission matrices representing the individual sections of a multisection directional coupler systematically generates the overall transmission matrix of each mode, and the scattering parameters can then be obtained [14]. The return loss (RL), insertion loss (IL), coupling factor (C), and directivity (D) are defined as

$$\begin{cases} RL\ (\text{dB}) = -20\log_{10}|S_{11}| \\ IL\ (\text{dB}) = -20\log_{10}|S_{21}| \\ C\ (\text{dB}) = -20\log_{10}|S_{31}| \\ D\ (\text{dB}) = -20\log_{10}(|S_{41}/S_{31}|). \end{cases} \quad (6)$$

For all identical coupling elements [$\theta_i = \theta$ and $X_i = X$ for all i, which results in $p_i \to p = \cos\theta - \hat{X}\sin\theta$, $q_i \to q = \sin\theta + \hat{X}(1+\cos\theta)$, and $r_i \to r = \sin\theta - \hat{X}(1-\cos\theta)$], the overall even- and odd-mode transmission matrices are simplified as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{even}} = \begin{bmatrix} T_m(p) & jZ_o q U_{m-1}(p) \\ jrU_{m-1}(p)Z_o & T_m(p) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{odd}} = \begin{bmatrix} \cos(m\theta) & jZ_o \sin(m\theta) \\ j\sin(m\theta)/Z_o & \cos(m\theta) \end{bmatrix} \quad (8)$$

where m denotes the number of coupling sections, and $T_m(.)$ and $U_m(.)$ in (7) indicate the first- and second-kind Chebyshev polynomials, respectively [15]. Therefore, the scattering parameters are derived as

$$S_{11} = S_{41} = \frac{1}{2}\left[\frac{jU_{m-1}(p)\cdot(q-r)}{2T_m(p) + jU_{m-1}(p)\cdot(q+r)}\right] \quad (9)$$

$$S_{21} = \frac{1}{2}\left[\frac{2}{2T_m(p) + jU_{m-1}(p)\cdot(q+r)} + e^{-jm\theta}\right] \quad (10)$$

$$S_{31} = \frac{1}{2}\left[\frac{2}{2T_m(p) + jU_{m-1}(p)\cdot(q+r)} - e^{-jm\theta}\right]. \quad (11)$$

III. Design Method

A. Uniform Directional Coupler

Let us consider the design approach of a multisection uniform directional coupler. At the midband, $p = 0$ holds. Therefore, $\hat{X}_o$, the midband value of $\hat{X}$, is expressed as

$$\hat{X}_o = \cot\theta_o \quad (12)$$

from the first equation of (5), where θ_o indicates the electrical length of the element at the midband. Therefore, S_{21} and S_{31}, given in (10) and (11), become a function of θ_o only.

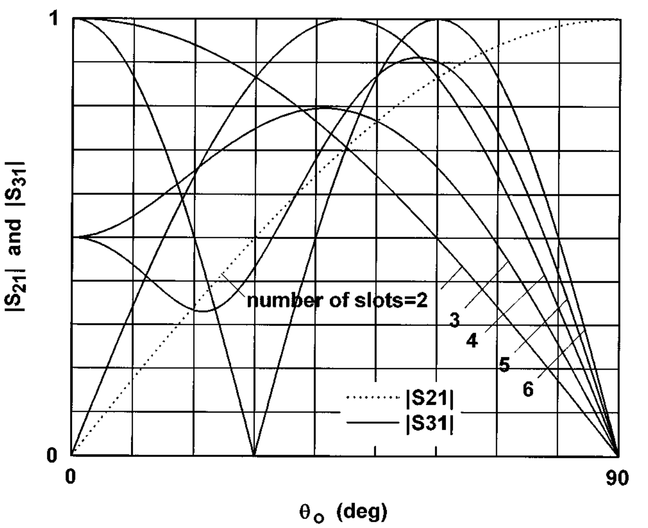

Fig. 3. Magnitudes of $|S_{21}|$ and $|S_{31}|$ as a function of the electrical length between the slots of multisection uniform directional couplers.

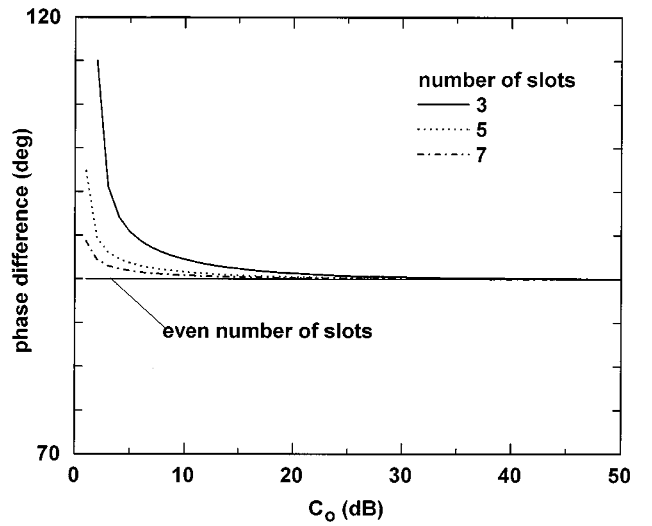

Fig. 4. Phase difference between S_{21} and S_{31} of multisection uniform directional couplers.

TABLE I
DESIGN VALUES OF 3- AND 10-dB UNIFORM DIRECTIONAL COUPLERS

number of slot	*3 dB*		*10 dB*	
	θ_o (*deg*)	$\hat{X}_o$	θ_o (*deg*)	$\hat{X}_o$
2	45.00	1.0000	71.57	0.3333
3	56.42	0.6640	77.57	0.2205
4	67.47	0.4149	80.78	0.1623
5	71.35	0.3375	82.59	0.1300
6	74.98	0.2684	83.86	0.1077
.	.	.	.	.
.	.	.	.	.
10	80.99	0.1586	86.31	0.0644

For a two-slot coupler, their magnitudes are simplified as

$$|S_{21}| = \sin\theta_o \quad \text{and} \quad |S_{31}| = \cos\theta_o \tag{13}$$

and depicted in Fig. 3. A desired midband coupling factor C_o produces the required θ_o, and $\hat{X}_o$ is, therefore, determined from (12). The results for other numbers of slots are also depicted in Fig. 3, and it is clear that both tight and loose directional couplers can be designed. If the number of slots is larger than two, several pairs of θ_o and $\hat{X}_o$ will have the same coupling factor. However, the shorter the electrical length, the larger the required value of $\hat{X}_o$, which results in longer coupling slots. Therefore, the strong interaction between the slots cannot be avoided, and the electrical length from 45° to 90° is reasonable to create both tight and loose couplings. Some design values of 3- and 10-dB directional couplers are listed in Table I.

The phase difference between S_{21} and S_{31} at the midband can also be computed from (10) and (11). The phase difference becomes 90° for an even number of slots, but deviates from 90° for an odd number. However, it tends to approach 90° as the number of slots and the coupling factor increase, as shown in Fig. 4. Therefore, a quadrature hybrid can be created by using this type of directional coupler.

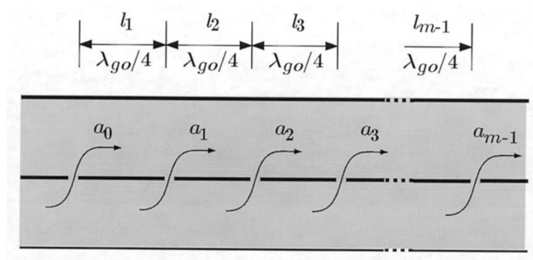

Fig. 5. Loose coupling scheme of a multisection nonuniform directional coupler.

B. Nonuniform Directional Coupler

The uniform directional coupler provides a simple means of coupling with a limited range of directivity. For applications requiring higher directivity over a broad frequency band, a multisection nonuniform directional coupler can be used. The design of such directional couplers needs more detailed consideration, but the loose coupling theory [16] produces reasonable analysis results and initial design data. Fig. 5 shows the structure of a multisection nonuniform directional coupler, where the slots are spaced at $l_i = \lambda_{go}/4$ intervals at the midband, where λ_{go} denotes the guide wavelength of the microstrip line. Since the loose coupling theory assumes that $(S_{21})_i = 1$ for each coupling element, S_{31} and S_{41} of the directional coupler are given as

$$S_{31} = e^{-j(m-1)\psi} \sum_{i=0}^{m-1} a_i \quad \text{and} \quad S_{41} = -\sum_{i=0}^{m-1} a_i e^{-j2i\psi} \tag{14}$$

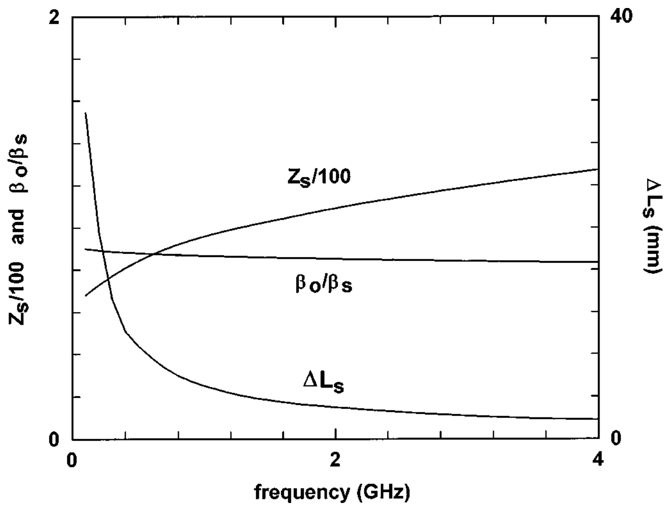

Fig. 6. Slotline characteristics ($h = 31$ mil, $\epsilon_r = 2.20$, and $W_s = 1.10$ mm).

where ψ represents the electrical length corresponding to the spacing $\lambda_{go}/4$, and a_i is the voltage coupling from the main to the coupled line at the ith slot. Therefore, the related coupling factor and directivity are then expressed as

$$C = -20 \log_{10} \left| \sum_{i=0}^{m-1} a_i \right|$$

and

$$D = -20 \log_{10} \left| \sum_{i=0}^{m-1} a_i e^{-j2i\psi} \right| - C. \quad (15)$$

Some design methods for multisection impedance matching circuits, such as the Chebyshev or binomial ones [17], can be applied to synthesize the desired directional coupler, and the required voltage coupling a_i can then be determined. Since a_i is a function of the structure parameters and can be calculated through the network analysis [10], the required slot dimension can also be determined. However, since the insertion loss and phase variation of a_i for each coupling element cannot be completely ignored, some corrections should be made by invoking an optimization scheme.

IV. Results and Discussion

The structure parameters of a chosen microstrip line and slotline are $W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, and $W_s = 1.1$ mm. The slotline characteristic impedance Z_s, the normalized phase constant β_s, and the extended slotline length ΔL_s as a function of frequency are calculated by using the rigorous field simulator for planar structures based on the method of moments.[1] Fig. 6 depicts these characteristics, and β_o is the phase constant of free space.

Three different types of slot are considered: a centered orthogonal slot (type 1), a centered inclined slot (type 2), and an off-centered orthogonal slot (type 3). Fig. 7(a)–(c) show the calculated n and resulting $\hat{X}_o$ as a function of L_s, θ_s, and d, respectively, at 2 GHz. The required value of $\hat{X}_o$ for a given coupling factor can then be obtained by choosing appropriate L_s, θ_s, and d independently or combining these parameters.

First, a 3-dB directional coupler operating at 2 GHz is designed with two identical slots of type 1. From Table I, $\theta_o = 45°$ and $\hat{X}_o = 1$ should be valid values. Therefore, the corresponding physical distance between the two slots becomes 13.63 mm, and the resulting slot length becomes 27.10 mm, as shown in Fig. 7(a). The computed return loss, insertion loss, coupling factor, directivity, and phase difference between S_{21} and S_{31} are shown in Fig. 8, along with the measured data over the frequency range from 1.5 to 2.5 GHz. The two results are in agreement. A directivity of 15 dB is obtained over a 10% of the bandwidth. In this frequency band, the coupling variation is approximately ±1 dB, and the quadrature phase deviation is less than 2°, which reflects a good phase quadrature.

It is clear from Fig. 7(a)–(c) that the required $\hat{X}_o$ can be obtained by using different types of slots. This idea is now tested by designing 10-dB directional couplers with two identical slots. From Table I, it is known that $\theta_o = 71.57°$, and this electrical length corresponds to the physical slot-to-slot distance of 21.68 mm. The required $\hat{X}_o$ of 0.3333 can be obtained by using three different types of slots independently. The structure parameters of these slots are determined from Fig. 7(a)–(c), and are listed in Table II. The results for type 1 are shown in Fig. 9. There is good agreement between the computed and measured values. A directivity of 15 dB is attained over a 20% of the bandwidth with ±1.3-dB coupling variation. The quadrature phase deviation is within 0.7° in this frequency band and 4.2° for an entire frequency band considered, revealing good broad-band phase quadrature. The results for the other two types are similar, as shown in Fig. 10, and this demonstrates the design flexibility of the present method.

The third step consists of designing a multisection uniform directional coupler to investigate bandwidth enhancement in terms of directivity. A 10-dB directional coupler with a midband frequency of 2 GHz is devised with five slots. As shown in Table I, the required θ_o and $\hat{X}_o$ are 82.5° and 0.1300, respectively. Therefore, the slot-to-slot distance becomes 25.02 mm, and L_s should be 5.55 mm, as determined from Fig. 7(a). Fig. 11 shows the computed results by the present theory and the rigorous solution, and their agreement is good. The deviation of the calculated coupling factor from the specified one becomes more noticeable as the frequency retreats from the midband. This deviation is mainly due to the frequency sensitivity of the slot reactance, which causes bandwidth contradiction [17]. The directivity has some sidelobes, and these values are, at most, 11 dB, while 140% of the bandwidth is evident for the directivity criterion of 10 dB. This sidelobe characteristics is similar to that of the radiation pattern of a uniform array antenna [18], where the first sidelobe level becomes 13 dB, at most, as the number of elements increases.

Next, a multisection nonuniform directional coupler requiring a high directivity over a broad frequency band is designed. The target coupling factor is 10 dB at the midband frequency of 2 GHz, and the directivity is 40 dB over 80% of the frequency band. According to the conventional Chebyshev design [17]

[1] HP Momentum, Hewlett-Packard Company, Santa Rosa, CA, 1997.

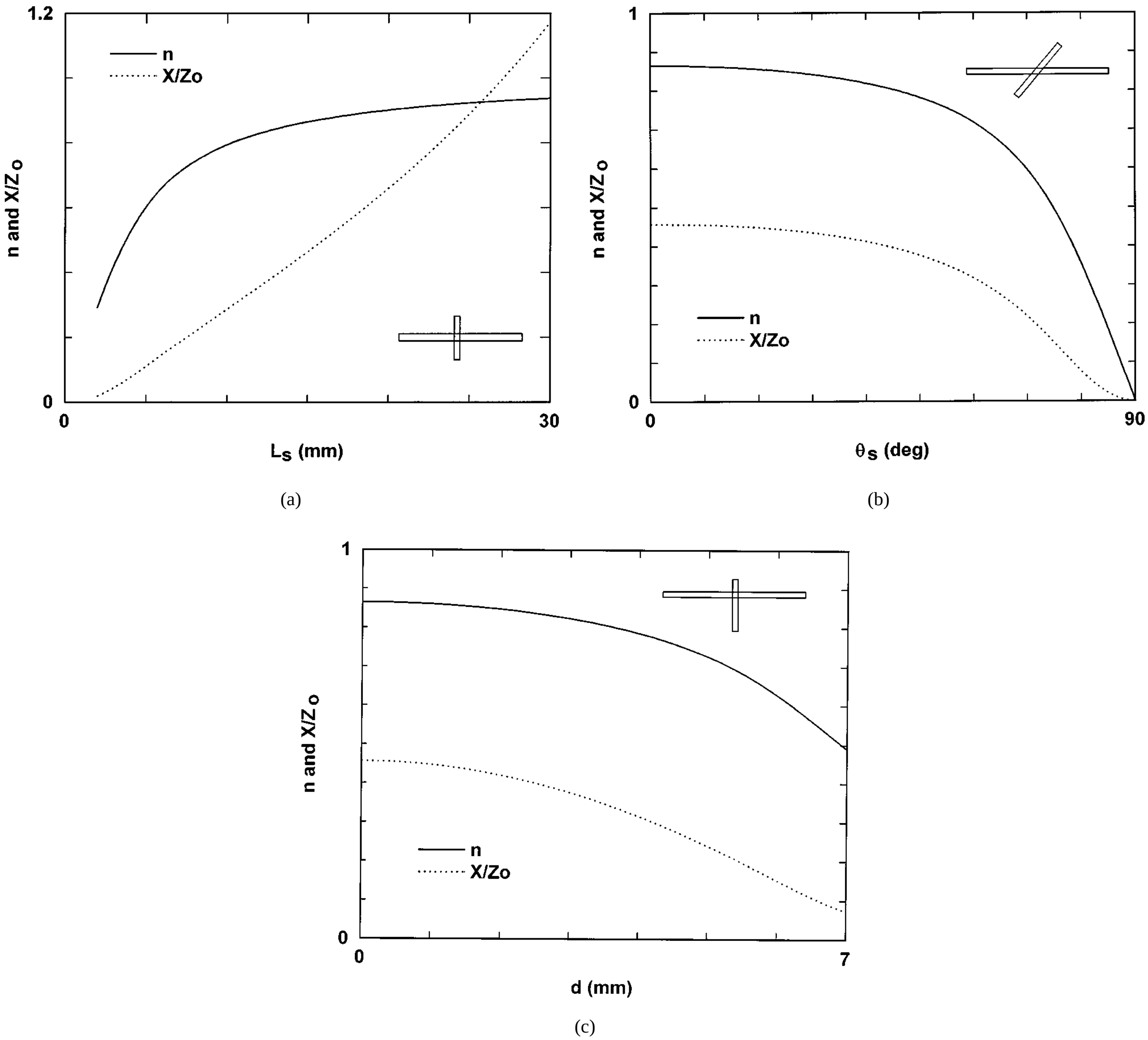

Fig. 7. Normalized equivalent reactance as a function of structure parameters ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm). (a) Slot-length effect ($\theta_s = 0^\circ$ mm and $d = 0$ mm). (b) Inclination-angle effect ($L_s = 15$ mm and $d = 0$ mm). (c) Offset-distance effect ($L_s = 15$ mm and $\theta_s = 0^\circ$).

and the loose coupling theory, the number of slots required for these specifications is at least six, and the required voltage couplings are listed in Table I. These coupling values can be attained by using orthogonal slots with different lengths. The scattering parameters of the coupling element as a function of L_s are depicted in Fig. 12, and the design values of the slot lengths become as shown in Table III, with an equal spacing of 27.26 mm. The computed characteristics of the directional coupler are shown in Fig. 13. Even though the specified coupling factor of 10 dB is obtained at 2 GHz, the midband in terms of directivity is lower than the design value. In addition, the obtained directivity is 30 dB at most, which is 10 dB lower than the target value, over less than 50% of the bandwidth. Therefore, some corrections should be made.

As shown in Fig. 12, the phase of S_{41} varies and decreases from 90° as the coupling increases. Therefore, the equivalent turnaround path becomes larger than $\lambda_{go}/2$ and causes the decreased midband. These results imply that the slot-to-slot distances should be corrected to meet the synchronous tuning condition [12], where the reflections from any pair of successive discontinuities are phased to produce maximum cancellation at the design frequency. In addition, since the other computed network parameters are slightly different from those obtained from the loose coupling assumption, further correction has to be made to meet the specifications. To do this, the slot-to-slot distances are optimized by using a microwave circuit simulator,[2] which are listed in Table III.

The directional coupler was fabricated with these design values. The measured data and computed results after optimization are shown in Fig. 13. The agreement between them is

[2]HP 85150B RF and Microwave Design Systems, Hewlett-Packard Company, Santa Rosa, CA 1997.

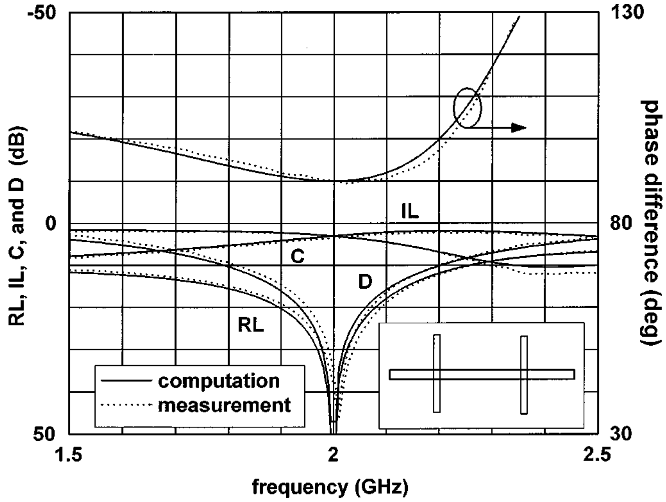

Fig. 8. Characteristics of a 3-dB two-slot uniform directional coupler ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm, $L_s = 27.10$ mm, $\theta_s = 0°$ mm, $d = 0$ mm, and spacing 13.63 mm). (a) Insertion loss, coupling factor, and directivity. (b) Phase difference between S_{21} and S_{31}.

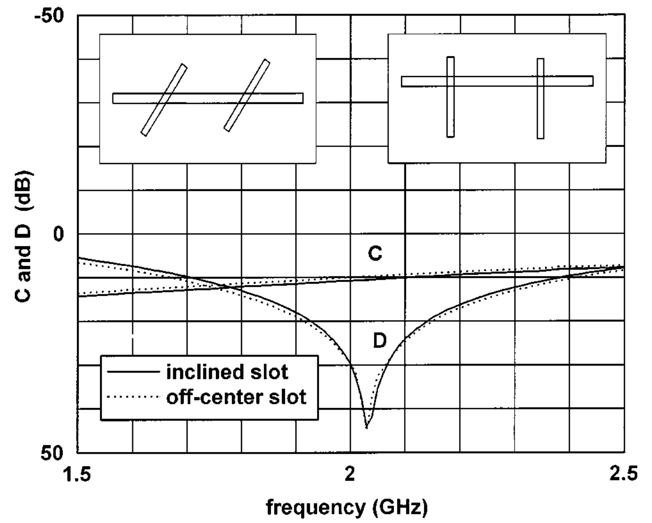

Fig. 10. Characteristics of a 10-dB two-slot directional couplers for the type 2 ($L_s = 15$ mm and $\theta_s = 58.14°$) and type 3 ($L_s = 15$ mm and $d = 3.87$ mm).

TABLE II
SLOT PARAMETERS OF THREE 10-dB DIRECTIONAL COUPLERS WITH TWO IDENTICAL SLOTS

coupling factor	*10 dB*		
types of slot	*type* 1	*type* 2	*type* 3
L_s (*mm*)	11.35	15.00	15.00
θ_s (*deg*)	0.00	58.14	0.00
d (*mm*)	0.00	0.00	3.87

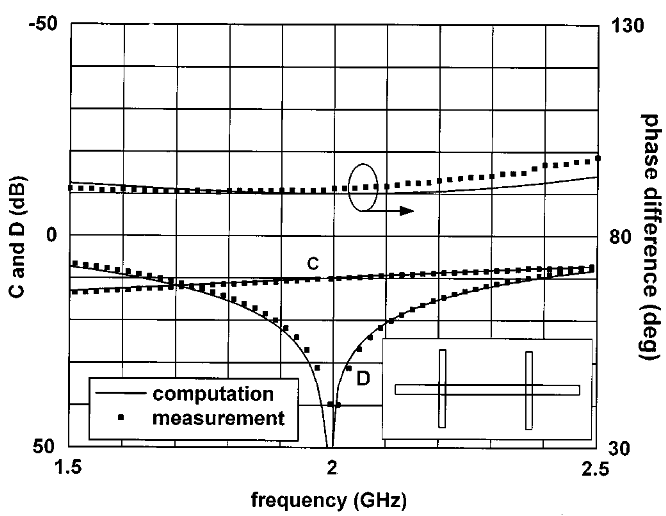

Fig. 9. Characteristics of a 10-dB two-slot directional coupler for the type 1 ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm, $L_s = 11.35$ mm, $\theta_s = 0°$ mm, $d = 0$ mm, and spacing 21.68 mm). (a) Coupling factor and directivity. (b) Phase difference between S_{21} and S_{31}.

reasonable, and comparable to the target design specifications. All those design examples validate the efficiency and accuracy of the proposed methodology.

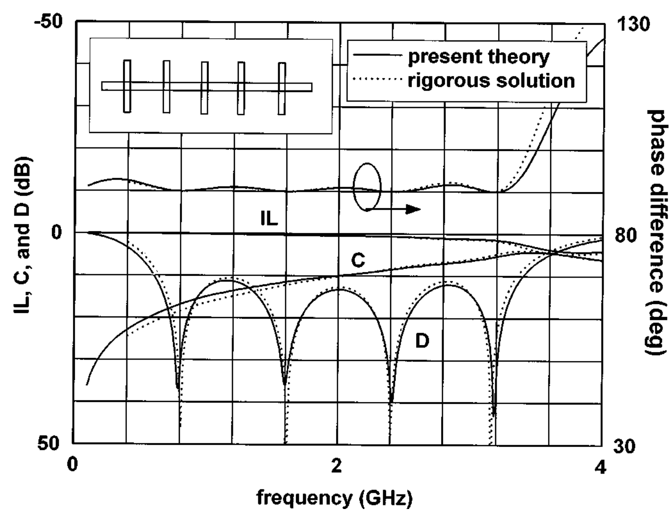

Fig. 11. Characteristics of a 10-dB five-slot uniform directional coupler ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm, $L_s = 5.55$ mm, $\theta_s = 0°$ mm, $d = 0$ mm, and spacing 25.02 mm). (a) Insertion loss, coupling factor, and directivity. (b) Phase difference between S_{21} and S_{31}.

V. CONCLUSIONS

This paper has developed a general theory to analyze and synthesize multislot back-to-back microstrip directional couplers. The related network parameters are explicitly calculated fromthe network analysis, and the resulting characteristics of the directional couplers are then obtained with the help of the even- and odd-mode analysis. This analysis includes the effects of various structure parameters, such as the length, inclination angle, and offset distance of a rectangular slot. Exact synthesis equations are derived for uniform directional couplers, and an approximate synthesis method combining the loose coupling theory with an optimization process is proposed for nonuniform directional couplers.

This theory was applied to several different configurations of the directional couplers. For the uniform directional coupler,

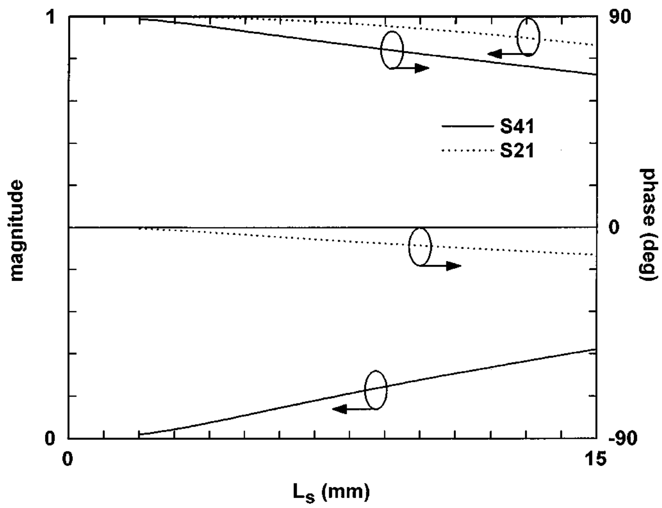

Fig. 12. Scattering parameters of the slot-coupling structure as a function of slot length at 2 GHz ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm, $\theta_s = 0°$ mm, $d = 0$ mm).

TABLE III
DESIGN PARAMETERS OF 10-dB MULTISECTION NONUNIFORM DIRECTIONAL COUPLER WITH 40-dB DIRECTIVITY OVER 80% BANDWIDTH

$index$	a_i	L_{si} (mm)	l_i (mm)
0	0.0163	2.60	.
1	0.0534	4.92	26.60
2	0.0884	6.94	24.77
3	0.0884	6.94	24.00
4	0.0534	4.92	24.77
5	0.0163	2.60	26.60

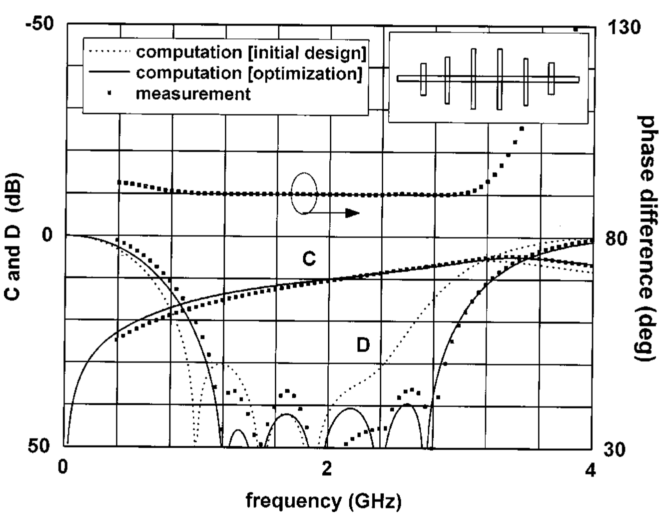

Fig. 13. Characteristics of a 10-dB six-slot nonuniform directional coupler ($W_m = 2.54$ mm, $h = 31$ mil, $\epsilon_r = 2.20$, $W_s = 1.10$ mm, $\theta_s = 0°$ mm, $d = 0$ mm). (a) Coupling factor and directivity. (b) Phase difference between S_{21} and S_{31}.

tight coupling such as 3 dB could be implemented by choosing the slot-to-slot distance and slot length according to the derived exact synthesis equations. It was demonstrated that a 10-dBdirectional coupler could be designed using three different slot arrangements. A longer slot-to-slot distance was required for loose coupling. Using a larger number of uniform slots created the possibility of a broader bandwidth in terms of directivity, but the sidelobe level was not shown to exceed 13 dB at most. Such poor directivity can be improved by using a nonuniform multislot design, and a 10-dB directional coupler with 40-dB directivity over 80% of the bandwidth was constructed by combining the proposed approximate scheme with an optimization process. For all directional couplers considered, quadrature phase difference was observed over the broad-band frequency range.

The measured results and those computed by the proposed theory for the coupling factor, directivity, and phase difference agreed very well for all the configurations, verifying the validity of the theory. Due to its simplicity and efficiency, the proposed analysis and synthesis method can be a powerful tool for designing various types of multislot back-to-back microstrip directional couplers.

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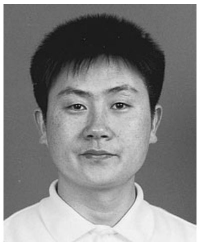

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