A Novel Coplanar-Waveguide Directional Coupler With Finite-Extent Backed Conductor

Chun-Lin Liao and Chun Hsiung Chen, *Fellow, IEEE*

***Abstract*—A novel edge-coupled coplanar-waveguide (CPW) directional coupler with a floating backed conductor is proposed. For design purposes, a theoretical transmission-line model for the coupler is established, which is based on the characteristic parameters of the related coupled CPW structures. To this end, the effective dielectric constants and characteristic impedances of the conductor-backed edge-coupled CPW structures are analyzed using the full-wave analysis based on the spectral-domain approach. Specifically, the coupling coefficient of this new coupler can be controlled by adjusting the width of the backed conductor. In this paper, two conductor-backed edge-coupled CPW directional couplers with moderate (−6 dB) and tight (−3 dB) coupling coefficients are designed and implemented based on the theoretical transmission-line model. The theoretical results are compared with the measured ones, and the agreement among them confirms the usefulness of the coupler design model, as well as the full-wave approach for the related coupled CPW structures.**

***Index Terms*—Coplanar waveguide (CPW), directional coupler.**

I. Introduction

The coplanar waveguide (CPW) receives increased attention due to the merits of easy integration with solid-state devices. Directional couplers are essential in implementing microwave components such as power dividers, phase shifters, balanced amplifiers, and balanced mixers. To develop the CPW-based directional couplers, various related coupled CPW structures were proposed and examined [1]–[4].

In 1970, an edge-coupled CPW directional coupler was proposed by Wen [1], which could achieve a −10-dB coupling by placing the two signal strips close to each other. However, it is difficult to enhance its coupling effect to a level such as −3 dB due to the limit in fabrication process. To increase the coupling effect, the broadside-coupled CPW directional couplers were proposed [4], but, in these coupler structures, the coupled signal strips should be placed in the different sides of the substrate. Alternatively, the multilayer and multimetal-level structures have been proposed to develop the compact directional couplers [5], [6]; however, their implementation requires a more complex fabrication process.

Recently, a conductor-backed edge-coupled CPW structure was proposed [7]. In this structure, a finite-extent backed conductor on the other side of the substrate is added to the conventional edge-coupled CPW structure [1]. This extra backed conductor can provide additional coupling mechanism so that the coupling effect may further be enhanced [7]. In this paper, this coupled structure is employed to fabricate the new conductor-backed edge-coupled CPW directional coupler.

Precise characteristic parameters of related coupled CPW structures are required in designing the CPW directional coupler. The conformal-mapping techniques were developed to handle the coupled CPW lines with upper shielding and infinite conductor backing [8], [9], as well as with finite substrate thickness [10]. The conductor loss of the coupled CPW structure with finite metallization thickness and finite conductivity was examined in [11]. However, these quasi-static techniques are not enough in handling the conductor-backed edge-coupled CPW structure, as proposed in [7]. Recently, a quasi-static analysis (QA) method based on the conformal-mapping technique [12] was developed to characterize the conductor-backed edge-coupled CPW structure [7], but the quasi-static formulas are only available for the odd CPW mode and not for the even CPW mode.

The full-wave methods for characterizing the effective dielectric constant, dispersion effect, and transient behavior of the conventional edge-coupled CPW structure were reported in [13]–[15]. However, in these analyses, the electric field component along the propagation direction was neglected and the modal characteristic impedances were not discussed.

In this paper, a novel conductor-backed edge-coupled CPW directional coupler, which has a finite-extent backed conductor on the another side of the substrate, is proposed. To implement this coupler, the characteristic parameters of the related coupled CPW structures are needed to establish a theoretical transmission-line model for coupler design purposes. To this end, the full-wave analysis (FA) based on the spectral-domain approach with a new set of basis functions is used to analyze the recently proposed edge-coupled CPW structure with a finite-extent backed conductor [7]. This FA is partly confirmed by comparing its results with those of the QA [12].

Based on the transmission-line design model, two conductor-backed edge-coupled CPW directional couplers of moderate (−6 dB) and tight (−3 dB) coupling coefficients are implemented and carefully examined. The measured results are then compared with the results of the theoretical design model and those of a commercial software (Ansoft Ensemble). Agreement among the coupler's theoretical and measured results again supports the usefulness of the coupler design model, as well as the full-wave approach for the related coupled CPW structures.

II. Coupled CPW Structures

A transmission-line design model will be established for the proposed edge-coupled CPW directional coupler with finite-ex-

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The authors are with the Department of Electrical Engineering, Graduate Institute of Communication Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: chunlin@mail2000.com.tw; chchen@ew.ee.ntu.edu.tw).

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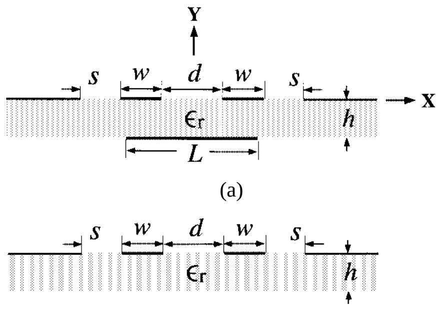

Fig. 1. Cross section of: (a) conductor-backed edge-coupled CPW structure and (b) conventional edge-coupled CPW structure.

tent backed conductor. For this purpose, the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] recently proposed in [7] will be carefully characterized. This coupled structure has identical strip width w and slot width s, and the dielectric constant and thickness of the substrate are ϵ_r and h, respectively. The two signal strips are separated by a distance d, which is the width of the central slot. For comparison, the conventional edge-coupled CPW structure [see Fig. 1(b)] [1] is also included and examined. All ground planes are connected together by bond wires or air bridges so as to suppress the unwanted coupled-slotline mode. For the structure of Fig. 1(a), the coupling mechanism may be controlled by the width L of the backed conductor. To simplify the analysis, each of these coupled CPW structures is enclosed by a conducting box, which is so large that it will not affect the coupling mechanism of the structure.

Three fundamental modes are supported by the multiconductor structure shown in Fig. 1(a). Here, all the ground planes have been connected together by the bond wires so that the structure has three conductors beside the ground planes. Among the fundamental modes, two of them are the odd CPW mode and even CPW mode, whose characteristics may be analyzed by introducing the electric and magnetic walls on the plane $x = 0$. The third one is called the microstrip-line (MS) mode. The coupling mechanism of this coupled CPW structure is mainly discussed by the characteristic parameters of these two CPW modes, therefore, the MS mode should properly be suppressed.

A. FA

To analyze the coupled CPW structure shown in Fig. 1(a), an FA method based on the spectral-domain approach will be used to characterize the effective dielectric constants and characteristic impedances of the odd CPW, even CPW, and MS modes. The unknowns in the governing integral equations are the electric fields over the slot regions on the upper conductors and the electric currents on the lower backed conductor. In this study, the unknown electric fields and currents for the even CPW and MS modes used in the spectral-domain computation are expressed as

$$E_x = \sum_{n=1}^{N} a_n e_{xcn}(x) + \sum_{n=1}^{N} b_n e_{xsn}(x) \tag{1}$$

$$E_z = \sum_{n=1}^{N} c_n e_{zcn}(x) + \sum_{n=1}^{N} d_n e_{zsn}(x) \tag{2}$$

$$J_x = \sum_{n=1}^{N} g_n \frac{\sin\left[2n\pi \frac{x}{L}\right]}{\sqrt{1-\left[\frac{2x}{L}\right]^2}} \tag{3}$$

$$J_z = \sum_{n=1}^{N} h_n \frac{\cos\left[2(n-1)\pi \frac{x}{L}\right]}{\sqrt{1-\left[\frac{2x}{L}\right]^2}}. \tag{4}$$

Here, the basis functions are chosen as

$$e_{xcn}(x) = \frac{\sin\left[(2n-1)\pi\frac{x}{d}\right]}{\sqrt{1-[\frac{2x}{d}]^2}}, \qquad n=1,2,3,\ldots$$

$$e_{zcn}(x) = \frac{\cos\left[(2n-1)\pi\frac{x}{d}\right]}{\sqrt{1-\left[\frac{2x}{d}\right]^2}}, \qquad n=1,2,3,\ldots$$

$$e_{xsn}(x) = \begin{cases} \phi_{n-1}(x-x_1)-\phi_{n-1}(x-x_2), \\ \qquad n=1,3,5,\ldots \\ \psi_{n-1}(x-x_1)+\psi_{n-1}(x-x_2), \\ \qquad n=2,4,6,\ldots \end{cases}$$

$$e_{zsn}(x) = \begin{cases} \phi_{n}(x-x_1)-\phi_{n}(x-x_2), \\ \qquad n=1,3,5,\ldots \\ \psi_{n}(x-x_1)+\psi_{n}(x-x_2), \\ \qquad n=2,4,6,\ldots \end{cases}$$

where

$$\phi_n(x) = \frac{\cos\left[\frac{n\pi x}{s}\right]}{\sqrt{1-\left[\frac{2x}{s}\right]^2}}$$

$$\psi_n(x) = \frac{\sin\left[\frac{n\pi x}{s}\right]}{\sqrt{1-\left[\frac{2x}{s}\right]^2}}$$

$$x_1 = \frac{(d+2w+s)}{2} = -x_2.$$

By substituting (1)–(4) into the governing integral equations, one may compute the effective dielectric constants ϵ_{eff} for the even CPW and MS modes. The odd CPW mode may similarly be treated with some modification.

The corresponding characteristic impedances are computed by

$$Z_o = \frac{V}{I} \tag{5}$$

where V is the voltage between the signal line and ground plane, while I is the current along the signal line. The coupling coefficient C for the coupled CPW structure is defined by [16]

$$C = 20\log\frac{Z_o^{\text{even}} - Z_o^{\text{odd}}}{Z_o^{\text{even}} + Z_o^{\text{odd}}} \tag{6}$$

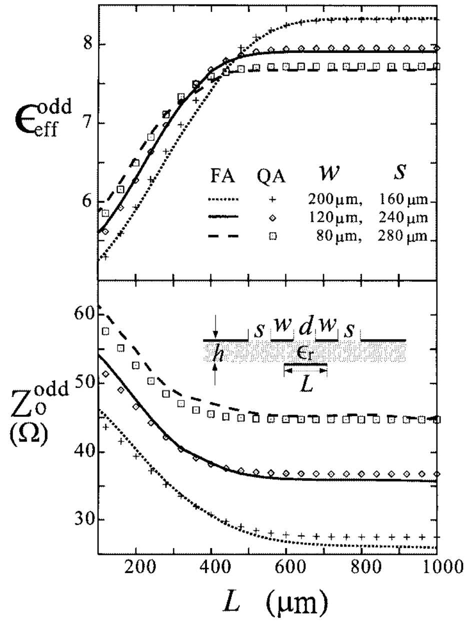

Fig. 2. Comparison of full-wave results (FA) and quasi-static results (QA) for the odd CPW mode of the structure [see Fig. 1(a)] with different w/s ratios ($\epsilon_r = 12.9, h = 100\,\mu$m, $d = 240\,\mu$m, $f = 1$ GHz).

where Z_o^{even} and Z_o^{odd} are the characteristic impedances of the even CPW and odd CPW modes, respectively.

B. *Results for Coupled CPW Structures*

As a first check, the characteristic impedances of the odd CPW and even CPW modes of the conventional edge-coupled CPW structure [see Fig. 1(b)] are calculated by the FA, which yields $Z_o^{odd} = 36.4\,\Omega$ and $Z_o^{even} = 68.4\,\Omega$. They are compared with the measured ones ($Z_o^{odd} = 35.8\,\Omega$ and $Z_o^{even} = 68.5\,\Omega$) in [1]. Good agreement among these results confirms the usefulness of the FA.

As a second test, both the FA and the QA based on the conformal-mapping technique [12] are used to characterize the conductor-backed edge-coupled CPW structure [see Fig. 1(a)]. Fig. 2 shows the corresponding effective dielectric constants ϵ_{eff}^{odd} and characteristic impedances Z_o^{odd} for the odd CPW mode calculated by the FA and QA methods. Good agreement among the theoretical results from both methods for various structure parameters (L, w, s) partly supports the accuracy of our FA method.

For the conventional edge-coupled CPW structure [see Fig. 1(b)], the coupling effect is mainly controlled by the distance d between the two signal strips. Fig. 3 shows the effective dielectric constants ϵ_{eff} and characteristic impedances Z_0 of odd and even CPW modes together with the associated coupling coefficients C. As the strip distance d decreases, the impedance of the odd CPW mode decreases so that the coupling coefficient increases, but its value is less than -5 dB, except that $d < 50\,\mu$m.

To increase the coupling effect of the conventional edge-coupled CPW structure [see Fig. 1(b)] with reasonable strip distance d, a finite-extent backed conductor is added to form the new conductor-backed edge-coupled CPW structure, as shown in Fig. 1(a). Fig. 4 shows the effect of backed-conductor width L

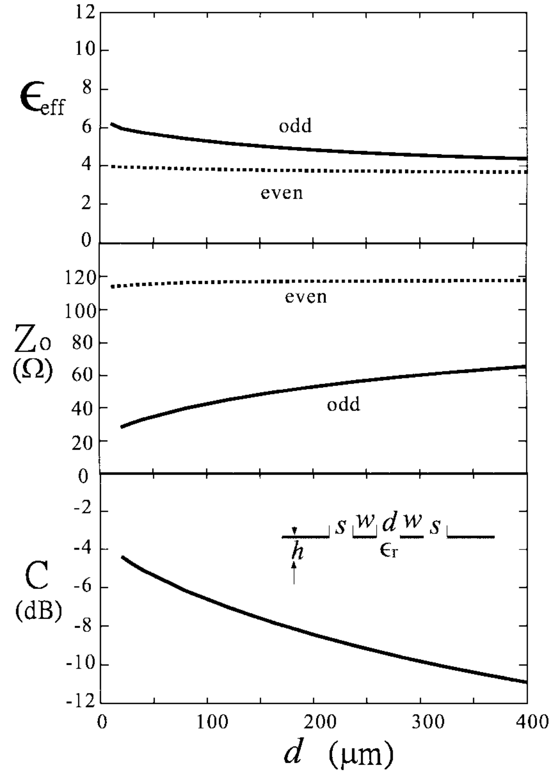

Fig. 3. Effect of strip distance d on effective dielectric constants, characteristic impedances, and coupling coefficients of the conventional edge-coupled CPW structure [see Fig. 1(b)] ($\epsilon_r = 12.9, h = 100\,\mu$m, $w = 200\,\mu$m, $s = 160\,\mu$m, $f = 3$ GHz).

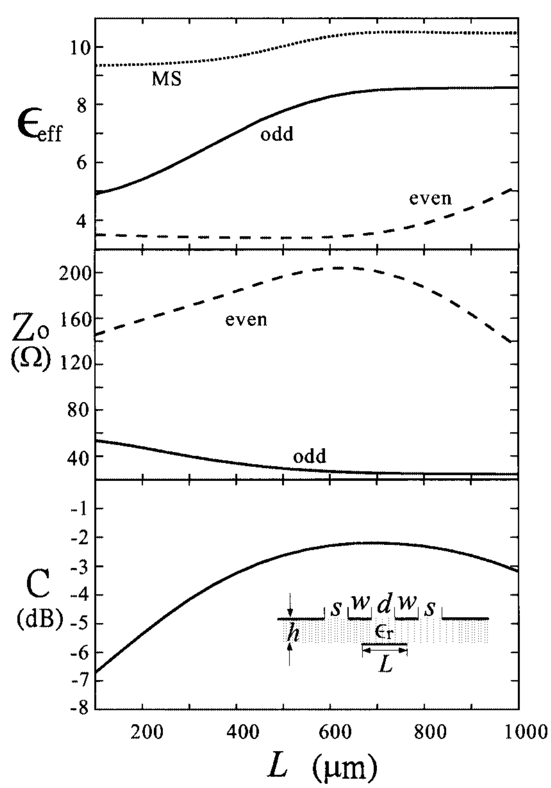

Fig. 4. Effect of backed-conductor width L on effective dielectric constants, characteristic impedances, and coupling coefficients of the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] ($\epsilon_r = 12.9, h = 100\,\mu$m, $w = 200\,\mu$m, $s = 160\,\mu$m, $d = 240\,\mu$m, $f = 3$ GHz).

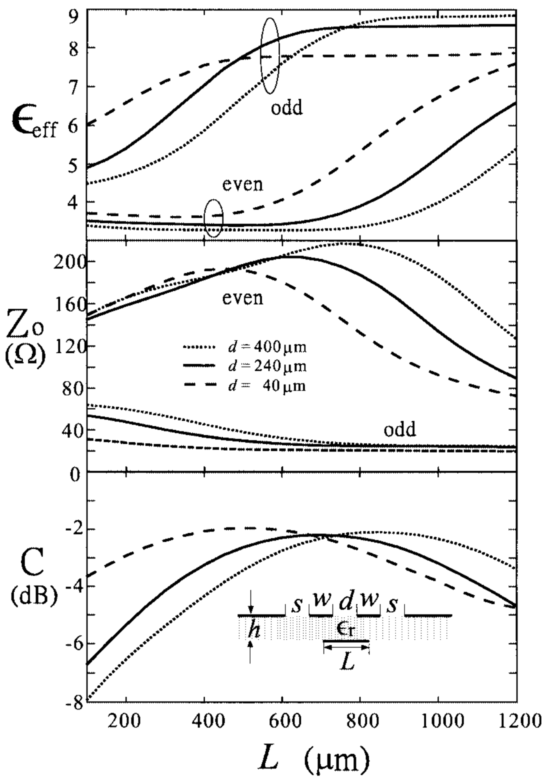

Fig. 5. Effect of strip distance d on effective dielectric constants, characteristic impedances, and coupling coefficients of the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] ($\epsilon_r = 12.9$, $h = 100\,\mu$m, $w = 200\,\mu$m, $s = 160\,\mu$m, $f = 3$ GHz)

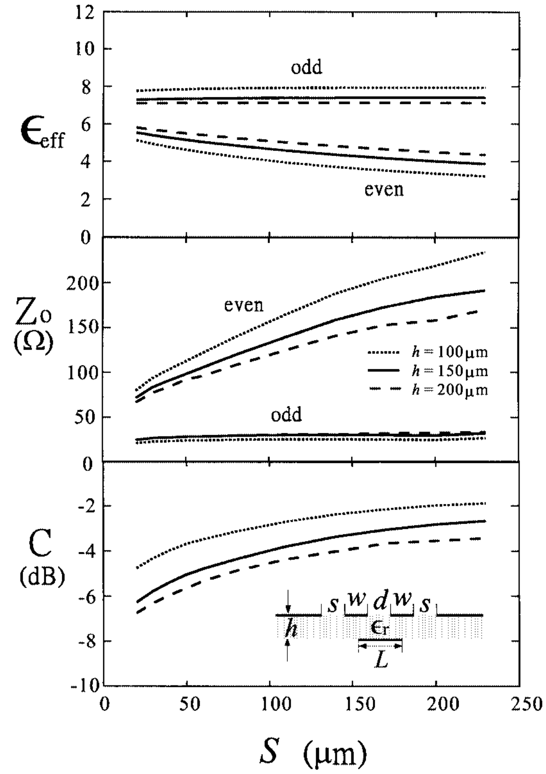

Fig. 6. Effect of slot width s on effective dielectric constants, characteristic impedances, and coupling coefficients of the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] ($\epsilon_r = 12.9$, $w = 200\,\mu$m, $d = 100\,\mu$m, $L = 500\,\mu$m, $f = 3$ GHz).

on this new coupled structure. It can be seen that, as the width L is increased ($L < 640\,\mu$m), the characteristic impedance Z_o^{odd} is decreased while Z_o^{even} is increased. The larger ratio between Z_o^{even} and Z_o^{odd} makes the coupling coefficient C larger than -3 dB. For $L > 640\mu$m (so that the backed conductor is wide enough to cover the upper two strips), the impedance Z_o^{even} decreases rapidly, which makes the coupling coefficient C decrease accordingly. Obviously, the coupled structure [see Fig. 1(a)] could produce stronger coupling between two signal strips, as reflected by Fig. 4. Also presented in Fig. 4 is the ϵ_{eff} curve for the third fundamental mode, which is called the MS mode, for which the backed conductor now serves as a signal line, and all upper conductors might be regarded as the ground planes.

Fig. 5 shows how the distance d between two signal strips affects the parameters ϵ_{eff}, Z_o, and C. As the distance d varies from 40 to 400 μm, the locations of maximum C vary accordingly, but the values of maximum C have no obvious different.

Fig. 6 shows the effect of slot width s on the characteristics of the conductor-backed edge-coupled CPW structure [see Fig. 1(a)]. As s becomes larger, the distance d between two strips becomes relatively smaller, and the characteristic impedance of the even mode is found to be larger. However, the odd mode's impedance only changes slightly as s is increased, making the associated coupling coefficient C increase accordingly. This property is very useful in the design of the directional coupler.

Fig. 7 shows the frequency dependence of effective dielectric constants, characteristic impedances, and coupling coeffi-

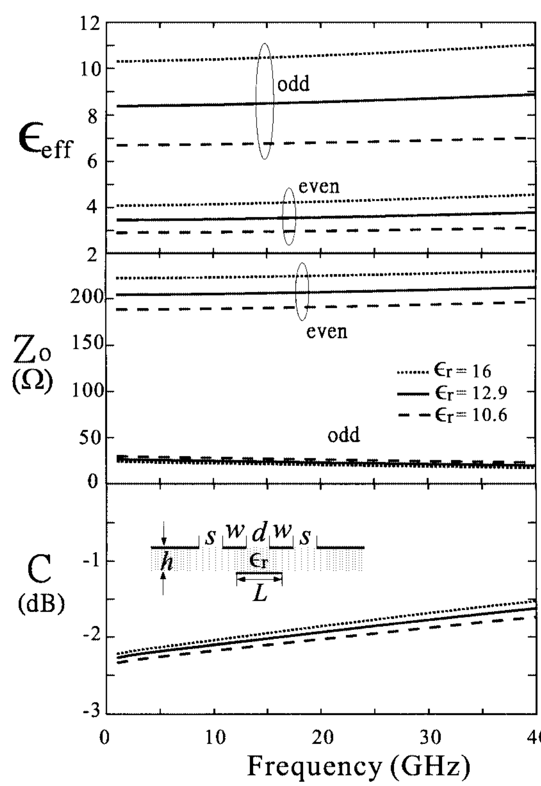

Fig. 7. Frequency dependence of effective dielectric constants, characteristic impedances, and coupling coefficients of the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] ($h = 100\,\mu$m, $w = 200\,\mu$m, $s = 160\,\mu$m, $d = 240\,\mu$m, $L = 640\,\mu$m).

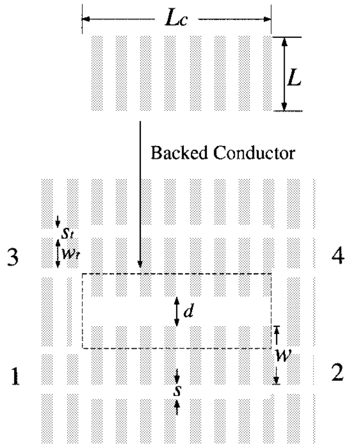

Fig. 8. Configuration of edge-coupled CPW directional coupler with finite-extent backed conductor ($\epsilon_r = 4.6$, $h = 1.6$ mm, $w = 10$ mm, $s = 1.6$ mm, $w_t = 4$ mm, $s_t = 0.4$ mm, $d = 2$ mm, $L_c = 48$ mm, center frequency $= 1$ GHz).

cients for the conductor-backed edge-coupled CPW structure [see Fig.1 (a)]. The dispersion effect is not serious as the backed conductor is added.

III. CPW Directional Couplers

By employing the coupled CPW structure of Fig. 1(a), a novel edge-coupled CPW directional coupler with a finite-extent backed conductor is proposed. This coupler has an edge-coupled CPW section of length L_c, which is backed by a floating conductor of length L_c and width L, as shown in Fig. 8. The edge-coupled section is then connected to the four CPW ports so as to suppress the unwanted MS mode.

A. Coupler Design Model

For coupler design purposes, a theoretical transmission-line model is established. In this model, the characteristic impedances of the odd and even CPW modes of the related conductor-backed edge-coupled CPW section [see Fig.1 (a)], as decided by (6), are chosen as

$$Z_o^t = \sqrt{Z_o^{\text{odd}} \cdot Z_o^{\text{even}}} \tag{7}$$

where Z_o^t is the characteristic impedance of the terminating CPW lines. By referring to Figs. 4–6, one may get the desired Z_o^{odd} by varying the parameters of d, w, and L. Finally, one may get the desired Z_o^{even} by adjusting the parameter s. The coupling length for the coupled CPW section is chosen as

$$L_c = \frac{\lambda_{\text{odd}} + \lambda_{\text{even}}}{8}. \tag{8}$$

The design model makes use of the conventional parallel-coupled transmission-line theory [17], which is based on our full-wave results (Z_o^{odd}, Z_o^{even}, $\epsilon_{\text{eff}}^{\text{odd}}$, and $\epsilon_{\text{eff}}^{\text{even}}$) for the related conductor-backed edge-coupled CPW section shown in Fig. 1(a). This model neglects the effects of the discontinuities and the power losses. By the use of workstation Sun Ultra 2 (UltraSPARC 200 MHz), it requires approximately 15 min to get a frequency point in Figs. 9–11.

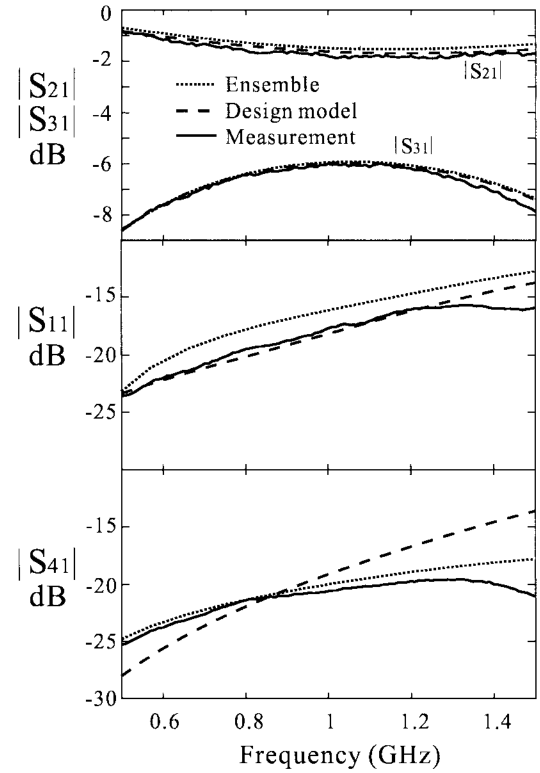

Fig. 9. Theoretical and measured results for −6-dB directional coupler ($L = 6$ mm).

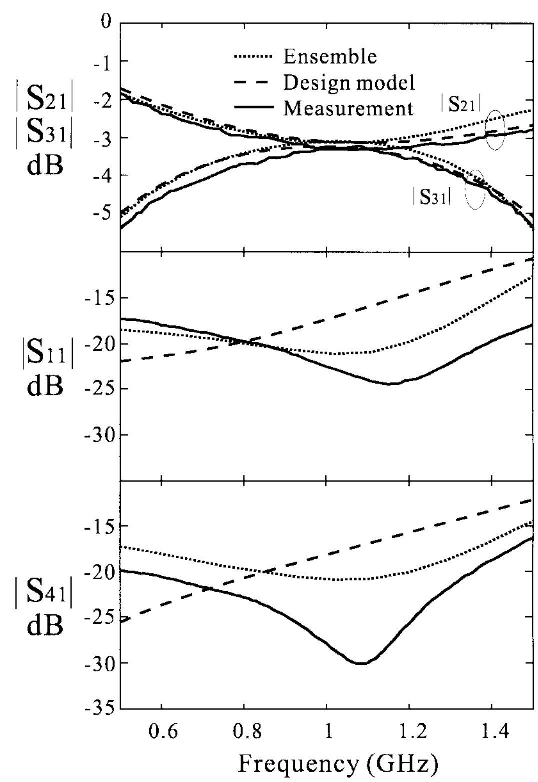

Fig. 10. Theoretical and measured results for −3-dB directional coupler ($L = 20$ mm).

To have a better prediction of the performance theoretically, the coupler is also simulated by the commercial software Ansoft

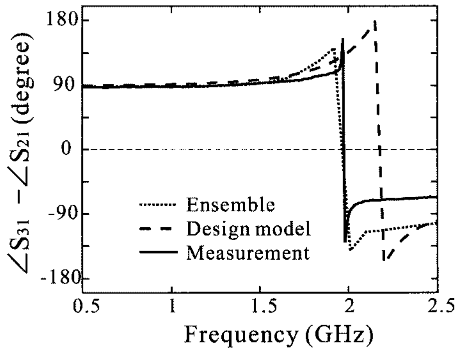

Fig. 11. Theoretical and measured results for phase differences between S_{31} and S_{21} of −3-dB directional coupler ($L = 20$ mm).

Ensemble. The results shown in Figs. 9–11 are calculated by a Pentium III 1-GHz personal computer (PC), and the running time is approximately 45 s for each frequency point.

B. Results for Directional Couplers

Two conductor-backed edge-coupled CPW directional couplers of moderate coupling (−6 dB) and strong coupling (−3 dB) are designed based on the transmission-line design model in Section III-A. These couplers, implemented on the FR4 substrate ($\epsilon_r = 4.6$, $h = 1.6$ mm), are designed with the center frequency at 1 GHz. The characteristic impedance Z_o^t of the terminating CPW lines is 50 Ω. The coupler configuration is shown in Fig. 8. From the coupling theory, the scattering parameter $|S_{31}|$ for the coupler in Fig. 8 is equal to the coupling coefficient C for the coupled CPW structure in Fig. 1(a).

In this study, two conductor-backed edge-coupled CPW directional couplers that have the same circuit configuration (Fig. 8) and parameters, but with different backed-conductor widths (L) are examined. Without the backed conductor, the coupling coefficient of this structure is approximately −8.6 dB. With the help of a narrow ($L = 6$ mm) or a wide ($L = 20$ mm) backed conductor, the coupling coefficient may be enhanced to the level of −6 or −3 dB, respectively. In order to avoid the unwanted MS mode, the coupler is fed by the CPW lines, as shown in Fig. 8, which then excite the desired odd and even CPW modes in the coupled region. Some bond wires should properly be added to suppress the unwanted coupled-slotline mode.

The coupler with four-ports is measured by the HP8510B network analyzer. In the measurement, the two ports under investigation are connected to the network analyzer and the other two ports are terminated by the 50-Ω kits. The moderate coupling (−6 dB) coupler has a narrower backed conductor ($L = 6$ mm), and its results are shown in Fig. 9. The corresponding measured return loss $|S_{11}|$ and isolation $|S_{41}|$ are all less than −15 dB.

Using the wider backed conductor ($L = 20$ mm), one can get a tight coupling (−3 dB) directional coupler, and its results are shown in Fig. 10. The differences between $|S_{21}|$ and $|S_{31}|$ are less than 1 dB from 0.75 to 1.31 GHz. Both results in Fig. 9 and Fig. 10 show that our theoretical transmission-line model agrees with the measured data quite well around the center frequency. The correctness of the full-wave results (discussed in Section II-B) for the related conductor-backed edge-coupled CPW structure [see Fig. 1(a)] are again confirmed by these measurements.

The phase differences (in degree) between S_{31} and S_{21} of the −3-dB directional coupler are shown in Fig. 11. The measured data show that the differences are within $90^\circ \pm 3^\circ$ up to 1.5 GHz. This figure also shows that the measured data and ensemble results have a narrower bandwidth than that of the theoretical design model. Physically, the transmission-line model ignores all the discontinuity effects, thus, it becomes less accurate in the higher frequency range.

The results in Figs. 9–11 also show that the unwanted MS mode can effectively be suppressed by using a proper CPW feeding structure so that the coupling mechanism may mainly be governed by the even and odd CPW modes.

IV. Conclusion

Novel conductor-backed edge-coupled CPW directional couplers have been implemented and carefully examined theoretically and experimentally. To design the coupler, a transmission-line design model based on the characteristic parameters of the related coupled CPW structures has been established. To this end, the conductor-backed edge-coupled CPW structure [see Fig. 1(a)] has been carefully characterized using the FA based on the spectral-domain approach. By this full-wave approach with more accurate basis functions, the coupling coefficient of the coupled CPW structure [see Fig. 1(a)] may be designed to be better than −3 dB. The dispersion effect is not serious as the backed conductor is added.

In this study, two conductor-backed edge-coupled CPW directional couplers (−6 and −3 dB) have been implemented based on the design model. These couplers have been carefully examined using the transmission-line design model, commercial software (Ansoft Ensemble), and measurement. The theoretical results agree well with the measured ones, thus, the simpler design model may well predict the coupler performance. The agreement among the coupler's theoretical and measured results again confirms the usefulness of the full-wave approach for the related coupled CPW structures. By using the proper CPW feeding structure to the coupler, the experimental results have shown that the unwanted MS mode may effectively be suppressed so that it would not affect the coupling mechanism associated with the coupler.

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Chun-Lin Liao was born in Yunlin, Taiwan, R.O.C., on June 19, 1970. He received the B.S.E.E. and M.S.E.E. degree from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1992 and 1995, respectively, and is currently working toward the Ph.D. degree in electrical engineering at the National Taiwan University.

His current research interests include the coupling effect of planar transmission lines and microwave circuits.

Chun Hsiung Chen (SM'88–F'96) was born in Taipei, Taiwan, R.O.C., on March 7, 1937. He received the B.S.E.E. and Ph.D. degrees in electrical engineering from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1960 and 1972, respectively, and the M.S.E.E. degree from the National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1962.

In 1963, he joined the Faculty of the Department of Electrical Engineering, National Taiwan University, where he is currently a Professor. From August 1982 to July 1985, he was Chairman of the Department of Electrical Engineering at the same university. From August 1992 to July 1996, he was the Director of the University Computer Center. In 1974, he was a Visiting Scholar with the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley. From August 1986 to July 1987, he was a Visiting Professor with the Department of Electrical Engineering, University of Houston, Texas. In 1989, 1990, and 1994, he visited the Microwave Department, Technical University of Munich, Munich, Germany, the Laboratoire d'Optique Electromagnetique, Faculte des Sciences et Techniques de Saint-Jerome, Universite d'Aix-Marseille III, Marseille, France, and the Department of Electrical Engineering, Michigan State University, East Lansing, respectively. His areas of interest include microwave circuit analysis and computational electromagnetics.