# Novel Directional Couplers Using Broadside-Coupled Coplanar Waveguides for Double-Sided Printed Antennas

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*Abstract*—**Two types of tight-coupling, broadband directional couplers employing open broadside-coupled coplanar waveguides (BC CPW's) are proposed which can easily be integrated with printed strip antennas. The first type uses the BC CPW's with dielectric overlays above and below the center substrate, while the second type uses the nonuniform BC CPW's. The scattering parameters of these directional couplers are derived with the even-odd mode analysis method based on the quasi-TEM wave approximation. Two 3-dB directional couplers, one for each type, are designed and measured characteristics are compared with theoretical results.**

## I. Introduction

Tight-coupling directional couplers are often required in the design of various beam forming printed array antennas. In practice, the most convenient form of these couplers should be one which can easily be integrated in the antenna structure. The microstrip branch line couplers or hybrid ring couplers have been extensively employed in printed array antennas. However, these couplers have inherently small bandwidths. An increased bandwidth can be achieved by connecting several branch line couplers in tandem, but this structure requires much space and manufacturing effort.

A broadband 3-dB directional coupler has been investigated for a dual-beam array antenna of double-sided printed strip dipoles [1]. This antenna is designed to operate at two frequency bands, and therefore, it requires very broadband directional couplers. Well-known edge-coupled microstrip lines may be useful for this purpose, but the drawback of this structure is its weak coupling. With a broadside-coupled structure, strong coupling coefficients can easily be produced and inherently wide bandwidth is achieved. Moreover, a broadside-coupled structure may be very suitable to be integrated in the antenna structure proposed in [1] which uses the strip dipoles with its arms printed on both sides of a dielectric substrate. Therefore, the characteristics of a 3-dB broadband directional coupler utilizing broadside-coupled coplanar waveguides (BC CPW's) have been investigated both experimentally [1] and theoretically [2] by the authors, where it was called the double-sided microstrip directional coupler.

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In this paper, we describe the result of investigation on BC CPW's and propose two types of directional couplers using BC CPW structures in inhomogeneous media. One type of the directional couplers uses BC CPW's with dielectric covers. The other type uses nonuniform BC CPW's. The scattering parameters of these directional couplers are derived from the even- and odd-mode parameters of the coupling section. The analysis is based on the use of the rectangular boundary division method [3] for solving the boundary value problem, including strip conductors in an inhomogeneous medium. Two experimental directional couplers with the design center frequency 1.2 GHz and 3 dB coupling strength near the frequencies 0.9 GHz and 1.5 GHz are fabricated and measured scattering parameters are compared with numerical results.

## II. Broadside-Coupled Coplanar Waveguide Structures for Directional Coupler Applications

Various coupled-line structures have been extensively employed in the past as building blocks for directional couplers and filters. A broadside-coupled structure in an inhomogeneous medium has been first proposed by Dalley [4] and its performances have been investigated by Allen *et al.* [5]. Although a broadside-coupled structure can have both tight- and loose-coupling, these structures in inhomogeneous media have a large difference between the even-mode and the odd-mode phase velocities which is undesirable for directional coupler applications. Such large mode velocity ratios of broadside-coupled striplines have been used in filter applications [6]. Extensive design data for broadside-coupled striplines in a homogeneous medium and various inhomogeneous media can be found in a book [7], but one can easily find that these structures in inhomogeneous media have intolerably large mode velocity ratios for backward wave coupler applications.

A broadside-coupled structure utilizing coplanar waveguides (CPW's) has been first introduced by Hatsuda [8]. The CPW transmission lines offer several advantages for use in microwave integrated circuits, and therefore, various broadside-coupled structures employing CPW's have been also proposed [9], [10]. Like broadside-coupled striplines, BC CPW's also offer high coupling coefficients which are always associated with large mode velocity ratios when used with inhomogeneous media. In [10], large mode velocity ratios of BC CPW's have been utilized in band-pass filter applications. On the other hand, the mode velocity ratio of BC CPW's can be lowered by means of filling the space above and/or

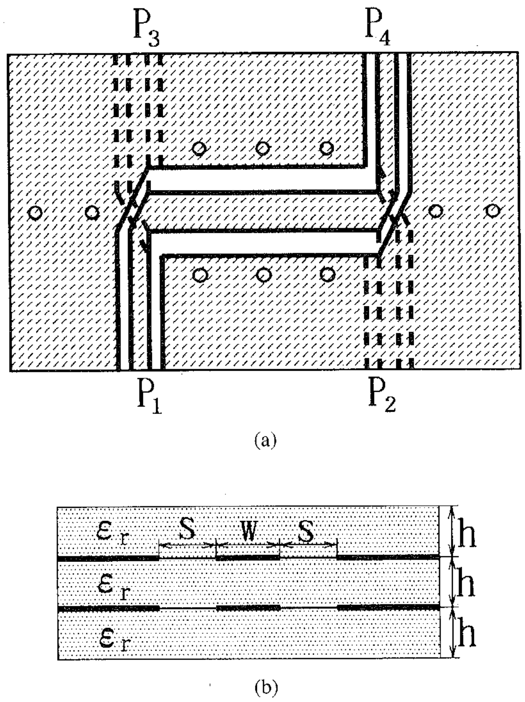



Fig. 1. Directional coupler of broadside-coupled dielectric covered coplanar wave guides: (a) schematic plan and (b) cross-sectional view.

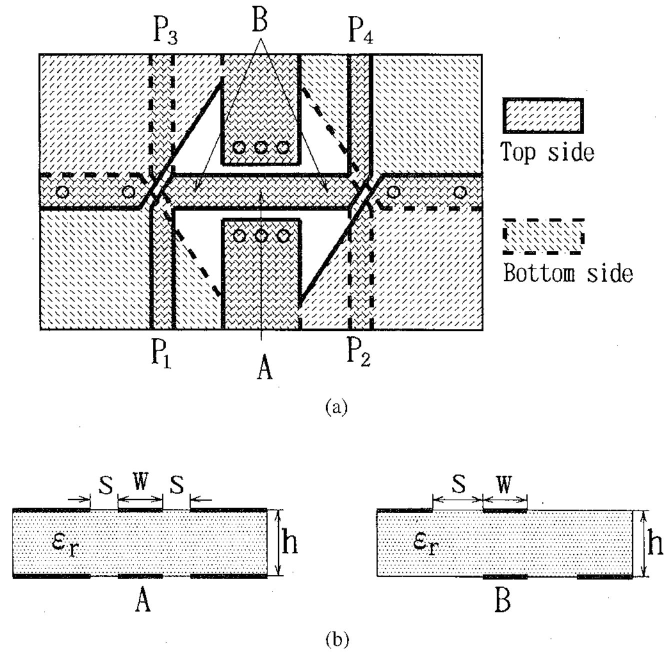



Fig. 2. Directional coupler of broadside-coupled nonuniform coplanar waveguides: (a) schematic plan and (b) cross-sectional views of the two regions.

below the CPW's with dielectric materials [9]. In an other application, the BC CPW's have been used for the transmission of electromagnetic power between two transmission lines deployed on different surfaces [11].

The configuration of a broadside-coupled structure is very suitable to be used as a broadband 3-dB directional coupler for an array antenna of double-sided printed strip dipoles [1] where an open structure without the top and bottom walls must be employed. Broadside-coupled lines with coplanar ground conductors may be a solution in this case. An ideal backward wave directional coupler with basic requirements of all matched ports and infinite directivity cannot be realized because of the inhomogeneous structure. Therefore, some means for lowering or compensating the large difference between the even-mode and the odd-mode phase velocities must be used. Dielectric overlays have been proposed to equalize the mode velocities in edge-coupled directional couplers [12].

We propose a directional coupler utilizing broadside-coupled dielectric cowered coplanar waveguides (BC CCPW's). The schematic plan of the BC CCPW directional coupler is shown in Fig. 1(a) and its cross-sectional view in Fig. 1(b). Of course, this is not very convenient structure because the dielectric overlays can be cumbersome in practice and even the reflection and isolation coefficients may not be as good enough as required. Nevertheless, this is a solution to the problem and involves very simple design procedure.

As another possible solution, the directional coupler of nonuniform BC CPW's, has been investigated [1], [2] since it offers large bandwidths. However, an analysis procedure of nonuniform coupled lines was proposed only for a few special cases such as one using exponential lines [13]. The theory and design of TEM-mode multi-section, nonuniform directional couplers using the nonuniform transmission line analogy has been presented [14]. A similar procedure has been used to construct ultra-wide-band nonuniform directional couplers in inhomogeneous media [15], [16], where a wiggly geometry has been employed to equalize the mode phase velocities. Increasing the length of the coupling section, very wide-band directional couplers can be realized under the perfect matching condition. The nonuniform directional coupler we propose, on the other hand, has a quarter wavelength section and the matching condition is satisfied only at the connecting output lines. The schematic plan of the directional coupler with nonuniform BC CPW's is shown Fig. 2(a). The coupling section is partly uniform (region A) and partly nonuniform (region B). The uniform region consists of two broadside-coupled strips placed near four coplanar ground conductors and is equivalent to a section of BC CPW's. The nonuniform region consists of two broadside-coupled strips placed near two nonuniform coplanar ground conductors and is equivalent to a section of broadside-coupled micro coplanar waveguides (BC MCPW's). The cross-sectional views of the BC CPW's and BC MCPW's are shown in Fig. 2(b).

The proposed directional coupler can be viewed as a broadside-coupled line section with nonuniform coplanar ground conductors. Only the gap width is changed through the coupling section. The even-mode parameters of the coupler are strongly influenced by the gap-width change, while the odd-mode parameters remain almost unchanged. As a result, the desired degree of the coupling strength can easily be obtained. However, our investigation of various trial coupler configurations showed that an abrupt change of the gap width such as the step from region A to region B is necessary for the overall good performance. This can be explained as fellows: as is well known, the backward coupling arises from the difference between the even- and odd-mode characteristic impedances of the coupled lines. On the other hand, the forward coupling may take place as well because of the difference between the even- and odd-mode phase velocities. The forward coupling is perhaps weakened by the step discontinuities in the coupling section. The other characteristics of the coupler may also be deteriorated by these discontinuities, however, this coupler worked well as the $L$-band directional couplers we were concerned. As the result, tight-coupling and broadband directional couplers have been realized which are very simple and easy to be fabricated.

The arrangement of the output ports of both structures shown in Figs. 1 and 2 is convenient for two reasons. First, by placing the output ports of the same plane on the opposite directions, the outgoing directed and coupled lines come from the same side of the coupler. Second, the four ground planes can be connected to each other through the short conductor pins. This is important because undesired waveguide modes may be generated if all four ground planes are not kept at the same potential.

## III. Method of Analysis

### A. Theory of the Four-Port Symmetrical Network

Both of the proposed directional couplers as shown in Figs. 1 and 2 employ symmetric coupled transmission lines. A symmetric directional coupler represents a reciprocal, linear four-port network with double symmetry with respect to the two symmetry planes $T_1$ and $T_2$, as shown in Fig. 3(a). The scattering parameters of the reciprocal four-port network can be computed with the even-odd mode analysis which are given as

$$S_{11} = (R_{eL} + R_{eK} + R_{oL} + R_{oK})/4 \quad (1a)$$
$$S_{21} = (R_{eL} - R_{eK} - R_{oL} + R_{oK})/4 \quad (1b)$$
$$S_{31} = (R_{eL} + R_{eK} - R_{oL} - R_{oK})/4 \quad (1c)$$
$$S_{41} = (R_{eL} - R_{eK} + R_{oL} - R_{oK})/4. \quad (1d)$$

The parameters $R_{eL}, R_{eK}, R_{oL}$, and $R_{oK}$ represent the input reflection coefficients, referenced to the characteristic impedance of the connecting output lines, when a certain combinations of the even (odd) mode and the open (short) circuit are applied to the symmetry plane $T_1$ and $T_2$, respectively, Fig. 3(b).

For a uniform symmetric directional coupler (Fig. 1), the expressions for reflection coefficients can easily be derived and common formulas can be used for designing a quarter wavelength coupler. For a directional coupler of the coupling coefficient, $k$, and the characteristic impedance, $Z_0$, the mode characteristic impedances and propagation constants must satisfy the following relations

$$Z_{0e} = Z_0\sqrt{\frac{1+k}{1-k}} \quad (2a)$$
$$Z_{0o} = Z_0\sqrt{\frac{1-k}{1+k}} \quad (2b)$$

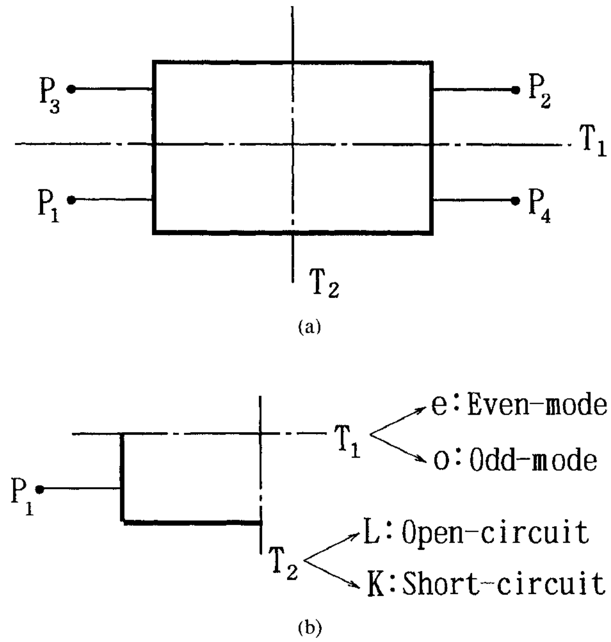


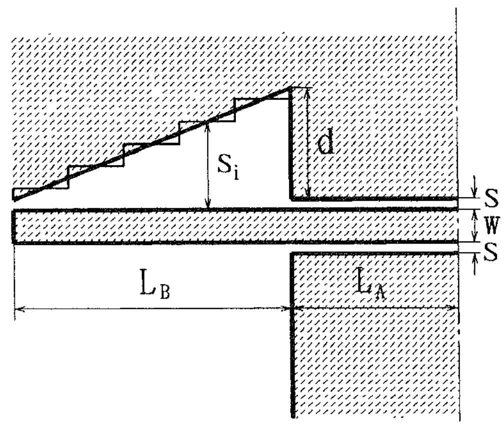

Fig. 3. (a) Four port symmetrical network. (b) Definition of the reflection coefficients.

$$L = \frac{\pi}{\beta_e + \beta_o} \quad (3)$$

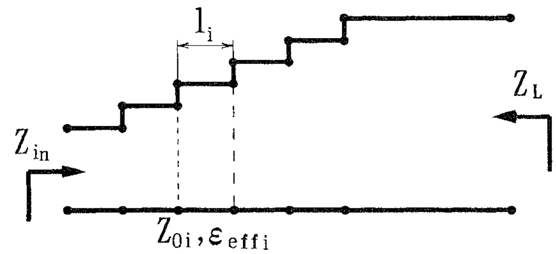
where $Z_{0e}$, $Z_{0o}$, and $\beta_e$, $\beta_o$ are the even-mode and the odd-mode characteristic impedances and propagation constants, respectively, and $L$ is the length of the coupler. Structural dimensions of the coupler are then determined from the knowledge of the mode parameters for a given dielectric substrate.

The nonuniform directional coupler of Fig. 2 can also be analyzed using 1(a)–(d). Considering the symmetry of the coupler, only half of the structure as shown in Fig. 4(a) is to be analyzed. The nonuniform region is divided into a reasonable number of sections and the values of $Z_{0e}$, $Z_{0o}$ and $\epsilon_{\text{eff}e}$, $\epsilon_{\text{eff}o}$ are calculated at the center of each section. The reflection coefficients are then computed from the cascaded transmission line network as shown in Fig. 4(b). The transmission characteristics of each section are manifested using the corresponding mode characteristic impedance and propagation constant.

To design this nonuniform coupler, however, an iterative procedure must be used. A directional coupler with the coupling coefficient, $k$, and the connecting output lines of characteristic impedance, $Z_0$, is designed by the following steps: First, the profile of the coupler at the connecting output lines (beginning of the coupler section) is determined from the given $Z_0$ and an initial coupling coefficient smaller than $k$. Using (2), the mode characteristic impedances of the coupler at the connecting output lines are calculated. Knowing these mode impedances, the line width, $w$, and the gap width at the connecting output lines, $s$, are determined for a given dielectric substrate. The same gap width is also selected for the uniform section although it may be different. The mode parameters of a uniform region are calculated at this stage. The total length of the coupler, $L = 2(L_A + L_B)$, is determined based on




(a)




(b)

Fig. 4. (a) Approximation of the nonuniform region with the cascaded uniform regions. (b) Equivalent transmission line network.

the odd-mode propagation constant. This was found to be a good estimation since the odd-mode propagation constant is almost unchanged through all coupling sections. Then, the mode parameters of the BC MCPW's with line width, $w$, and a range of gap widths are calculated and tabulated. For the convenience, from these data sets, approximate polynomial formulas are derived using the least square method. These approximate formulas will be very useful in the next step when the mode parameters of divided sections of the nonuniform region with specified values of $L_B$ and $d$ are to be calculated. The mode parameters and lengths of the uniform region and each divided section of the nonuniform region are required as the input data to compute the input reflection coefficients of the network as shown in Fig. 4(b) and consequently the scattering parameters 1(a)–(d) of the coupler. The number of divided sections is selected by observing the convergence of the scattering parameters. Calculation experience indicates that about ten to fifteen divided sections are enough to ensure the convergence of numerical results.

In the second step, an iterative procedure is employed. Starting with the values of $L_B = L_A$ and $d \geq s$, the coupling strength at the center frequency is repeatedly calculated by increasing the distance $d$ until the required coupling coefficient $k$ is reached. Frequency characteristics of the coupler are then examined, and if the input return loss and the isolation are not satisfactory, the length $L_B$ is changed and the procedure repeated. If this iterative procedure fails to give satisfactory results, then we go back to the first step and change the gap width of the uniform region, calculate the new mode parameters of this region and return to the second step.

### *B. Quasi-TEM Wave Characterization of BC CPW's, BC MCPW's, and BC CCPW's*

A simple quasi-static approximation method can be used for the even–odd mode analysis because it has been shown that BC CPW structures have very low dispersions [17]. The even- and odd-mode characteristic impedances and effective permittivities of three kinds of BC CPW structures are computed under the quasi-TEM wave approximation, where the problem is attributed to the calculation of the mode capacitances. The configuration we are dealing are BC CPW's, BC MCPW's, and BC CCPW's.

The mode capacitances for a given structure are computed by utilizing the rectangular boundary division method, which has been discussed in detail in [3]. The mode characteristic impedances and effective permittivities are given as

$$Z_{om} = (v_0 C_{0m} C_m)^{-1/2} \tag{4}$$

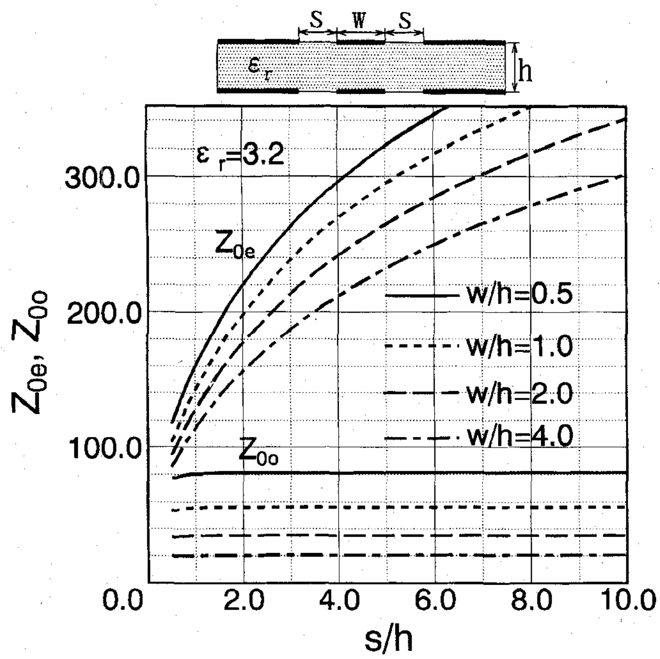
$$\epsilon_{\text{eff}m} = \frac{C_m}{C_{0m}} \tag{5}$$

where $m$ stands for the even-mode or the odd-mode. $C_{0m}$ denotes the even-mode or the odd-mode capacitance in the case where the dielectric substrate in the structure is replaced by vacuum. $v_0$ denotes the phase velocity in vacuum.

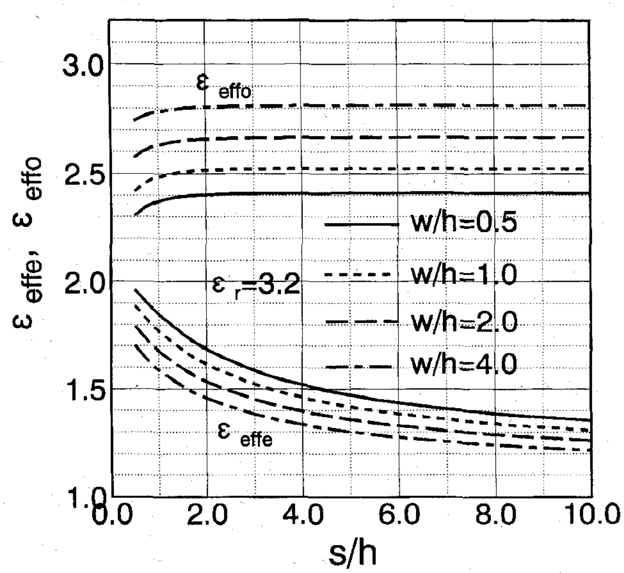
Numerical results of the even- and odd-mode characteristic impedances and effective permittivities of the BC CPW's are plotted in Fig. 5(a) and (b), respectively, versus the normalized gap width, $s/h$, for $\epsilon_r = 3.2$ and $w/h = 0.5, 1.0, 2.0,$ and 4.0. It is seen that as the gap width is increased the even-mode characteristic impedance and effective permittivity are increased and decreased, respectively, whereas those for the odd-mode remain virtually the same. In fact, the odd-mode parameters change slowly as the gap width is increased up to a certain limit. Further increase of the gap width has no effect on the odd-mode parameters, and the odd-mode configuration behaves as an open microstrip. The mode parameters of BC CPW structures with the gap widths smaller than the mentioned limit value can be calculated with very useful closed form expressions reported in [9]. For larger gap widths, however, a numerical procedure such as one used here is necessary for accurate prediction of the even-mode parameters.

Variation of the even- and odd-mode characteristic impedances and effective permittivities of the BC MCPW's as a function of the normalized gap width, $s/h$, are shown in Fig. 6(a) and (b), respectively. As can be seen, the BC MCPW's having almost the same odd-mode characteristic impedances and effective permittivities as those for the BC CPW's, has a higher and a lower even-mode characteristic impedances and effective permittivities, respectively.

The third structure to be analyzed is BC CCPW's. A BC CCPW structure which uses the same dielectric substrate for both cover layers and the center layer is considered here, although an arbitrary structure may be analyzed. Fig. 7(a) and (b) show the even- and odd-mode characteristic impedances and effective permittivities of the BC CCPW's, respectively, as a function of the normalized gap width, $s/h$. By placing the dielectric overlays above and below the center dielectric

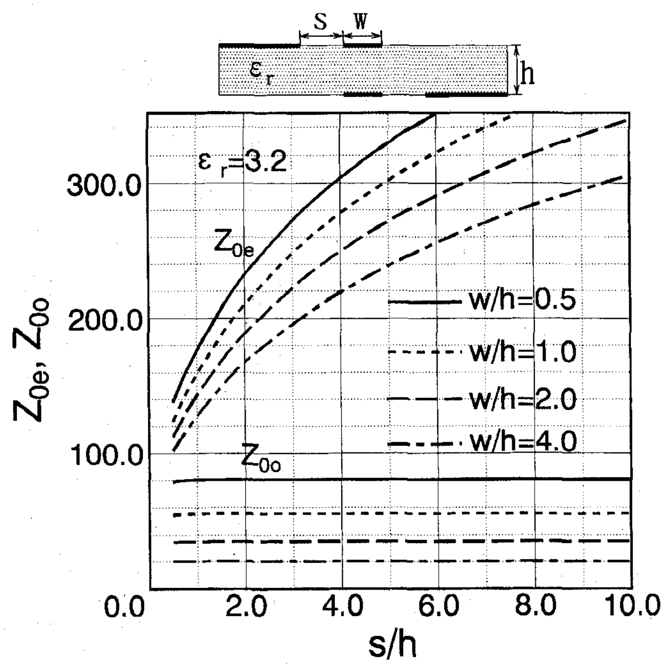



(a)

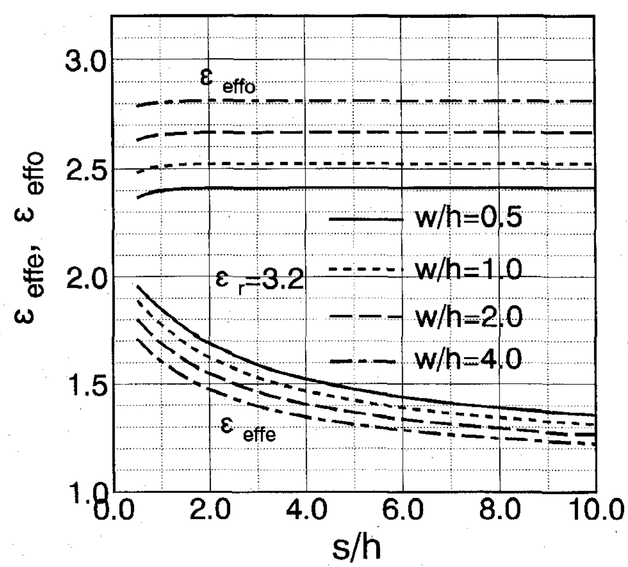



(b)

Fig. 5. Even- and odd-mode characteristic impedances (a) and effective permittivities (b) of a BC CPW's versus $s/h$.




(a)




(b)

Fig. 6. Even- and odd-mode characteristic impedances (a) and effective permittivities (b) of a BC MCPW's versus $s/h$.

substrate, the difference between the mode phase velocities is lowered as expected, but both mode impedances are also lowered.

In order to compare the properties of the analyzed broadside-coupled structures, their coupling coefficients and mode velocity ratios are plotted in Fig. 8(a) and (b), respectively. The typical property of the three structures is that the increase of the coupling coefficient is always associated with the increase in the mode velocity ratio. A BC MCPW's is characterized with slightly high coupling coefficient compared with a corresponding BC CPW's because of the higher even-mode characteristic impedance. Using dielectric overlays results in the decrease of both the coupling coefficient and the mode velocity ratio. However, a larger decrease is observed in the mode velocity ratio than that in the coupling coefficient.

## IV. 3-dB Directional Couplers Design and Performances

Two 3-dB directional couplers using broadside-coupled dielectric covered CPW's and nonuniform CPW's have been designed as practical examples. The coupling strength of a coupler has been designed as 2.65 dB at the center frequency of 1.2 GHz, resulting in the coupling coefficient of about 3

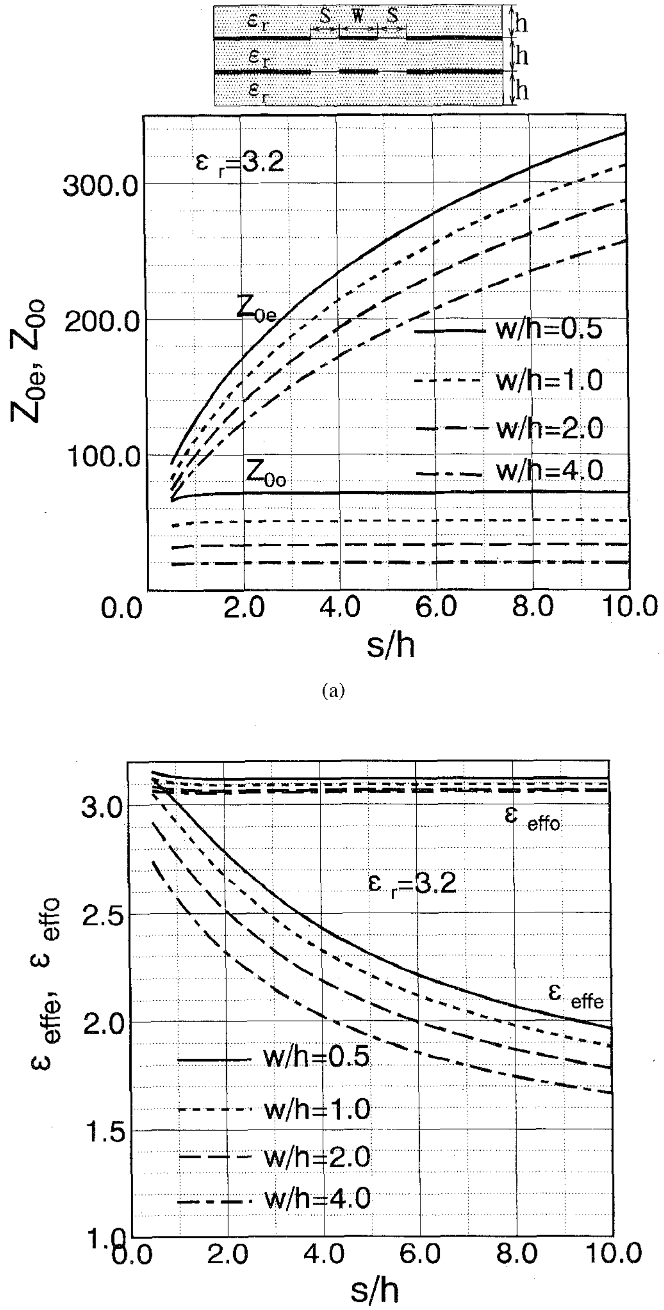



Fig. 7. Even- and odd-mode characteristic impedances (a) and effective permittivities (b) of a BC CCPW's versus $s/h$.

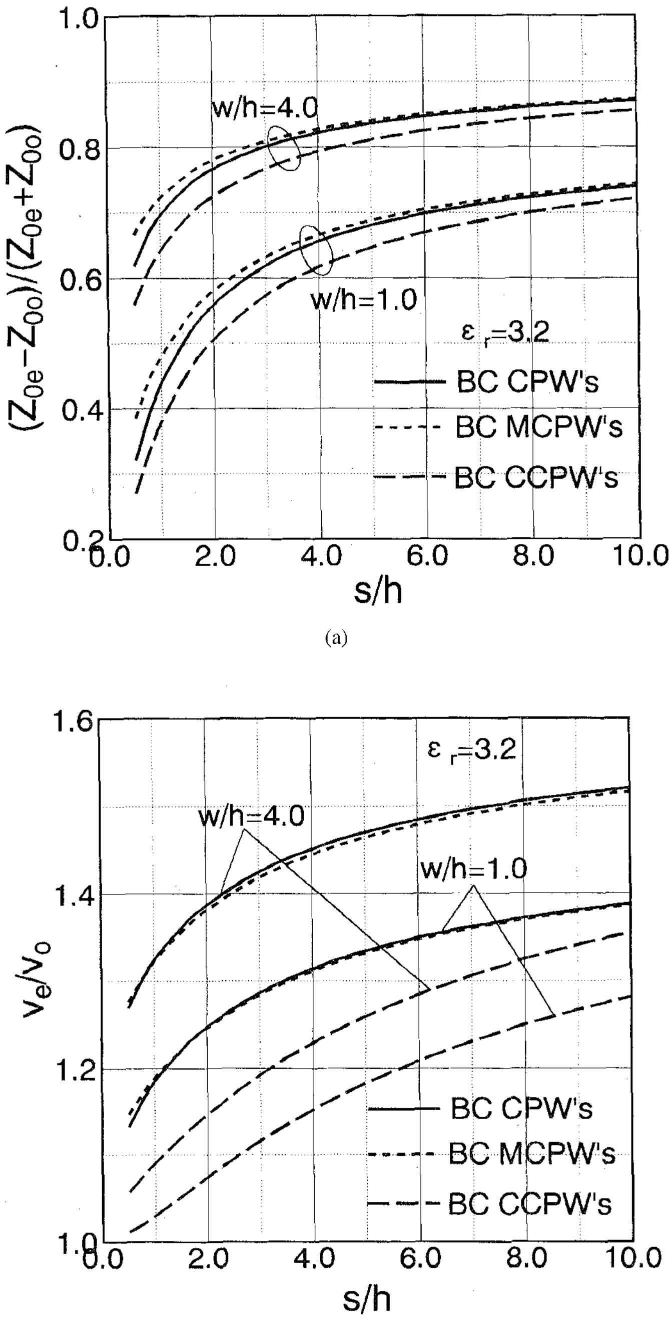



Fig. 8. Comparison of the coupling coefficients (a) and the mode velocity ratios (b) of the three broadside-coupled structures.

dB near the frequencies of 0.9 GHz and 1.5 GHz. Such a coupler can be employed as a hybrid circuit in a array antenna operating at two frequency bands [1]. The couplers were fabricated on the dielectric substrate of thickness $h = 1.6$ mm and relative permittivity $\epsilon_r = 3.2$. The connecting output lines of $Z_0 = 50\Omega$ characteristic impedance were used. Measurements were performed using a conventional automatic network analyzer.

The structural dimensions of the uniform directional coupler of BC CCPW's as shown in Fig. 1, have been determined as: $w = 6.5$ mm, $s = 3.5$ mm, and $L = 38.5$ mm. The mode parameters of this structure have been calculated as: $Z_{0e} = 128.96\Omega$, $Z_{0o} = 19.54\Omega$, $\epsilon_{\text{eff}e} = 2.28$, and $\epsilon_{\text{eff}o} = 3.06$. Theoretical analysis of this inhomogeneous coupler with the mode velocity ratio of 1.158 predicted the input return loss and the isolation coefficients to be below $-20$ dB in the frequency range 0.7 GHz–1.7 GHz as shown in Fig. 9. The measured scattering parameters of this coupler are also included in Fig. 9 which are shown to agree well with theoretical predictions. The connecting output lines of this coupler were realized in the form of dielectric covered CPW with backed ground conductor. The discrepancies between theory and experiment

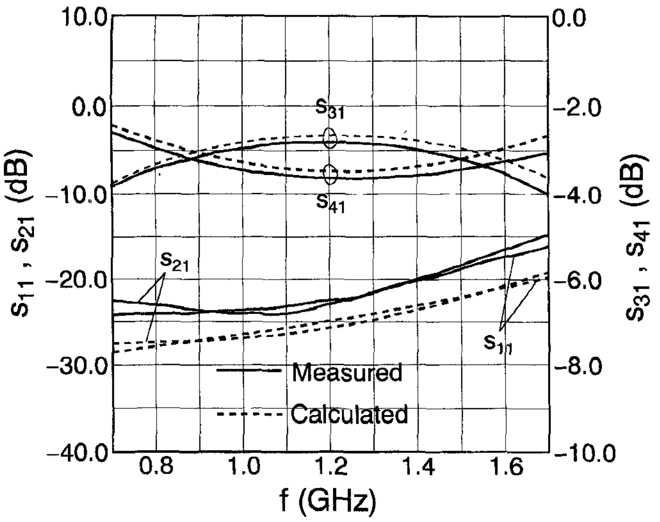



Fig. 9. Calculated and measured scattering parameters of the experimental 3-dB directional coupler of BC CCPW's.

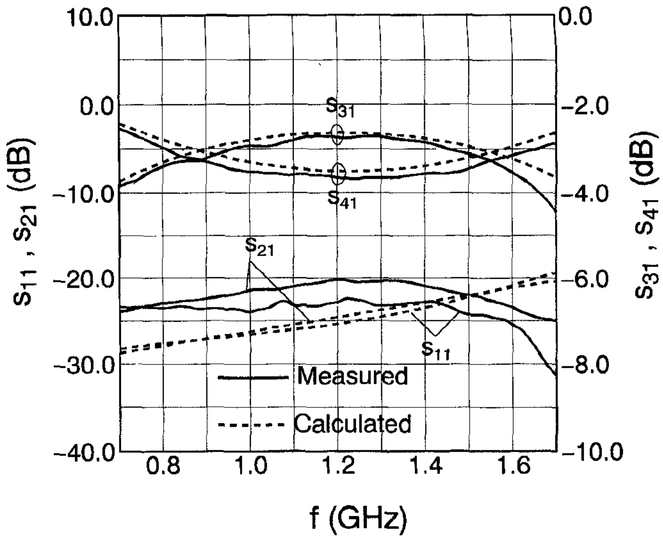



Fig. 10. Calculated and measured scattering parameters of the experimental 3-dB directional coupler of nonuniform BC CPW's.

may be due to the connector transition errors and various neglected losses.

The directional coupler with nonuniform CPW's as shown in Fig. 2, has been designed using the iterative procedure described in the previous section. The microstrip lines of 50 Ω characteristic impedance were used as the connecting output lines. The line width and the gap width of the coupler at the connecting output lines have been determined as $w = 6.0$ mm and $s = 1.0$ mm, respectively, with the same gap width for the uniform region. The odd-mode effective permittivities of the BC CPW's and BC CCPW's with these dimensions have been calculated as 2.767 and 2.769, respectively, and therefore, the total length of the coupler has been determined as $L = 37.5$ mm. Finally, an iterative procedure has been employed to find $d = 14.3$ mm and $L_B/L_A = 1.5$. Calculated and measured scattering parameters of this coupler are shown in Fig. 10. Again good agreement between theory and experiment is observed. It is verified both theoretically and experimentally that the negative effect caused because of the large mode velocity ratio of BC CPW's can be compensated by using the nonuniform BC CPW's. The coupler may be designed to operate at higher frequencies as far as its characteristics are not seriously affected due to the discontinuities in the coupling region.

## V. Conclusion

In this paper, we investigated the BC CPW's in inhomogeneous media and their application in directional couplers. Two types of BC CPW directional couplers have been proposed and analyzed with a quasi-TEM wave characterization method. The means such as dielectric overlays or nonuniform CPW's have been used for lowering or compensating the large mode velocity ratio which is the characteristic of the broadside-coupled lines in inhomogeneous media. The designed $L$-band 3-dB directional couplers showed good performances and their measured scattering parameters were found to be in good agreement with theoretical predictions.

A directional coupler with nonuniform BC CPW's was found to be very attractive due to its simplicity of manufacture, tight coupling, and reasonable wide bandwidth. The coupler has simple configuration which is very well suited to double-sided printed strip antennas. The simplicity of the coupler may make it also attractive for application in other double-sided or multilayered printed circuits.

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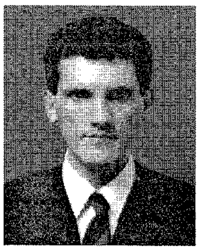

**Faton Tefiku** (S'91–M'93) received the Dipl.Ing. degree from the University of Prishtina, Kosovo, Yugoslavia, in 1981, the M.S. degree from the University of Zagreb, Croatia, in 1988, and the Doctor of Engineering degree from the University of Electro-communications, Tokyo, Japan, all in electrical engineering.

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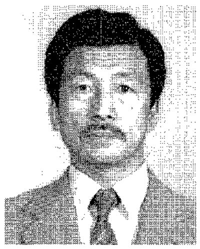

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