Fast and Accurate Analytic Formulas for Calculating the Parameters of a General Broadside-Coupled Coplanar Waveguide for (M)MIC Applications

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Abstract —Fast and accurate analytic formulas for calculating the quasi-static TEM parameters of a general broadside-coupled coplanar waveguide (GBSC CPW) are presented. Simplicity, high speed of computation, and accuracy recommend the use of these formulas for (M)MIC CAD programs. Numerical calculations are presented in order to investigate various electrical properties of the structure. An asymmetrical BSC CPW, as well as the single CPW resulting from connecting the two coupled strips of the GBSC CPW at the input and the output ports, is also analyzed. Criteria are obtained to ensure the coplanar behavior of the structure.

I. Introduction

In spite of several advantages offered by coplanar waveguides (CPW's), their use in actual (M)MIC design has somehow been less widespread than would be expected. Among the reasons for this are the limited variety of circuit elements available and the lack of CAD facilities in coplanar circuit design. Some fast analytic formulas for calculating the parameters of some CPW structures, which are suitable for (M)MIC CAD programs, are already available in the literature. These are for the symmetrical CPW's with infinite [1] and finite [2]–[5] substrate thicknesses, with [2] and without [3], [4] ground plane, with [5] and without [1]–[4] finite strip thickness, symmetrical CPW's with coplanar ground planes of finite extent with infinite and finite substrate thickness [6], asymmetrical CPW's with infinite and finite substrate thickness [7]–[8], single-sided CPW's with infinite [9] and finite [9]–[10] substrate thickness, with [10] and without backed ground plane, and edge-coupled CPW's with infinite substrate thickness [11]. Analytic formulas which consider the effect of the presence of a top cover on the parameters of CPW's with finite substrate thickness, with and without backed ground plane, are also available [6].

The configuration we are dealing with (Fig. 1(a)) is similar to the one which has been introduced and analyzed numerically by Hatsuda [12] (by using the finite difference method) under the name of symmetrical two-strip-conductor coplanar-type stripline. In this contribution, fast and accurate analytic formulas are presented for the quasi-static TEM parameters of general broadside-coupled coplanar waveguides (with general dielectric interface, GBSC CPW). The approach used is based on isolating the odd and even modes by assuming an electric wall in the case of the odd mode and a magnetic wall for the even mode. The cross section of each mode is then divided into two regions, with the field in each region represented by a capacitance for

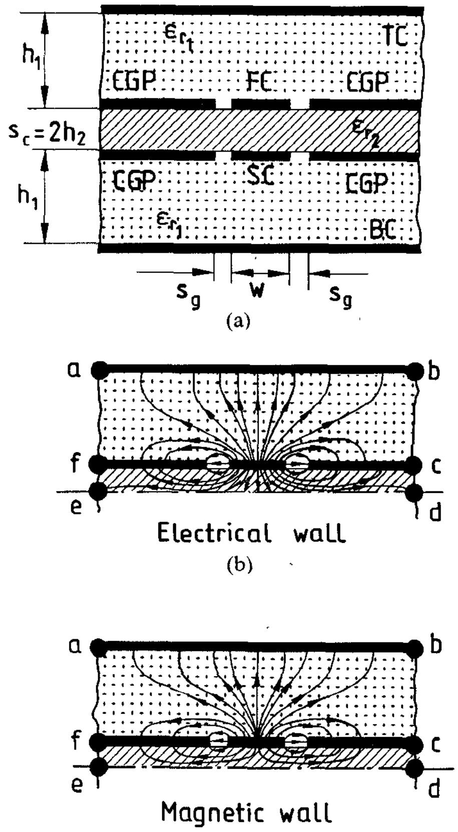

Fig. 1. (a) Cross-sectional view of the GBSC CPW. (b) Field distribution of the GBSC CPW under an odd-mode excitation. (c) Field distribution of the GBSC CPW under an even-mode excitation.

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which expressions are available in the literature. Numerical results are presented in order to investigate various properties of the structure. Analytic formulas and numerical results are also presented for an asymmetrical BSC CPW as well as for the single CPW which results from connecting the two coupled strips of the GBSC CPW at the input and output ports. High speed of computation and accuracy recommend the use of these formulas in (M)MIC CAD programs. Criteria are also obtained to ensure the coplanar behavior of the structure. The question about the practical usefulness of the quasi-static analytic formulas for calculating the parameters of CPW's has been already pointed out by Ghione and Naldi [6] and we also believe that the presented quasi-static TEM analytic formulas can be used in the design of coplanar MMIC's up to 40 GHz (Section VI). Moreover, they are always required as the basis for any future attempt to obtain frequency-dependent formulas.

II. Analytic Formulas and Results for the GBSC CPW

The configuration we are dealing with is shown in Fig. 1(a). It consists of two coupled strips placed face to face on a dielectric layer of thickness s_c and relative dielectric constant ϵ_{r2} (middle dielectric material). These two strips are denoted by FC and SC, respectively. They are placed near four coplanar ground planes (CGP's) and at a distance (slot width) equal to s_g. The structure may be covered by top and bottom metallic plates, TC and BC, respectively, positioned at a distance h_1 from the surfaces of the dielectric material. The spacing between the middle dielectric and the metallic top and bottom covers may be filled by another dielectric material whose thickness is h_1 and relative dielectric constant is ϵ_{r1}. Let us call them the upper and lower dielectric materials, respectively. This structure supports two fundamental modes, namely odd and even. They can be isolated by assuming an electric wall for the odd mode and a magnetic wall for the even mode, as shown in Fig. 1(b) and (c), respectively. The analytic formulas of the odd- and even-mode parameters of the structure can be obtained as follows.

A. Odd Mode

The analytic expression for the odd-mode capacitance (Fig 1(b)) can be obtained by modeling the two slots as magnetic walls. This assumption is always verified as long as the structure behaves as a coplanar line. Criteria to ensure this behavior will be discussed in Section V. The total odd-mode capacitance per unit length can then be considered as the sum of two components, C_{o1} and C_{o2}, representing the electric field in the upper and middle dielectric materials, respectively. The expressions for these two components (C_{o1} and C_{o2}) have already been derived [2] by mapping each of the regions first into a half-plane and then into the well-known parallel-plate configuration. The resulting odd-mode capacitance per unit length can be obtained by rewritting the results of [2] in accordance with our physical dimensions as follows:

$$C_o = C_{o1} + C_{o2} \tag{1}$$

$$C_{oi} = 2\epsilon_0\epsilon_{ri}\frac{K(k_{oi})}{K(k'_{oi})} \qquad (i=1,2) \tag{2}$$

where

$$k_{oi} = \tanh\left(\frac{\pi w}{4h_i}\right)\Big/\tanh\left(\frac{\pi(w+2s_g)}{4h_i}\right) \tag{3}$$

with $K(k)$ and $K(k')$ as the complete elliptic integral of the first kind and its complement, and $k'=\sqrt{1-k^2}$.

Accurate expressions for the ratio $K(k)/K(k')$ are available in [14]. These are given below:

$$\frac{K(k)}{K(k')} = \begin{cases} \frac{1}{\pi}\ln\left[2(1+\sqrt{k})/(1-\sqrt{k})\right], & 0.5 \leqslant k^2 \leqslant 1 \\ \pi/\ln\left[2(1+\sqrt{k'})/(1-\sqrt{k'})\right], & 0.0 \leqslant k^2 \leqslant 0.5. \end{cases} \tag{4}$$

B. Even Mode

The total even-mode capacitance per unit length can be derived in the same way, the only difference being that we have a magnetic wall at the lower bound of the middle dielectric. The result, in this case, is as follows:

$$C_e = C_{e1} + C_{e2} \tag{5}$$

where

$$C_{e1} = C_{o1} \tag{6}$$

and

$$C_{e2} = 2\epsilon_0\epsilon_{r2}\frac{K(k_{e2})}{K(k'_{e2})} \tag{7}$$

with

$$k_{e2} = \sinh\left(\frac{\pi w}{4h_2}\right)\Big/\sinh\left(\frac{\pi(w+2s_g)}{4h_2}\right). \tag{8}$$

Odd- and even-mode characteristic impedances, effective dielectric constants, and velocities of propagation can be calculated by using (1) to (8) as well as the following well-known equations:

$$Z_{0(o,e)} = \left[c_v\sqrt{C_{(o,e)}C^a_{(o,e)}}\right]^{-1} \tag{9}$$

$$\epsilon_{\text{eff}(o,e)} = C_{(o,e)}/C^a_{(o,e)} \tag{10}$$

and

$$v_{(o,e)} = c_v\Big/\sqrt{\epsilon_{\text{eff}(o,e)}} \tag{11}$$

where $c_v = 2.9979\cdots\times10^8$ m/s is the velocity of light in vacuum and $C^a_{(o,e)}$ is the capacitance when replacing the dielectric materials by air.

Odd- and even-mode characteristic impedances and effective dielectric constants calculated by using the derived formulas are plotted in Fig. 2(a) and (b), respectively, for

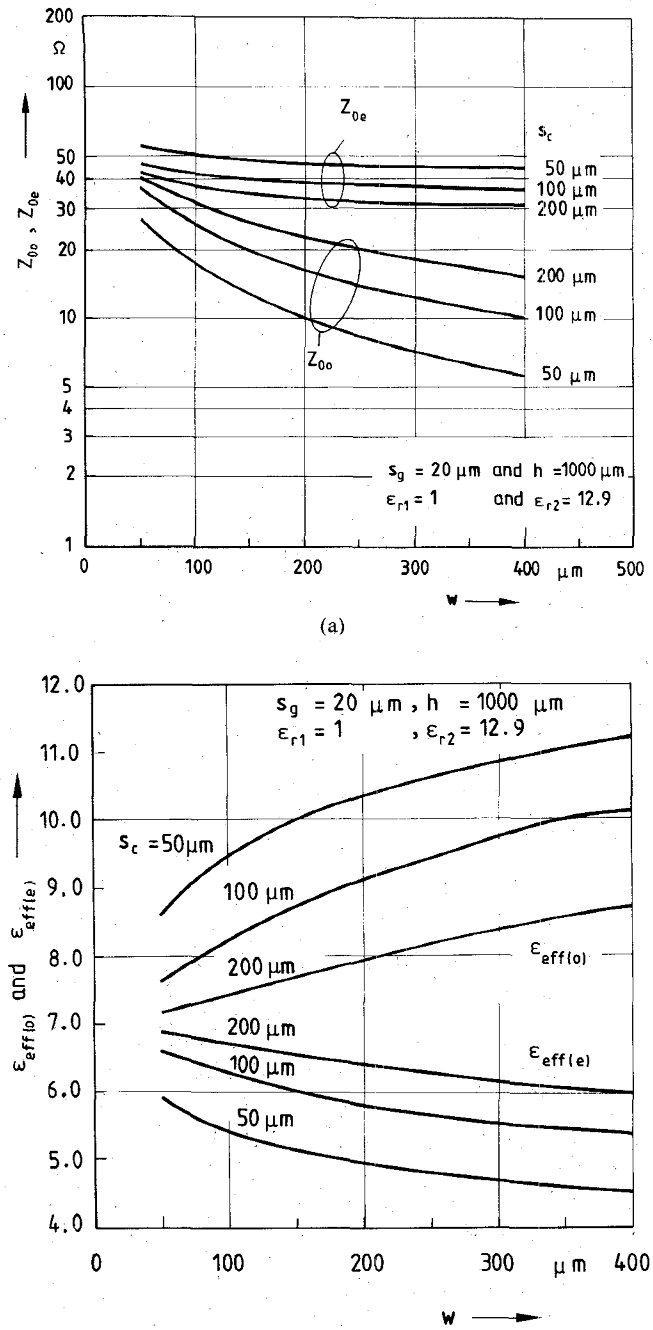


Fig. 2. Variation of the odd- and even-mode design parameters with typical values of physical dimensions. (a) Characteristic impedances. (b) Effective dielectric constants.

$\epsilon_{r1} = 1$ (air), $\epsilon_{r2} = 12.9$ (GaAs), $h_1 = 1000$ μm, $s_g = 20$ μm, $w = 50$–400 μm, and $s_c = 50100$ and 200 μm. These generally demonstrate relatively low values for the odd- and even-mode characteristic impedances as well as relatively high values of odd- and even-mode effective dielectric constants. In order to obtain a deeper insight into the properties of this coupled structure, the coefficient of coupling C_c (at the center frequency) and the mode velocities ratio v_e/v_o are plotted in Fig. 3(a) and (b), respectively, for $\epsilon_{r1} = 1$ (air), 3.78 (quartz), and 10 (alumina), $h_1 = 5000$ μm, $\epsilon_{r2} = 12.9$ (GaAs), $s_c = 50$ μm, $s_g = 50$–400 μm, and $w = 50$–400 μm. The following properties (some of them are typical of all broadside-coupled MIC structures, while the other are peculiar to the coplanar structure discussed here) are observed:

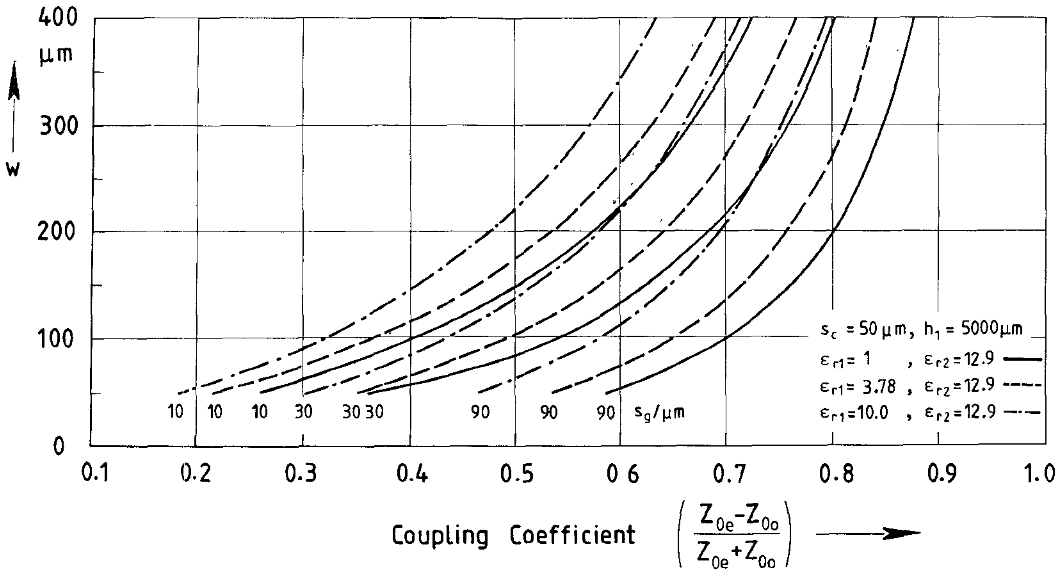
1) The increase of the coupling coefficient C_c is always associated with a corresponding increase in the mode velocity ratio v_e/v_o.
2) The decrease of the middle substrate thickness, $s_c = 2h_2$, results in an increase of both C_c and v_e/v_o.
3) The increase of slot width, s_g, results in an increase of both C_c and v_e/v_o.
4) The increase of the width, w, of the coupled strips increases both C_c and v_e/v_o.
5) The increase of the relative dielectric constant ϵ_{r2} of the middle substrate increases both C_c and v_e/v_o.
6) Increasing the relative dielectric constants ϵ_{r1} of the upper and the lower dielectric material results in a decrease of both C_c and v_e/v_o. However, a larger decrease is observed in v_e/v_o than in C_c. For example, in the case of $\epsilon_{r1} = 10$ (alumina) and $\epsilon_{r2} = 12.9$ (GaAs), the mode velocity ratio v_e/v_o is less than 1.1 while a good coupling coefficient of 0.791 can still be achieved.

This type of interface of two dielectric materials of nearly equal dielectric constants is sometimes desirable in particular circuit applications. Moreover, the presence of the lower dielectric material will serve as a support for the middle GaAs substrate, which is typically thin and fragile, in (M)MIC applications. This will result in an improvement of the mechanical strength as well as the average power-handling capability of the entire structure. However, the presence of the upper dielectric material will not permit the insertion of series and parallel lumped passive and active elements, which is considered the most important advantage of CPW structures over the microstrip configuration. One solution is to remove, partially, the upper dielectric material from some part of the circuit to allow for such an insertion. The other is to derive new analytic formulas that can deal with CPW structures where only the upper dielectric material is replaced by air.

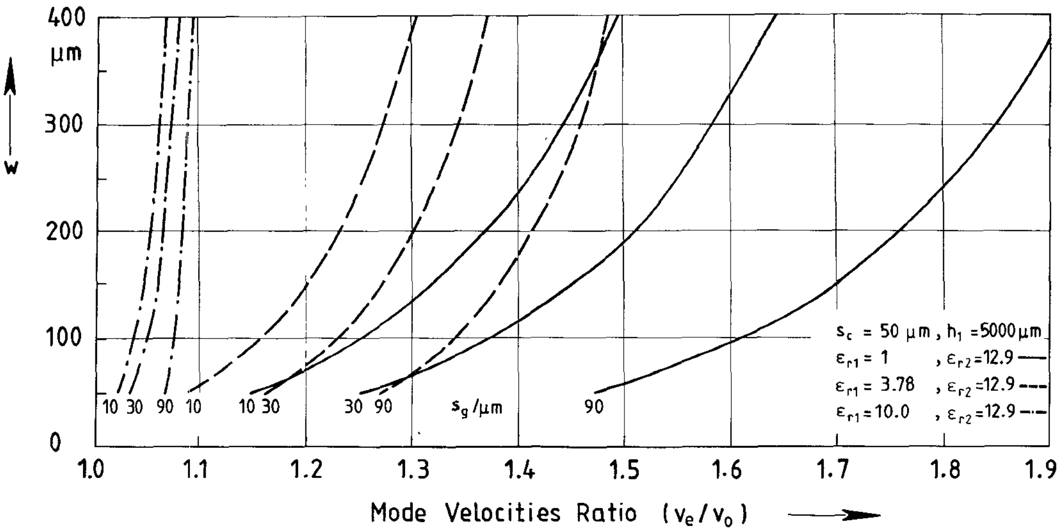
III. Analysis of an Asymmetric Supported BSC CPW

The new structure which is shown in Fig. 4(a) may be called an asymmetrical supported broadside-coupled coplanar waveguide (ASBSC CPW) and can be analyzed by considering it as asymmetrical coupled lines.

In this case, two modes will be propagating on the lines but with unequal model characteristic impedances seen by each of the lines. The model characteristic impedances and effective dielectric constants are calculated using the self- and mutual capacitances and inductances per unit length of the ASBSC CPW C_{11}, C_{22}, C_{12}, L_{11}, L_{22}, and L_{12} as well as [15, eq. (5)] after replacing the suffixes L and R [15] (standing for the left and right lines, respectively) by



(a)



(b)

Fig. 3. (a) Variation of the coupling coefficient C_c of the GBSC CPW with typical values of physical dimensions (b) Variations of the mode velocity ratio v_e/v_o of the GBSC CPW with typical values of physical dimensions.

the suffixes 1 and 2 (standing for the first and second strips, respectively). It should be pointed out here that [15, eq. (5a)] has been incorrectly interpreted from [16] and should read as follows:

$$\epsilon_{\mathrm{eff}(C,\Pi)} = c_v^2(L_{11}C_{11} + L_{22}C_{22} - 2L_{12}C_{12} \pm \lambda)/2 \quad (12a)$$

$$Z_{C1} = \frac{c_v}{\sqrt{\epsilon_{reC}}}(L_{11} - L_{12}/R_\Pi) \quad (12b)$$

$$Z_{\Pi 1} = \frac{c_v}{\sqrt{\epsilon_{re\Pi}}}(L_{11} - L_{12}/R_C) \quad (12c)$$

$$Z_{C2} = -R_C R_\Pi Z_{C1} \quad (12d)$$

$$Z_{\Pi 2} = -R_C R_\Pi Z_{\Pi 1} \quad (12e)$$

where

$$\lambda = \sqrt{4(L_{12}C_{22} - L_{11}C_{12})(L_{12}C_{11} - L_{22}C_{12}) + (L_{22}C_{22} - L_{11}C_{11})^2} \quad (12f)$$

and

$$R_{(C,\Pi)} = \frac{(L_{22}C_{22} - L_{11}C_{11}) \pm \lambda}{2(L_{12}C_{22} - L_{11}C_{12})}. \quad (12g)$$

In this case, the expressions for the self- and mutual capacitances per unit length C_{11}, C_{22}, and C_{12} can be written with reference to Fig. 4 and by using (1) to (8) as follows:

$$C_{12} = (C_{o2} - C_{e2})/2$$
$$C_{11} = C_{o1}^a + C_{e2} + C_{12}$$
$$C_{22} = C_{o1} + C_{e2} + C_{12}. \quad (13)$$

The self- and mutual inductances L_{11}, L_{22}, and L_{12} can be calculated from the self- and mutual capacitances per unit

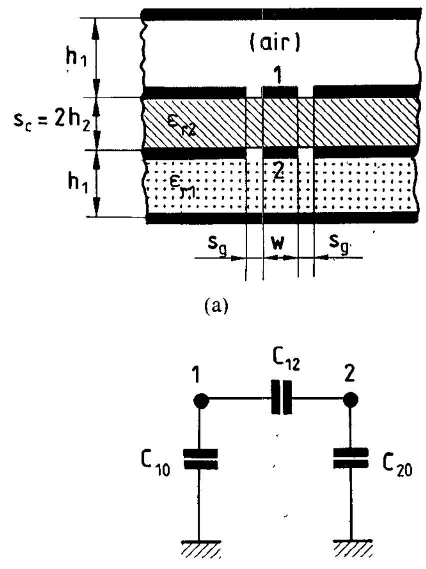


Fig. 4. (a) Cross-sectional view of the ASBSC CPW. (b) Equivalent circuit showing the self- and mutual capacitances per unit length of the ASBSC CPW.

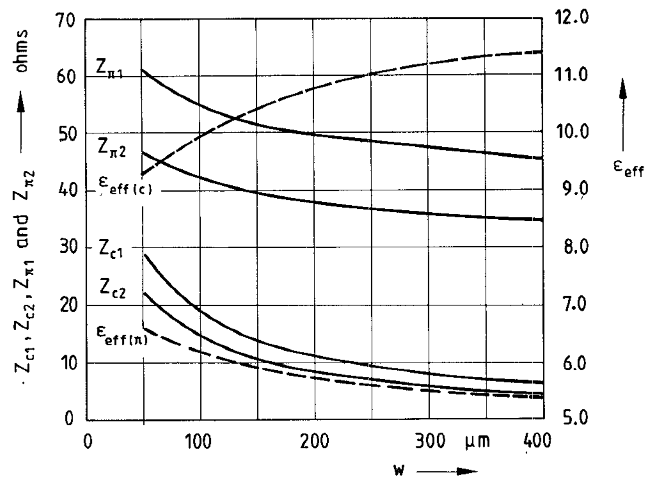


Fig. 5. Variations of the mode (C and Π) characteristic impedances and effective dielectric constants of the ASBSC CPW with typical values of physical dimensions.

length C_{11}^a, C_{22}^a, and C_{12}^a when replacing the dielectric material by air:

$$L_{11}\ [\text{nH/cm}] = \frac{10C_{22}^a\ [\text{pF/cm}]}{9\Delta C^a\ \left[(\text{pF/cm})^2\right]}$$

$$L_{22}\ [\text{nH/cm}] = \frac{10C_{11}^a\ [\text{pF/cm}]}{9\Delta C^a\ \left[(\text{pF/cm})^2\right]},$$

$$L_{12}\ [\text{nH/cm}] = \frac{10C_{12}^a\ [\text{pF/cm}]}{9\Delta C^a\ \left[(\text{pF/cm})^2\right]}$$

with

$$\Delta C^a = C_{11}^a C_{22}^a - \left(C_{12}^a\right)^2\ \left[(\text{pF/cm})^2\right]. \quad (14)$$

Calculated values for Z_{C1}, Z_{C2}, $Z_{\Pi 1}$, $Z_{\Pi 2}$, $\epsilon_{\text{eff}(C)}$, and $\epsilon_{\text{eff}(\Pi)}$ are plotted in Fig. 5 for $\epsilon_{r2} = 12.9$, $h_1 = 1000\ \mu$m, $s_g = 20\ \mu$m, $w = 50$–$400\ \mu$m, and $s_c = 50\ \mu$m; the upper dielectric is air, while the lower dielectric is quartz ($\epsilon_{r1} = 3.78$).

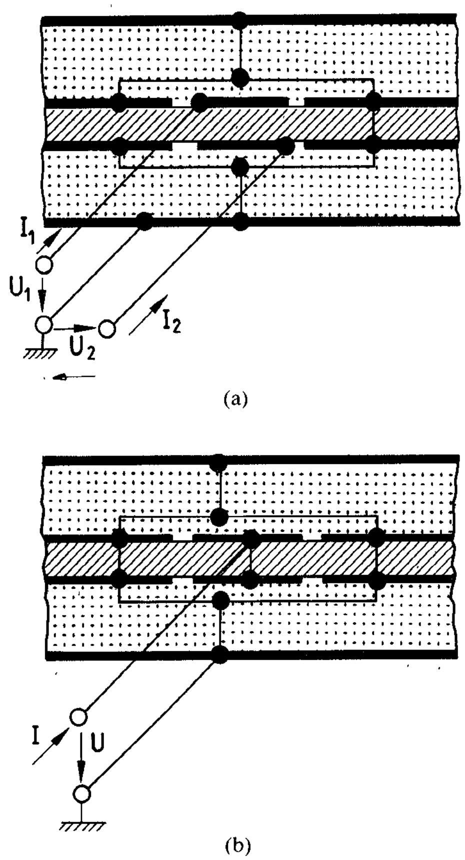


Fig. 6. Two possible connections for different uses of the GBSC CPW

IV. The Use of the GBSC CPW as Single CPW

Two connections for the GBSC CPW to an external input source are suggested. Fig. 6(a) shows the normal way of connection as two coupled lines to be used as building blocks for (M)MIC's, especially as directional couplers which permit tight coupling or for the transmission of electromagnetic power between two CPW's deployed on different surfaces [17]. Fig. 6(b) also shows the use of the GBSC CPW as a single CPW [12]. This can be achieved by connecting the two coupled strips to the same potential. In this case, only the even mode will be excited along the strips. The design parameters of the resultant single CPW can then be written as follows:

$$C_s = 2C_e \qquad C_s^a = 2C_e^a \quad (15)$$

$$Z_{0(s)} = 0.5\left[c_v\sqrt{C_s C_s^a}\right]^{-1} \quad (16)$$

and

$$\epsilon_{\text{eff}(s)} = C_s / C_s^a \quad (17)$$

where C_e and C_e^a are given above by (7) and (8). Typical numerical results for the characteristic impedance as well as for the effective dielectric constant compared with those of the conventional CPW with finite substrate thickness are displayed in Table I. It is observed that this configuration gives nearly half the characteristic impedance of the

TABLE I
COMPARISON BETWEEN THE DESIGN PARAMETERS OF THE CONVENTIONAL CPW (LINE 1) AND THE GBSC CPW WHEN USED AS SINGLE CPW (LINE 2)

h μm	s_g μm	w μm	Z_0 (ohm) line 1	Z_0 (ohm) line 2	ε_{re} line 1	ε_{re} line 2
50	10	50	41.29	20.83	6.37	6.25
		400	33.54	17.50	5.30	4.97
	30	50	63.87	32.55	5.86	5.64
		400	49.09	25.83	4.69	4.23
	50	50	81.88	42.12	5.46	5.16
		400	60.96	32.56	4.31	3.78
200	10	50	35.87	17.95	6.90	6.89
		400	26.08	13.18	6.30	6.17
	30	50	49.70	24.90	6.83	6.80
		400	34.84	17.68	6.08	5.90
	50	50	58.84	29.51	6.75	6.71
		400	41.14	20.95	5.90	5.69

conventional CPW, while their effective dielectric constants are nearly the same. This means that, by using the connection of Fig. 6(b) with the proposed GBSC CPW, it is possible to obtain a single CPW with the same values of the characteristic impedance but with better slot width manufacturing tolerance allowances. It should be pointed out that it is possible to obtain a similar effect on the impedance in the presence of a nearby backed ground plane; however the decrease in the characteristic impedance will always be associated with an increase in the effective dielectric constant.

V. CRITERIA FOR THE COPLANAR BEHAVIOR OF THE STRUCTURE

If the slot width s_g or the top cover height h_1 increases, their effects on the characteristics of the structure can be ignored. Moreover, increasing the slot width s_g up to a certain limit will cause some electric field lines to cross the dielectric interface (at the slot) and reach the electric wall (in the case of the odd mode) or the ground planes (in the case of the even mode). In this case, the assumption of modeling the slot width as a magnetic wall will not be verified. This effect (due to the increase of the value of s_g) is more critical in the case of the odd mode than in the case of the even mode. Thus the discussion will concentrate on the odd mode which is identical to the case of a single coplanar waveguide with top cover and metallic backed ground plane [6]. Four limiting cases are shown in Fig. 7(a)–(d).

Case 1 (h_1 is comparable to h_2 and s_g is smaller than a critical slot width s_{gc} to be defined) in which the odd-mode configuration behaves as a single coplanar structure with top cover and metallic ground plane [6].

Case 2 (h_1 is much larger than h_2 but still s_g is smaller than s_{gc}) in which the odd-mode configuration behaves as a single coplanar structure with backed metallic ground plane only [2].

Case 3 (h_1 is comparable to h_2 but s_g is much greater than s_{gc}) in which the odd-mode configuration behaves as a covered microstrip line [18].

Case 4 (h_1 is much larger than h_2 and s_g is much larger than s_{gc}) in which the odd-mode configuration behaves as an open microstrip [19].

Only the first and the second cases (in which the coplanar structure behaves as coplanar line) will be considered here. A critical slot width s_{gc} can be defined theoretically as the slot width s_g beyond which the parameters of the coplanar structure are different from those of the corresponding microstrip line by a value δ to be defined according to the user's needs. The variation of the theoretical critical slot width to height ratio s_{gc}/h is plotted in Fig. 8 as a function of w/h (0.2 to 10) and for different values of $\delta = 10$, 1, 0.1, and 0.01 percent, respectively.

It should be pointed out that the value of the critical slot width which will be used in practice would be expected to be larger than the theoretical one, and neither decreases with the ratio w/h (dashed lines in Fig. 8). This is because there are two different definitions. In theory, it is the slot width beyond which the expressions for the microstrip configurations [18], [19] can replace those of the coplanar structure within a required accuracy. However, in practice, we search for the slot width beyond which there is no electric coupling between the center conductors and the adjacent coplanar ground plane. The above discussion gives the main reason why we require the presented formulas to be exact for the calculation of the design parameters of the proposed GBSC CPW structure. The only assumption we have made is that we have modeled the slots as magnetic walls. This has been proved to be always valid as long as the structure behaves as a coplanar line. It should also be pointed out that the same discussion is applicable to the analytic formulas previously presented by Ghione and Naldi [2], [6]; hence they may be considered to be exact in the same sense.

VI. CONCLUSION

Fast and accurate analytic formulas are presented for calculating the design parameters of general broadside-coupled waveguides (GBSC CPW's). The high-speed computation feature of the formulas recommends their use in (M)MIC CAD programs. Numerical results are presented in order to investigate the various properties of the structure. It has been observed that some properties are typical of all broadside-coupled MIC lines, while others (properties 3) and 6) of Section II) are peculiar to the proposed configuration. The possibility of using different materials for the upper and lower dielectric materials, where the lower dielectric may be, for example, quartz while the upper is air, can be used to advantage when designing (M)MIC's on GaAs substrates. In this case, the quartz will serve as a supporting material that increases both the mechanical strength and the average power-handling capability of the structure. Moreover, the presence of air above the first CPW will permit the insertion of series and parallel lumped passive and active components. Formulas are also presented for a single CPW which results from

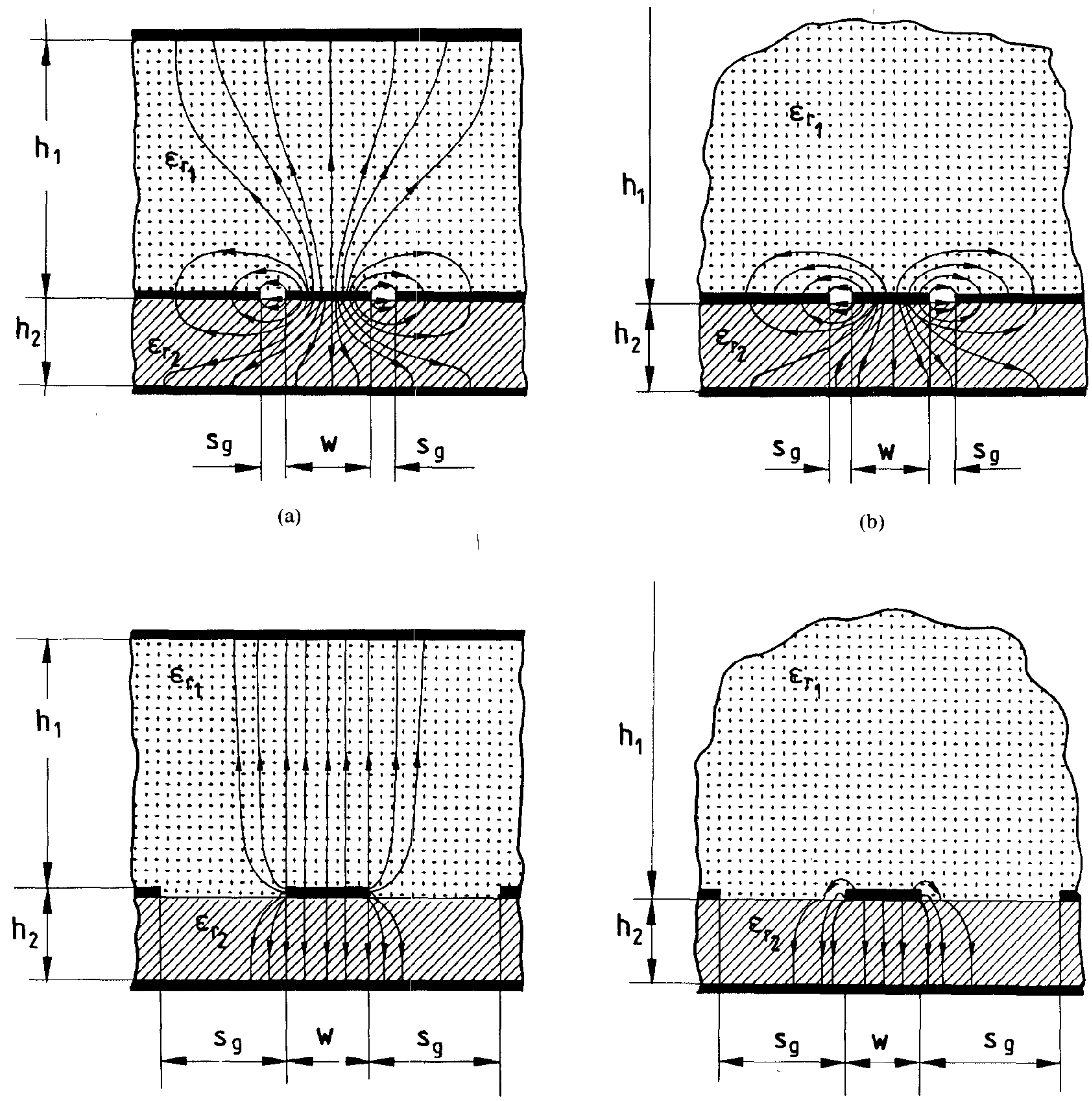


Fig. 7. The four limiting cases of the GBSC CPW under an odd-mode excitation.

connecting the two coupled strips to the same potential. Differences in electrical behavior in relation to the conventional CPW are also highlighted. Theoretical and practical critical slot widths that ensure the coplanar behavior of the structure have also been discussed. It is found that the derived formulas can be considered exact as long as they are used for the design of coplanar circuits. Design charts have not been supplied, since the presented fast computation formulas can be used by the designers to generate as much data as they need.

Finally, designers should note that these are quasi-static TEM formulas which are rigorously valid only at zero frequency. However, by virtue of the fact that coplanar waveguides in MMIC's are, generally, less sensitive for frequency dispersion, we believe that the presented formulas can be used in the design of coplanar MMIC's up to 40 GHz. This is due to the fact that the values of ground plane spacing in MMIC coplanar waveguides are typically small. It should also be noted that the deviation in the MMIC CPW design parameters due to frequency dispersion would be highly dependent on the absolute values of their physical dimensions. In order to form some notion of these amounts as functions of frequency and line physical dimensions, data which are obtained by the rigorous spectral-domain hybrid-mode approach [20] will be presented here. Two single CPW's will be considered. Both are deployed on GaAs substrate ($\epsilon_r = 12.9$ and thickness = 200 μm), while the whole structure is mounted over quartz dielectric material of $\epsilon_r = 3.78$ (in order to serve as a supporting material for the thin and fragile GaAs substrate). The first CPW (of main center strip width $w = 120$ μm and slot width $s_g = 200$ μm) shows deviations at a frequency $f = 45$ GHz in the characteristic impedance and the effective dielectric constant by amounts of 2.19 and 2.08 percent, respectively. However, the second CPW, which has the same value of strip width but with slot

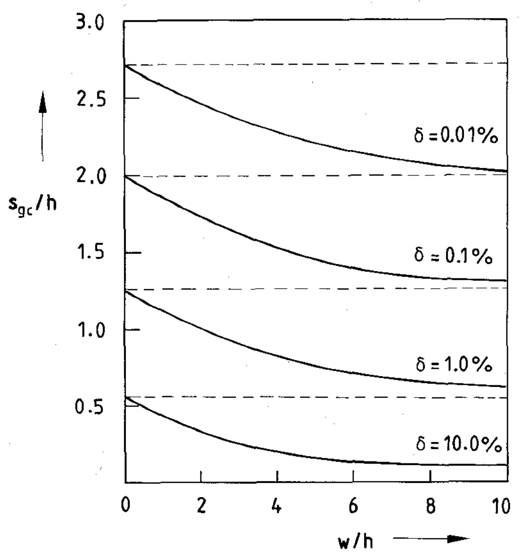


Fig. 8. Variation of the critical slot width to height ratio s_{gc}/h with the strip to height ratio w/h and different values of δ.

width $s_g = 20$ μm, shows deviations in the characteristic impedance and the effective dielectric constant, at a frequency $f = 65$ GHz, by -0.29 and 2.23 percent, respectively.

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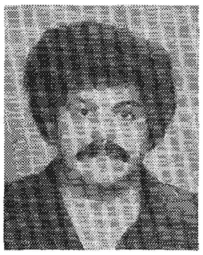

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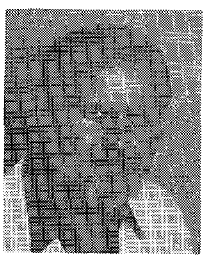

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