Short Papers

Transient Coupling Reduction and Design Considerations in Edge-Coupled Coplanar Waveguide Couplers

Michael R. Lyons and Constantine A. Balanis

***Abstract*— Edge-coupled coplanar waveguide (CPW) forward directional couplers are studied using an even/odd mode analysis. Specific height combinations of multilayer substrates are found which equalize the phase velocities of the even and odd modes. These modal velocity equalization points are seen to be relatively constant over a wide band of frequencies. Results of simulated pulse distortion are presented in a multilayer compensated structure showing a dramatic reduction in transient signal coupling and overall distortion. Design considerations for practical circuit designs are also discussed.**

I. Introduction

As planar microwave circuits become more complex, the effects due to surrounding circuits and transmission lines become increasingly important and must be accounted for in the design of practical monolithic and monolithic microwave integrated circuits (MIC and MMIC's). When considering nonperiodic pulses with picosecond rise times, resulting bandwidths well above 50 GHz are common. The successful prediction of pulse propagation in complex planar circuits must include the frequency dependent nature of the entire system. It has been shown that dispersion effects at high frequencies lead to distortion of pulse output with amplitude reduction, pulse widening, and ringing [1]. Also, at higher operating frequencies, quasi-TEM approximations for circuit characteristics are no longer valid and more accurate full-wave analyses must be employed.

At present, MMIC technology has shown a trend toward more coplanar waveguide (CPW) and hybrid circuit designs [2]–[4]. The CPW structure has been studied extensively as a single element transmission line [2], [3], and [5]. While a variety of computational methods have been employed to calculate the frequency dependent characteristics in CPW's and other planar circuits, the spectral domain approach (SDA) is often chosen for its efficiency and speed. Multilayer substrate and superstrate configurations are readily considered using a simple recursive formulation for the spectral domain admittance terms [6]. Picosecond pulse propagation on isolated CPW's has also been studied for selected suspended configurations [7], [8]. However, the circuit complexity is increased when an additional CPW is introduced into the system as in edge-coupled CPW directional couplers. In this coupled configuration, the circuit is conveniently analyzed using an even/odd mode approach [6], [9]. Propagation characteristics of edge-coupled CPW forward directional couplers have also been studied [10], and pulse propagation analysis has also been presented [9]. However, no analysis leading to transient coupling reduction over a wide range of parameters in edge-coupled CPW forward directional couplers has yet been reported.

This paper utilizes a full-wave spectral domain analysis to characterize the even/odd mode phase constants and address pulse distortion in multilayer edge-coupled CPW directional couplers. First, the effective dielectric constant (ϵ_{reff}) for each orthogonal mode of the structure is calculated using the well-known spectral domain approach (SDA), applicable toward slot structures [11]. These frequency domain values are then used together to calculate the time-domain response using an inverse Fourier transform [6], [9]. Transient pulse distortion is examined for single layer (uncompensated) and multilayer (compensated) substrate edge-coupled CPW structures. Through even/odd mode phase velocity equalization, it is shown that transient coupling in edge-coupled CPW forward directional couplers can be reduced using specific combinations of multilayer substrates. Design considerations when using multilayer substrates to reduce transient coupling in practical circuits are also discussed.

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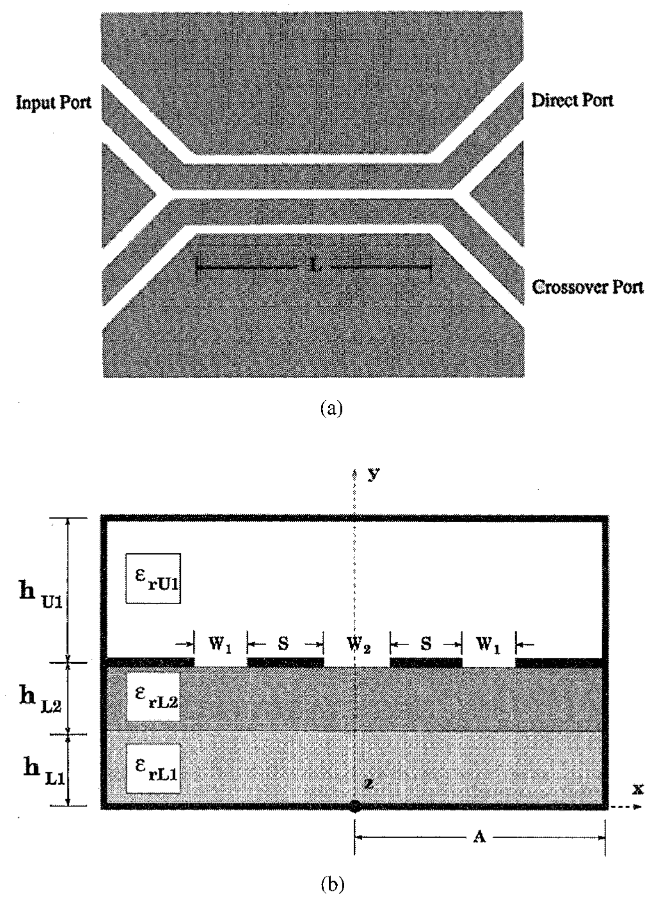

Fig. 1. (a) Top view of a three-slot CPW edge-coupled directional coupler. (b) Geometry of a general symmetric, edge-coupled, multilayer CPW forward directional coupler.

II. Theory

A symmetric, multilayer, edge-coupled CPW directional coupler is depicted in Fig. 1(a) with accompanying cross-section shown in Fig. 1(b). Although two substrates and one superstrate are depicted, any finite number of layers may be considered using a simple recursion relation as in [6]. To incorporate shielding effects, conductors have been introduced at $x = \pm A, y = 0$ and $y = h_{L1} + h_{L2} + h_{U1}$.

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The conductors are assumed to be negligibly thin and perfectly conducting, and all dielectrics are assumed lossless. The SDA is well documented in [12] and [13], therefore only the most relevant steps are included here.

After solving the boundary value problem in the spectral domain, the transformed longitudinal and transverse electric current densities on the center conductors, $\tilde{J}_z$ and $\tilde{J}_x$, may be expressed in terms of the spectral domain tangential electric fields in the slots, $\tilde{E}_z$ and $\tilde{E}_x$, using a multilayer Green's function applicable to slot structures [11]

$$\tilde{J}_z = \frac{-j}{\omega\mu_0}[\tilde{E}_z\tilde{G}_{zz} + \tilde{E}_x\tilde{G}_{xz}] \quad (1)$$

$$\tilde{J}_x = \frac{-j}{\omega\mu_0}[\tilde{E}_z\tilde{G}_{zx} + \tilde{E}_x\tilde{G}_{xx}]. \quad (2)$$

Since the slots in the edge-coupled CPW coupler structure cover a relatively small area compared to the center conductor, it is more appropriate to expand the electric fields in the slots into sets of known basis functions instead of the currents on the conductors. Due to the symmetry of the structure, the problem may be separated into two simpler problems using an even/odd mode analysis and electric field configurations in the coplanar slots are formed as in [9]. Using Galerkin's technique and setting the determinant of the resulting matrix equal to zero determines nontrivial solutions for the phase constants, β_z, of each orthogonal mode and thus, the effective dielectric constant, ϵ_{reff}, at a given frequency, where $\epsilon_{\text{reff}} = (\beta_z/\beta_0)^2$.

Pulse propagation through a coupler is simulated using a single wide-band pulse in the input port of the coupler at position $z = 0$ which is allowed to propagate along the length of the coupler, as in Fig. 1(a). A unit Gaussian pulse is used for an input signal which has a unit signal response given as $e^{-\ln(2)(t/\tau)^2}$, where τ is the signal half-width, half-maximum (HWHM) time duration. The outputs at direct and crossover ports are calculated using even- and odd-mode signal responses after the pulse has propagated along the coupler of length L [6], [9].

III. Results

The preceeding method was utilized to investigate picosecond pulse propagation along multilayer, edge-coupled CPW's. Transient coupling in symmetric coupled lines is directly related to the difference between the even- and odd-mode phase velocities (or effective dielectric constants) [6]. Therefore, the goal of using multilayer substrates is to equalize both modal phase velocities using a combination of substrate heights and materials. In this analysis, the total substrate height, referred to as h_{tot}, is held constant while all other parameters are varied.

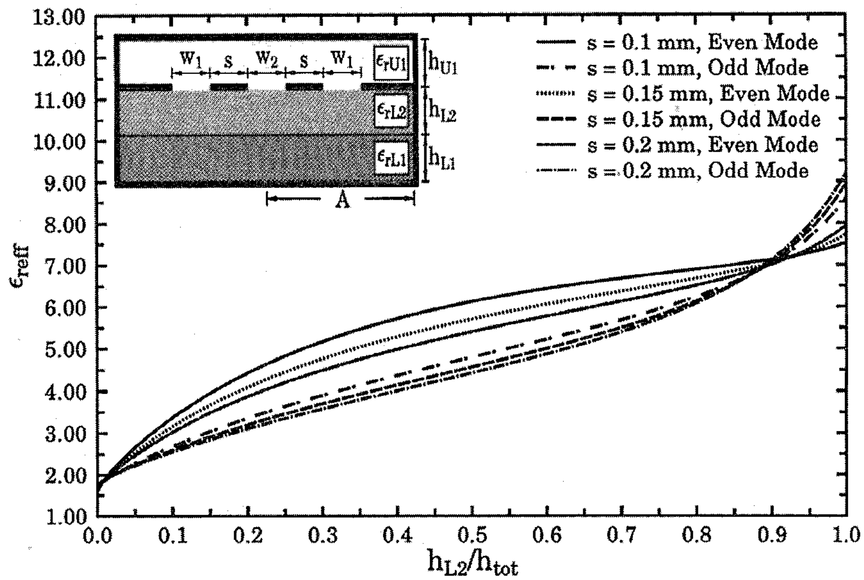
The even- and odd-mode characteristics of symmetric coupled CPW's are well known for single substrate and traditional configurations [9]. However, when more than one substrate is used, these properties can change dramatically. Fig. 2(a) shows how the effective dielectric constants for both even- and odd-modes at a given frequency vary as a function of the ratio of the upper height of the substrate to the total height while keeping the total substrate height, h_{tot}, constant, in a multilayer, edge-coupled CPW coupler. The slot spacing, s, is also varied for three separate cases. The geometry arrangement reduces to a single substrate when the height ratio, h_{L2}/h_{tot}, is 0.0 or 1.0, corresponding to a substrate with dielectric constant of $\epsilon_{r_{L1}}$ or $\epsilon_{r_{L2}}$, respectively. In each of these two special single substrate cases, the odd-mode effective dielectric constant is always greater than the even-mode, which is typical for single layer coupled CPW structures using a lower ground plane. However, when a multilayer substrate combination is used, the even- and odd-mode effective dielectric constants can vary greatly and actually equalize at specific multilayer substrate height combinations as shown in Fig. 2(a). It is seen that the even- and odd-mode effective dielectric constants are exactly equal at two specific height ratio combinations of about 0.9 and 0.01 for a slot separation of $s = 0.1$ mm. When the slot separation is increased to $s = 0.15$ mm and $s = 0.2$ mm, the height combinations shift slightly but do not appear to change appreciably. It should also be mentioned that these equalization height ratios stay relatively constant as a function of frequency [6], [11]. Therefore, a single height combination can be utilized that equalizes both even- and odd-mode phase velocities to satisfy a wide range of coupler slot geometries.

Another key parameter to consider is the combination of dielectrics in the lower substrates. It is important to note that the upper substrate dielectric constant, $\epsilon_{r_{L2}}$, must be greater than the lower substrate dielectric constant, $\epsilon_{r_{L1}}$, for even- and odd-mode phase velocity equalization to occur, a characteristic similar to multilayer coupled microstrips [6]. However, it is still left to be determined how much greater the upper substrate dielectric constant must be for modal equalization. Fig. 2(b) demonstrates this for an edge-coupled CPW using an upper substrate with dielectric constant equal to 13.6, simulating gallium arsenide, while the lower substrate dielectric constant is varied. The lower portion of the abscissa of Fig. 2(b) corresponds to the first modal equalization height ratio, or first low-coupling root, while the upper portion of the abscissa corresponds to the second low-coupling root. As the lower substrate dielectric constant is varied for values $1.0 \leq \epsilon_{r_{L1}} \leq 7.5$, both low-coupling roots move closer to each other and eventually meet at a single substrate height combination. For values of $\epsilon_{r_{L1}} > 7.5$, there is no substrate height combination for which the even- and odd-modes can be completely equalized. Since, this upper range of values does not lead to modal equalization, a value of $\epsilon_{r_{L1}} \approx 7.5$ is considered an upper limit for the dielectric constant of the lower substrate. For dielectric constants above this maximum value, only a single height ratio can be found that minimizes, but does not eliminate, the difference between the phase velocities of each mode, as shown in Fig. 2(b). However, to guarantee at least two modal equalization points, the dielectric constant of the lower substrate, $\epsilon_{r_{L1}}$, should be chosen such that it is much less than that of the upper substrate, $\epsilon_{r_{L2}}$.

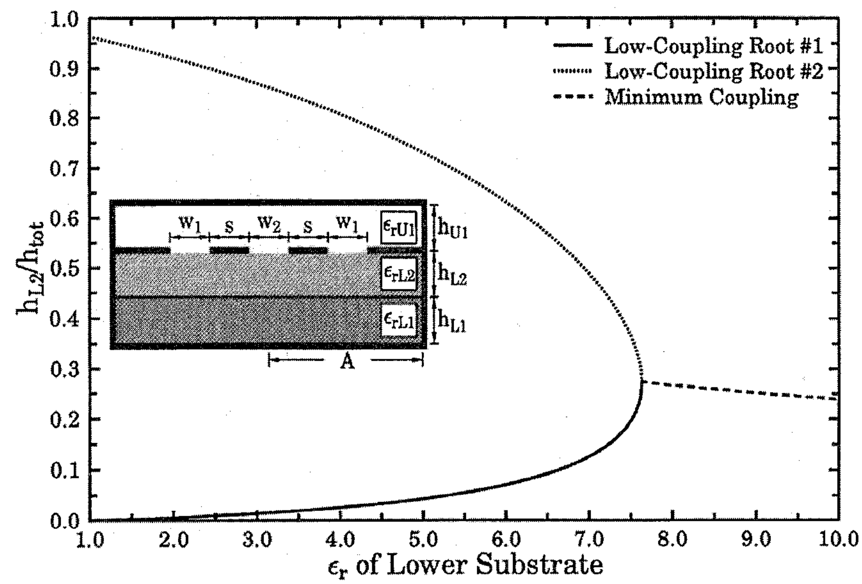
To demonstrate the effectiveness of this modal velocity equalization technique, two edge-coupled CPW structures are considered: uncompensated and compensated. The uncompensated structure is chosen such that it uses only one substrate of gallium arsenide ($\epsilon_r = 13.6$) while the compensated structure uses a multilayer substrate configuration such that the heights are chosen using a low-coupling root or height ratio as in Fig. 2(b) when using a substrate of gallium arsenide above a duroid ($\epsilon_r = 2.2$) layer. The uncompensated case will be addressed first, followed by the compensated structure.

Fig. 3(a) shows the even- and odd-mode effective dielectric constants as a function of frequency for the uncompensated structure. When only one substrate is used, the odd-mode ϵ_{reff} is greater than the even-mode over all frequencies. In the frequency range under 60 GHz, only the odd-mode increases slightly while the even-mode remains relatively constant. As the frequency is increased, the even-mode begins to show more dispersion and asymptotically approaches the odd-mode ϵ_{reff} at high frequencies. Although both even- and odd-modes show only small dispersion in the low frequency range (especially the even-mode), the difference in effective dielectric constants (or phase velocities) of the two modes is sufficient to cause severe pulse distortion when using wide-band pulses.

To investigate pulse propagation and distortion in edge-coupled CPW's, a Gaussian pulse with unit amplitude and HWHM of 10 ps is used. For such a pulse the most significant amplitude distribution



(a)

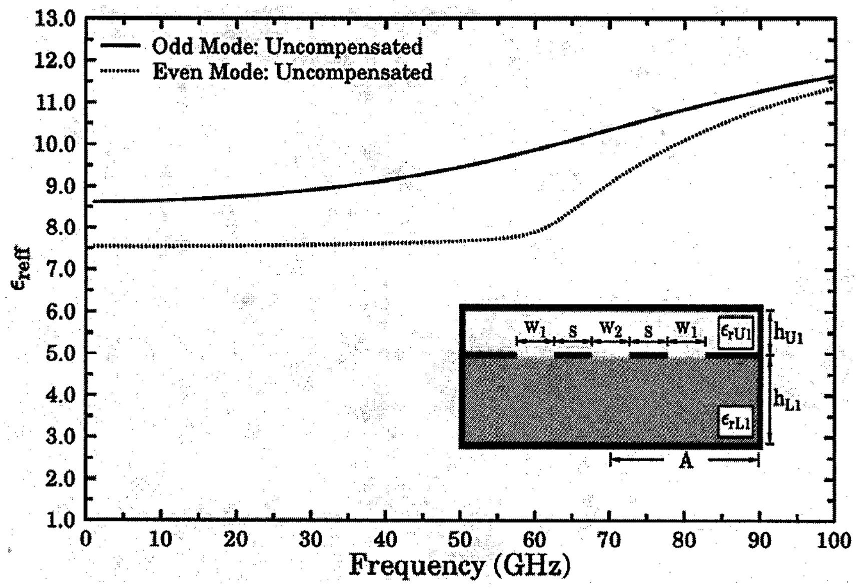


(b)

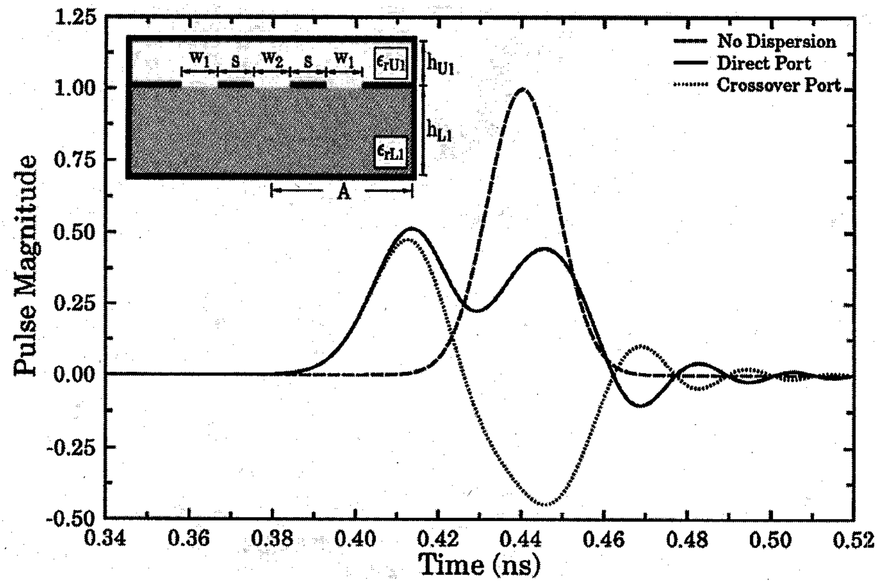
Fig. 2. (a) Even- and odd-mode ϵ_{reff} as a function of substrate height ratio for various slot spacings ($\epsilon_{rL1} = 2.2$). (b) Low-coupling points versus ϵ_r of lower substrate in a multilayer edge-coupled CPW coupler ($s = 100$ μm). (Geometry parameters: $w_1 = 50$ μm, $w_2 = 30$ μm, $f = 1$ GHz, $\epsilon_{rL2} = 13.6, \epsilon_{rU1} = 1.0$, $A = 1$ mm, $h_{U1} = 10$ mm, $h_{\rm tot} = h_{L1} + h_{L2} = 100$ μm.)

is bandlimited, in this case $\approx$ 50 GHz, and higher frequencies do not critically affect the overall spectrum. Pulse propagation in the uncompensated edge-coupled CPW structure of 45 mm length is depicted in Fig. 3(b). A single pulse is incident at the direct port, and the outputs at both direct and crossover ports are plotted at a distance along the coupler [see Fig. 1(a)]. The distances for each pulse are scaled appropriately so that the pulses arrive at similar times since each travels at a different speed along the line. This more clearly demonstrates the distortion mechanisms seen in each pulse. The undistorted pulse is also shown for reference. Referring to Fig. 3(b), the pulse at the direct port shows distortion in the form of amplitude reduction by almost 50 percent and significant pulse spreading. The coupling at the crossover port is also seen to have amplitude of almost 50 percent that of the input pulse. The effects of both even- and odd-modes are quite apparent for this case with the direct port separating into two separate positive pulses, and crossover port separating into one positive and one negative pulse. Since the even-mode is faster than the odd-mode in this case, the leading edge of the pulse at the crossover port is positive while the trailing edge is negative. Dispersion distortion is also present in the form of pulse ringing seen on the trailing edge at each output port. Clearly, the effects of even- and odd-mode distortion can lead to extremely degraded signal output and significant coupling on adjacent lines.

The compensated configuration attempts to equalize the modal velocities using the second low-coupling height ratio in Fig. 2(b). Referring to Fig. 2(b), this corresponds to a value of $h_{L2}/h_{\rm tot}$ equal to 0.911 when using duroid ($\epsilon_{r_{L1}} = 2.2$) as a lower substrate. The total substrate height is the same as used in the uncompensated



(a)



(b)

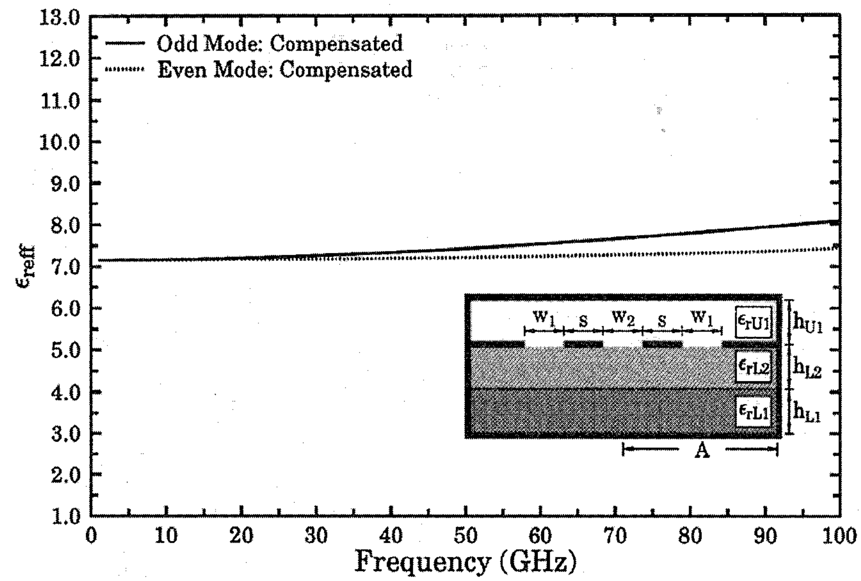
Fig. 3. (a) Even- and odd-mode effective dielectric constants as a function of frequency for an uncompensated structure. (b) Gaussian pulse distortion on edge-coupled CPW forward directional coupler, uncompensated case (τ = 10 ps, L = 45 mm). (Geometry parameters: $w_1 = 50\ \mu\text{m}, w_2 = 30\ \mu\text{m}, s = 100\ \mu\text{m}, \epsilon_{rL1} = 13.6, \epsilon_{rU1} = 1.0, A = 1$ mm, $h_{U1} = 10$ mm, $h_{L1} = 100\ \mu$m.)

structure, and a thin lower substrate is inserted with height equal to 8.9 μm while the upper substrate height is set at 91.1 μm. Fig. 4(a) shows the even- and odd-mode effective dielectric constants as a function of frequency for the compensated structure and should be compared to Fig. 3(a) of the uncompensated geometry. The even- and odd-modes are equalized quite well for low frequencies less than 20 GHz but begin to diverge gradually with increasing frequency. Although the even- and odd-mode phase velocities are not equalized for all frequencies in the compensated structure, the difference between the velocities has been successfully reduced using the low-coupling substrate height configuration, especially in the lower frequency range. The even-mode is less dispersive than the odd-mode in the compensated case; however, both modes show little dispersion over the frequency range considered. Although the modal dispersion effects seen here are quite minimal, it should be noted that the dispersion of each mode may also contribute to the overall distortion of a pulse [6].

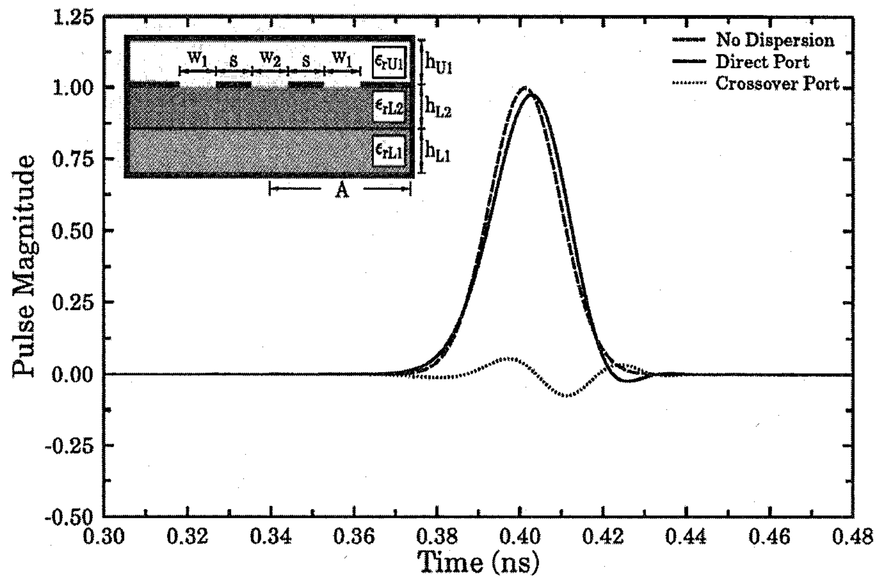
Pulse propagation and distortion along the compensated structure is shown in Fig. 4(b) over the same length used in the uncompensated case as in Fig. 3(b). After traveling a distance of 45 mm, the output pulse at the direct port appears to have suffered only a slight shift with respect to the undistorted pulse as shown in Fig. 4(b). At the crossover port, there is a small signal with maximum amplitude less than about 8 percent of the undistorted pulse. In contrast to the uncompensated case of Fig. 3(b), the pulse distortion and dispersion has been greatly reduced using a low-coupling height ratio design.

IV. Design Considerations

In practical circuit designs of low-coupling structures using multilayer substrates, the choice of substrate dielectric constants and



(a)



(b)

Fig. 4. (a) Even- and odd-mode effective dielectric constants as a function of frequency for a compensated structure. (b) Gaussian pulse distortion on edge-coupled CPW forward directional coupler, compensated case ($\tau = 10$ ps, $L = 45$ mm). (Geometry parameters: $w_1 = 50\ \mu$m, $w_2 = 30\ \mu$m, $s = 100\ \mu$m, $\epsilon_{rL1} = 2.2$, $\epsilon_{rL2} = 13.6$, $\epsilon_{rU1} = 1.0$, $A = 1$ mm, $h_{U1} = 10$ mm, $h_{L1} = 8.9\ \mu$m, $h_{L2} = 91.1\ \mu$m.)

heights are extremely important. To achieve low-coupling in a multilayer edge-coupled CPW structure, the upper substrate dielectric constant must be greater than the lower substrate dielectric constant, as previously noted. It was shown that there are two low-coupling height ratios for such a structure. If the dielectric constant of the upper substrate is close in value to the lower substrate, the low-coupling height ratios tend to vary as a function of frequency. However, if the dielectric constant of the upper substrate is much greater than that of the lower substrate, the low-coupling height ratios remain essentially constant as a function of frequency, which is important in the design of low-coupling and low pulse distortion structures. Typically, to ensure at least two different low-coupling points that are relatively constant as a function of frequency, the ratio of upper substrate dielectric constant to lower substrate dielectric constant must be at least 2 : 1.

The choice of low-coupling height ratio is also important. Depending on which height ratio is chosen, different combinations of thick and thin substrates result. Typically, the first low-coupling height ratio requires a very thin upper substrate above a thick lower substrate while the second low-coupling height ratio uses a thick upper substrate above a very thin lower substrate. The combination of substrates is chosen based upon the circuit application and typical materials available. For example, a circuit using primarily gallium arsenide ($\epsilon_r = 13.6$) as a substrate would most likely use the second low-coupling height ratio with a very thin lower substrate of smaller dielectric constant (such as air or duroid) inserted below the gallium arsenide substrate. However, a circuit using primarily duroid ($\epsilon_r = 2.2$) as a substrate may use the first low-coupling height ratio with a very thin upper substrate of high dielectric constant inserted above a lower duroid substrate.

Consideration must also be made concerning whether such a mode equalizing structure is physically realizable. Referring to Fig. 2(b), the low-coupling height ratios shown exactly equalize the even- and odd-modes at a given frequency which may not be physically realizable in many circuit designs. However, choosing height combinations as close as possible to these ideal low-coupling height ratios will tend to minimize the overall effects of pulse distortion and coupling in edge-coupled CPW's.

V. Conclusion

A full-wave analysis was used to calculate the effective dielectric constants for even- and odd-modes of edge-coupled, CPW forward directional couplers in multilayer substrate structures using a conductor-backed ground plane. It was found that the phase velocities of both even- and odd-modes can be equalized for specific multilayer substrate height combinations over a wide range of slot geometries, suggesting that a single multilayer substrate configuration may be used to control pulse distortion and coupling for wideband signals. When the lower substrate dielectric constant is much less than the upper substrate dielectric constant, it was found that these low-coupling height combinations can lead to circuit designs using combinations of thick and very thin substrates. Dispersion and coupling of a 10ps Gaussian pulse were presented for uncompensated and compensated configurations. It was shown that a multilayer structure using substrate height combinations that equalize both even- and odd-mode phase velocities can significantly reduce coupling and distortion effects. Design guidelines applicable toward practical MIC and MMIC structures were also presented.

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Computation of Excess Capacitances of Various Strip Discontinuities Using Closed-Form Green's Functions

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***Abstract*—An efficient quasi-static method to compute excess (equivalent) capacitances of various strip discontinuities in a multilayered dielectric medium is presented. The excess charge distribution on the surface of a conductor is obtained by solving an integral equation in conjunction with closed-form Green's functions. A complete list of expressions of the closed-form Green's functions for a point charge, a line charge, and a semi-infinite line charge is presented. An open end, a bend, a step junction, and aT junction are considered as numerical examples.**

I. Introduction

Quasi-static analysis is often performed to characterize strip discontinuities when the dimensions of the discontinuities are much smaller than the wavelength. Under the quasi-static analysis, the dominant effect of strip discontinuities is fringing fields due to the physical irregularities of discontinuity geometries. The modeling of these fringing fields in terms of an excess capacitance is discussed in this paper.

Numerous papers have been published to compute excess capacitances of various microstrip discontinuities, and a summary of popular methods can be found in [1]. The most successful approach is one based on the formulation of an integral equation in terms of the excess charge distribution, which was first proposed by Silvester and Benedek [2] and has been applied to analyze various microstrip discontinuities [2]–[5]. The Green's function for a layered medium is employed in this approach. For N dielectric layers, the expression for this Green's function would consist of an $N - 1$ nested infinite series [6]; hence, in practice, this form of the Green's function may

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