# Enhanced Dominant Mode Operation of a Shielded Multilayer Coplanar Waveguide Via Substrate Compensation

Michael R. Lyons, James P. K. Gilb and Constantine A. Balanis

*Abstract*—**The cutoff frequency of the first higher-order even mode in a shielded multilayer coplanar waveguide (CPW) is studied using the spectral domain approach (SDA). The effective dielectric constant for the dominant odd mode and first higher-order even mode in a shielded multilayer CPW is computed and compared to other published numerical results. Dielectric constant and substrate height are varied with respect to even mode cutoff frequency and plotted for several CPW structures. Different combinations of internal substrates are shown to produce even mode cutoff frequency maximization for increased odd mode operation bandwidth.**

## I. Introduction

Current monolithic microwave integrated circuits (MMICs) are showing trends in fabrication toward coplanar and hybrid designs. The symmetrical multilayer coplanar waveguide (CPW) is one such device and with increasing use, it is necessary to characterize its higher order modes and examine dominant mode operation for practical application. Due to the dual slot-line geometry of the CPW, two fundamental modes can exist, even and odd. The dominant mode of a symmetrical mutilayer CPW structure is generally referred to as the odd mode, which converges to the quasistatic or quasi-TEM mode for low frequencies [1]. Most research involving the CPW has dealt with the dominant odd mode and its propagation characteristics.

Comparisons of the CPW to simpler constructions such as a conductor backed slab or parallel plate waveguide have been made in regard to simple design considerations [2]. More accurate frequency dependent solutions have been obtained using full-wave analyses such as the spectral domain approach (SDA) [3]–[7], a technique known for its computational efficiency and speed. Increased interest in higher operating frequencies necessitates accurate and efficient frequency domain analyses of the CPW for future circuit designs.

Multilayer substrate and superstrate configurations have been studied and considered for CPW as well as other planar transmission line structures, such as microstrip [3], [5], [8]–[10]. The versatility of using multilayer substrates for coupled microstrips can be seen in [11] for even and odd mode phase velocity equalization. While the ideal CPW is generally considered to have infinite lateral ground planes and an infinitely thick supporting substrate, practical circuits cannot be infinite. Therefore it is necessary to consider finite conditions, such as side walls and upper and/or lower shielding. In some MMIC packages, external upper, lower, and lateral shielding may seriously affect circuit behavior and must be taken into account. Design guidelines for dominant mode operations of an ideal CPW have been established [2]. Dispersion effects of shielded multilayer CPWs have also been reported [3], [7]. However, no full-wave analyses for maximizing bandwidth of the dominant odd mode for shielded multilayer CPWs have been presented.

In this paper, the spectral domain approach (SDA) [8] is implemented to characterize shielded multilayer CPWs and their higher-order modes with respect to the dominant odd mode and operating bandwidth. The first higher-order mode of a shielded multilayer CPW, the even mode, exhibits a cutoff frequency that can be calculated efficiently using an SDA formulation. Propagation characteristics for the odd and even mode are presented for the shielded multilayer CPW and compared with previously reported data [3]. The cutoff frequency of the even mode is computed for different substrate combinations and dielectric constants ($\epsilon_r$). These results show that the bandwidth of a shielded multilayer CPW may be increased using certain multilayer combinations.

## II. Analysis

Solving the CPW boundary value problem in the spectral domain $(\beta_x, \beta_z)$ yields two equations relating the Fourier transformed conductor currents to the electric fields. These equations can be expressed as [8]

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

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

where $\tilde{H}_{zz}$, $\tilde{H}_{xx}$, $\tilde{H}_{xz}$, and $\tilde{H}_{zx}$ are the dyadic Green's functions for the system. The currents are eliminated using Galerkin's method, and the electric fields are expanded in sets of known basic functions.

The cutoff frequency for a given mode in a waveguiding system can be calculated when $\beta_z = 0$. Setting the determinant of the electric field and Green's function coefficient matrix

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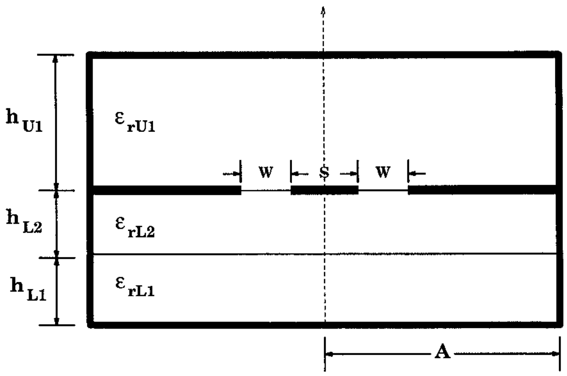


Fig. 1. Geometry for a symmetric, shielded, 3-layer CPW.

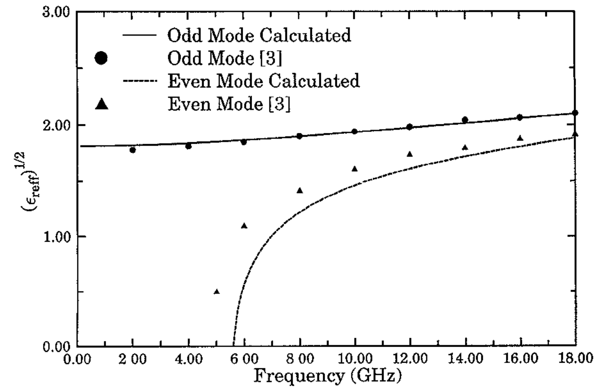


Fig. 2. $\sqrt{\epsilon_{reff}}$ of the dominant odd mode and first higher-order even mode as a function of frequency in a shielded multilayer CPW ($h_{L1} = h_{U1} = 4.5$ mm, $h_{L2} = 1.0$ mm, $A = 10.0$ mm, $w = s = 2.0$ mm, $\epsilon_{rL1} = \epsilon_{rU1} = 1.0$, $\epsilon_{rL2} = 9.35$).

equal to zero determines the cutoff frequencies for the higher-order modes of the system.

## III. Results

Dispersion characteristics for a shielded multilayer CPW were investigated using the SDA. A general 3-layer shielded CPW structure is depicted in Fig. 1. Fig. 2 shows a plot of $\sqrt{\epsilon_{reff}}$ versus frequency for a 3-layer shielded CPW. Data points from [3, Fig. 6.9] have been plotted on the figure for comparison. The dominant odd mode's $\sqrt{\epsilon_{reff}}$ showed less than 1.0% error from [3], while the even mode showed greater discrepancy. Two significant factors in calculating higher-order mode characteristics are the choice of basis function and number of basis functions used in expansion. For this investigation, the expansion functions used were those of Uwano and Itoh [12] which account for the edge condition of the conductors. Three expansion functions were used for $\tilde{E}_x$ and two expansion functions for $\tilde{E}_z$. Note the weak frequency dependence of the dominant odd mode in Fig. 2. This characteristic makes the dominant odd mode the desired propagating mode for wide-band operation. As the frequency is increased, the even mode $\epsilon_{reff}$ ($\epsilon_{reffe}$) gradually approaches the dominant odd mode $\epsilon_{reff}$ ($\epsilon_{reff_o}$). This behavior is typical of a symmetrical CPW [6] and also the dual problem of coupled symmetric microstrip lines [11].

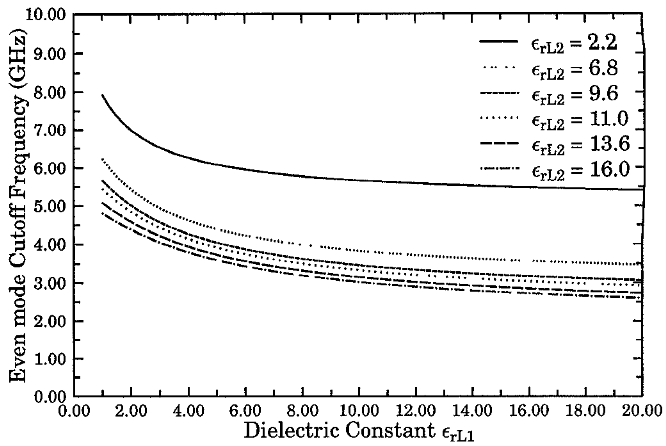


Fig. 3. Even mode cutoff frequency as a function of substrate dielectric constant in a shielded 3-layer CPW ($h_{L1} = h_{L2} = 1.0$ mm, $h_{U1} = 5.0$ mm, $A = 10.0$ mm, $w = s = 1.0$ mm, $\epsilon_{rU1} = 1.0$).

Maximizing the operating bandwidth of the dominant odd mode implies maximizing the cutoff frequency of the first higher-order mode, the even mode. The CPW is, by nature, locally dependent or locally contained. This means that the dominant electric fields are locally bound near or in the coplanar slots of the CPW. Therefore, any significant changes in circuit performance should be from local changes near or around the coplanar slots. In this initial investigation there were two degrees of freedom considered for controlling the cutoff frequency of the higher-order even mode in the shielded multilayer CPW: (1) substrate dielectric constant and (2) substrate thickness (which also incorporates upper and lower shielding effects).

The even mode cutoff frequency of a shielded multilayer CPW is dependent on the dielectric constant of the substrates. Fig. 3 demonstrates the effect of varying the dielectric constant of one layer in a 3-layer shielded CPW. For this geometry, $\epsilon_{rL1}$ is varied for six values of $\epsilon_{rL2}$. Of the six cases shown, the highest cutoff frequency for any given structure is seen for the lowest possible dielectric constant (i.e., $\epsilon_{rL1} = 1.0$ or air). However, a maximum even mode cuttoff frequency may be achieved for certain multilayer CPW configurations. It is necessary to develop maximum even mode cutoff frequency guidelines as will be later shown. Note in Fig. 3 that the even mode cutoff frequency is less dependent on the value of $\epsilon_{rL1}$ as it increases. This is true for all six cases in Fig. 3. The lower substrate of $\epsilon_{rL1}$ has less effect on circuit performance, since electric field penetration is reduced in this layer as the value of $\epsilon_{rL1}$ increases.

The height of each substrate layer also affects the cutoff frequency of the even mode. There are three possible height variations for the shielded multilayer CPW, upper shielding, lower shielding, and internal substrates (i.e., substrates not touching the upper or lower shielding). By increasing the upper and/or lower shielding height, the size of the enclosure is increased. Fig. 4 shows the cutoff frequency of the even mode versus the upper shielding height for a 3-layer shielded CPW structure. The even mode cutoff frequency is seen to decrease with increasing upper shielding (or upper superstrate)

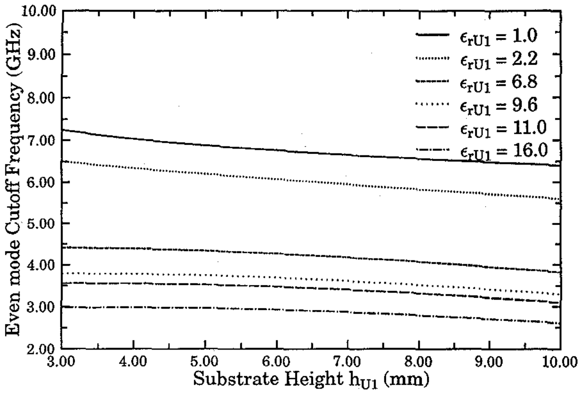


Fig. 4. Even mode cutoff frequency as a function of upper shielding height in a shielded 3-layer CPW ($h_{L1} = h_{L2} = 1.0$ mm, $A = 10.0$ mm, $w = s = 1.0$ mm, $\epsilon_{rL1} = \epsilon_{rL2} = 2.2$).

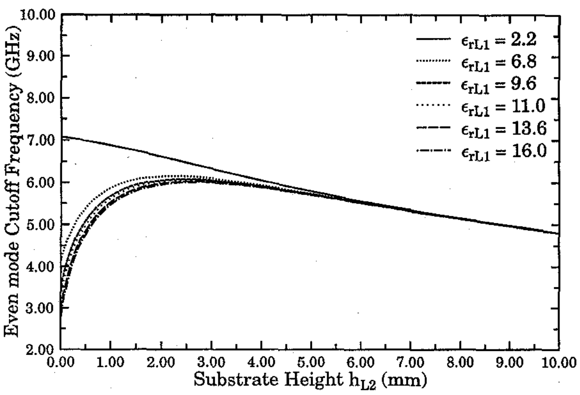


Fig. 5. Even mode cutoff frequency as a function of internal supporting substrate height ($h_{L2}$) with lower dielectric constant ($\epsilon_{rL1}$) varied in a shielded 3-layer CPW ($h_{L1} = 1.0$ mm, $h_{U1} = 5.0$ mm, $A = 10.0$ mm, $w = s = 1.0$ mm, $\epsilon_{rL2} = 2.2$, $\epsilon_{rU1} = 1.0$).

height. The same trend is observed when the height of the lower shielding (or lower substrate) is increased.

Multilayer (more than 3) structures all have at least one internal substrate. Internal substrate variation is the most likely candidate for maximizing the cutoff frequency of the even mode in a shielded CPW. This is evident since internal substrates are near or in contact with the coplanar slots. Therefore, changes at the slots should have a greater effect on a given system, due to the localized fields in the slots. This is indeed the case as seen in Fig. 5. There appears to be a maximization point for the cutoff frequency of the even mode in all six cases. For the case of $\epsilon_{rL1} = 2.2$, it is maximized when $h_{L2} = 0$. However, for the other five cases, the even mode cutoff frequency is maximized for a specific multilayer combination, i.e., $h_{L2} \neq 0$. The introduction of an additional supporting substrate layer, of height on the order of the lower substrate, allows the cutoff frequency of the even mode to reach a maximum value. For certain structures, varying the supporting substrate height can have dramatic effects on the even mode cutoff frequency.

Fig. 6 shows the even mode cutoff frequency versus substrate height ($h_{L2}$) for a 3-layer shielded CPW. The lower substrate dielectric constant is kept constant at $\epsilon_{rL1} = 13.6$ for GaAs, and the supporting substrate dielectric constant $\epsilon_{rL2}$ is varied. Note for the case where $\epsilon_{rL2} = 2.2$, the cutoff frequency of the even mode may be maximized to twice that of having no internal substrate (i.e., $h_{L2} = 0$) by the addition of a supporting substrate layer with height approximately $h_{L2} = 2.6$ mm. The same maximization is also seen for the next three cases, but to a smaller extreme. Even mode cutoff frequency maximization for a 3-layer CPW using an internal substrate ceases when the dielectric constant of the supporting substrate ($\epsilon_{rL2}$) is greater than or equal to the lower substrate dielectric constant ($\epsilon_{rL1}$). This is due to the reduced electric field penetration within the supporting substrate layer, as the dielectric constant $\epsilon_{rL2}$ is increased.

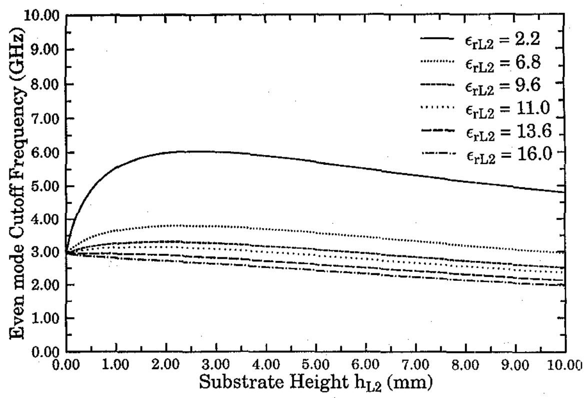


Fig. 6. Even mode cutoff frequency as a function of internal supporting substrate height ($h_{L2}$) for varied supporting substrate dielectric constant ($\epsilon_{rL2}$) in a shielded 3-layer CPW ($h_{L1} = 1.0$ mm, $h_{U1} = 5.0$ mm, $A = 10.0$ mm, $w = s = 1.0$ mm, $\epsilon_{rL1} = 13.6$, $\epsilon_{rU1} = 1.0$).

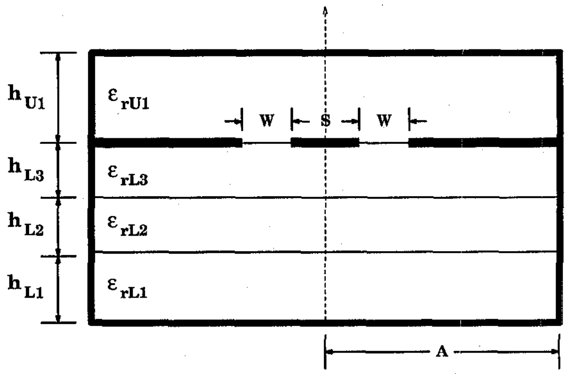


Fig. 7. Geometry for a symmetric, shielded, 4-layer CPW.

This technique of maximizing the even mode cutoff frequency was also studied in a 4-layer shielded CPW structure as shown in Fig. 7. In Fig. 8, a 4-layer shielded CPW with air for upper and lower dielectrics and two supporting substrates was examined. By varying the height of the direct supporting substrate $h_{L3}$, a similar even mode cutoff frequency maximization effect is seen for varying supporting substrate dielectrice $\epsilon_{rL3}$.

## IV. Conclusions

The effects of dielectric constant and substrate height on the propagation characteristics of multilayer shielded symmetrical CPWs were examined using a full-wave SDA analysis. It was found that the shielded CPW's effective dielectric constant displayed a cutoff frequency for the even mode. Internal

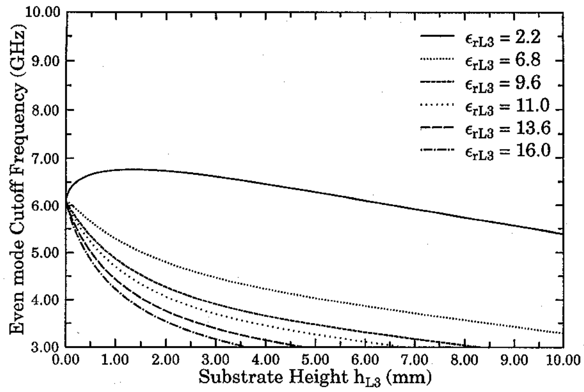


Fig. 8. Even mode cutoff frequency as a function of internal supporting substrate height ($h_{L3}$) for varied supporting substrate dielectric constant ($\epsilon_{rL3}$) in a shielded 4-layer CPW ($h_{L1} = h_{L2} = 1.0$ mm, $h_{U1} = 3.0$ mm, $A = 10.0$ mm, $w = s = 1.0$ mm, $\epsilon_{rL1} = \epsilon_{rU1} = 1.0$, $\epsilon_{rL2} = 9.6$).

substrates adjacent to the coplanar slots were found to have the greatest even mode cutoff frequency control due to the localized slot fields. A maximization effect for the even mode cutoff frequency was demonstrated using internal substrate compensation. This was seen for low values of internal, or supporting, dielectric constants when the supporting substrate dielectric constant was less than or equal to the lower substrate dielectric constant.

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