Effects of Metal Thickness and Finite Substrate Width on Leaky Waves in Coupled Microstrip Lines

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Abstract

The propagation characteristics of leaky waves in *thick* coupled microstrip lines integrated on substrate with *infinite* and *finite* widths are presented. The field-theoretic results, based on the full-wave mode-matching method incorporating the metal modes, show that the thickness of metal strips can convert a non-leaky bounded mode into a leaky wave. On the other hand, when the infinite substrate width is reduced to a finite value, a leaky wave may become a bounded propagation mode and additional leaky waves are found. The effects of metal thickness and finite substrate width on leaky waves are discussed.

Introduction

Leaky modes have been found to exist in many planar or quasi-planar transmission lines such as microstrip lines [1,2,3], coplanar strips [4,5,6], slotlines [4,6], broadside-coupled microstrips [7], and coplanar waveguides (CPWs) [4,8]. Besides the serious power loss from the guided regions, the leaky energy is spread out at an angle from the transmission line, and may cause undesirable crosstalks between neighboring elements and unexpected package effects in the circuits [9].

In the past, the investigations on the leakage effects have undergone the assumption that the integrated substrate is extended into infinity. Therefore the results reported thereby can not account for the practical situation that the integrated substrate has finite dimension, since the substrate discontinuity will change the propagation characteristics of the leaky waves. Besides it is well known that the metal strip thickness may change the dominant mode propagation constant appreciably for certain quasi-planar transmission lines [10]. It is likely that the leakage effects may occur unexpectedly for certain transmission lines using thick metal strips. To authors' knowledge the effects of finite substrate width and metal thickness on the leaky modes have never been discussed. In this paper, rigorous investigations on such effects are conducted. For example, the coupled microstrip lines shown in Fig. 1, which considers the finite metal thickness and conductivity, will be studied. The substrate of relative dielectric constant ϵ_r can be infinite or finite in size. A top cover plate is also included in Fig. 1. A network representation of full-wave mode-matching method incorporating the air modes and metal modes [11,12] is applied to solve the propagation characteristics of Fig. 1. The descriptions of the formulation had been reported in [11].

In this paper, the dispersion curves of the thick coupled microstrip lines are compared to those reported by Carin [7]. Interestingly a non-leaky mode in the coupled microstrip lines assuming infinitely thin metal strips can become leaky if the metal strips are assumed to be thick enough. The dispersion characteristics of the three dominant modes [7], namely, EM1, EM2, and EE, are compared and discussed in Section II. Assuming that the metal strips have the same thickness, Section III reports a comparative study for the dispersion characteristics of the coupled microstrip lines integrated on finite or infinite substrates. The leaky-wave properties for these two guided structures are quite different. Section IV concludes the important effects of the metal thickness and the finite substrate width on the leaky-wave propagations.

Effects of Metal Thickness on Leaky Waves

The guided-wave structure shown in Fig. 1 is a special case of the broadside-coupled microstrip with an electric wall (symmetry) in the horizontal plane (See Fig. 1 of [7], pp. 561). Therefore three quasi-TEM dominant modes exist, namely, EM1, EM2, and EE. The first two modes, EM1 and EM2, have even symmetry about y-axis while the third mode, EE, has odd symmetry. Using the same structural parameters given by Carin [7], we compare the dispersion characteristics of the coupled microstrip lines assuming finite and infinitely thin metal thicknesses. The dispersion data for the case assuming infinitely thin metal thickness are extracted from Fig. 2 of [7]. Here we assume the finite metal thickness of 30 μm for the comparative study.

Carin's data [7], obtained by assuming infinitely thin metal strips, are plotted under square symbols connected by dash-dotted lines for the normalized phase constants and attenuation constants in Fig. 2 and Fig. 3, respectively. The solid lines shown in Fig. 2 and Fig. 3 are the corresponding data assuming metal strips of 30 μm thickness. All the phase constants for the case assuming 30 μm metal thickness have lower values than their counterparts. Such phenomenon is well known for microstrip, of which the value of propagation constant is decreased by increasing the metal strip thickness [10].

The EE mode, which does not leak when assuming infinitely thin metal thickness, becomes a leaky wave at about 14 GHz since its phase constants are decreased and below those of the partially filled parallel-plate TM_0 mode, shown by the broken line in Fig. 2, by increasing the metal thickness. The attenuation constants for the EM1 leaky wave and the new leaky EE wave caused by thick metal strips are shown in Fig. 3. When the leaky wave happens, it leaks in the form of partially filled parallel-plate TM_0 mode. The new leaky EE wave leaks at an angle nearly parallel to the coupled microstrip lines.

Effects of Finite Substrate Width on Leaky Waves

Keeping the same metal thickness of 30 μm and substrate relative permittivity $\epsilon_r = 4$, Fig. 4 and Fig. 5 compare the dispersion characteristics of coupled microstrip lines integrated on substrate with either finite width, $w_D = 3w$, or infinite width, $w_D = \infty$. The three bounded EM2, leaky EE and leaky EM1 dominant modes assuming $w_D = \infty$ are denoted by triangles, squares and circles, respectively. The three corresponding dominant modes assuming finite substrate width $w_D = 3w$ are plotted in solid lines and enumerated as EM2', EE' and EM1', respectively. When comparing EM2 mode with EM2' mode in Fig. 4, one observes significant variation in phase constants near low frequency region. EM2' extends more of its electromagnetic energy into the outside air region, i.e., $|x| > s/2 + w + w_D$. Therefore the normalized phase constants are reduced in the low frequency region.

The leaky EE wave, which leaks in the form of TM_0 parallel-plate waveguide mode at all frequencies, now converts to the non-leaky bounded EE' mode. The normalized phase constants become higher than those of the TEM parallel-plate mode, $\beta/ko = 1$. Therefore it can't leak when $w_D = 3w$. The EE mode found here is very similar to that reported by Carin [7] even when both metal thickness and finite conductivity are considered here.

As shown in Fig. 4 and Fig. 5, the leaky EM1 wave converts itself into a non-leaky bounded EM1' mode, which is very similar to the dominant image guide mode with even symmetry in terms of its electromagnetic field pattern. Again the finite substrate width does affect the leaky-wave propagations.

Additional leaky waves for the image-guide-like higher-order modes are found. Their dispersion curves, denoted by dotted lines, are also shown in Fig. 4 and Fig. 5, respectively. These leaky waves leak in the form of TEM parallel-plate mode. Above the leaky wave region, $\beta/k_o > 1$, their electromagnetic field patterns resemble the image-guide modes except some perturbations occur near the metal strips.

Conclusions

The effects of metal thickness and finite substrate width on the leaky wave propagations of the coupled microstrip lines are presented. Integrated on the infinite substrate, the coupled microstrip lines are found to convert a non-leaky bounded EE mode assuming infinitely thin metal thickness into a leaky EE wave travelling nearly parallel to the coupled microstrip lines when assuming 30 μm thick metal strips.

Given the same metal thickness of 30μm, the leaky EE and EM1 modes assuming infinite substrate width becomes a bounded EE' and EM1' modes assuming finite substrate width. On the other hand, additional leaky waves are found when assuming finite substrate width. Above the cutoff frequencies of these newly found leaky waves, they are the well-known bounded image-guide modes.

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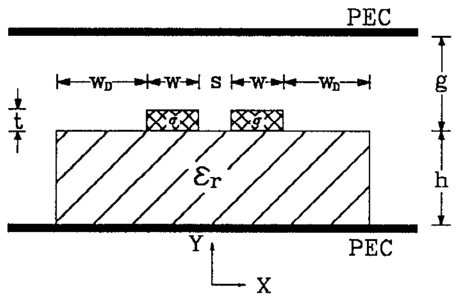

Fig. 1 Cross-sectional view of the thick coupled microstrip lines. Structural parameters: w = s = h = 0.6 mm, t = h/20 = 0.03 mm, Top cover height = g+h = 0.75 mm, and conductivity σ = 3.33×10^7 mhos/m. Dielectric constant ϵ_r = 10 (Figs.2 and 3) or ϵ_r = 4 (Figs. 4 and 5). w_D = ∞ for infinite-width substrate (Figs. 2, 3, 4 and 5) and w_D = 3w for finite-width substrate (Figs. 4 and 5).

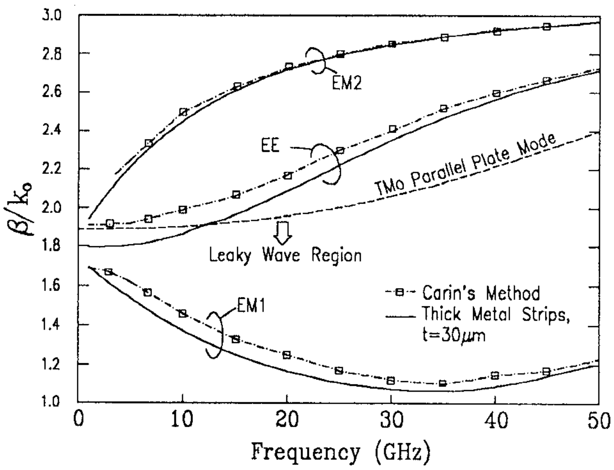

Fig. 2 Comparison of the dispersion characteristics of coupled microstrip lines assuming metal strips of finite and infinitely thin thickness. (a) Normalized phase constants, β/k_o (for w_D = ∞ and ϵ_r = 10).

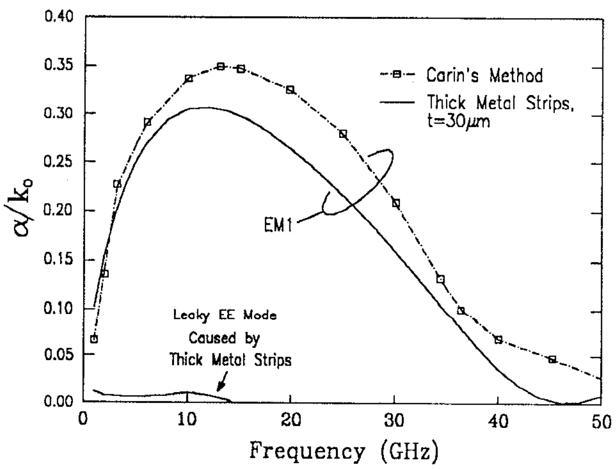

Fig. 3 Comparison of the dispersion characteristics of coupled microstrip lines assuming metal strips of finite and infinitely thin thickness. (b) Normalized attenuation constants, α/k_o (for w_D = ∞ and ϵ_r = 10).

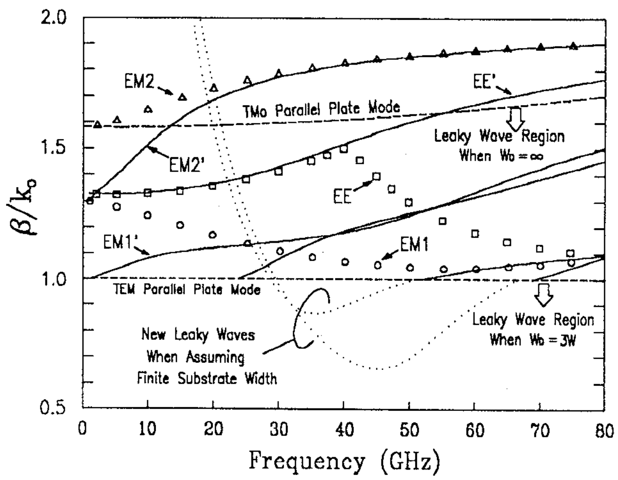

Fig. 4 Comparison of dispersion characteristics of coupled microstrip lines integrated on substrate of ϵ_r = 4 with either finite width or infinite width. (a) Normalized phase constants, β/k_o. Solid and dotted lines denote the results assuming finite substrate width, w_D = 3w. Symboled lines represent the results assuming infinite substrate width, w_D = ∞.

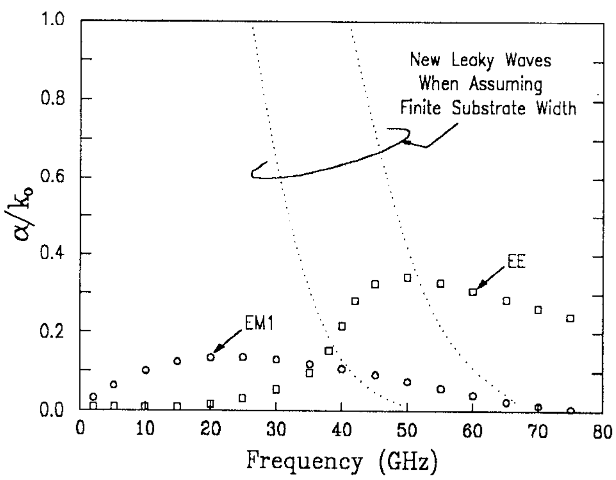

Fig. 5 Comparison of dispersion characteristics of coupled microstrip lines integrated on substrate of ϵ_r = 4 with either finite width or infinite width. (b) Normalized attenuation constants, α/k_o. Solid and dotted lines denote the results assuming finite substrate width, w_D = 3w. Symboled lines represent the results assuming infinite substrate width, w_D = ∞.