NOVEL MODAL TRANSITION FOR LEAKY MODES ON MICROSTRIP LINES

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ABSTRACT

In this paper it is shown that a novel transition may occur for dominant leaky modes on microstrip line, between a leaky mode that leaks into the TM_0 surface-wave and one that leaks both into the TM_0 surface wave and into space. The evolution of these leaky modes is studied as a function of frequency by means of a full-wave spectral domain approach, and it is shown that such a transition may occur on microstrip lines that have a critical strip width, which is relatively large. The continuous-spectrum current excited by a finite source can be significantly enhanced when the frequency is near the transition frequency, resulting in very high spurious effects.

INTRODUCTION

The study of leaky modes on printed-circuit lines has received considerable attention in recent years, due to their role in the representation and explanation of spurious transmission effects, especially at high frequencies. Such undesirable effects include power loss, crosstalk with adjacent lines or circuits, and interference between the fundamental quasi-TEM mode and the continuous spectrum (often dominated by the leaky mode) excited by practical sources [1], [2].

For unshielded structures (such as microstrip lines) two types of leaky modes may generally exist, i.e., surface-wave leaky modes (SFWLM) and space-wave leaky modes (SPWLM). The former type of mode leaks into one or more surface waves supported by the planar background structure (i.e., the grounded slab), whereas the latter type of mode radiates also into space. For microstrip lines, the quasi-TEM bound mode (BM) never transitions into a leaky mode as the frequency changes, and hence such bound mode always exists independently of the leaky modes [3]. Furthermore, until now, a transition between a SFWLM and a SPWLM has never been observed at any frequency. It is shown here that such a transition is possible, when the width of the microstrip line is fairly wide. In particular, when the strip width is equal to a critical value, a transition frequency will exist at which the SFWLM will transition into a SPWLM. At the transition frequency the phase constant of the leaky mode is exactly equal to k_0, and its attenuation constant is zero.

Besides being an interesting new phenomenon, it has important physical consequences. When the microstrip line is excited by a practical source, the continuous-spectrum current on the line becomes significantly enhanced near the transition frequency out to large distances z from the source. For frequencies that are close, but not too close, to the transition frequency, this is due to the fact that the leaky mode has a very small attenuation constant. However, when the frequency becomes extremely close to the transition frequency, the leaky-mode current decreases in amplitude because the residue of the relevant leaky pole in the complex longitudinal wavenumber k_z plane approaches zero as the pole approaches the branch point at $k_z = k_0$ (which is the pole location at the transition frequency). In this frequency region the close proximity of the pole to the branch point results in a very large and slowly decaying "free-space residual-wave current" on the microstrip line [4], which becomes responsible for the spurious effects.

BACKGROUND

The complex propagation constant and the modal currents of a given mode on a microstrip line can be easily calculated with the method of moments in the spectral domain, which requires performing integrations in the complex transverse wavenumber k_x plane. Different integrations paths in the k_x plane results in a different type of mode (BM, SFLWM, SPWLM) [5]. The three possible paths that correspond to different physical regimes are reported in Fig. 1(a), where the TM_0 poles of the spectral Green's function of the background structure are also shown. On the other hand, the Green's function of the microstrip line presents in the longitudinal k_z plane two types of branch-point singularities as shown in Fig. 1(b): a logarithmic-type branch point k_0 and an algebraic-type branch point k_{TM_0} [5].

A convenient method for studying the importance of leaky modes and the continuous spectrum on lines that are excited by practical sources is to consider the gap voltage source excitation, as introduced in [5]. In particular, a one-Volt gap source is assumed to excite an infinite line at $z = 0$. The resulting current on the line is expressed via an inverse Fourier transform as

$$I(z) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \tilde{I}(k_z) \mathrm{e}^{-jk_z z} \, dk_z \, . \tag{1}$$

By deforming the original integration path along the real axis of the k_z plane, the total strip current (TC) can be decomposed into a BM current (the quasi-TEM microstrip mode), a leaky-mode (LM) current and a set of two residual-wave (RW) currents (see Fig. 1(b)). Both the BM and LM currents correspond to a residue path around the BM and LM pole, respectively. The latter can be captured or not during the path deformation depending on the sheet of the k_z plane where it resides. The two RW currents arise from by two steepest-descent paths (SDPs), that are the vertical paths descending from k_0 and k_{TM_0} .

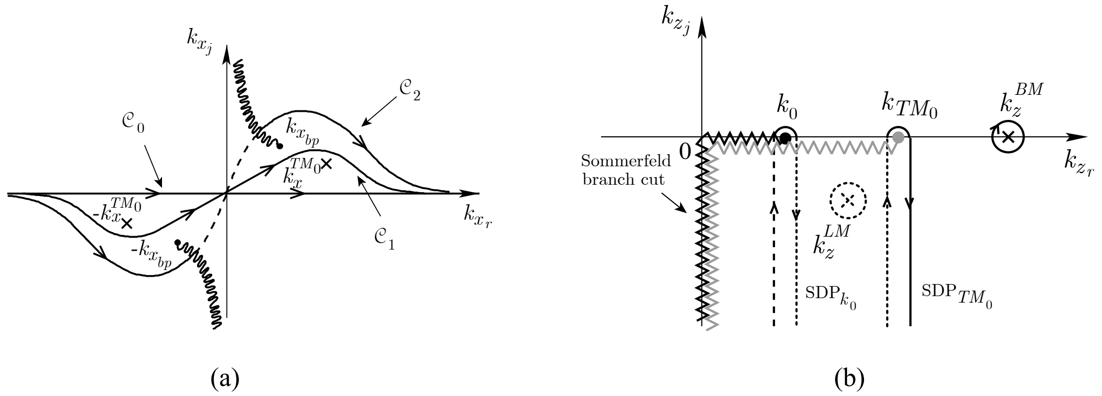


Fig. 1. Spectral complex plane for an unshielded microstrip line. (a) Complex plane for the transverse spectral variable k_x, with three integration paths that give rise to different modal solutions. (b) Complex plane for the longitudinal spectral variable k_z, showing the k_0 and k_{TM_0} branch points, a bound-mode pole k_z^{BM} , and a leaky-wave pole k_z^{LM} .

TRANSITION FROM SPACE-WAVE TO SURFACE-WAVE LEAKAGE

Figure 2 shows a dispersion diagram for two leaky modes supported by a microstrip line with substrate permittivity $\varepsilon_r =$ 10.2, substrate thickness $h = 1$ mm, and strip width $w = 3$ mm, in a frequency range from 0 to 30 GHz. This strip width happens to be the critical strip width for this particular substrate. The SPWLM is calculated with the C_2 path (see Fig. 1(a)) in the k_x plane (*gray lines*), while the SFWLM is calculated with the C_1 path (see Fig. 1(a)) in the k_x plane (*black lines*). Only the physical parts of the dispersion curves, corresponding to the leaky-wave poles being captured [5], are reported.

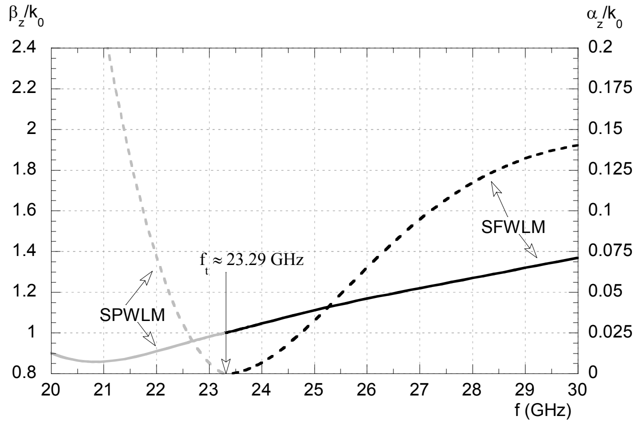
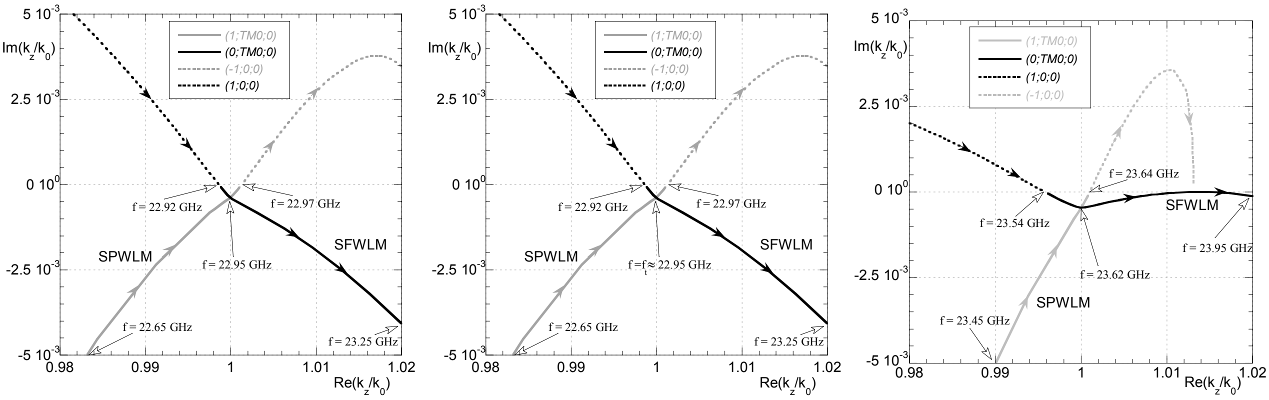


Fig. 2. Normalized phase and attenuation constants for the SPWLM and SFWLM modes of a microstrip line with $\varepsilon_r = 10.2$, substrate thickness $h = 1$ mm, and strip width $w = 3$ mm

The transition from SPWLM to SFWLM can be clearly observed. At the transition frequency $f_t \approx 23.29$ GHz the normalized phase constants of both modes are equal to one, while their attenuation constants are equal to zero, so that the associated poles in the complex k_z plane *both* merge at the k_0 branch point. In order to illustrate the features of the above transition, Fig. 3 shows the k_z-pole trajectories corresponding to the SPWLM (i.e., a (1;TM0;0) pole, *solid gray line*) and the SFWLM (i.e., a (0;TM0;0) pole, *solid black line*) for three different values of the strip width, i.e., $w = 2.9$ mm, $w = w_c = 3$ mm, and $w = 3.1$ mm. The notation for the paths is that discussed in [6]. The solutions corresponding to the non-physical paths (1;0;0) and (-1;0;0) are also shown with *dashed lines*. It can be observed that, when the strip width is equal to the critical value w_c, both poles pass through the k_0 branch point at the transition frequency f_t, resulting in a direct transition from a space-wave to a surface-wave leaky regime. However, by changing the strip width, the k_z-poles fail to pass through the branch point, and a direct transition no longer occurs. The SPWLW and SFWLW pole trajectories still cross, at a point slightly below the real axis in the k_z plane, but since the poles are on different sheets, they do not actually intersect on the Riemann surface. In this case, there may or may not be a spectral-gap region (i.e., a frequency range where none of the two leaky modes is physical), depending on the frequencies at which the physical poles cross the vertical line $\mathrm{Re}\{k_z\} = k_0$.



(a) (b) (c)

Fig. 3. Pole trajectories in the k_z complex plane, for a microstrip as in Fig. 2 with three different values of the strip width w: (a) $w = 2.9$ mm, (b) $w = w_c = 3$ mm, (c) $w = 3.1$ mm.

In order for a physical SPWLM to evolve into a physical SFWLM, the SPWLM pole trajectory in the k_z plane must evolve according to one of the following two possible scenarios: (a) the pole approaches the branch point at k_0, and after coalescing with the branch point, it re-emerges as a SFWLM solution, i.e., it changes sheets on the k_z Riemann surface at the branch point; (b) the pole crosses the Sommerfeld branch cut on the real axis at some point k_z to the left of k_0, and at this point it changes sheet. The first case is the actual scenario that is observed. It can be shown via the reciprocity theorem ([4]) that the following equation is a necessary condition that would enable a SPWLM to transition into a SWLM after passing through the branch point k_0:

$$\frac{\tilde{J}_{s,z}(k_x^{TM_0})}{\tilde{J}_{s,x}(k_x^{TM_0})} = -\frac{k_x^{TM_0}}{k_0} \tag{2}$$

where $k_x^{TM_0} = \sqrt{k_{TM_0}^2 - k_0^2}$ and $\tilde{J}_{s,z}$, $\tilde{J}_{s,x}$ are the Fourier transforms of the longitudinal and transverse currents on the microstrip line, respectively. This result seems to indicate that such a transition is not likely to occur for narrow strips, since the transverse current $\tilde{J}_{s,x}$ on the microstrip line would be in this case very small, and therefore Eq. (2) could not be satisfied. However, for wide strips, where both components of the current exist, it is certainly possible. With a similar approach, based on the reciprocity theorem, it can concluded that a transition from SPWLM to SFWLM is not possible by crossing the branch cut [4].

EXCITATION OF THE MICROSTRIP LINE BY A FINITE SOURCE

The effects of the excitation of either the SPWLM or the SFWLM in a neighborhood of the transition frequency have been studied by considering the current excited on an infinite microstrip line by a voltage gap source. The analysis has been performed by means of a spectral-domain moment-method approach as in [7]. Figure 4 shows the amplitudes of the TC and of the BM current as a function of the normalized distance z/λ_0 from the source for a microstrip line with parameters as in Fig. 2, at two different frequencies. The amplitude of the BM current (i.e., the fundamental quasi-TEM EH_0 mode) does not depend on the distance from the source, and it also remains relatively constant with respect to frequency in the considered frequency range. The TC, in contrast, clearly shows large oscillations about the BM current as the distance increases, due to the interference with the CS current. Such oscillations decay with the distance from the source, corresponding to the decay of the CS current. However, such decay tends to disappear as the transition frequency is approached, as evidenced in Fig. 4(b). The fact that the decay of the CS current with distance decreases as the transition frequency is approached corresponds to the fact that the attenuation constant of the relevant leaky mode (the SFWLM in this case) tends to zero in this limit.

However, considering frequencies *extremely* close to f_t, an interesting phenomenon can be observed as shown in Fig. 5: the LM current decreases in amplitude as f_t is approached, while the RW current increases in amplitude, and it also decays more slowly with distance. Thus, for frequencies extremely close to the transition frequency, the RW component accounts almost entirely for the behavior of the CS current.

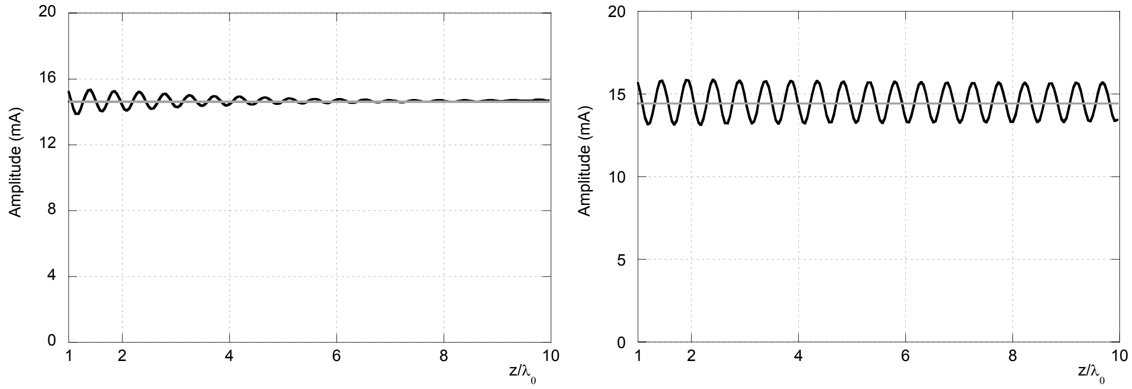


Fig. 4. Amplitude of the current excited on an infinitely-long microstrip line with physical parameters as in Fig. 2, by a gap voltage source. (a) f=22 GHz, (b) f = 23.2 GHz. *Legend*: TC, *black solid line*; BM current, *gray solid line*.

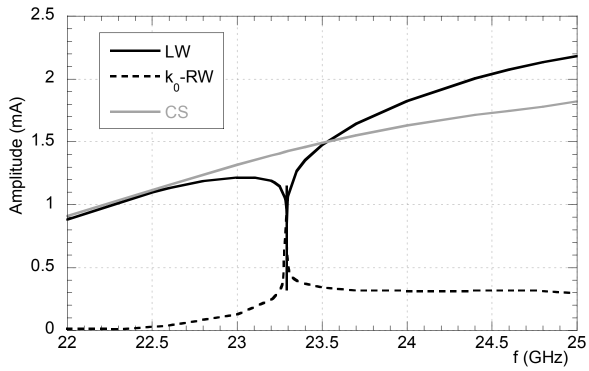


Fig. 5. Amplitude of the CS current, the LW current, and the k_0-RW current, at a fixed distance $z = \lambda_0$ from the source as a function of the frequency f, for the same structure as in Fig. 2.

CONCLUSIONS

In this paper examples have been reported of a new modal transition between surface-wave and space-wave leaky modes on a microstrip line. This transition occurs at a particular transition frequency when the strip width has a critical value, which is fairly wide. By considering a microstrip line excited by a voltage gap source, it has been shown that interference between the continuous-spectrum current and the bound-mode current may give rise to noticeable spurious effects close to the critical frequency.

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