High Frequency Leaky-Mode Excitation on Microstrip Line

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Abstract — **The excitation of leaky modes and the continuous spectrum on microstrip line at high frequenies is studied. It is shown that the current excited from a practical source or discontinuity exhibits spurious effects at high frequencies due to the excitation of the continuous spectrum (radiation spectrum), which may or may not be dominated by a leaky mode, depending on the frequency range and the substrate permittivity. In some cases the spurious effects are due to a leaky mode, while in other cases the effects are due to the excitation of one or more "residual-wave" currents, which have not been previously studied for open microstrip line.**

I. Introduction

The existence of leaky modes on printed circuit transmission lines has been well established for a variety of structures. One of the most commonly used structures is microstrip line. It was shown in [1] that a leaky mode may exist on microstrip line at high frequencies, when the substrate thickness approaches roughly one tenth of a wavelength. It was also demonstrated experimentally in [1] that spurious transmission effects may occur on microstrip line at high frequencies. These spurious effects include signal attenuation as well as significant oscillations in the current or voltage that is excited on the line by a source. In [1] these effects were attributed to the existence of a leaky mode, although there was no direct evidence to support this, since only the propagation characteristics of the modes on the microstrip line were studied, and not the current excitation due to a practical source.

More recently, a semi-analytical spectral-domain technique has been introduced for calculating the current on an infinite printed-circuit transmission line, due to a practical source such as a delta-gap feed on the line [2]. This technique not only allows for the calculation of the total current on the line, but it also gives a convenient physical decomposition of the current into its constituent parts. In particular, this method shows that the total current on the line due to the source is composed of one or more *bound* modes and a *continuous spectrum* (*radiation*) current. The bound-mode current is normally the desirable current, since the bound mode propagates without attenuation. The continuous-spectrum current is a current that decays with distance from the source due to radiation loss. As discussed in [3], the continuous-spectrum current consists of two parts; one part is the sum of one or more physical leaky-mode currents, and the other part is the sum of one or more *residual-wave* currents. Physically, the residual-wave currents represent that part of the continuous spectrum that is not channeled into a leaky mode. The residual-wave currents thus correspond (loosely speaking) to the line current induced by direct radiation from the source discontinuity, as opposed to a leaky-mode current, which behaves as a quasi-guided mode.

For an open structure such as microstrip, two types of leaky modes may exist; one that leaks into a surface wave and one that also leaks into space. Furthermore, two types of residual waves may exist. One type (referred to here as the modal type) propagates from the source with the wavenumber of a parallel-plate mode, and decays with distance as $1/z^{3/2}$. In addition, there is a free-space type of residual wave that propagates with the wavenumber of free space, and decays with distance as $1/z^2$ [4].

The goal of the present work is to examine, for the first time, the nature of the current excitation from a practical source on open microstrip line, and to establish the mechanisms by which spurious transmission effects occur at high frequencies.

II. OVERVIEW OF ANALYSIS METHOD

A one-Volt delta-gap source on an infinite microstrip line is shown in Fig. 1. The current on the line is written as an inverse Fourier transform, as

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

where C_z is a path from minus infinity to infinity that detours around pole and branch-point singularities that appear on the real axis [2]. The Fourier transform of the current may be calculated in closed form by applying a Galerkin method in the spectral domain [2].

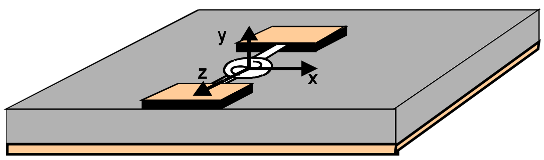

Fig. 1. An infinite microstrip line excited by a delta-gap voltage source at $z = 0$.

The residues from the bound-mode poles on the real k_z axis define the launching amplitudes of the bound-mode (BM) currents. An integration around the branch cuts in the k_z plane defines the continuous-spectrum (CS) current. This integration path may be deformed into a set of vertical steepest-descent paths that descend from the branch points, together with residue contributions from leaky-mode poles [3]. The continuous-spectrum current is thus resolved into a set of residual-wave (RW) currents and one or more leaky-mode (LM) currents. As explained in [4], branch points appear at the wavenumbers of the substrate surface-wave modes, and also one at k_0. Hence, the residual-wave currents are categorized as modal type and free-space type, having the properties mentioned previously.

III. RESULTS

Normalized phase constants (β / k_0) for the bound and substrate-leaky modes are shown in Figs. 2 and 3 for a moderate permittivity substrate (ε_r = 2.2) and high permittivity substrate (ε_r = 10.2), respectively. In both cases, $w = h = 1$ mm. The wavenumber k_{TM0} for the dominant TM_0 surface-wave mode is also shown for comparison. It is seen that physical leakage (where β of the leaky mode is less than k_{TM0} but greater than k_0) begins at a lower frequency for the high- permittivity substrate. No physical space-leaky solution is found in this frequency range.

Figures 4-6 show the total current versus distance from the source, for three cases: an air substrate, a moderate permittivity substrate (ε_r = 2.2), and high permittivity substrate (ε_r = 10.2), for $w = h = 1$ mm. In all cases, the current amplitude is relatively flat with distance at low frequencies (as expected if only the bound mode is excited), but shows spurious effects at higher frequencies.

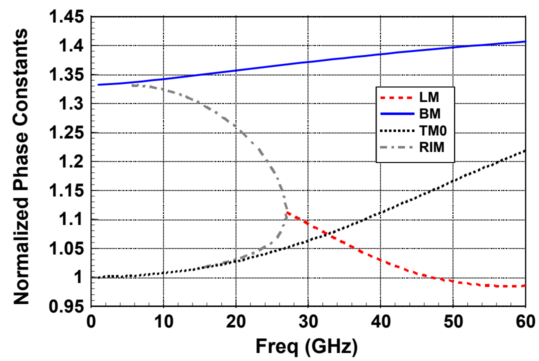

Fig. 2. Normalized phase constants of the bound mode, leaky mode, and TM_0 surface-wave mode, versus frequency. ε_r = 2.2, $w = h = 1$ mm.

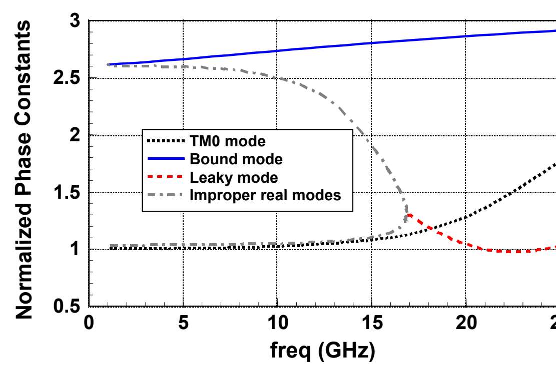

Fig. 3. Normalized phase constants of the bound mode, leaky mode, and TM_0 surface-wave mode, versus frequency. ε_r = 10.2, $w = h = 1$ mm.

The overall level of the spurious effect is the lowest for the air substrate, and is highest for the moderate and high permittivity substrates.

For an air substrate, the current shows a monotonically decreasing behavior with distance. This is due to the fact that there is no leaky mode and also no modal RW current. The only currents excited are the bound mode and the free-space RW current. Both of these propagate with a wavenumber of k_0, and hence there is always a constant phase difference between the two wave types.

When a substrate permittivity is introduced, the BM, modal RW, and free-space RW currents all propagate with different wavenumbers. A physical leaky mode may also exist, depending on the frequency (see Figs. 2 and 3), which has yet a different phase constant. Hence, oscillations in the total current are observed at high frequencies, due to interference effects between the different wave types.

In Figs. 5 and 6, the spurious oscillations are due to interference between the BM current and the CS current. In order to explore the nature of the CS current, Fig. 7

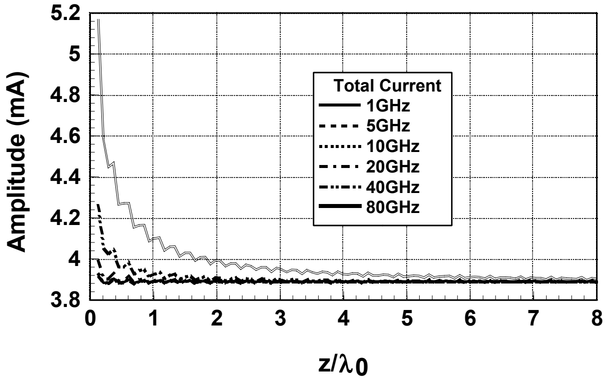

Fig. 4. The total current on the strip due to the delta-gap source, at various frequencies. $\varepsilon_r = 1.0$, $w = h = 1$ mm.

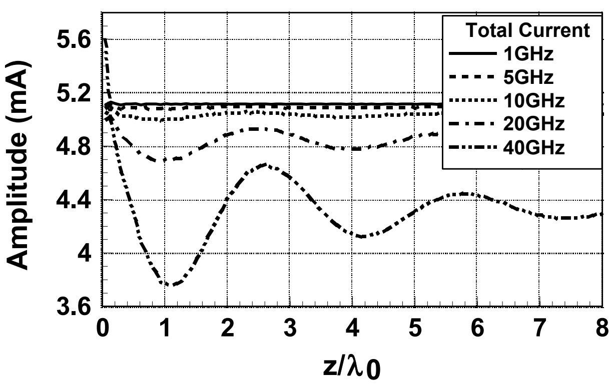

Fig. 5. The total current on the strip due to the delta-gap source, at various frequencies. $\varepsilon_r = 2.2$, $w = h = 1$ mm.

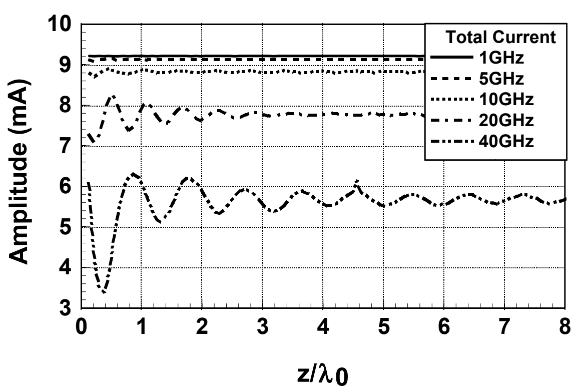

Fig. 6. The total current on the strip due to the delta-gap source, at various frequencies. $\varepsilon_r = 10.2$, $w = h = 1$ mm.

shows the CS current and its constituent parts, the free-space residual wave (labeled k_0 RW) and a single modal (TM_0) residual wave. (There is no physical leaky mode at this frequency.) It is seen that the TM_0 residual wave dominates the CS current, and is thus responsible for the oscillations in the total current.

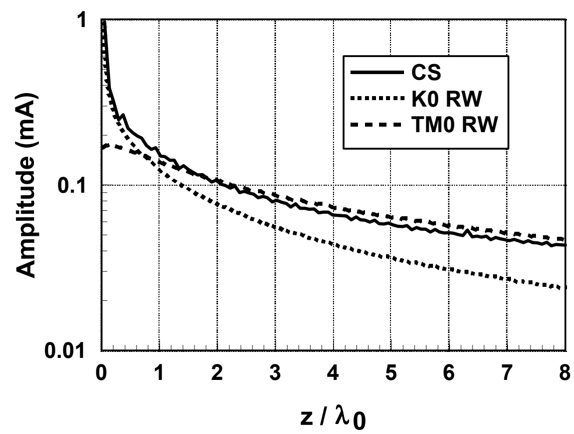

Fig. 7. The continuous-spectrum (CS) current on the strip due to the delta-gap source at 20 GHz, along with its constituent parts, the TM_0 residual-wave current and the k_0 residual-wave current. $\varepsilon_r = 2.2$, $w = h = 1$ mm.

Figure 8 shows that same type of results at a higher frequency of 40 GHz ($h / \lambda_0 = 0.133$). The CS current now consists of a physical leaky mode in addition to the two RW currents. It is seen that the LM current dominates the CS current near to the source, but not overwhelmingly so. Further from the source, the TM_0 RW current dominates the CS current. Hence, it is the LM current that is responsible for spurious high-frequency effects near to the source, but the TM_0 RW current is responsible further from the source.

Figure 9 shows results for the CS current for the high-permittivity case at 20 GHz. This result reveals that near to the source a leaky mode is the dominant part of the CS current (although the k_0 RW and TM_0 RW currents are not negligible). Due to the exponential decay of the leaky mode, the spurious oscillations in the total current die out with distance rather quickly. Further from the source, the TM_0 RW current dominates the CS current, but the amplitude is quite small.

Figure 10 shows results for the high permittivity case at 40 GHz. At this high frequency two substrate surface-wave modes can propagate, the TM_0 mode and the TE_1 mode. The spurious oscillations in Fig. 6 are very pronounced here, and interestingly, it is seen from Fig. 10 that the TE_1 RW current now dominates the CS current.

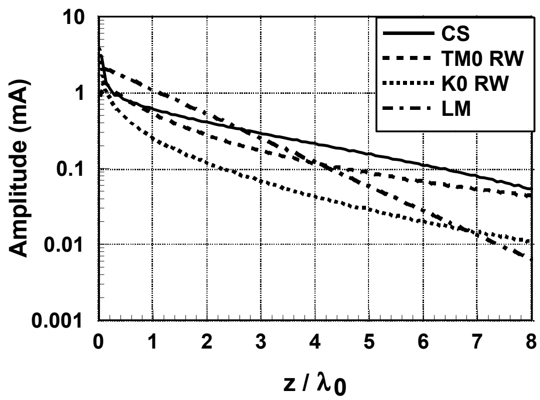

Fig. 8. The continuous-spectrum (CS) current on the strip due to the delta-gap source at 40 GHz, along with its constituent parts, the leaky mode current, the TM_0 residual-wave current, and the k_0 residual-wave current. $\varepsilon_r = 2.2$, $w = h = 1$ mm.

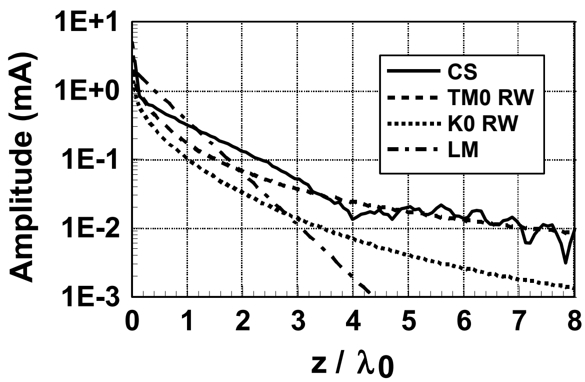

Fig. 9. The continuous-spectrum (CS) current on the strip due to the delta-gap source at 20 GHz, along with its constituent parts, the leaky mode, the TM_0 residual-wave current, and the k_0 residual-wave current. $\varepsilon_r = 10.2$, $w = h = 1$ mm.

Hence, it is a residual-wave current that is responsible for these spurious high-frequency effects for the high permittivity case. (At this frequency the leaky mode has entered the nonphysical spectral-gap region, and is consequently not shown).

III. CONCLUSION

High-frequency spurious transmission effects on microstrip have been investigated. Results show that spurious effects increase with frequency and become very severe when the substrate thickness is about a tenth of a wavelength. At moderately high frequencies, the spurious

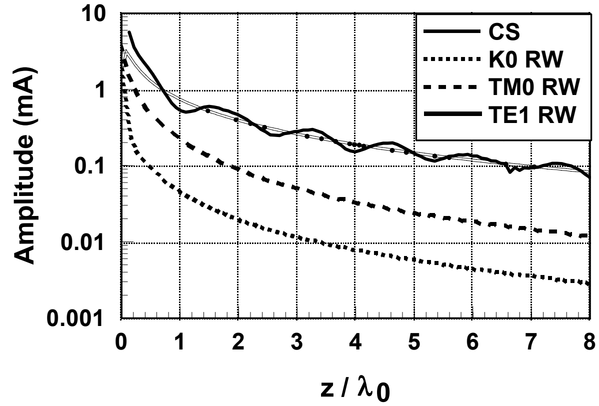

Fig. 10. The continuous-spectrum (CS) current on the strip due to the delta-gap source at 40 GHz, along with its constituent parts, the TM_0 residual-wave current, the TE_1 residual-wave current, and the k_0 residual-wave current. $\varepsilon_r = 10.2$, $w = h = 1$ mm.

effects for a moderate permittivity substrate are due mainly to the TM_0 residual wave. At higher frequencies the spurious effects are due partly to a leaky mode in a region close to the source, but further away they are due once again to the TM_0 residual-wave current.

For high-permittivity substrates the spurious effects at moderately high frequencies are due to a leaky mode in the near-source region, and due to the TM_0 residual wave further away. At higher frequencies the spurious effects are due to the TE_1 RW current.

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