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LOW-FREQUENCY EXCITATION OF LEAKY MODES IN A MICROSTRIP LINE WITH A TOP COVER

J. Bernal

Department of Applied Physics 3
University of Seville
ETS de Ingeniería, Camino de los descubrimientos s/n, 41092-Seville, Spain

F. Mesa

Department of Applied Physics 1
University of Seville
ETS de Ingeniería Informática, Avda. Reina Mercedes s/n, 41012-Seville, Spain

D. R. Jackson

Department Electrical and Computer Engineering
University of Houston, Houston, TX 77204-4005, USA

Abstract—This paper studies the excitation of a physical leaky mode in a covered microstrip structure at low frequencies. We calculate the current excited in the line by a delta-gap voltage source via a full wave analysis based on a mixed potential integral equation scheme. The current in the line is decomposed into its bound mode and continuous spectrum components. The bound mode component is associated with the propagation effects whereas the continuous spectrum component is associated with reactive and/or radiative effects and contains the contribution of the leaky mode. Our analysis also includes a detail study of the dispersion relations of the bound and leaky modes along with their corresponding electric fields. At low frequencies, in the covered microstrip structure with a low top cover height, we have found that the bound mode role is superseded by the leaky mode, in the sense that it is the leaky mode which partially or totally carries the signal energy. Therefore, the spurious effects associated with the excitation of a leaky mode, which usually appear at high frequencies in open

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Corresponding author: Joaquin Bernal Mendez (jbmendez@us.es).

microstrip lines, appear here in the low frequency range. This effect may have very relevant practical consequences in the performance of such systems.

1. INTRODUCTION

The current trends in microwave integrated circuits and digital circuits in very large scale integration technology are towards the use of signals with faster rise times. Therefore high-frequency effects in the guiding systems (commonly dispersion and power loss in microstrip lines and/or coplanar waveguides) are becoming a serious concern [1]. Also, microstrip technology is currently employed in a wide range of applications [2–8]. High-frequency effects in microstrip and stripline structures are often associated with the spurious excitation of a leaky mode (LM) as well as other constitutive components of the continuous spectrum (CS) [9–12]; although the excitation of leaky modes can also be advantageously used for the design of antennas [13–21]. At low frequency, the situation is often much simpler since currents and fields are dominated by the contribution of the bound mode (BM). In this case, the propagation constant of the line is taken as the low-frequency propagation constant of the BM component of the current and fields. Hence, the low-frequency distortion of the signal is expected to be mainly associated with the frequency dispersion of the BM, which can be accounted for by conventional transmission-line theory along with CAD formulas [22, 23].

However, a troublesome situation may arise if a physical LM happens to be excited at low frequencies. A typical structure that can support a strong leaky mode is a microstrip line with a metallic top cover (see Figure 1) [24–26]. In practice, microstrip lines are embedded in microwave circuits that are placed into packages that often include a metallic top cover. Thus, an important practical issue is to determine the influence of the metallic top cover on the propagation

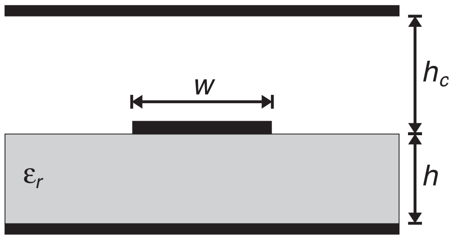


Figure 1. Cross section of a covered microstrip line.

characteristics of the covered microstrip line. As reported in [26], one of the most relevant effects of the top cover is to raise the phase constant of the dominant TM_0 surface wave of the background waveguide (i.e., a parallel-plate inhomogeneous waveguide mode) and, consequently, to lower the frequency at which physical leakage begins. In fact, leakage at all frequencies is possible for a sufficiently small cover height. In this scenario the spurious effects associated with leaky-mode excitation are clearly expected to be more severe.

The influence of the top cover of the package on the excitation of leaky modes has been previously studied in the frequency domain in [25, 26]. However, in these works the current on the strip is calculated only for some particular example cases. In the present work we have carried out a detailed study of the role of the BM and LM components of the total excited current as a function of the frequency. This study makes use of a mixed-potential integral equation (MPIE) formulation [27–30] to compute the modal wavenumber, currents, and electric fields associated with the bound mode and the physical leaky mode. A further 3D analysis that includes a delta-gap voltage source in the analysis is then carried out to determine the extent to which each component of the current is excited at different frequencies and at different distances from the source [31]. This analysis allows us to study in detail the effects caused by the variation of the height of the metallic cover, and more specifically, to demostrate the gradual dominance of the LM component of the current at low frequencies as the cover height is lowered.

Additionally, in this work we compare the wavenumbers of the modes on the line to the expected low-frequency value obtained from a quasi-static analysis in order to show that the low-frequency LM wavenumber can, in some cases, coincide with the quasi-static value. This last value is computed via the quasi-TEM approach reported in [32] (which yields the quasi-TEM C and L p.u.l. parameters of the line). As a final complement, the electric fields for the BM and LM components of the signal are calculated and discussed.

2. ANALYSIS

The covered microstrip structure shown in Figure 1 can be very efficiently analyzed via a Mixed Potential Integral Equation (MPIE) scheme such as that previously employed by the authors in [33] and [34]. In those works the required kernel of the MPIE, namely, the spatial-domain Green's functions associated with the scalar and vector potentials, are obtained in closed form from their corresponding spectral versions (which are computed by means of a transmission-line network analog of the layered medium). This technique can be applied to study both the bound and leaky regimes.

Once the space-domain kernels are obtained, the integral equation is solved by using the Galerkin moment method. Chebyshev polynomials of the first and second kinds weighted by the edge condition are used as basis functions, and a quasi-analytical evaluation of the Galerkin matrix entries is carried out. More details can be found in [33, 34]. From the solution of the integral equation we obtain the modal wavenumbers of the bound and the leaky modes that can be excited in the line, along with their corresponding longitudinal and transverse currents. Once the modal wavenumber and current are known, the spatial domain Green's functions of the structure can be employed to calculate the modal electric field in the cross section of the structure.

However, to determine to what extent a particular mode is excited on the line, a source of excitation must be included in the analysis. Thus, after the above described 2D analysis, we have performed an additional 3D analysis that includes the source. In this work we consider that the covered microstrip line is excited by a time-harmonic gap voltage source. The gap voltage source is an impressed electric field on a narrow region of length $\Delta \ll \lambda_0$ on the surface of the conducting strip that models a practical source on the line [11, 31].

The frequency-domain current due to the gap voltage source on the transmission line, $I(\omega, z)$, can be obtained from the following spatial inverse Fourier transform:

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

where z is the longitudinal spatial coordinate and k_z the longitudinal wavenumber. The spatial transform of the current in the integrand, $\tilde{I}\ (\omega, k_z)$, is calculated by using the efficient MPIE scheme reported in [31].

By deforming the path of integration in the k_z plane, the total current on the conducting strip given by (1) can be decomposed into two components: the current associated with the BM and the continuous-spectrum (CS) current [11, 12]. The BM current is determined by the residue of the BM pole in the complex k_z plane, captured during the path deformation. The bound mode is the mode that is generally accounted for by transmission-line theory. However, at high frequencies, the amplitude of this bound mode is not accurately predicted by transmission-line theory. The CS current corresponds to a reactive and/or radiating type of current that cannot be predicted by transmission-line theory. The CS current is calculated by integrating around the branch cuts that exist in the complex k_z plane. This integration path can be further deformed into a steepest-descent path of integration [12]. This allows us to decompose the CS current into two additional components: the physical LM current and the so-called residual-wave current. The physical LM current includes the contribution of all the physical leaky modes existing at a given frequency [11]. The physical LMs are those corresponding to the improper poles in the k_z plane that are captured during the branch-cut path deformation to the steepest-descent path. The residual-wave current is the part of the CS current that is left over from the LM current, corresponding to the contribution from the steepest-descent integration. The reader is referred to [11, 12] for more details about this decomposition of the current.

3. RESULTS

The reliability and numerical accuracy of the employed computer code has been previously checked by the authors by comparing with commercial electromagnetic solvers [31, 35]. Therefore this necessary validation will not be repeated here.

3.1. Dispersion Relation

Figure 1 shows the cross section of the covered microstrip line under study. Looking at the structure without the conducting strip, it should be noted that the addition of a top cover at a height h_c makes that the corresponding surface wave of the grounded substrate without top cover turn into a parallel-plate waveguide mode. The presence of the top cover also has an important influence in in the dispersion diagram of the line, which will be studied next.

Figure 2 shows the dispersion diagram for the normalized phase and attenuation constants of the bound mode, the parallel-plate TM_0 waveguide mode, and the leaky mode for $h_c = 0.7\,\mathrm{mm}$. The normalized quasi-TEM phase constant is also included as a cross sign in the left vertical axis. It can be observed that the phase constant of the BM tends to the quasi-static value as the frequency goes to zero. This is the typical behavior on an open microstrip line (without a top cover). Moreover, at low frequencies the leaky mode becomes nonphysical (when the phase constant of the leaky mode is above that of the TM_0 parallel-plate mode) and its contribution to the overall current and fields is expected to be negligible. However, when the metallic top cover is brought nearer to the substrate, the phase constant of the parallel-plate waveguide mode raises and consequently there is an important lowering in the frequency at which the physical leakage

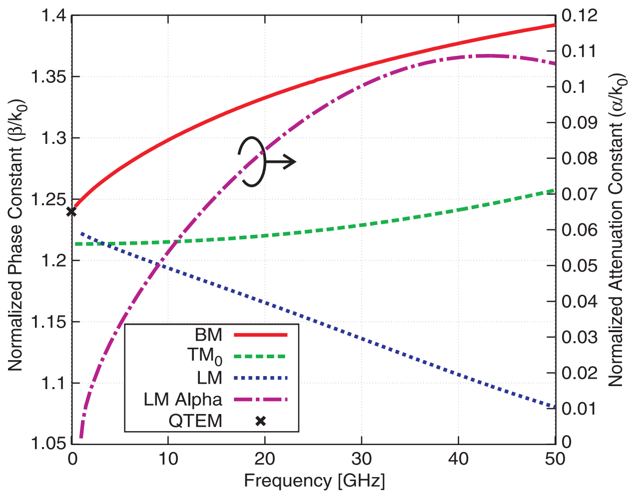


Figure 2. Dispersion diagram for a covered microstrip transmission line with $w = h = 1\,\text{mm}$, $h_c = 0.7\,\text{mm}$, and $\varepsilon_r = 2.2$. The normalized quasi-TEM phase constant (from quasi-static theory) is represented by a cross symbol on the left vertical axis.

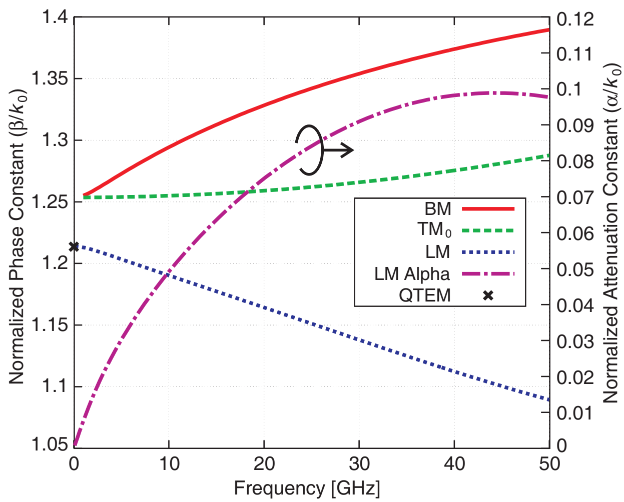


Figure 3. Dispersion diagram for a covered microstrip transmission line with $w = h = 1\,\text{mm}$, $h_c = 0.5\,\text{mm}$, and $\varepsilon_r = 2.2$. The normalized Quasi-TEM propagation constant is represented in the vertical axis.

appears. This can be seen in Figure 3, where the dispersion diagram of the covered microstrip for $h_c = 0.5$ mm is depicted. This figure shows that the dispersion curve of the BM phase constant does not approach the corresponding quasi-static phase constant of the line at low frequencies. Surprisingly, for this small top-cover height case, the LM remains physical at very low frequencies and its phase constant is the one that tends to the quasi-static value for low frequencies. This suggests that the fields and current of the LM at low frequencies should resemble those corresponding to the quasi-static limit.

The necessary physical continuity of the solutions also suggests that the transition from the case shown in Figure 2 ($h_c = 0.7$ mm) to the situation of Figure 3 ($h_c = 0.5$ mm) must be gradual. To show this fact we have plotted in Figure 4 the normalized phase constants of the BM, the LM, and the parallel-plate TM_0 waveguide mode versus the top cover height at 1 GHz. We have also plotted the curve of the quasi-static normalized phase constant. It can be seen that for $h_c \gtrsim 0.7$ mm the BM phase constant is quite close to the quasi-static value, as expected. In fact at these values of h_c the LM does not actually exist (instead we have two improper real modes). However, for $h_c \lesssim 0.55$ mm, the quasi-static phase constant is much closer to the phase constant of the LM, which is physically meaningful now. A transition zone where the quasi-TEM is not close to either the BM or the LM can be observed for $0.55 < h_c(\text{mm}) < 0.7$.

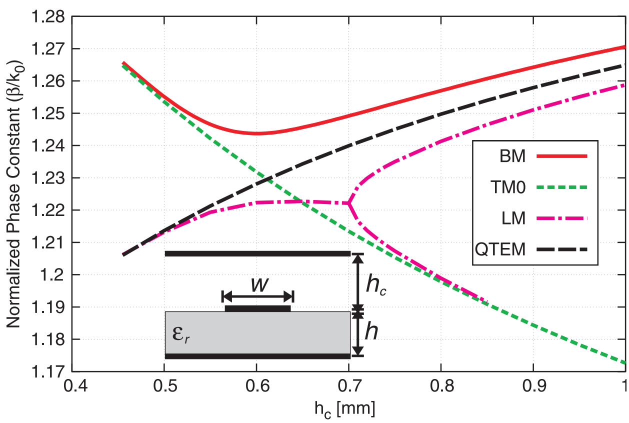


Figure 4. Normalized phase constants at 1 GHz for a covered microstrip line with $h = w = 1$ mm and $\varepsilon_r = 2.2$ as a function of the top cover height, h_c.

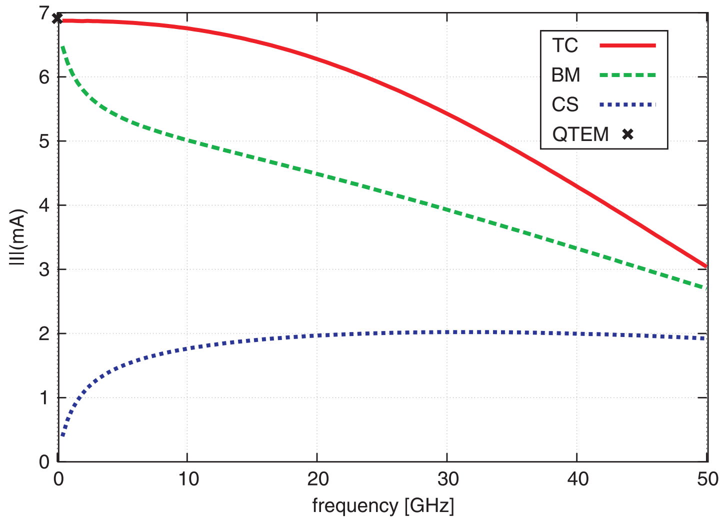
3.2. Current Excited on the Line

Since the 2D full-wave analysis carried out in the previous section provides no information as to the extent the BM and the LM currents are actually excited on the line by a practical excitation source, this information is drawn from a 3D full-wave analysis that includes the source [31]. Thus, Figures 5(a) and 5(b) show the magnitude of the current excited in the line along with its BM and CS components as a function of the frequency at two different distances from the source ($z = 5\,\text{mm}$ and $z = 50\,\text{mm}$) for $h_c = 0.7\,\text{mm}$. The magnitude of the current provided by conventional transmission line theory (TLT) from the quasi-TEM C and L parameters [32] is represented as a black cross on the left vertical axis. This latter magnitude is independent of the frequency and, obviously, the total current must approach this value at low frequencies, as shown in Figures 5(a) and 5(b). At a given frequency, since the CS component is associated with reactive/radiative effects, its magnitude should decrease far from the source. In contrast, the magnitude of the BM (in a lossless case) is independent of the distance from the source, which causes a progressive dominance of the BM with respect to the CS for increasing distances from the source. If the electrical length is not large enough, as happens for the low frequencies in Figures 5(a) and 5(b), the above fact is not yet apparent. Thus, the magnitudes of the BM and CS currents at low frequency are about the same in Figures 5(a) and 5(b).

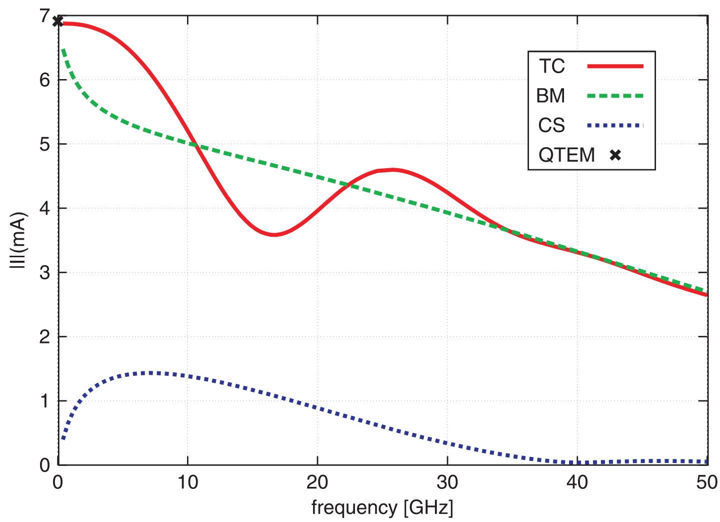
In these figures (for $h_c = 0.7\,\text{mm}$) it is also apparent that the BM component is the dominant component of the current at low frequency. This is the same behavior that is found in open microstrip structures, where the influence of the CS component is expected to be noticeable only at high frequencies (and mainly near the source).

In Figures 6(a) and 6(b) we plot the magnitude of the current and its components as a function of the frequency for $h_c = 0.5\,\text{mm}$. For this low top-cover height the LM is physical over the entire frequency range. The explicit contribution of the LM current is then plotted in these figures. It can be seen in Figures 6(a) and 6(b) that the total current approaches the quasi-TEM current at low frequencies, as expected. However, at low frequency, the BM component is only weakly excited and the LM component is the dominant component of the current. Therefore, for this structure, the low frequency signal power will be mainly carried by the LM component, whose phase constant is much closer to the quasi-TEM phase constant of the line.

In the covered microstrip under study we have seen that the dominant role of the BM and CS components of the current at low frequency is completely interchanged as the top cover height is lowered from 0.7 mm to 0.5 mm. In order to show the transition between these

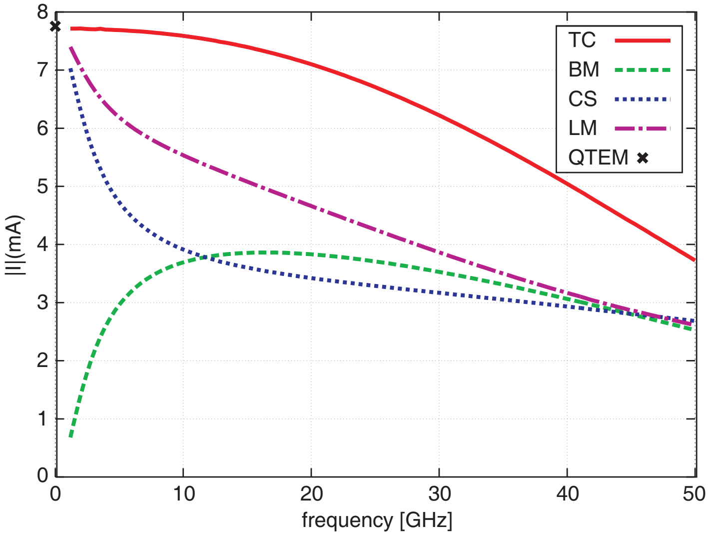


(a) $z = 5$ mm

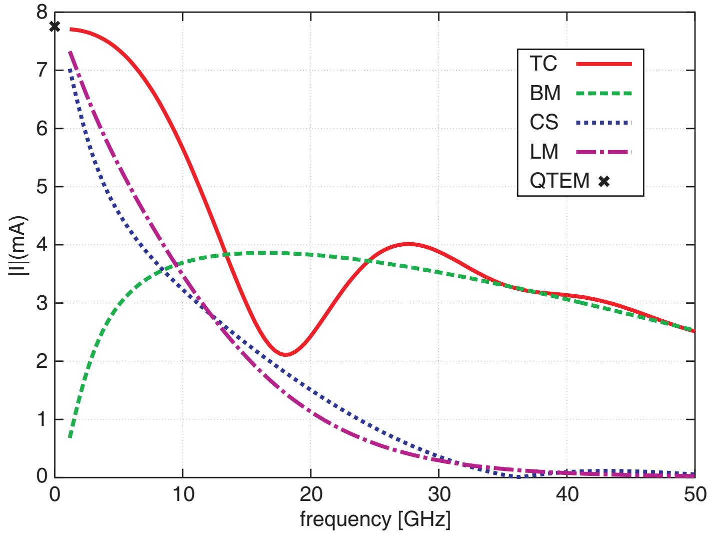


(b) $z = 50$ mm

Figure 5. Frequency behavior of the magnitude of the total current (TC) and its BM and CS components at two different distances from the source for a covered microstrip with $w = h = 1$ mm, $h_c = 0.7$ mm, and $\varepsilon_r = 2.2$.



(a) $z = 5$ mm



(b) $z = 50$ mm

Figure 6. Frequency behavior of the magnitude of the total current (TC) and its BM and CS components at two different distances from the source for a covered microstrip with $w = h = 1\,\mathrm{mm}$, $h_c = 0.5\,\mathrm{mm}$, and $\varepsilon_r = 2.2$.

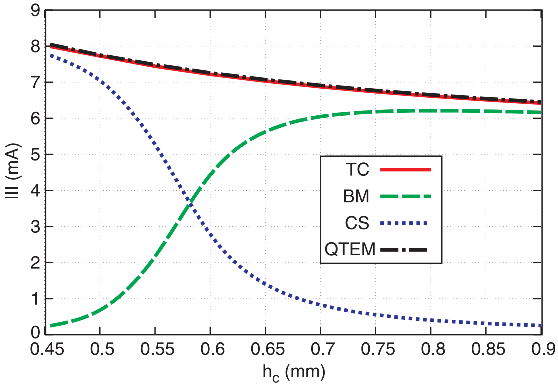


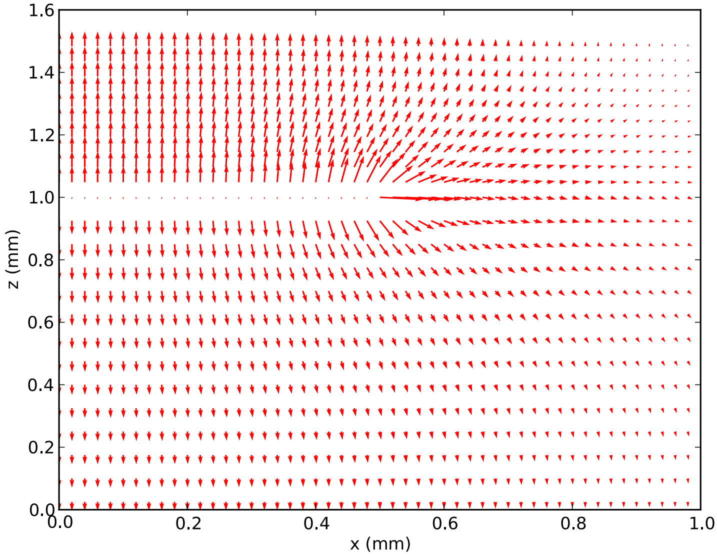
Figure 7. Magnitude of the total current (TC) along with its BM and CS components as a function of h_c (top cover height) on a covered microstrip with $w = h = 1\,\text{mm}$ and $\varepsilon_r = 2.2$. The magnitude of the quasi-static current given by transmission line theory (QTEM) is also represented. The currents are plotted at 1 GHz for $z = 5\,\text{mm}$.

two situations we have plotted in Figure 7 the magnitude of the total current and its BM and CS components at 1 GHz as a function of the top cover height h_c. These currents have been calculated at a distance $z = 5\,\text{mm}$ from the source. In Figure 7 we can see that at 1 GHz the total current is found to be very close to the corresponding quasi-TEM value for any value of h_c, as somewhat expected due to the low value of the operation frequency. However the relative importance of the BM and CS components of the current greatly changes with h_c. For $h_c \gtrsim 0.7\,\text{mm}$ the BM is the dominant component of the current whereas the CS component is the dominant component for $h_c \lesssim 0.5\,\text{mm}$. For $0.5\,\text{mm} \lesssim h_c \lesssim 0.7\,\text{mm}$ there exists a transition zone where the signal power at low frequency would travel partly as a bound mode and partly as a leaky mode. Thus, the use of lines whose h_c is within the transition zone can give rise to important spurious interference effects due to the multimodal nature of the excited field. Out of this transition region the spurious interference effects are not expected to be so noticeable. The fact that the LM is responsible for the low-frequency propagation of the signal for low values of h_c might be surprising but it is not expected that the leaky mode will cause any spurious interference effects. However, the fact that the signal is being propagated as a leaky mode may increase the total attenuation of the mode due to radiation loss. For larger values of h_c, the only spurious effects that are expected are those provided by the usual dispersive nature of the bound mode.

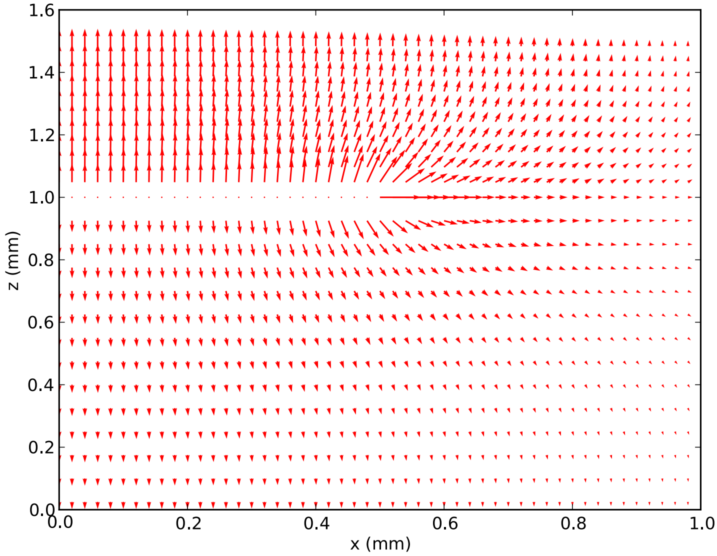
3.3. Electric Field

For a low top-cover height we have seen that the leaky mode dominates the low-frequency current in the covered microstrip structure. This suggests that the electric field associated with this leaky mode should resemble the electric field provided by a quasi-TEM analysis. To check this we have calculated and depicted in Figure 8 the BM and LM transverse electric fields excited in this structure for a low cover height ($h_c = 0.5\,\mathrm{mm}$) at 1 GHz. Given the symmetry of the problem, only the right side of the cross section of the structure is represented. Figure 8 shows that, for this low frequency, the BM and LM transverse fields are very similar. However, a close inspection shows that the BM field in the dielectric layer is larger than the LM field (for corresponding points), whereas the LM electric field is larger than the BM field in the air region. As a consequence, the BM phase constant is larger than the LM one as we have shown in Figure 3.

From Figure 8 it is difficult to discern whether the BM or the LM transverse electric fields have a quasi-TEM pattern. To measure to what extent the transverse fields behave like quasi-TEM fields we have numerically calculated the line integral of those electric fields from the top metallic plate to the lower metallic plate. The chosen integration path is a straight vertical line in the middle of the cross section of the structure (the vertical axis in Figures 8(a) and 8(b)). For the quasi-TEM electric field this line integral must be zero (since both metallic plates are assumed to be perfect ground planes with the same potential). Given the direction and sense of the electric field, a positive line integral means that the voltage drop is larger in the dielectric layer than in the air region, and vice-versa. The results for the line integral of the BM and LM fields for the structure of Figure 8 are plotted in Figure 9(a) as a function of the frequency. To obtain these results we have normalized the current on the conducting strip so that the scalar potential is 1 V on this conducting strip. Since the full-wave electric field also includes the contribution of the vector potential, the computed line integral is not zero in general. Figure 9(a) shows that, at high frequencies, neither the LM nor the BM fields resemble a quasi-TEM field (their line integrals are far from zero), as expected. However, at low frequencies, the LM transverse field gives a nearly zero line integral, a clear hint that the LM transverse field is a quasi-TEM-like field. At these low frequencies and for the present value of h_c, the BM field does not fit a quasi-TEM field pattern, but Figure 9(b) clearly shows that for a higher top cover height ($h_c = 1\,\mathrm{mm}$) the BM field becomes quasi-TEM at low frequencies, as usually happens in most transmission lines. In this last figure, the line integral of the LM field is only plotted in the range of frequencies where the LM is

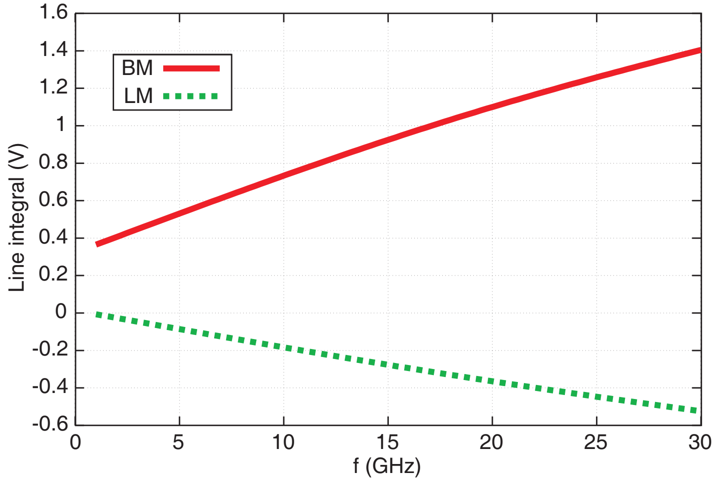


(a) Bound mode

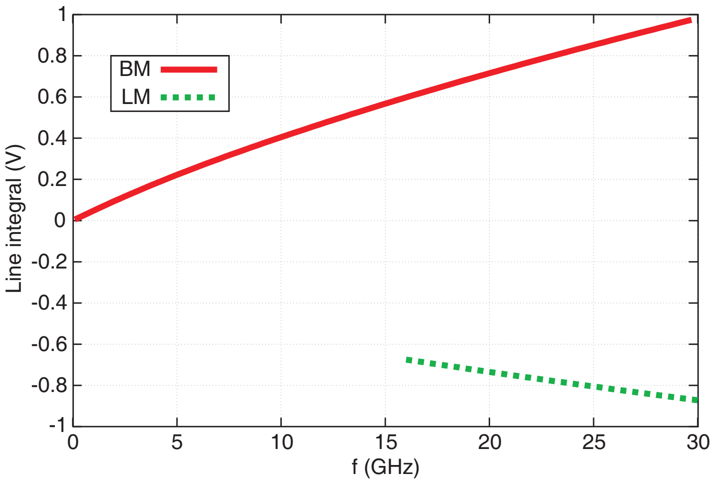


(b) Leaky mode

Figure 8. Magnitude of the transverse modal electric fields in the cross section of a covered microstrip with $w = h = 1\,\mathrm{mm}$, $\varepsilon_r = 2.2$, and $h_c = 0.5\,\mathrm{mm}$ at $1\,\mathrm{GHz}$.



(a) $h_c = 0.5$ mm



(b) $h_c = 1$ mm

Figure 9. Line integral of the bound mode and leaky mode fields as a function of the frequency for a covered microstrip with $w = h = 1\,\text{mm}$ and $\varepsilon_r = 2.2$ for two different top cover heights.

physical.

As mentioned above, the current on the conducting strip has been normalized so that the scalar potential on the conducting strip is 1 V. Since the contribution of the scalar potential to the full-wave electric field is dominant at low frequencies, the average magnitude

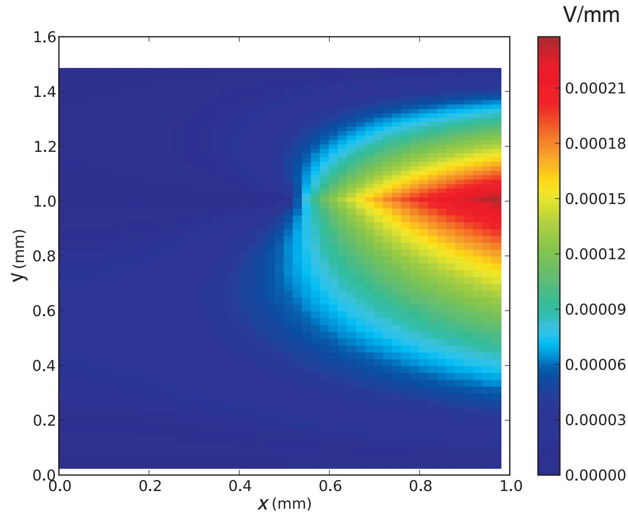


Figure 10. Magnitude of the longitudinal electric field (in V/mm) of the leaky mode at 1 GHz in the cross section of a covered microstrip line with $h_c = 0.5\,\text{mm}$, $h = w = 1\,\text{mm}$, and $\varepsilon_r = 2.2$.

of the low-frequency transverse electric field in the dielectric region below the conductor for a structure with $h = 1\,\text{mm}$ and $h_c = 0.5\,\text{mm}$ is around 1 V/mm whereas in the air region above the conductor is around 2 V/mm. By comparison with these values we have checked that, at low frequencies, the longitudinal field is much smaller than the transverse field for both the BM and the LM fields. As an example, Figure 10 shows a map of the LM longitudinal electric field in the cross section of a covered microstrip structure with low top-cover height ($h_c = 0.5\,\text{mm}$) at $f = 1\,\text{GHz}$. This figure shows that, at this low frequency, the longitudinal field is quite small (and, of course, null on the strip surface) and also that this field grows as we move laterally away from the strip. This behavior is found to be the same for higher frequencies although, as expected, the magnitude of the LM longitudinal electric field increases with frequency. This can be seen in Figure 11, which shows the magnitude of the LM longitudinal electric field in the interface air-dielectric for several frequencies. Since the electric field is maximum in the air-dielectric interface and it grows with frequency, this LM field is expected to cause crosstalk with adjacent lines. The analysis of multiconductor covered microstrip structures to study the actual influence of this leaky mode in the coupling between the lines will be undertaken in a future work.

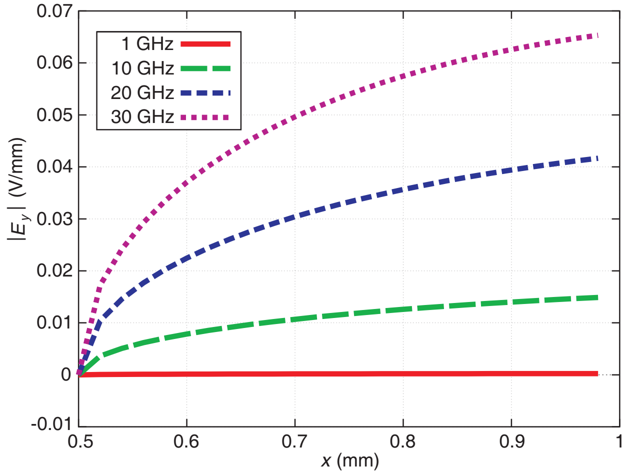


Figure 11. Magnitude of the longitudinal electric field of the LM for a covered microstrip ($w = h = 1\,\mathrm{mm}$, $\varepsilon_r = 2.2$ and $h_c = 0.5\,\mathrm{mm}$) in a segment of the interface between the dielectric and the air layers starting at the edge of the conducting strip ($x = 0.5\,\mathrm{mm}$).

4. CONCLUSIONS

In this work we have analyzed the excitation of leaky modes on a covered microstrip line. We have found that a physical leaky mode can be excited on the line at low frequencies when the top cover of the line is brought close to the dielectric layer. We have checked that the wavenumber and the low-frequency transverse fields of this leaky mode may become quite similar to those expected for a quasi-TEM mode.

The analysis of the excitation of the line by a delta gap voltage source has shown that the LM current can actually become the dominant component of the current at low frequencies for a sufficiently small top-cover height. This leaky mode could therefore be excited by a source intended to excite quasi-TEM fields in the line, thus leading to spurious effects such as interference, radiation, and power loss on the line. Since the longitudinal component of the electric field associated with this leaky mode has been found to grow as the lateral distance from the conducting strip increases (this component being more relevant as frequency increases), additional unexpected effects such as coupling and crosstalk with adjacent lines may also appear on this type of structure.

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