RADIO SCIENCE, VOL. 45, RS1004, doi:10.1029/2009RS004139, 2010

Numerical and experimental study of the voltage excited along a slotline by a current source

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Received 6 January 2009; revised 13 July 2009; accepted 22 October 2009; published 28 January 2010.

[1] This paper presents an analysis of a slotline excited by a current source connected across the slot. The method of moments applied in the spectral domain is used. As a result, the voltage of a wave composed of bound and leaky modes as well as residual waves is calculated along the slot. Interesting behavior of the voltage wave in the neighborhood of the source is shown. Both numerical and measured results are given.

Citation: Kotlan, V., F. Mesa, and J. Machac (2010), Numerical and experimental study of the voltage excited along a slotline by a current source, *Radio Sci.*, *45*, RS1004, doi:10.1029/2009RS004139.

1. Introduction

[2] Planar transmission lines have been widely investigated in the last four decades by many researchers throughout the world [*Gupta et al.*, 1979]. Among these lines, the slotline has been one of the most studied structures. In particular, much effort has been devoted to studying the properties of its dispersion characteristics and characteristic impedance [*Itoh and Mitra*, 1971]. Most of the analyses have dealt with eigen waves, i.e., waves that can propagate along the line and that are described without taking any source into consideration. These studies have mainly focused on the propagation characteristics of the bound mode, as it represents the required line working regime. Like other open planar transmission lines, however, the slotline is capable of exciting leaky waves [*Zehentner et al.*, 1998a]. These waves usually affect the expected propagation behavior of the line, causing strong attenuation of the transmitted signal and other spurious effects.

[3] A qualitatively higher form of analysis takes into account a source that excites waves on the transmission line [*Mesa et al.*, 1999; *Jackson et al.*, 2000]. This analysis makes it possible to compute the actual amplitudes of the corresponding waves excited by a particular source, or at least to know the ratio between bound and leaky modes of various kinds.

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0048-6604/10/2009RS004139$11.00

[4] Most work related to the excitation of planar transmission lines has focused on microstrip lines, one of the most widely used lines. Waves excited by a voltage source connected into a gap in the strip of this line were studied by *Mesa et al.* [1999], *Jackson et al.* [2000], and *Mesa et al.* [2001]. The model of the wave excitation presented in the above papers is applicable for a number of planar transmission lines after employing the appropriate Green functions [*Neto and Maci*, 2003]. It is known that the bound mode propagates along the microstrip line in a wide frequency band, theoretically at all frequencies, and the leaky modes propagate simultaneously from a certain frequency. However, the slotline has a different behavior, which has been shown, e.g., by the eigenmode analysis [*Zehentner et al.*, 1998a]. The bound mode propagates from zero up to a certain cutoff frequency. At higher frequencies only the leaky and residual waves propagate. An investigation of the fields excited under these specific conditions in the slotline is one of the main goals of the present work.

[5] Thus, this paper presents the results of a study of the waves propagating along a slotline fed by a current source connected across the slot (some preliminary results on this topic were reported by *Kotlan et al.* [2009]). The distribution of the voltage across the slot of the wave excited on the line is calculated using the spectral domain method [*Mesa et al.*, 2001]. This method applied to a slotline is briefly presented, and a code based on it has been implemented. The analytical and numerical studies are complemented and validated with the measurements of the voltage distribution along the line. This experimental study has confirmed our theoretical/numerical predictions that the excited voltage wave is composed of the bound and leaky modes together with the residual wave [*Jackson et al.*, 2000]. All the above

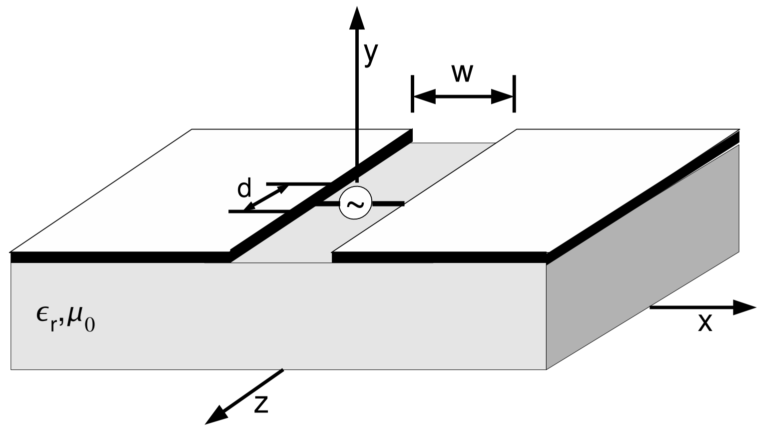

Figure 1. A slotline of infinite length, excited by a current source located at $z = 0$, $y = h$.

results are consistent with the dispersion characteristics of the slotline calculated using the spectral domain [*Zehentner et al.*, 1998a, 2004].

2. Analysis

[6] The problem to be solved in this section is a feeding current source, placed across the slot of the slotline, which excites a voltage wave along the slot of an infinitely long transmission line. The structure is assumed to be lossless, laterally unbounded, and with metallizations of zero thickness. This line with the exciting source is sketched in Figure 1. A substrate with relative permittivity ϵ_r and h in thickness is used. The slot is w in width.

[7] The current, $J_x(x, z)$, imposed by the source can be related to the x component of the electric field within the slot, $E_x(x, z)$, via Green's function $G_{xx}^{\mathrm{JE}}(x - x', z - z')$ [*Balanis*, 1989] in the following way:

$$J_x(x,z) = \int_{-\infty}^{\infty} \int_{-w/2}^{w/2} G_{xx}^{\mathrm{JE}}(x - x', z - z') E_x(x', z')\, \mathrm{d}x' \mathrm{d}z'. \quad (1)$$

In order to keep the analytical derivations as simple as possible, we will limit our analysis to an electrically narrow slot so that the electric field can be assumed to have only the transverse component E_x; this, in turn, will be expressed by a single basis function $E_x^{\mathrm{bas}}(x)$. The transverse electric field within the slot, which is a function of the two coordinates x and z, is then decomposed as the product of a longitudinal function, $C(z)$, and the transversal function $E_x^{\mathrm{bas}}(x)$,

$$E_x(x,z) = E_x^{\mathrm{bas}}(x) C(z)\,. \quad (2)$$

[8] The single basis function, which satisfies the appropriate boundary conditions, is taken according to *Collin* [1991] as

$$E_x^{\mathrm{bas}}(x) = \frac{T_0\left(\frac{2x}{w}\right)}{\sqrt{1 - \left(\frac{2x}{w}\right)^2}}, \quad (3)$$

where T_0 is the Tchebycheff polynomial. The spectral domain expression of the basis function is then given by

$$\tilde{E}_x^{\mathrm{bas}}(k_x) = \pi \frac{w}{2} J_0\left(k_x \frac{w}{2}\right), \quad (4)$$

where J_0 is the Bessel function of the first kind and zero order.

[9] The imposed current density can be similarly separated into the following transversal and longitudinal parts:

$$J_x(x,z) = T(x) L(z)\ , \quad (5)$$

where the transversal part is taken constant but normalized as $\int_{-w/2}^{w/2}$ dx = 1. The longitudinal part is chosen as

$$L(z) = \frac{1 \mathrm{e}^{-\frac{1}{2}\left(\frac{z}{d}\right)^2}}{d\sqrt{2\pi}} \quad (6)$$

to obtain rapid convergence in the spectral domain [*Di Nallo et al.*, 1998] (d is the longitudinal effective width of the source). This function has the following Fourier transform:

$$\tilde{L}(k_z) = \mathrm{e}^{-\frac{1}{2}(k_z d)^2}\,. \quad (7)$$

Performing a Fourier transform in the longitudinal direction (z), making use of (2), equation (1) reduces to

$$\tilde{J}_x(x, k_z) = \tilde{C}(k_z) \int_{-\infty}^{\infty} G_{xx}^{\mathrm{JE}}(x - x', k_z) E_x^{\mathrm{bas}}(x')\, \mathrm{d}x'\,. \quad (8)$$

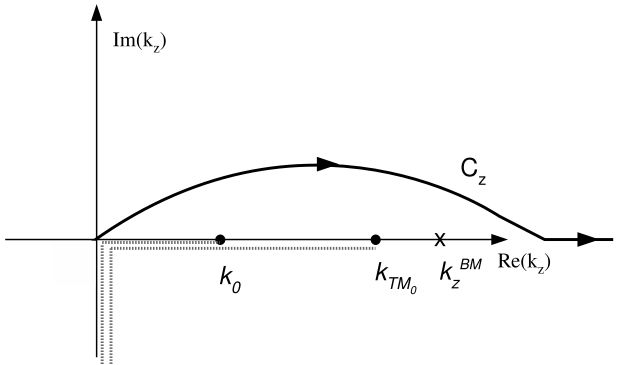

Figure 2. Singularities of $\tilde{C}(k_z)$ appearing on the positive real axis of the k_z complex plane. The branch points at k_0 and k_{TM_0} are shown together with bound-mode pole k_z^{BM}. Branch cuts associated with the branch points are drawn in dashed lines. The path of integration, C_z, in (14) must detour around the above singularities.

The above integral equation is now solved via Galerkin's method, leading to the following expression for the longitudinal function $\tilde{C}(k_z)$:

$$\tilde{C}(k_z) = \frac{\int_{-w/2}^{w/2} E_x^{\mathrm{bas}}(x) J_x(x,k_z)\,\mathrm{d}x}{\frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}_x^{\mathrm{bas}}(-k_x)\tilde{G}_{xx}^{\mathrm{JE}}(k_x,k_z)\tilde{E}_x^{\mathrm{bas}}(k_x)\,\mathrm{d}k_x}, \tag{9}$$

where the reaction integral in the denominator has been transformed to the spectral domain in the transverse direction after applying Parseval's identity. The spectral domain Green's function can be written as [*Itoh*, 1989]

$$\tilde{G}_{xx}^{\mathrm{JE}} = \frac{1}{k_x^2 + k_z^2}\left[k_x^2 D_{\mathrm{TM}} + k_z^2 D_{\mathrm{TE}}\right], \tag{10}$$

where $D_{\mathrm{TM}} = \frac{jk_0}{|k_x|\eta_0}(\epsilon_r + 1)$ and $D_{\mathrm{TE}} = \frac{2|k_x|}{jk_0\eta_0}$, with k_0 being the free-space wave number and η_0 the free-space characteristic impedance.

[10] The path of integration of the denominator in (9) is the real axis of the complex k_x plane [*Mesa et al.*, 2002]. This integral is efficiently computed by using an appropriate asymptotic treatment. In particular, we have employed the following form of the asymptotic Green's function for large values of $|k_x|$:

$$\tilde{G}_{xx}^{\mathrm{JE}}\Big|_{|k_x|\gg 0} = \frac{k_0}{\mathrm{j}|k_x|\eta_0}\left[(\epsilon_r + 1) - \frac{2k_z^2}{k_0^2}\right], \tag{11}$$

This approach speeds up the numerical solution since it calculates the "asymptotic" reaction integral via closed-form expressions, as described by *Amari et al.* [1998].

[11] The spatial-domain counterpart of the longitudinal function is computed by means of the following inverse Fourier transform:

$$C(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{C}(k_z)\mathrm{e}^{-\mathrm{j}k_z z}\,\mathrm{d}k_z. \tag{12}$$

The expression for voltage $V(z)$ across the slot is taken as the integral of the electric field across the slot:

$$V(z) = \int_{-w/2}^{w/2} E_x(x,z)\,\mathrm{d}x. \tag{13}$$

Since function $\tilde{C}(k_z)$ is even, the total voltage within the slot excited by a source can finally be written as

$$V(z) = \frac{w}{2}\int_{0(C_z)}^{\infty}\tilde{C}(k_z)\cos(k_z z)\,\mathrm{d}k_z. \tag{14}$$

The path of integration in (14), C_z, must be located in the first quadrant of the k_z complex plane and must detour around the singularities of $\tilde{C}(k_z)$ placed on the positive real axis of the k_z plane [*Mesa et al.*, 2002]. This path is shown in Figure 2.

[12] The total voltage can be further decomposed into its bound-mode contribution plus the continuous-spectrum contribution. Following *Mesa et al.* [1999], this decomposition is achieved after deforming the original integration path, C_z, to another path detouring around the branch cuts (integration along the branch cuts gives rise to the continuous-spectrum contribution). In this deformation the original path sweeps the bound-mode pole, k_z^{BM}, located on the real axis, giving place to a closed path around this pole that accounts for the bound-mode contribution. This latter contribution can be written as

$$V_{\mathrm{BM}} = \frac{\mathrm{j}\pi w}{2}\mathrm{Res}\{\tilde{C}(k_z^{\mathrm{BM}})\}\,\mathrm{e}^{-\mathrm{j}k_z^{\mathrm{BM}}z}, \tag{15}$$

where $\mathrm{Res}\{\tilde{C}(k_z^{\mathrm{BM}})\}$ stands for the residue of $\tilde{C}(k_z)$ at $k_z = k_z^{\mathrm{BM}}$.

3. Numerical Results

[13] A computer code based on the procedure explained above has been implemented to calculate the voltage across the slot of the wave excited along the slotline. Using this code the behavior of the waves on the slotline will be investigated at different frequencies and also for various geometries and substrate permittivities. Apart from its academic interest, the above investigation can be very useful from a practical point of view. In fact,

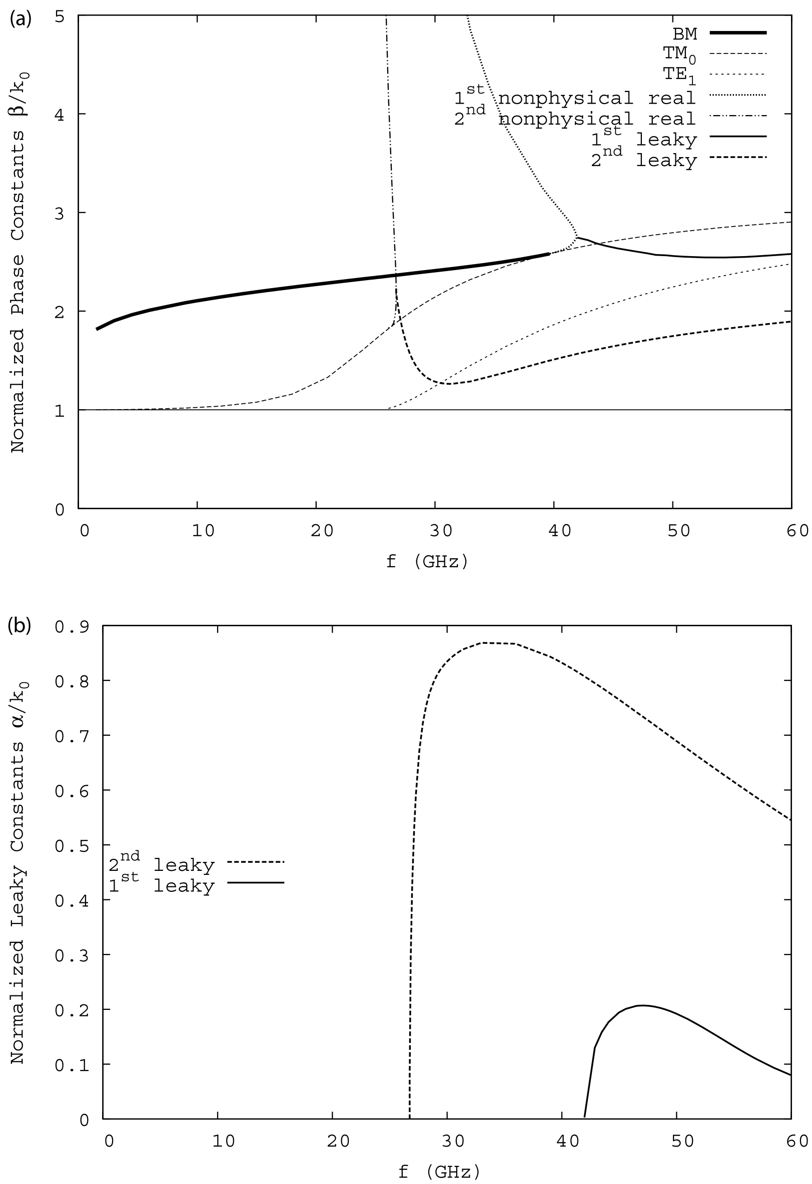

Figure 3. (a) Normalized phase and (b) attenuation constants versus frequency for a slotline with w = 0.25 mm, h = 1 mm, and ε_r = 9.9.

the spurious effects due to the appearance of the slot mode in many practical printed-circuit elements fabricated in coplanar waveguide technology are a very important practical issue [*Mirshekar-Syahkal and Danneel*, 1994]. Our numerical results will be validated via a comparison with data from the eigenvalue analysis of the sourceless slotline performed by the APTL code [*Zehentner et al.*, 2004] (which gives the dispersion characteristics of modes and their characteristic impedances, if defined). The dispersion characteristics were calculated using three basis functions in the x direction and two basis functions in the z direction. Additional validation will be carried out by comparing our results with measurements.

[14] First we show in Figures 3a and 3b the normalized propagation and attenuation constants (dispersion relation) of a slotline with typical dimensions employed in microwave printed circuits: w = 0.25 mm, h = 1 mm, and ϵ_r = 9.9. The bound mode starts to propagate from zero up to about 40 GHz. Beyond 40 GHz, the bound-mode solution is mathematically continued by the solution of a

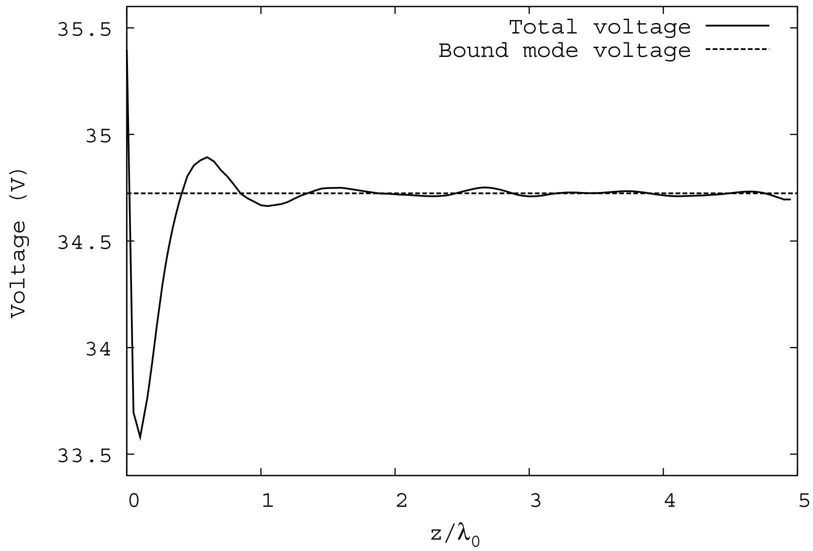

Figure 4. Total voltage and the bound-mode, calculated along the slot for slotline with w = 0.25 mm, h = 1 mm, and ε_r = 9.9 at frequency f = 5 GHz. The source is placed at z = 0, with d = 1 mm.

dispersion equation in the form of the 1st nonphysical real mode. The complex solution of the dispersion equation corresponding to the so-called 1st leaky mode starts at about 42 GHz with α = 0. This complex dispersion solution is physically meaningful from about 43 GHz, where its phase constant is lower than the TM_0 surface mode wave number, k_{TM0}, and simultaneously higher than the TE_1 surface mode wave number k_{TE1}. The other complex solution of the dispersion equation corresponding to the so-called 2nd leaky mode arises from two real nonphysical modes that meet together at about 27 GHz. This complex dispersion solution is physically meaningful above 31 GHz approximately, where its phase constant is lower than the TE_1 surface mode wave number, k_{TE1}, and simultaneously higher than the free space wave number k_0. The high values of the normalized attenuation constant of this leaky mode, plotted in Figure 3b, indicate that this leaky mode is only expected to be relevant at very short distances from the source.

[15] For the above structure, Figure 4 shows the difference between the bound-mode wave voltage and the total voltage wave at a frequency of 5 GHz, where only the bound mode propagates along the slotline. The curve of the total voltage shows that, in the vicinity of the source, the field is strongly influenced by the continuous spectrum wave (here mostly of reactive nature), which in this situation is entirely accounted for by the residual wave contribution [*Jackson et al.*, 2000; *Mesa et al.*, 2001]. Far from the source, the contribution of the continuous spectrum fades out and, consequently, the total voltage wave reduces to only the bound-mode voltage. This voltage is described by (15).

[16] The behavior of the excited voltage wave for various frequencies is shown in Figure 5. The evolution of the longitudinal voltage profile as frequency increases is consistent with the dispersion characteristics of the modes that can propagate along the slotline at particular frequencies. Figure 5 shows that the voltage contribution associated with the bound mode decreases as the frequency increases; this can be related to the fact that its characteristic impedance falls with growing frequency. This rationale applies in the frequency range where only the bound mode propagates. In agreement with the dispersion relation, Figure 5 shows that above approximately 40 GHz there is no bound mode propagating along the line. Beyond the cutoff frequency of the bound mode, the energy only leaks, causing the voltage amplitude to strongly decrease with distance along the line. Physically, the leakage out of the line starts from about 31 GHz in the slotline considered in Figure 5. In Figure 5 it is apparent that at 10, 20, and 30 GHz the voltage consists mainly of the bound mode. At 40 GHz and mainly at 50 GHz the constant amplitude of the bound mode disappears and the total voltage falls as the energy leaks in the form of leaky and/or residual waves. The present analysis shows that there are no sharp boundaries between the specific frequency ranges of propagation of particular waves predicted by eigenmode analysis (a finer frequency study not shown here

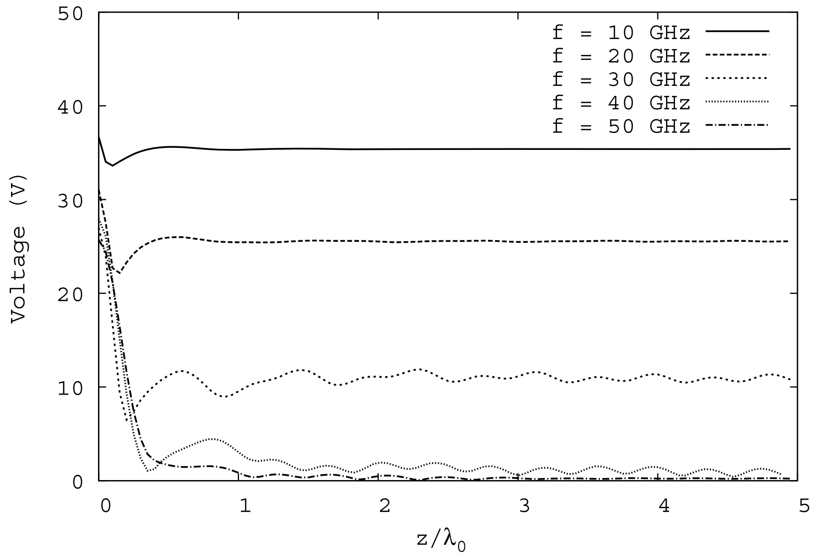

Figure 5. Total voltage calculated along the slot at different frequencies. The source is placed at $z = 0$. Solution for a slotline defined in Figure 3.

clearly demonstrates this fact). The character of the excited wave varies continuously, and, therefore, the field decay caused by leakage losses evolves gradually with increasing frequency.

[17] As has been pointed out above, the slotline shows important qualitative differences in the behavior of propagating waves with respect to that of the microstrip line, although both lines are open planar transmission lines. Since most of the previous studies have dealt with the microstrip line, the specific behavior of the slotline will be documented here in some detail. In this way, a parametric study of the above structure will be carried out to see how the different structural parameters affect the behavior of the voltage wave excited in the slotline.

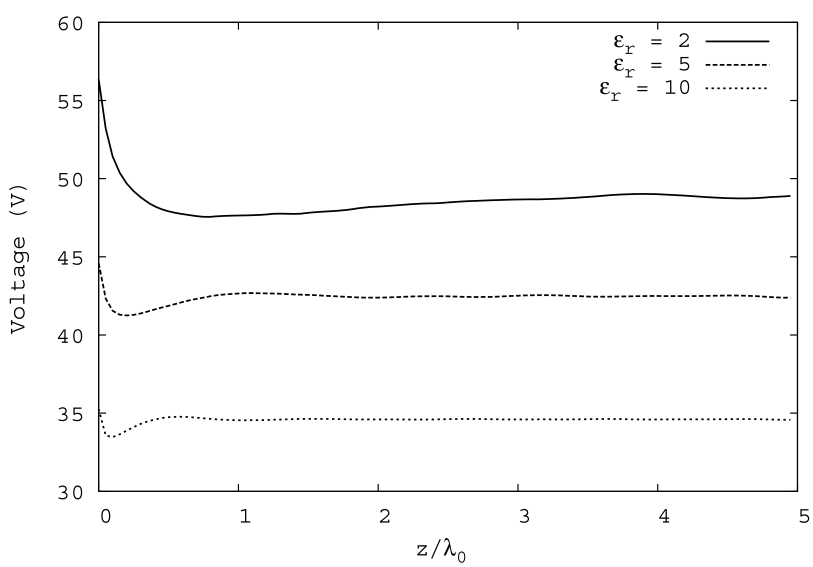

Figure 6. Total voltage calculated along the slot for the line with different substrate permittivities. The source is placed at $z = 0$. Solution for a slotline with $w = 0.25$ mm, $h = 1$ mm, and $f = 5$ GHz.

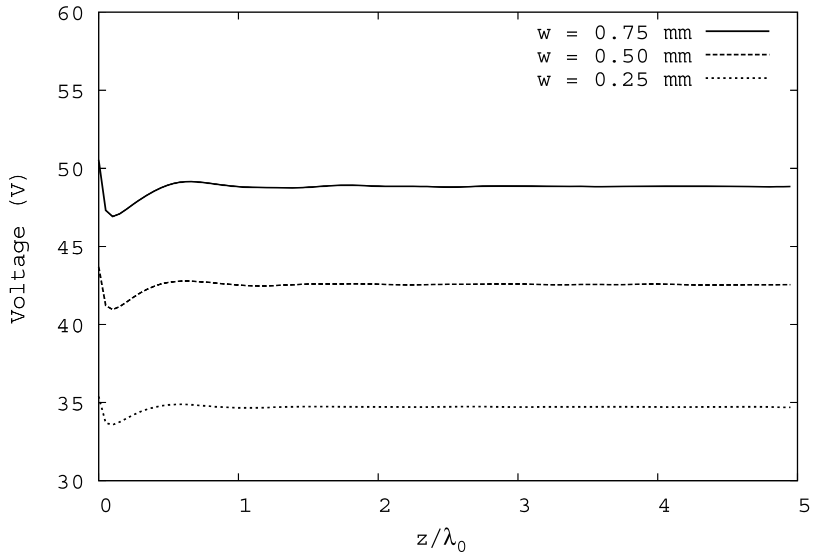

Figure 7. Total voltage calculated along the slot for the line with different widths of the slot. The source is placed at $z = 0$. Solution for a slotline with $h = 1$ mm, $\varepsilon_r = 9.9$, and $f = 5$ GHz.

Specifically we will study the influence of the substrate permittivity, the width of the slot, and the thickness of the substrate.

[18] Along with this parametric study we will carry out a partial but important validation of our results. For this purpose, we will compare the value of our computed bound-mode voltage amplitude with the value of the voltage resulting from the product of the characteristic impedance of the line given by *Zehentner et al.* [1998a] and the current supplied by the source. Following a similar rationale as in the work of *Mesa and Jackson* [2005], and taking into account that the current source of amplitude I_0 is located at the middle of the infinite line with characteristic impedance Z_0, the bound-mode voltage can be approximately expressed as

$$V_{\rm BM} \approx \frac{I_0}{2} Z_0 \,. \quad (16)$$

Since we assumed a source of current amplitude $I_0 = 1$ A, the numeric value of Z_0 should coincide approximately with two times the computed bound-mode voltage amplitude.

[19] The profile of the total voltage for different substrate permittivities is plotted in Figure 6 at a frequency of 5 GHz. In Figure 6, the bound-mode voltage amplitude can be read as the value of the total voltage amplitude far from the source (in this case, the continuous-spectrum contribution is almost negligible several wavelengths away from the source). Figure 6 shows that the bound-mode voltage is lower for the substrate of higher permittivity, in agreement with the corresponding decrease in the characteristic impedance with increasing relative permittivity. A comparison between the values of $V_{\rm BM}$ read from Figure 6 (which coincide with the values given by equation (15)) and the values of the characteristic impedance given by *Zehentner et al.* [1998a] is reported in Table 1. The good agreement observed in Table 1 is a clear hint of the correctness of our proposed method. Moreover, following *Mesa and Jackson* [2005], it shows that the characteristic impedance of the bound modes in slotlines can be efficiently computed via a simple numerical procedure; namely, Z_0 can be calculated from equation (16) using $I_0 = 1$ A and voltage $V_{\rm BM}$ determined by equation (15). Figure 6 also shows that the influence of the residual wave (there is no leaky wave at this low frequency) is weaker with increasing permittivity, as the voltage ripple of the wave is canceled closer to the source.

[20] Since the width of the slot is one of the most important parameters of the slotline, the behavior of the

Table 1. Values of the Bound Mode Voltage Compared to Values of Characteristic Impedance for Different Substrate Permittivities[a]

	$\varepsilon_r = 2$	$\varepsilon_r = 5$	$\varepsilon_r = 10$
$2V_{\rm BM}$ (V)	97.4	85	69.2
Z_0 (Ω)	96.3	84.6	69.6
Error (%)	1.1	0.5	0.6

[a]Parameters of the line are those of Figure 6.

Table 2. Values of the Bound Mode Voltage Compared to Values of Characteristic Impedance for Different Widths of the Slot[a]

	w = 0.25 mm	w = 0.50 mm	w = 0.75 mm
$2V_{\mathrm{BM}}$ (V)	69.4	85.2	97.6
Z_0 (Ω)	69.8	86.8	99.8
Error (%)	0.6	1.8	2.2

[a]Parameters of the line are those of Figure 7.

Table 3. Values of the Bound Mode Voltage Compared to Values of Characteristic Impedance for Different Thicknesses of the Substrate[a]

	h = 1 mm	h = 2 mm	h = 3 mm
$2V_{\mathrm{BM}}$ (V)	69.4	63	58.6
Z_0 (Ω)	69.8	63.5	59.1
Error (%)	0.6	0.8	0.8

[a]Parameters of the line are those of Figure 8.

total voltage amplitude with respect to this parameter is plotted in Figure 7. Table 2 again shows the good matching between the values of the bound-mode voltage amplitude computed via (15) and (16); the relative error is also mentioned Table 2. Figure 7 shows that the slot width has a strong influence at the level of the total voltage. Since the characteristic impedance of the slotline increases with increasing slot width [*Gupta et al.*, 1979], assuming a constant value of the feeding current amplitude, the bound mode voltage grows as well.

[21] Like the width, the height of the substrate, *h*, has a fundamental influence on the total voltage on the slot, although in the reverse sense as in the case of *w*. The calculated voltage distributions for different substrate heights are plotted in Figure 8. Table 3 shows again the good matching between the values of the bound-mode voltage amplitude computed via (15) and (16). Since the characteristic impedance decreases as the substrate thickness increases, the same is then valid for the bound-mode voltage V_{BM}.

[22] Next the structure to be used for the measurements will be analyzed (the capabilities of our experimental setup make that the dimensions of this structure have to be larger than usual in microwave printed circuits). First, Figure 9 shows the dispersion relation of this slotline. The bound mode propagates along the line from zero frequency up to 5.3 GHz. From that cutoff frequency up to 6.15 GHz there is a spectral gap on the line [*Zehentner et al.*, 1998a]. Above 5.7 GHz a dispersion-equation complex solution appears (the so-called first leaky mode), which starts to be physical at 6.15 GHz as its phase constant goes down crossing the TM_0 surface mode wave number. The second leaky mode sets in at 4.2 GHz, but starts to be physically meaningful at 4.9 GHz, where it becomes lower than the TE_1 surface mode wave number. The first leaky mode and the second

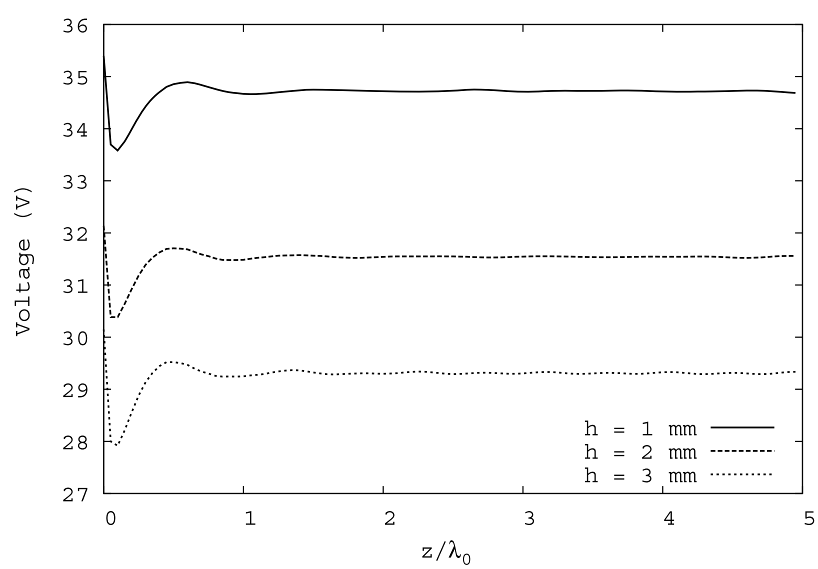

Figure 8. Total voltage calculated along the slot for the line with different thickness, *h*, of the substrate. The source is placed at z = 0. Solution for a slotline with w = 0.25 mm, ε_r = 9.9, and f = 5 GHz.

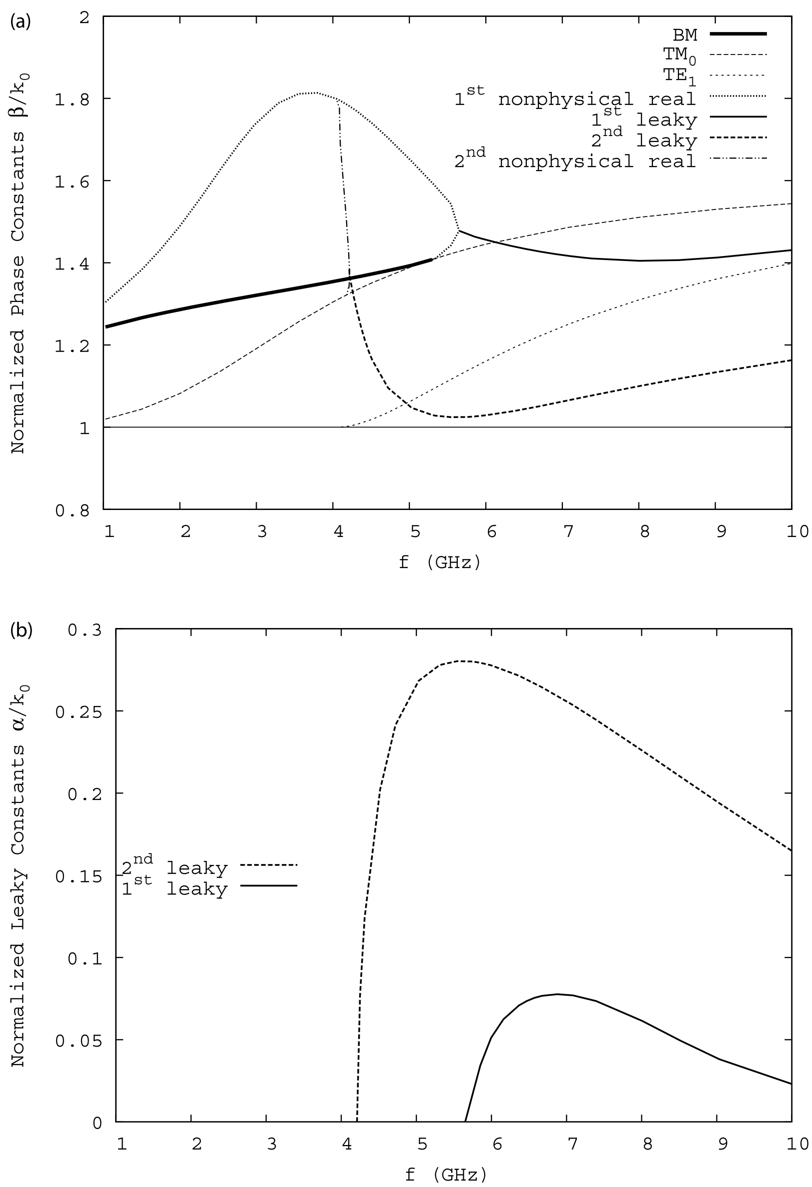

Figure 9. Frequency behavior of the (a) phase and (b) leaky constants for the measured slotline on a substrate with w = 5.6 mm, h = 14.6 mm, and ε_r = 2.6.

leaky mode attenuation constants are plotted in Figure 9b. Figure 9b shows that the second leaky mode is much more attenuated than the first leaky mode, and therefore it is expected that the second leaky mode only influences the total voltage at very short distances from the source.

[23] The computed longitudinal profile of the total voltage amplitude along the slot of the previous structure is shown in Figure 10. The three working regimes defined by the dispersion relation in Figure 9 are compared here. The total voltage at 3 GHz comprises the bound mode contribution in addition to the residual wave contribution. At 5 GHz, the total voltage shows the combined influence of the bound mode, the second leaky mode, and the residual wave. The last curve for 8 GHz shows the composition of the two leaky modes (the first leaky mode plus the second leaky mode) together with the residual wave.

[24] The interesting behavior of the total voltage at 5 GHz is studied in more detail in Figure 11a. Both the bound mode and the physically meaningful second leaky

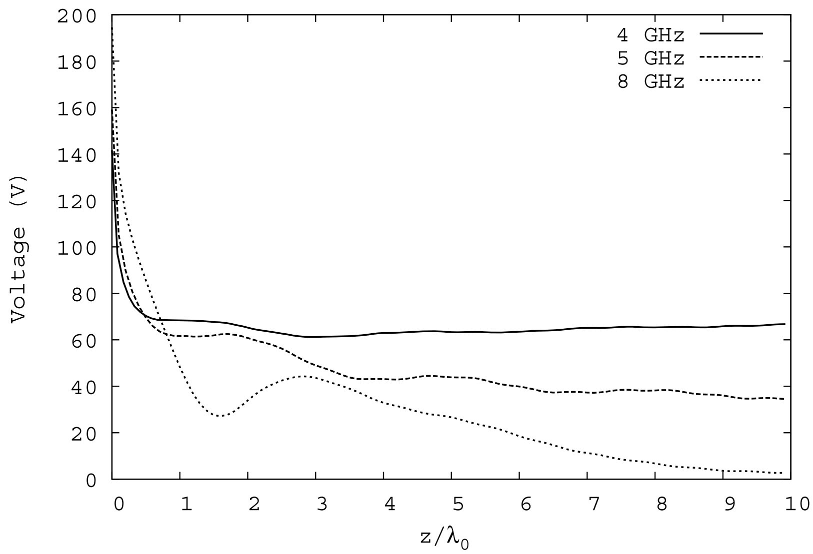

Figure 10. Total voltage amplitude for a slotline with w = 5.6 mm, h = 14.6 mm, and ε_r = 2.6, calculated for various frequencies.

mode can propagate along the line at this frequency. The second leaky wave is strongly attenuated in accordance with the dispersion characteristic in Figure 9. The difference between the total voltage and the sum of the leaky and bound-mode contribution represents the residual wave. Figure 11b shows the profiles of the total voltage and the two leaky modes at 8 GHz. The difference between the sum of the leaky modes and the total voltage represents the residual wave. In this case, it can be observed that the total voltage falls to zero after a certain distance from the source, due to leakage of energy caused by the absence of a bound mode.

4. Measured Results

[25] The setup of our measuring system (see Figure 12) contains computer-controlled mechanical hardware which allows us to move the electric field probe in the z direction. The minimum probe step can be set to 0.1 mm. The measured data is sent to a computer system for evaluation and storing. The measured slotline is terminated by an absorbing material placed on its metallization across the slot. The substrate edges are ended by a wedge at an angle of 45° in order to reduce reflections as much as possible. The substrate dimensions are 500 × 500 mm. In contrast to the finite dimensions of the problem, our computed results are obtained assuming a laterally unbounded line with an infinite longitudinal dimension. The thickness of the metallization is assumed to be negligible (≈40 μm).

[26] The voltage of the wave excited on the slotline fed by a coaxial cable connected across the slot was measured along the line defined in Figure 12. The measurement was taken by the monopole probe located across the slot very close above the substrate. This probe integrates the transversal component of electric field across the slot, and thus the measured signal corresponds to the voltage amplitude.

[27] The measured voltage amplitudes are compared in Figures 13a–13c with our computed data. The two sets of data are conveniently normalized for comparison purposes, and thus they are represented in arbitrary units of voltage. The results are plotted at three distinct frequencies corresponding to the three different working regimes commented above. At 4 GHz, only the bound mode propagates along the slot and, therefore, the voltage is nearly constant along the line far from the source, as can be seen in Figure 13a. At 5 GHz, both the bound mode and the second leaky wave can propagate. In this case, shown in Figure 13b, the voltage decreases due to the leakage close to the source and, starting from a distance of about 200 mm, remains constant. Figure 13c shows the voltage distribution at 8 GHz. At this frequency, only the first and second leaky waves can propagate but not the bound mode. So the voltage goes down very quickly, because all energy is radiated in the form of leaky and residual waves within a short distance [*Zehentner et al.*, 1998b].

[28] The calculated and measured voltages agree satisfactorily, although the measured curves are deteriorated by a standing wave caused by the bound or leaky modes reflected from the line ends at the substrate edges. The wavelengths of the measured standing waves agree with the theoretically predicted wavelengths. The difference

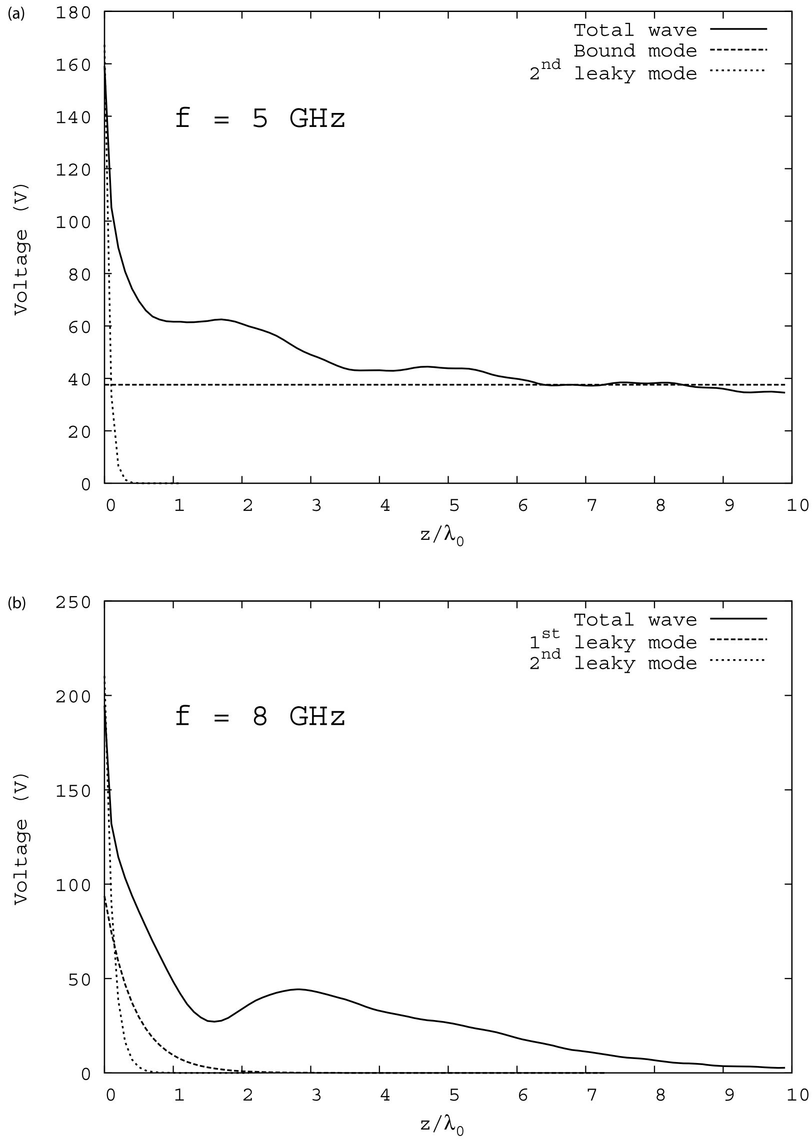

Figure 11. Total voltage and leaky modes voltage calculated along the slot for slotline with w = 5.6 mm, h = 14.6 mm, ε_r = 2.6. (a) f = 5 GHz and (b) f = 8 GHz.

of the voltages close to the source is probably due to the non symmetrical connection of the feeding point to the coaxial cable. This feeding does not correspond exactly to the model used in our simulation.

5. Conclusions

[29] This paper briefly presents the spectral domain method applied to the analysis of voltage waves excited on the slotline by a realistic current source connected across the slot. A computer code based on this method has been developed. Some results obtained by this code are presented here.

[30] The investigation, both theoretical and experimental, offers a new insight into those waves propagating along the slotline and enhances general knowledge about this transmission line, based only on eigen-mode analysis till now. One of our conclusions is that there are no sharp boundaries between slotline working regimes as somewhat expected from a pure eigen-mode analysis. The field of excited waves evolves continuously with changing frequency and changing line parameters.

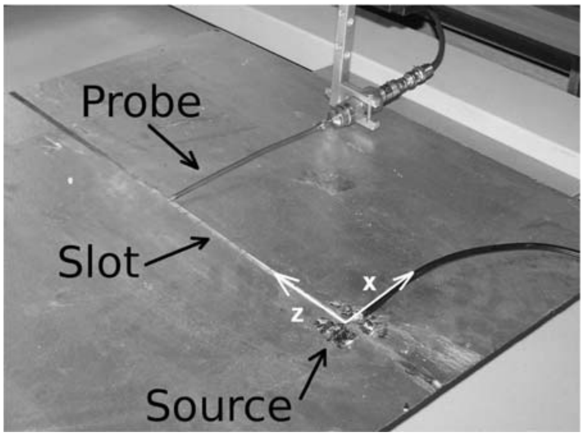

Figure 12. Our measurement setup. The slotline has w = 5.6 mm, h = 14.6 mm, and ε_r = 2.6.

[31] The results show that the total voltage distribution along the slotline is affected both by the dimensions of the slotline and by the permittivity of the substrate. This voltage is also strongly influenced in the neighborhood of the current source by the parameters of this source. Far from the source, only the bound mode exists at low frequencies, therefore the voltage amplitude is constant here. At higher frequencies, where the slotline is not able to transmit the bound mode, the propagating field is strongly attenuated along the slot due to the leakage of energy.

[32] The voltage distribution along the slotline has been studied at three distinct frequency ranges, corresponding to different mode-dispersion regimes; namely, a low-frequency regime, where only the bound mode and the residual waves exist, a medium-frequency regime, characterized by the superposition of the bound mode with the second leaky mode as well as the residual waves, and finally a high-frequency regime with no bound mode

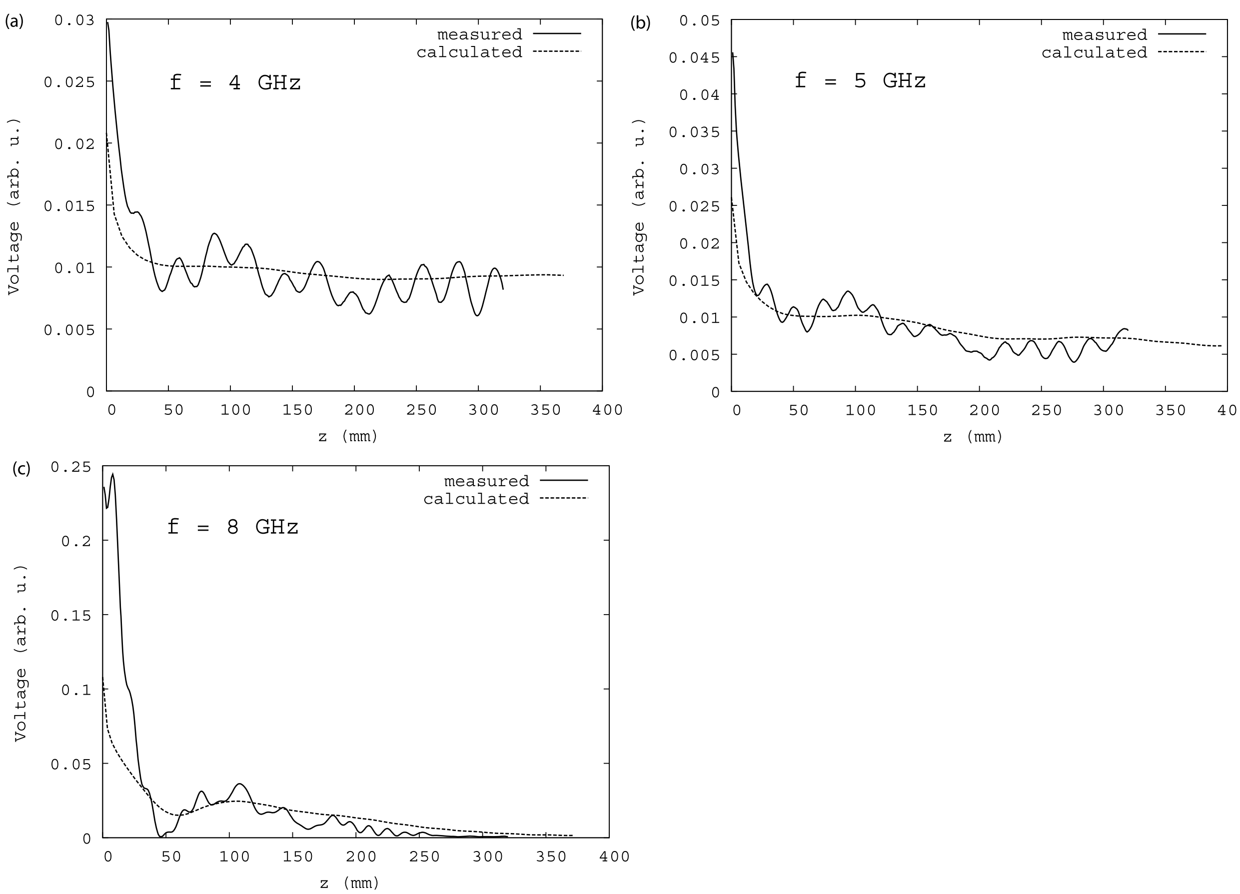

Figure 13. Total voltage along the slotline with w = 5.6 mm, h = 14.6 mm, and ε_r = 2.6 at various frequencies. The source is placed at z = 0. (a) f = 4 GHz, (b) f = 5 GHz, and (c) f = 8 GHz.

propagating. Our results clearly explain the behavior of particular waves in these regimes. The numerical results were successfully validated by measurements.

[33] **Acknowledgments.** The work of V. Kotlan and J. Machac has been supported by the Grant Agency of the Czech Republic under project 102/08/H018 "Modelling and Simulation of Fields" and under project 102/09/0314 "Investigation of Metamaterials and Microwave Structures With the Help of Noise Spectroscopy and Magnetic Resonance." The work of F. Mesa has been partially supported by the Spanish Ministerio de Educación y Ciencia and European Union FEDER funds (project TEC2007-65376).

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