

Comparative analysis of the dispersion characteristics of a slotline and a microstrip line

Vaclav Kotlan ^{#1}, Jan Machac ^{#2}, Francisco Mesa ^{*3}

[#]Czech Technical University in Prague
Technicka 2, 166 27 Praha 6, Czech Republic

¹kotlav1@fel.cvut.cz

²machac@fel.cvut.cz

^{*}University of Seville

41012 Seville, Spain

³mesa@us.es

Abstract — This paper compares the dispersion characteristic of a slotline with that of a microstrip line. A full wave analysis of a slotline including the excitation source is presented. All kinds of modes are taken into account, including a bound mode, leaky modes, and a residual wave. The line is excited by a time-harmonic source of constant current connected across the slot of the line. The theoretically predicted results have been verified by experiments and by simulations in the CST Microwave Studio. A continuous behaviour is documented, rather than the step-like behaviour of waves propagating along the investigated lines as predicted by a pure eigenmode analysis.

Index Terms — Slotline, microstrip line, bound mode, leaky waves, residual wave, full wave method, eigenmode analysis.

I. INTRODUCTION

Open planar transmission lines are the basic components of all planar microwave circuits, and they have therefore been of great interest to many researchers in the last four decades [1]. There have been many studies of the properties of waves propagating along the microstrip line and the slotline, aimed mainly at determining their dispersion characteristics and their characteristic impedance [2]. However, both lines, like other transmission lines, are capable of exciting leaky waves in addition to transmitting the bound mode [2], [3]. These leaky waves affect the behaviour of the line, as they may cause strong attenuation of the transmitted signal and other spurious effects. The dispersion characteristics of the lines are determined by solving an eigenmode problem, as for instance in [2], [3]. As a result, the propagation constants and field distribution of modes that can propagate along the line are obtained. A superior way of analysis takes also into account a source that excites a field on the transmission line [4]. It provides a tool for determining the actual field of a total wave in the line.

Most work with planar transmission lines has focused on microstrip lines and various strip lines. Waves excited by a voltage source connected into a gap in the strip of the microstrip line were studied in [4], [5], and in the case of striplines in [6].

This paper presents the dispersion characteristics of the microstrip line and slotline, but mainly shows the results of an investigation of a slotline fed by a current source connected across the slot. The distribution of the voltage along the slotline of the excited wave is calculated using the spectral domain method [4]. The calculated voltage distributions have been verified by measuring the electric

field along the line, and by simulating the slotline structure with CST Microwave Studio. The results show that the excited wave is composed of a bound mode and leaky modes, together with a residual wave. In this way we obtain a precise picture of the wave behaviour in a wide frequency band, including inside the spectral gap predicted by the eigenmode analysis. The field distribution, and therefore the slotline transmission properties, evolve continuously as frequency increases. The total wave excited on the slotline “does not see” the spectral gap, when its frequency increases, and is excited in accordance with [7] even in this gap.

II. SLOTLINE VERSUS MICROSTRIP LINE

First, a homogeneous microstrip line was investigated. The configuration of the slotline, fed by a current source, is shown in Fig. 1(a). The line has strip width $w = 5$ mm, and it was fabricated on a plexiglass substrate with relative permittivity $\epsilon_r = 2.6$ and thickness $h = 5$ mm.

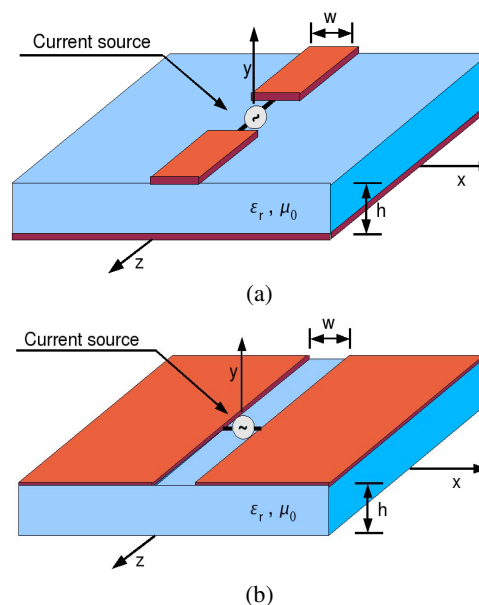


Fig. 1 Sketch of the microstrip line (a), and the slotline (b). The current source is connected inside the strip (a), across the slot (b), respectively, at $z = 0$, and $y = h$.

The bound mode on the microstrip line can propagate from zero frequency up to theoretically infinite frequency. This is documented by the dispersion characteristic of the microstrip

line in Fig. 2. In practice, the bound mode naturally cannot propagate up to infinite frequency as this is prevented by increased losses and by radiation. In distinction of this, the bound mode on the slotline is able to propagate from zero frequency up to a certain cut-off frequency. This frequency is determined by the onset of leaky modes [3].

The differences in the behaviour of these lines are remarkable in the distributions of the calculated and measured transversal electric field along the slotline and of the electric current along the strip.

Secondly, the longitudinally homogeneous slotline on a dielectric substrate of infinite width is investigated here. A sketch of this line is shown in Fig. 1(b). The dielectric substrate is h in thickness with relative permittivity ϵ_r , and the slot width is w . The slotline model was built on a plexiglass sheet $h = 14.6$ mm in thickness and $\epsilon_r = 2.6$. The slot width was chosen 5.6 mm. The line is assumed to be lossless. Only modes with even symmetry of the transversal electric field component are considered.

Applying the standard eigenmode analysis of the microstrip line and also of the slotline, which uses the method of moments applied in the spectral domain [1], [3], we obtain the dispersion characteristics as well as the electromagnetic field distributions of the modes that can propagate along these lines. The dispersion characteristic in the form of the frequency dependence of the normalized phase, β/k_0 , and attenuation, α/k_0 , constants of the investigated microstrip line is plotted in Fig. 2, and the dispersion plot of the slotline is plotted in Fig. 3, k_0 is the free space wavenumber.

The dispersion plot in Fig. 2 shows the typical behaviour of the waves excited along the microstrip line. We can see that the bound mode can exist from zero frequency and continue up to infinity. The complex solution of the dispersion equation, the 1st leaky mode, appears at a frequency around 5 GHz. However, this mode is physically meaningful from 6.2 GHz, where its phase constant is lower than the TM_0 surface mode propagation constant k_{TM_0} up to approximately 8 GHz, where its phase constant is lower than the free space wavenumber. In this frequency range the leaky mode exists simultaneously with the bound mode.

Next, we will focus on the electromagnetic behaviour of the slotline. Looking only at the dispersion characteristic shown in Fig. 3, we can deduce the subsequent “black and white” mode behaviour. The bound mode propagates along the slotline starting from zero frequency up to its cutoff frequency [3], read from Fig. 3, at 5.3 GHz. For this line, there is a “spectral gap” that is rather wide, up to 6.15 GHz. This gap does not exist in dispersion plots of the microstrip line. Within the gap of the slotline, the complex solution of the dispersion equation corresponding to the 1st leaky mode sets in at 5.7 GHz, and this mode starts to be physical at 6.15 GHz, where its phase constant becomes lower than the TM_0 surface mode propagation constant k_{TM_0} . The complex solution of the dispersion equation, corresponding to the 2nd leaky mode, sets in at about 4.1 GHz. This mode starts to be

physical at 4.9 GHz, where its phase constant becomes lower than the TE_1 surface mode propagation constant k_{TE_1} . The eigenmode analysis does not, however, tell us if the modes are actually excited and with which amplitude, *i.e.*, which part of the power delivered by a real source goes to a particular mode. This is due to the absence of a source in the analysis.

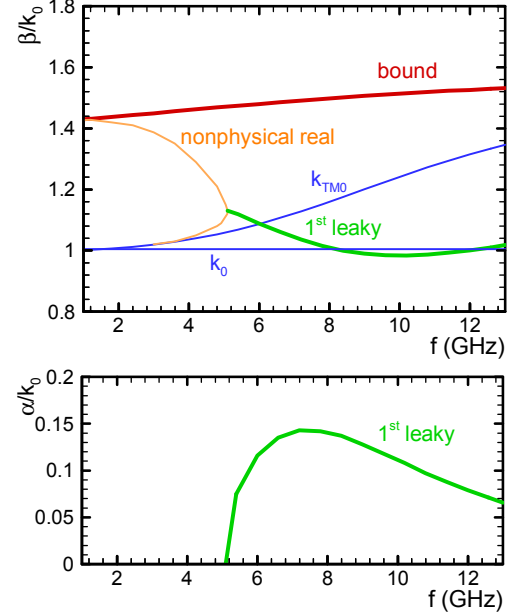


Fig. 2 Normalized phase and leakage constants for the microstrip line defined in the text.

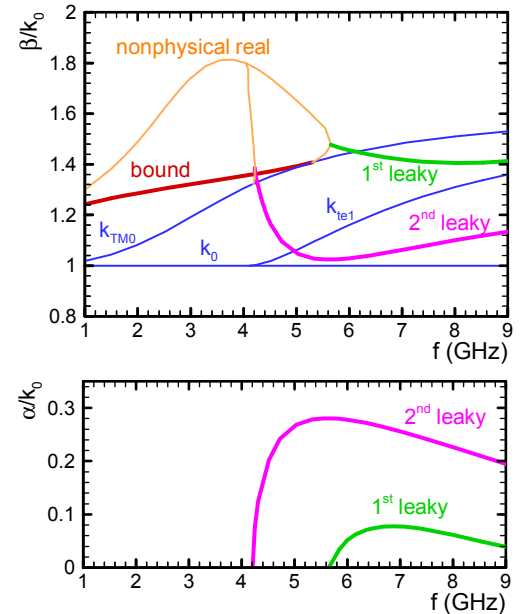
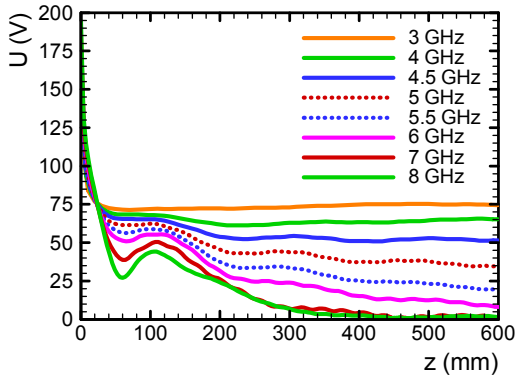


Fig. 3 Normalized phase and leakage constants for the slotline defined in the text.

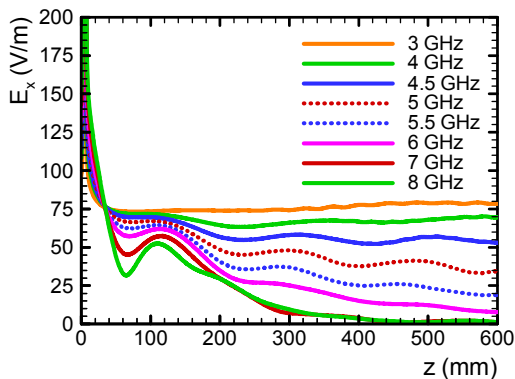
The feeding point of the slotline can be modeled by a time-harmonic source of constant current connected across the slot. The current supplied by this source is along the slot, see

Fig. 1(b), modeled by a Gaussian function in the z direction. This analysis results in the electromagnetic field distribution of the wave excited on the slotline [8]. The particular mode complex propagation constants coincide with the positions of the poles in the complex k_z propagation constant plane [4].

The voltage distribution of a wave excited by a current source along the slotline defined above was calculated at various frequencies, as shown in Fig. 4(a). A first conclusion drawn from this figure is that there are no abrupt onsets of leakage at the frequencies proposed in the dispersion characteristic of Fig. 3. Similarly, the presence of the “spectral gap” does not seem to have any significant effect on this plot. All curves show a rapid decrease in voltage very close to the source caused by the field evolution itself on the line and then the interference of the bound mode with all other possibly excited waves. Far from the source, the voltage at low frequencies is nearly constant, as expected in a lossless line when only the bound mode propagates. The bound-mode field amplitude is equal to the residue at the corresponding pole. This residue, as well as the amplitude, decreases as the frequency increases. Starting from 4.5 GHz, the voltage decays due to the energy leakage. Finally, at some frequency between 5.5 and 6 GHz, it can be observed that the bound mode disappears, and, at higher frequencies, the voltage decreases rapidly to zero due to leakage effects.



(a)



(b)

Fig. 4 Voltage calculated along the slot using the moments method (a) and field distributions along the slotline calculated by the CST Microwave Studio (b) at various frequencies.

To compare the wave excited along the slotline with a typical wave excited along the microstrip line, we simulated the behaviour of the previously defined microstrip line in the CST Microwave Studio. The result of this full wave simulation is shown in Fig. 5, where we plot the longitudinal component of the electric field, 0.2 mm above the strip center, which corresponds to the current along the strip. The constant value of the field far from the source clearly demonstrates the presence of the bound mode at each frequency. The differences in the level of the bound mode are due to an impedance frequency variability.

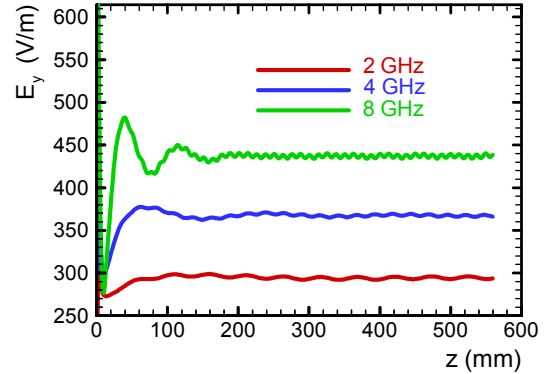


Fig. 5 Field distribution along the microstrip line calculated in the CST Microwave Studio.

III. EXPERIMENT DISCUSSION

Let us first verify the correctness of our results. Fig. 4(b) shows the transversal component of the electric field at the slot center, E_x , calculated by the CST Microwave Studio. This field is a linear measure of the voltage across the slot. Except for the absolute values caused by non-calibrated measurement, the behaviour of the field distributions at the corresponding frequencies is exactly the same as the voltage distributions plotted in Fig. 4(a). In the CST Microwave Studio, the slotline is modeled using “open” boundary conditions at the substrate edges (*i.e.*, as with infinite dimensions) and therefore without reflections at these edges. The slotline was fed by a “point” source connected across the slot.

Electric field component E_x was measured along the slot using a computer-driven system taking 1D field distributions (see Fig. 6). The main problem of the experiment performed here is the excitation of a standing wave caused by reflection of the bound mode at the line end. This is remarkable in the case of plots taken for frequencies below 5.5 GHz; it has been observed that the lower the frequency, the higher the amplitude of the standing wave. We attribute this spurious effect to the non-ideal nature of the line termination provided by the absorbing material bedded on the line end across the slot. Other problems come from reflections from the substrate edges, since the slotline was fabricated on a dielectric sheet with finite dimensions 500x500 mm. Fig. 6 compares the calculated and measured field distributions at two different

frequencies. As the measuring equipment was not calibrated, the experimental curves are normalized to obtain comparable magnitudes of the voltage and the electric field. There is a good agreement between the measured and calculated data, except for the character of the standing wave.

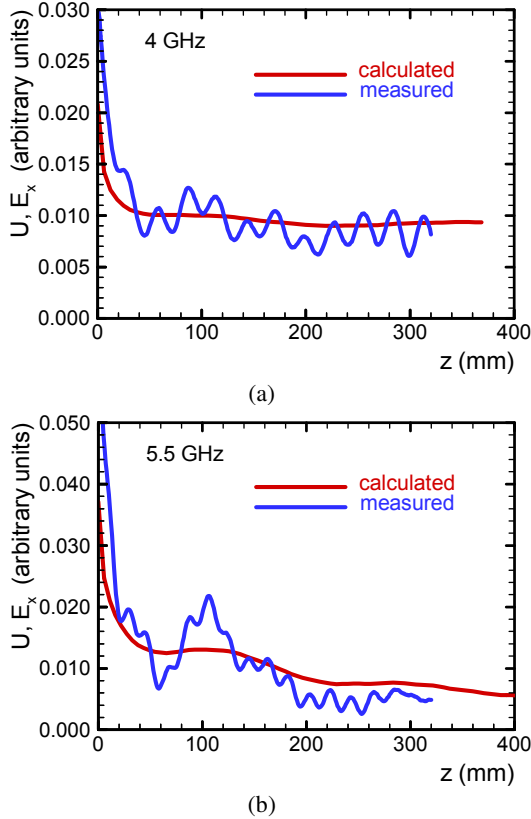


Fig. 6 Measured and calculated field distributions along the slotline at 4 GHz (a), 5.5 GHz (b).

IV. CONCLUSIONS

This paper studies the important practical issue of the electromagnetic behaviour of the slotline. This behaviour is compared to the microstrip line. The waves propagating along the slotline are excited by a current source of finite dimensions. The field distributions of these waves are calculated by the spectral domain method. Measurements of the field distributions together with the simulations performed by the CST Microwave Studio fully validate the theoretical results.

The behaviour of waves on the slotline is different from that in the microstrip line. The bound mode propagates along the microstrip line in a relatively wide frequency band, theoretically infinite, and the leaky modes are excited simultaneously with it. This means in practice that the attenuation due to the leaky waves is less severe here.

The bound mode in the slotline is excited only up to a certain cutoff frequency determined exactly by the eigenmode analysis. At higher frequencies, only the leaky and residual waves are excited and, therefore, the propagating

wave is attenuated to zero far from the source. However, the residual wave decays more slowly than a leaky wave, which makes the attenuation less strong than that corresponding to the leakage itself.

The present analysis also shows that there are no sharp boundaries between the specific frequency ranges of propagation of particular waves predicted by eigenmode analysis. The character of the excited wave varies continuously, and, therefore, the field decay caused by leakage losses evolves gradually with increasing frequency. In view of this, it is not essential to keep the application of the slotline in microwave circuits strictly according to the limits determined by the cutoff frequencies resulting from a pure eigenmode analysis, like that performed in [3]. This is in full correspondence with the naturally continuous (rather than steplike) behaviour observed for this line.

ACKNOWLEDGEMENT

The experiment performed in this work was supported by the Grant Agency of the Czech Republic under projects 102/09/0314 "Investigation of Metamaterials and Microwave Structures with the Help of Noise Spectroscopy and Magnetic Resonance", and the theoretical work was supported by project 102/08/H018 "Modelling and Simulation of Fields," and by the Spanish Ministerio de Educación y Ciencia and European Union FEDER funds, project TEC2007-65376.

REFERENCES

- [1] K. C. Gupta, R. Garg, I. J. Bahl, "Microstrip Lines and Slotlines," Dedham, Artech House, 1979.
- [2] T. Itoh, R. Mitra, "Dispersion Characteristics of Slotline," *Electron. Lett.*, Vol. 7, No 13, pp. 364-365, 1971.
- [3] J. Zehentner, J. Machac, M. Migliozi, "Upper cut-off frequency of the bound wave and new leaky wave on the slotline," *IEEE Transactions Microwave Theory and Techniques*, Vol. MTT-46, No. 4, pp. 378-386, April 1998.
- [4] F. Mesa, C. Di Nallo, D. R. Jackson, "The theory of surface-wave and space-wave leaky-mode excitation on microstrip lines," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 2, pp. 207-215, February 1999.
- [5] F. Mesa, D. R. Jackson, and M. Freire, "High frequency leaky-mode excitation on microstrip line," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 49, No. 12, pp. 2206-2215, December 2001.
- [6] D. R. Jackson, F. Mesa, M. J. Freire, D. P. Nyquist, C. Di Nallo, "An excitation theory for bound modes, leaky modes, and residual-wave currents on stripline structures," *Radio Science*, Vol. 35, No. 2, pp. 495-510, February 2000.
- [7] A. A. Oliner, D. R. Jackson, "On spectral gaps at the transition between bound and leaky modes," 1995 International Symposium on Electromagnetic Theory, URSI, St. Petersburg, Russia, Proc. pp. 764-766, May 1995.
- [8] V. Kotlan, F. Mesa, J. Machac, "Voltage excited along a slotline by a current source," *Radio Science*, submitted for publication.