Slotline Operating within a Wide Frequency Band: Excitation of Waves by a Real Source

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***Abstract* — This paper presents a full wave analysis of a slotline including the excitation source. All kinds of modes are taken into account, including a bound mode, leaky modes, and a residual wave. The line is excited by the source of constant current connected across the line slot. The paper specifies more correctly or improves some of our views about wave transmission along the slotline obtained by an eigen mode analysis. This considers namely slotline applications and wide frequency bands. The theoretically predicted results are verified by experiments and by simulations in the CST Microwave Studio.**

***Index Terms* — Bound mode, leaky waves, microstrip line, slotline, spectral domain method.**

I. INTRODUCTION

Planar transmission lines are the basic building blocks of all planar microwave circuits, and thus they have 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 slotline, aimed at determining their dispersion characteristics and characteristic impedance [2]. However, the slotline, like other transmission lines, is capable of exciting leaky waves in addition to transmitting the bound mode [3]. These leaky waves affect the behavior of the line, as they may cause strong attenuation of the transmitted signal. The dispersion characteristics were determined by solving the eigenmode problem, in the first studies, e.g., in [2], [3]. As a result one gets propagation constants and field distribution of modes that can propagate along the line. A superior way of analysis takes into account a source that excites a field on the transmission line [4]. Here we have a tool for determining the real field of a total wave on a line. Choosing properly the integration path, we can even determine the particular components of this wave with proper amplitudes.

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 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 at the CST Microwave Studio. These document 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 behavior in a wide frequency band, including inside a spectral gap predicted by the eigenmode analysis. The field distribution, and therefore the slotline transmission properties, evolve continuously with raised frequency. 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. EIGENMODE ANALYSIS VERSUS EXCITATION PROBLEM

The longitudinally homogeneous slotline on a dielectric substrate of infinite width is investigated here. A sketch of this line is shown in Fig. 1. 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, therefore, the analysis was performed on the line on this substrate. Consequently, we use permittivity ε_r = 2.6, and 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.

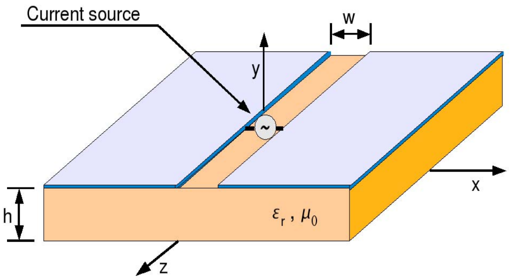


Fig. 1 Sketch of the slotline. The current source is connected across the slot at $z = 0$, and $y = h$.

Applying the standard eigenmode analysis of the slotline, which uses the method of moments applied in the spectral domain [3], we obtain the dispersion characteristics as well as the electromagnetic field distributions of the modes that can propagate along this line. 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 slotline is plotted in Fig. 2, k_0 is the free space propagation constant.

Looking only at the dispersion characteristic shown in Fig. 2, one could deduce subsequent “black and white” mode behavior. The bound mode propagates along the slotline starting from zero frequency up to its cutoff frequency [3], read from Fig. 2, at 5.3 GHz. For this line, there is a "spectral gap" that is rather wide, up to 6.15 GHz. Within this gap, the dispersion equation complex solution 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 constants become lower than the TM_0 surface mode propagation constant k_{TM0}. The dispersion equation complex solution corresponding to the 2nd leaky mode sets in at about 4.1 GHz, the cutoff frequency of the TE_1 surface mode. 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_{TE1}. The eigenmode analysis does not, however, tell us if the modes are actually excited and at which amplitude, i.e., which part of the power delivered by a real source goes to a particular mode. The reason is the absence of a source in the analysis.

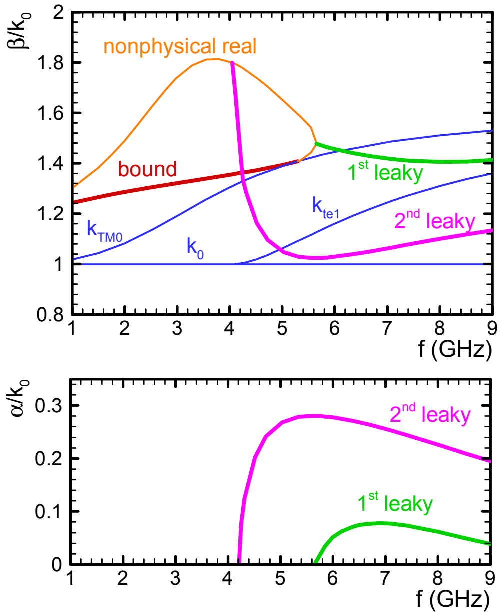


Fig. 2 The normalized phase and leakage constants for the slotline defined in the text.

The real source feeding the slotline can be modeled by a source of a constant current of finite dimensions connected across the slot. The current supplied by this source is along the slot, i.e., in z direction, see Fig. 1, modeled by a Gaussian function. This analysis results in the electromagnetic field distribution of the wave excited on the slotline [8], [9]. The particular mode complex propagation constants are equal to the positions of the poles in the complex k_z propagation constant plane [4]. To this extent, the propagation constants determined by the code written in the framework of [8] correspond to the complex propagation constants plotted in Fig. 2. The calculated voltage distributions were verified by experiment together with simulations made by the CST Microwave Studio.

The voltage distribution of a wave excited by a current source along the slotline defined above was calculated at different frequencies, as shown in Fig. 3. 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. 2. Similarly, the presence of the "spectral gap" does not seem to have any effect on this plot. All curves show a fast 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 quickly to zero due to leakage and radiation effects.

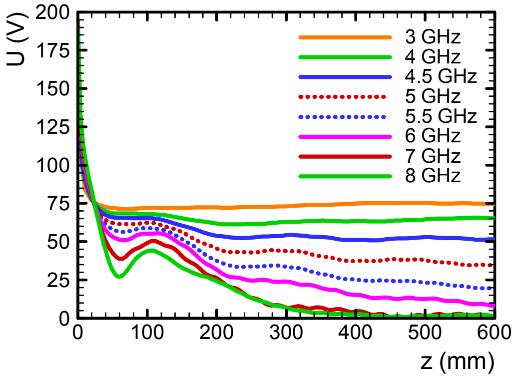


Fig. 3 Voltage calculated along the slotline defined in the text at various frequencies.

III. Discussion of Results and Experiment

Let us first verify the correctness of our results. Fig.4 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 behavior of the field distributions at the corresponding frequencies is exactly the same as the voltage distributions plotted in Fig. 3. In 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 [10]. 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. 5 shows a comparison of the calculated and measured field distributions at three 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 standing wave character measured at 4 and 5.5 GHz.

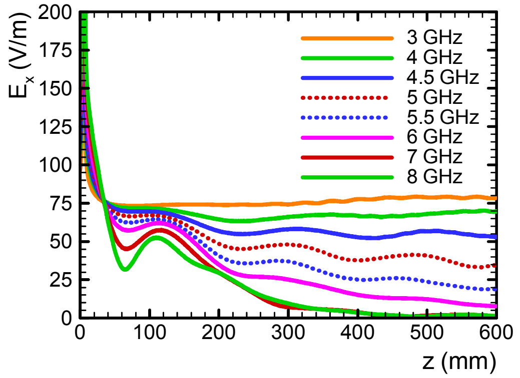
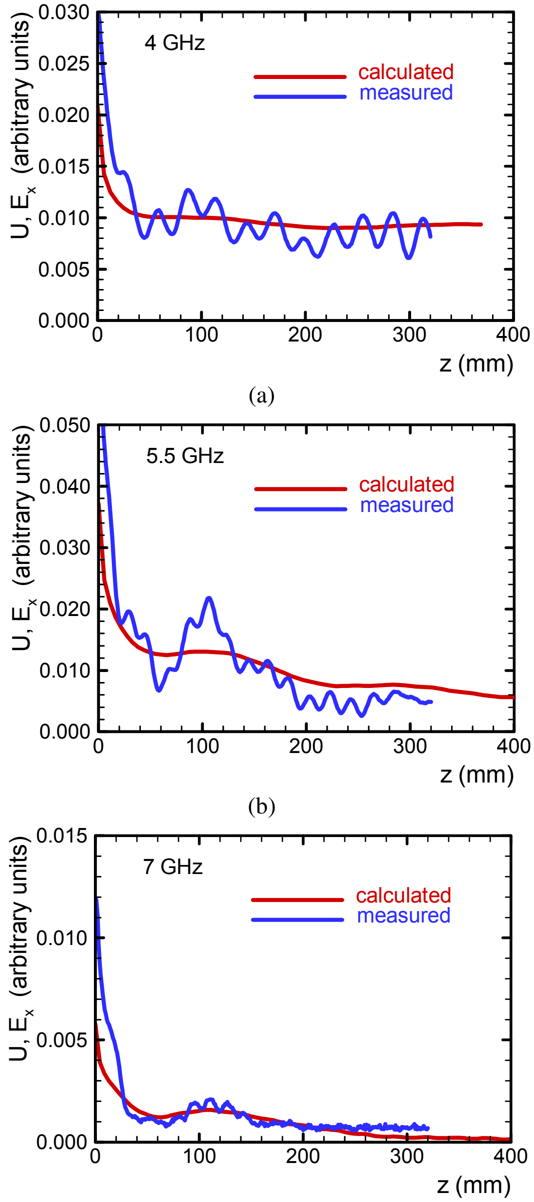


Fig. 4 Field distributions calculated by the CST Microwave Studio at various frequencies.

Figs. 6 and 7 show a problem raised when comparing the voltage of the total wave excited along the slotline with the distributions of the bound mode and the 1st and 2nd leaky waves (whose amplitudes are equal to the residues at the poles and the propagation constants to the pole positions in the k_z complex plane). These normalized propagation constants are: at 5 GHz, β/k_0=1.39388 for the bound mode and β/k_0=1.04694 α/k_0=0.26825 for the 2nd leaky wave; at 8 GHz, β/k_0=1.40471 α/k_0=0.06142 for the 1st leaky wave and β/k_0=1.10007 α/k_0=0.22584 for the 2nd leaky wave. The figures show that the total wave amplitude decreases more slowly than the field of the leaky waves. The difference between the field magnitudes of the total wave and the leaky waves together with the bound mode has been explained by the existence of the residual wave [5]. Consequently, this residual wave, which represents the continuous wave spectrum of the excited field not related to leaky waves, is responsible for the slower decay of the field and, far away from the source, it dominates over the leaky waves (assuming there is no propagating bound mode). The plots shown in Figs. 6 and 7 verify that the residual wave does not decrease exponentially like a leaky wave, but decays algebraically as $z^{-3/2}$ as described in [6]. For comparison, a function decreasing as $z^{-3/2}$ is plotted in Figs. 6 and 7, in Fig. 6 at 5 GHz this function is offset by the bound mode amplitude.

At 5 GHz in Fig. 6 the excited wave is composed of the bound mode, the residual wave, and the 2nd leaky wave. The two latter waves decay to zero, so finally the wave amplitude equals the bound mode amplitude. The measured electric field and the calculated voltage are again normalized with the aim of comparing their profiles. The field distributions shown in Fig. 7 are calculated/measured at 8 GHz, so there is no bound mode included in the total field, which decreases to zero far from the source. The wave is composed of the residual, 1st, and 2nd leaky waves.



(a)

(b)

(c)

Fig. 5 Measured and calculated field distributions along the slotline at 4 GHz (a), 5.5 GHz (b), and 7 GHz (c).

IV. CONCLUSIONS

This paper studies the important practical issue of the electromagnetic behavior of the slotline in a wide frequency band. 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 done by the CST Microwave Studio fully validate the theoretical results.

The behavior 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 and the leaky modes are excited simultaneously with it. This means in practice that the attenuation due to the leaky waves is not so severe here.

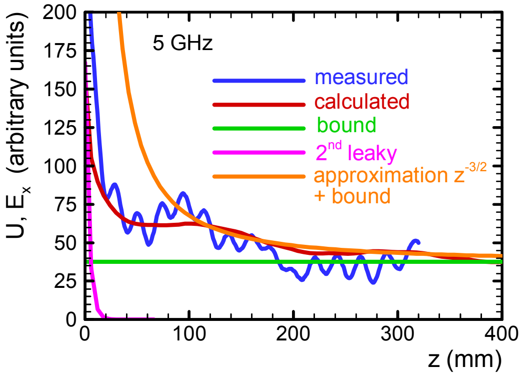


Fig. 6 Calculated voltage and measured field of the total wave on the analyzed slotline together with the distributions of the bound mode, the 2nd leaky wave and function decreasing as $z^{-3/2}$ superimposed on the bound mode. The frequency is 5 GHz.

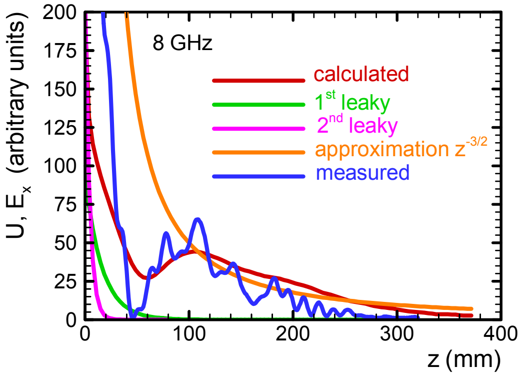


Fig. 7 Calculated voltage and measured field of the total wave on the analyzed slotline, together with the distributions of the 1st and 2nd leaky waves and function decreasing as $z^{-3/2}$. The frequency is 8 GHz.

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. In spite of this, the leaky waves radiate energy into the substrate. Consequently, the effect of parasitic mutual coupling between different circuit parts, together with signal dispersion, still affect the wave transmission along the slotline regardless the residual wave behavior.

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 would not be so important to keep strictly the application of the slotline in microwave circuits 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 to the naturally continuous (rather than steplike) behavior observed for this line.

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