Experimental Verification of Theoretically Revealed Modes on the Conductor-Backed Slotline

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Abstract **The theoretical background leading to analysis of the conductor-backed slotline (CBSL) is presented. The even dominant mode, substrate and space leaky modes are investigated. The theoretically predicted dominant mode and substrate leaky modes are experimentally verified on a CBSL designed for frequencies not exceeding 12.5 GHz. The findings provide a better insight into the properties and behaviour of the CBSL in a wide frequency range.**

Key words: **conductor-backed slotline, leaky mode analysis, dominant and leaky mode field measurements**

1. Introduction

The conductor-backed slotline (CBSL), one of the printed-circuit lines, has for years attracted little interest from designers, presumably due to power leakage into the substrate which results in an undesirable coupling to the neighbouring circuits. This leakage occurs, according to [1], at any frequency. The CBSL is therefore not suitable for power transmission, even though it enables circuits to be located on a metal base, which ensures greater mechanical strength, good heat sinking and easy dc biasing. There are only a few publications [1-3] analyzing the CBSL. However, our recent investigation of the ability of the CBSL to radiate has, as a by-product, thrown up new unexpected findings. These suggest that it is worth taking a new look at the CBSL.

In this paper we present a theoretical background leading to a calculation of the CBSL dispersion characteristics. Our analysis concerns a lossless, laterally and longitudinally unbounded CBSL, the cross-section of which is shown in Fig. 1. The easiest and simplest excitation of the CBSL is by

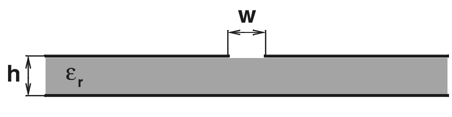

Fig. 1 Cross-section of an infinite conductor-backed slotline

means of a coaxial line connected across the slot. We therefore confine our inquiry into the CBSL to the even modes. Their transversal electric field component within the slot has an even symmetry with regard to the plane of the line symmetry. This plane is an electric wall with the backed metallization potential. We carried out and present here an experimental verification of the suprising theoretical findings. For this purpose an enlarged CBSL was designed in order to map the field at frequencies lower than 12.5 GHz, where measuring equipment is easily accessible and the investigated effects appear. We believe that the revealed features of the CBSL will contribute to a better understanding of this line behaviour and will introduce the unexpected evolution of its dispersion characteristics, as yet not observed on other printed-circuit lines.

2. Analysis of the Conductor-Backed Slotline

We analyzed the CBSL by the method of moments applied in the spectral domain. For this purpose the line, i. e., the substrate and conductors, is assumed infinite. We produced a code calculating the propagation constant of the selected mode and a code for the electric field distribution on the cross-sectional plane [4]. The normalized dispersion characteristics of the even dominant and even leaky modes are shown in Fig. 2. Our analysis shows - in contrast to [1],

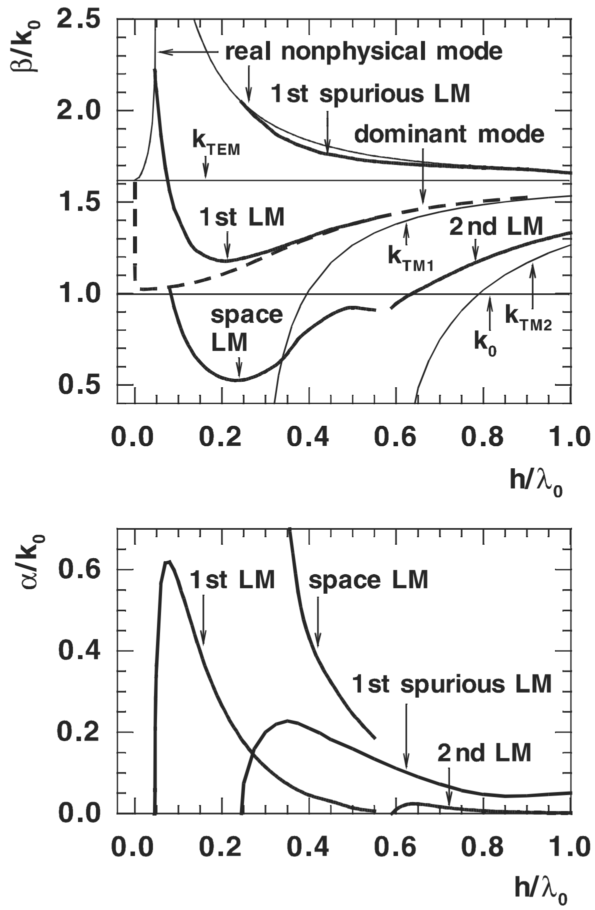

Fig. 2 Normalized dispersion characteristics of the even dominant and even leaky modes on the CBSL with w=6 mm, h=6 mm and ε_r=2.6.

which states that the CBSL will always leak power into the dielectric-filled parallel-plate region - that the even dominant mode may propagate alone on the CBSL from dc up to the frequency at which the first leaky mode sets up. Consequently there is a frequency band in which the only dominant mode propagates.

The solution of the determinantal dispersion equation for the even dominant mode results from integration of particular equation terms along the real axis of the complex plane of the Fourier transform variable. The singularities of the contingent terms lying on the real axis have an odd symmetry towards the pole position and therefore do not contribute to the integral. The dominant mode is not a bound mode. Its propagation constant, plotted in Fig. 3, is only a real phase constant which tends from zero to $k_{TEM}=\sqrt{\varepsilon_r}k_0$, the

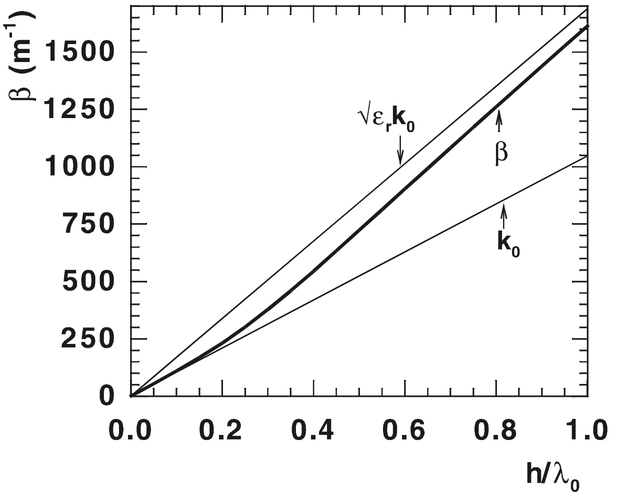

Fig. 3 Phase constant of the even dominant mode on the CBSL when w=6 mm, h=6 mm and ε_r=2.6.

propagation constant of the TEM parallel-plate mode, and can unattenuatedly propagate itself. The mode has the standing wave feature perpendicular to the line axis with laterally constant amplitude [4].

The first leaky mode characteristic splits off from the real nonphysical solution and becomes a physical wave at frequencies when its phase constant falls below k_{TEM}. The second leaky mode carrying power as the TEM parallel-plate mode and simultaneously as the first TM_1 mode appears at higher frequencies. The even space leaky mode may also occur on the CBSL. Its relatively great leakage constant implies considerable leakage in the substrate, rather than high radiation efficiency.

An increase in the slotwidth results in the dramatic change in the appearance of the dispersion characteristics given in Fig. 4. The previous true and spurious first leaky modes merge, the spurious solution becomes physical and an ambiguous first leaky mode solution with two different propagation constants appears. In addition, in a one of the frequency band the phase constant of the even dominant mode becomes less than k_0. This is the consequence of the appearance of a new integrand pole related to the wave number in the air region of the line.

Two even space leaky mode characteristics are also plotted in Fig. 4. The first one, with simultaneous leakage in the TEM parallel-plate mode, is inapplicable due to the great leakage constant. The second one, leaking in addition in the TM_1 mode, is physical for h/λ_0 from 0.33 up to 0.51. Even leaky waves are always accompanied by the even dominant wave, as follows from Figs. 2 and 4. Notice that the mechanism for creating the dominant wave differs from the mechanism for setting up a leaky wave.

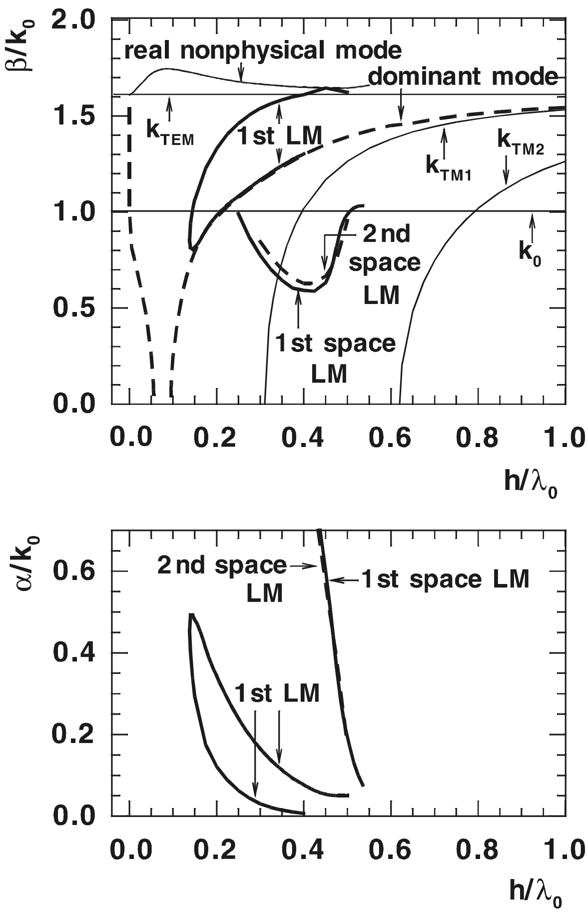

Fig. 4 Dispersion characteristics of the even modes on the CBSL with w=12 mm, h=6 mm and ε_r=2.6.

3. Experimental Verification of Theoretically Predicted CBSL Features

We measured the electric field along the slot of the CBSL and transversally to its axis at the edge of the substrate in the set-up used in [1]. The CBSL was made on a plexiglass substrate with 2.6 permittivity and 6 mm in thickness. The substrate was 2 m in width and 1.5 m in length. We observed the even dominant mode on the CBSL with slotwidth 6 mm at 1.8 GHz, when h/λ_0=0.036, since only this mode is allowed to propagate at this frequency, as follows from Fig. 2. Its calculated and measured wavelengths were 163.4 mm and 160.0 mm, respectively. The real axis was the integration path along which particular terms of the dispersion determinantal equation were integrated. The singularity linked to the TEM parallel-plate mode was in this case extracted. However, a vestige of this pole remained in the field distribution. We checked the lateral standing wave feature of this wave, known already from the calculated field distribution in [4]. It turned out that the standing wave wavelength equals 2π/Re(TEM pole). The calculated and measured adjacent node distances were 66.9 mm and 65.3 mm, respectively. No leaky wave was observed at 1.8 GHz.

On the same CBSL but at 8 GHz, when h/λ_0=0.16, the even dominant mode and the first leaky mode can appear, see Fig. 2. The appearance of the space leaky mode is not considered since its leakage constant is extremly great. Now only superposition of those two waves is accessible, therefore measurement of their wavelengths is impossible. The measured field distribution shown in Fig. 5 documents the presence of the even dominant wave. The measured wavelength of the standing wave in the lateral direction 31.9 mm compares well with the calculated wavelength 31.2 mm.

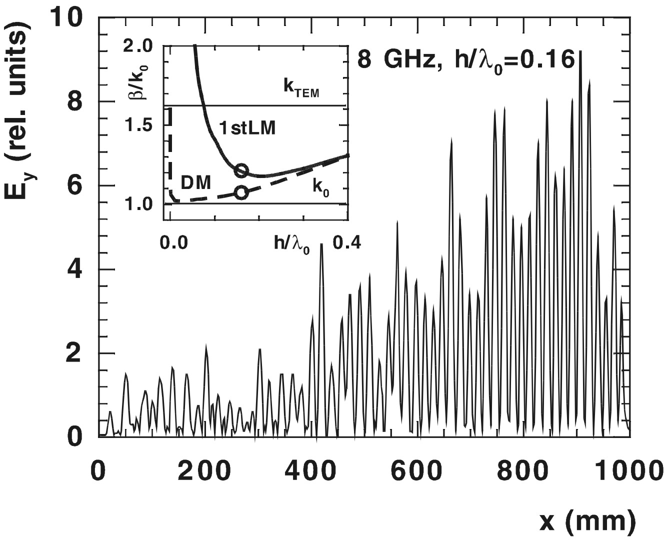

Fig. 5 Electric field component perpendicular to conductors in the cross-section of the CBSL, measured at the front edge of the substrate from the line axis towards the lateral substrate edge, at 8 GHz when w=6 mm, h=6 mm and ε_r=2.6.

The coaxial excitation of the line was at a distance of 98 cm from the front edge of the substrate where the electric field was recorded. The calculated and measured leakage angles, defined in [1,2], were 42.75 degrees and 42.80 degrees, respectively. The leakage constant is relatively great, so application of the leakage angle formula according to [5] provides 45.45 degrees.

It follows from Fig. 4 that, when the slotwidth is 12 mm and the frequency equals 8.7 GHz, the even dominant mode and the leaky mode can appear on the CBSL. The electric field record on the cross-sectional plane along the front substrate edge is shown in Fig. 6. The presence of the dominant wave and also the leaky wave is evident. Excitation of the line was at a distance of 50 cm from the front substrate edge. The leakage angle 46.86 degrees can be estimated from the measured pattern. However, this does not agree either with 40.6 degrees calculated according to [1,2], or with 44.5 degrees calculated according to [5]. The following speculation may explain the observed discrepancy. One case is known from the past, when the improper solution of the dispersion equation was considered as physically meaningful

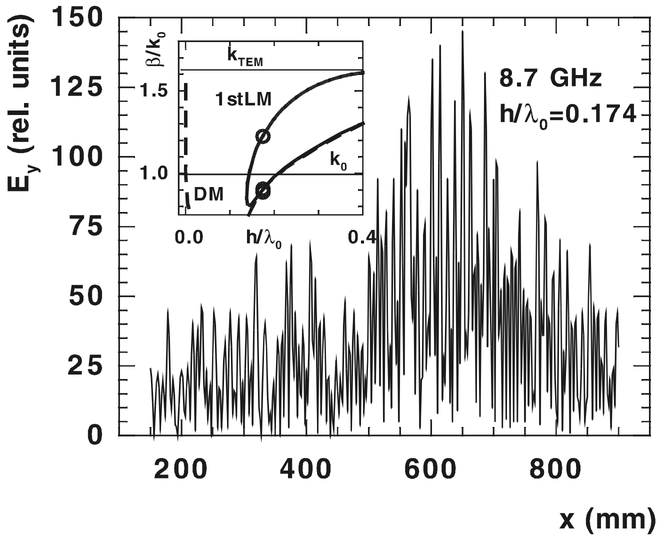

Fig. 6 Measured electric field distribution, as in Fig. 5, but now at 8.7 GHz when w=12 mm, h=6 mm and ε_r=2.6.

and contributing to the total excited field on the coplanar strips and on the slotline [6,7]. Let us assume that the nonphysical solution of the leaky mode in Fig. 4 at 8.7 GHz also contributes to the field. Then when we account for the leakage constant and calculate the leakage angle according to [5] we get 44.5 degrees for the physical solution and 56.0 degrees for the nonphysical solution. Superposition of two such leaking waves could form the pattern plotted in Fig. 6. Another approach to explain the leakage angle discrepancy may be based on an observation reported in [8]. The total radiated field is much larger than that for the leaky mode due to the radiation from the residual wave, which alters the shape of the total field.

An increase in the frequency at 12.25 GHz, when h/λ_0= 0.245, allows the appearance of two leaky modes, at the same CBSL with w=12 mm, as is shown in Fig. 4. The even dominant wave was again present and detected. The measured and calculated wavelengths of its lateral standing wave were 20.0 mm and 21.0 mm, respectively. The excitation point was at a distance of 72.5 cm from the edge of the substrate edge. The calculated angle of leakage for the mode with lower phase constant according to [1] and [5] is the same, since the leakage constant is low. It is 48.2 degrees and compares well with the measured value of 47.8 degrees. We did not detect the wave with a greater phase constant shown in Fig. 4 even on shorter lines 50 and 25 cm length. The reason for this is not clear. At 8.7 GHz this solution is physical and should retain its feature also at 12.25 GHz. The cause of the rise in the observed beats in Fig. 7 with increased half-wavelength is also not clear.

We should interpret measured field records carefully on the background of the theoretical analysis performed in the sourceless region. However, the field mapping was carried

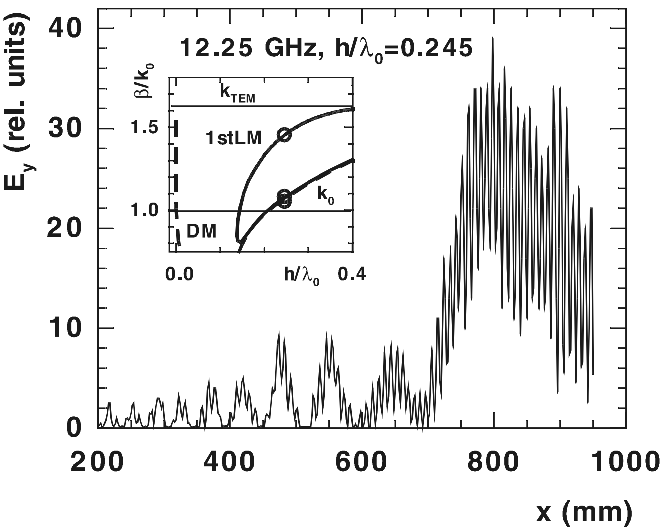

Fig. 7 Measured electric field distribution, as in Fig. 5, but now at 12.25 GHz when w=12 mm, h=6 mm and ε_r=2.6.

out on a CBSL with limited dimensions and excited by a specific feeder. It is known [8,9] that the field excited by a practical source evolves continuously with increasing frequency and the sharp boundaries between operation modes fade away. It is therefore occasionally difficult to identify and extract one theoretically predicted mode that has not yet developed to its full strength.

4. Conclusions

The measurement confirmed the existence and the field distribution of the even dominant wave propagating on the CBSL at all used frequencies. There is a frequency range above dc in which only this wave propagates. Leaky waves are always accompanied by this wave. This finding clears up the ripples in the electric field pattern presented in [1] without explanatory comment. The measurement at 8 GHz confirmed known results already presented in [1]. The measured electric field distribution on the cross-sectional plane of the CBSL with the slotwidth w=12 mm confirmed leakage of power at 8.7 GHz. Unfortunately, the measured leakage angle differs from the calculated value. Admitting that the nonphysical solution contributes to the total field may remove this discrepancy. On the same CBSL and at 12.25 GHz only one leaky wave with the lower phase constant was identified. Why the second solution with a greater phase constant was not observed is unresolved. A phase constant of the even dominant mode less than k_0 follows from the dispersion equation. At first glance, such a mode can not exist. Nevertheless, we did record the field of this mode, including its laterally standing wave. The calculated standing wave wavelength is still determined by Re[TEM pole]. This effect is worth further investigation from the theoretical point of view. From the CBSL analysis and measured fields at various frequencies and with varied slotwidths it follows that this line is not suitable for power transmission. The power flows in the area outside the central part of the line cross-section as a consequence of the effective permittivity placement in the cross-sectional plane. The questions raised above and the measured total field may in addition be influenced by the so called “residual wave”, which probably also excites on the CBSL. Analysis of the odd modes on the CBSL shares a number of aspects with the even modes approach.

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