UPPER CUT-OFF FREQUENCY OF THE BOUND WAVE AND NEW LEAKY WAVE ON THE SLOTLINE

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ABSTRACT

This paper contributes to a more profound understanding of uniplanar circuit behaviour. A simple closed-form formula providing the upper cut-off frequency of the bound wave propagating over the slotline is presented. A new leaky wave which brings down this limit due to the overlapping of the bound- and leaky-mode regions is identified and reported. This wave can deteriorate circuit performance, especially in the mm-wave band. Conclusions made for the slotline hold generally for open printed-circuit lines.

INTRODUCTION

Planar transmission lines used in microwave, millimetre wave and optical integrated circuits have been investigated intensively over the last fifteen years, e.g. [1-5]. Besides the attempt to minimize natural losses in them, attention has been paid to leakage that can result in cross-talk between neighbouring components or portions of the circuit, in a lowering of their quality factors, or in outright loss of power. Leakage has a significant effect on circuit performance. Shigesawa, Tsuji and Oliner [4] have summarized all earlier findings about effects which may occur in open printed-circuit lines.

In this paper we will deal with a new, previously unidentified leaky wave on the slotline, with its influence on the upper limit of the dominant bound wave frequency band, and will present closed-form formulae for this limit suitable for CAD. The paper is a contribution to the general discussion on characteristics of open planar transmission lines, particularly the slotline.

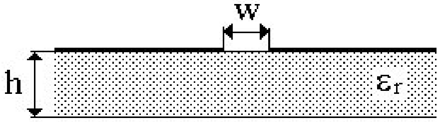

Fig. 1 Cross-section of the slotline

We have analysed the open slotline, Fig. 1, by the method of moments modified as in the Galerkin testing procedure in the spectral domain with successive complex root searching. The integration path in the spectral domain was deformed from the real axis to include the residue contributions associated with the propagation of the corresponding surface waves. The accuracy of our calculation was checked by comparison of the normalized phase constant β/k_0 and the normalized leakage constant α/k_0 with their plotting published in [4]. Thus, the program provides us with all solutions known and published until now.

THE 2ND LEAKY WAVE

However, besides these solutions the dispersion equation of the slotline also has a further solution that is new and interesting. Let us denote its already known complex solution as

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the 1st leaky mode, and the new complex solution, which we are reporting here, as the 2nd leaky mode. The behaviour of the latter is illustrated in Fig. 2, and belongs to the slotline taken over from [4]. Between the cut-off frequency of the TE_1 surface wave f_1 and f_2 when the 2nd leaky mode sets in, the solution is improper real. Between f_2 and f_3, at which point the phase constant of the 2nd leaky wave becomes equal to that of the TE_1 surface wave, the leaky wave is nonphysical in the sense of the generalized condition of leakage [5]. By chance f_3 (0.2695) is here only slightly lower than f_4 (0.2780), the uper cut-off frequency of the pure dominant bound wave. The conventional frequency gap from f_4 to f_5 now disappears due to the presence of the 2nd leaky wave. At frequencies higher than f_3 energy can leak into the TE_1 and TM_0 surface waves. Leakage to the TE_1 surface wave occurs at a lower angle than to the TM_0 surface wave. Corresponding leakage constant a_2 is greater than a_1, Figs. 2,3,4.

When w/h increases, e.g. to 0.5, f_3 is distinctly lower than f_4 and the bound and the 2nd leaky wave are present simultaneously in this overlapping region, Fig. 3. From f_6 to f_7 the wave is nonphysical since b/k_0 does not comply with the generalized condition of leakage [5].

These newly-revealed characteristics are more expressive on the higher permittivity substrate, e.g. when $e_r=10.8$, w/h=0.236 (w=0.15 mm and h=0.635 mm), Fig. 4. Now the overlapping interval from $f_3=46.0$ GHz to $f_4=59.9$ GHz is sufficiently significant for practical purposes. The 2nd solution either improper real Figs. 2,3, or improper complex Fig. 5, always sets in at the TE_1 cut-off frequency f_1 and has the same value as the 1st leaky wave at this split-off point. The 2nd leaky wave has much greater influence on the behaviour of the slotline of a narrower slotwidth Figs. 2,3,4, while for a wider slotwidth its influence is negligible, since f_3 and f_6 are too close together, Fig. 5.

UPPER CUT-OFF FREQUENCY OF THE BOUND WAVE

To avoid trouble caused by surface leakage it is necessary to know the upper frequency cut-off of the dominant bound wave. In the case of a spectral gap this is given by f_4 denoted hereafter as f_c. When simultaneous propagation of the bound and the 1st leaky wave occurs, the upper frequency cut-off f_{c1} is equal to f_5 as in Fig. 5. If the region of the bound and the 2nd leaky wave overlap, the cut-off frequency f_{c2} is given by f_3, e.g. Fig. 4.

The normalized upper frequency cut-off (h/λ_c) instead of f_c depending on the relative dimension w/h and permittivity ε_r is shown in Fig. 6. Designers will appreciate the closed-form formula

$$\left(h/\lambda_c\right) = A_1\left[A_2 + A_3\left(w/h\right)^{A_4}\right]^{A_5} \qquad (1)$$

where A_1, A_2, A_3, A_4, A_5 are simple functions of ε_r. Owing to limited space in this paper, the complete records will be given in the talk. Eqn. 1 holds when $0.01 \le w/h \le 1$ and $2 \le \varepsilon_r \le 16$. These intervals of validity are the same also for Eqns. 3 and 5.

The equation

$$\left(h/\lambda_{cb1}\right) = \Big[0.76388 + 0.20999\ . \\ .\ \left(w/h - 0.493\right)^{0.08212}\Big]^{24.589} \qquad (2)$$

satisfies the condition $f_c=f_{c1}$ and controls the boundary line separating the left pure bound wave region from the right region of simultaneous propagation of the bound and the 1st leaky waves.

Similarly, normalized (h/λ_{c1}) instead of f_{c1} is also plotted in Fig. 6. The formula

$$\left(h/\lambda_{c1}\right) = \left[B_1 + B_2\left(w/h\right)^{-B_3}\right]^2 \qquad (3)$$

describes f_{c1}. B_1, B_2, B_3, the ε_r dependent functions will be specified in the talk.

The condition $f_c = f_{c2}$ produces the equation

$$\left(h/\lambda_{cb2}\right) = \left[0.00816 + 0.14095\,.\,\left(w/h - 0.037\right)^{0.68218}\right]^{0.49415} \qquad (4)$$

defining the boundary line separating the left pure bound wave region from the right region of simultaneous propagation of the bound wave and the 2nd leaky wave, Fig.7.

The normalized upper frequency cut-off (h/λ_{c2}) instead of f_{c2} is also drawn in Fig. 7 and

$$\left(h/\lambda_{c2}\right) = \left[C_1 + C_2\left(w/h\right)^{-C_3}\right]^{C_4} + C_5 \qquad (5)$$

where C_1, C_2, C_3, C_4, C_5 are ε_r dependent functions. Their reading will be given in the talk. It stands to reason that either the 1st or the 2nd leaky wave brings down the upper frequency limit of the bound wave.

CONCLUSIONS

We believe that the new effects revealed on the slotline may also occur on other open printed-circuit lines and possess generality encoded in the multi-valued solution of their dispersion equations. This paper presents new findings regarding the behaviour of the slotline in the mm-wave band. It also provides useful formulae for CAD, particularly in determining the desired operation frequency band in which only the bound wave can be propagated.

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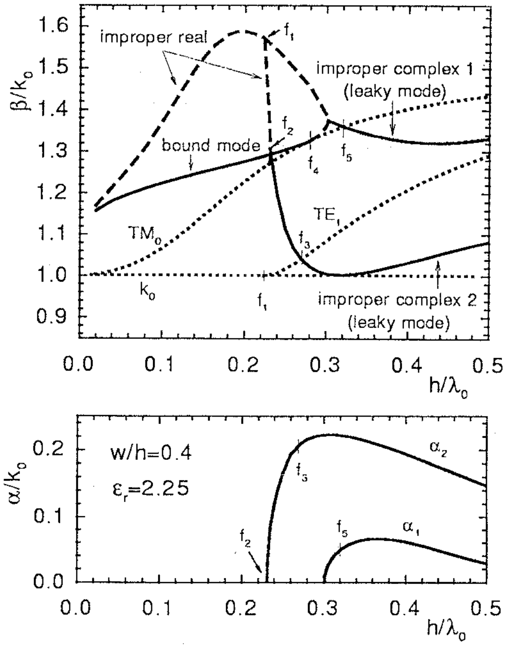

Fig. 2 The normalized phase and leakage constants for the slotline with w/h=0.4 and ε_r=2.25 as a function of normalized frequency (h/λ_0).

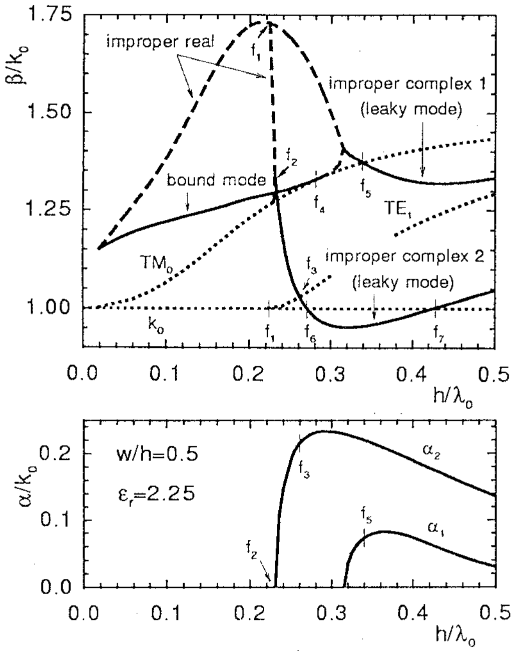

Fig. 3 A plot similar to that in Fig. 2 but for wider slotwidth w/h=0.5.

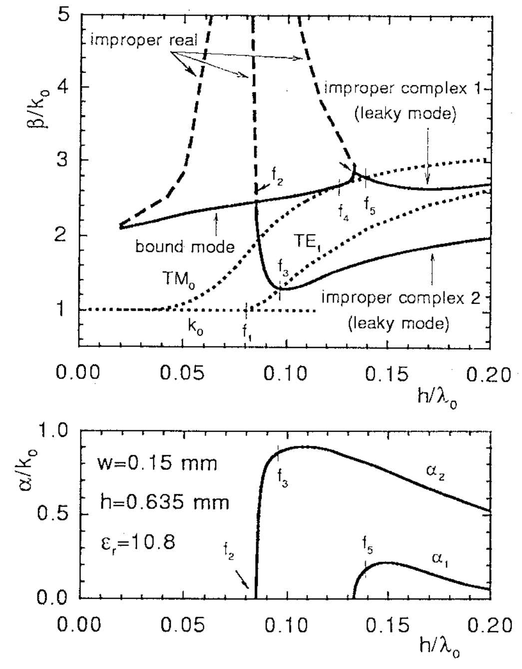

Fig. 4 A plot similar to that in Fig. 2 but for narrower slotwidth w/h=0.236 and higher substrate permittivity ε_r=10.8.

Fig. 7 A plot similar to that in Fig. 6 but the normalized upper frequency cut-off of the dominant bound wave (h/λ_{c2}) is now determined by simultaneous propagation of the 2nd leaky wave . →

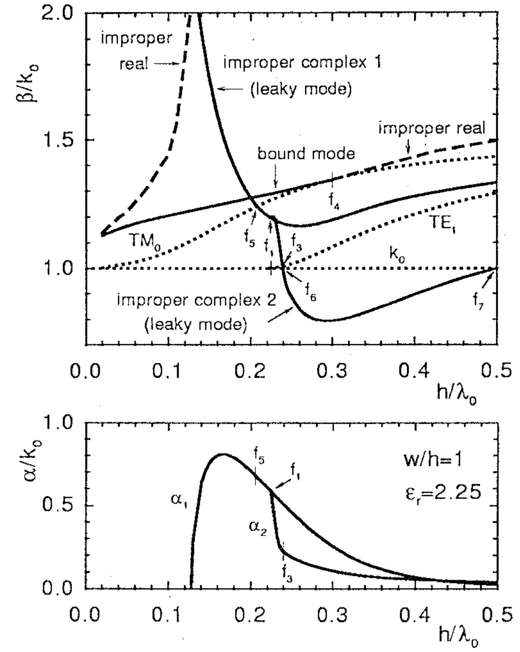

Fig. 5 A plot similar to that in Fig. 3 but for still wider slotwidth w/h=1.

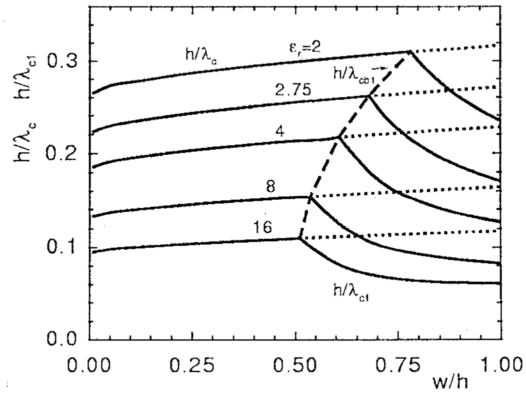

Fig. 6 The normalized upper frequency cut-off of the dominant bound wave determined by the spectral gap (h/λ_0) and by simultaneous propagation of the 1st leaky wave (h/λ_{c1}).