# FULL-WAVE ANALYSIS OF CONDUCTOR LOSSES ON MMIC TRANSMISSION LINES

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## ABSTRACT

A mode-matching analysis of lossy planar transmission lines is presented. In contrast to the usual perturbation methods it includes metallic loss by a self-consistent description without any skin-effect approximation.

The approach is validated by comparison to previous work. First results on microstrip and slot line are given.

## INTRODUCTION

State-of-the-art MMIC technology demands for highly accurate CAD descriptions. Developing such modeling tools, however, one faces some specific problems that need further consideration, e.g. the field-theoretical analysis of conductor losses on MMIC transmission lines.

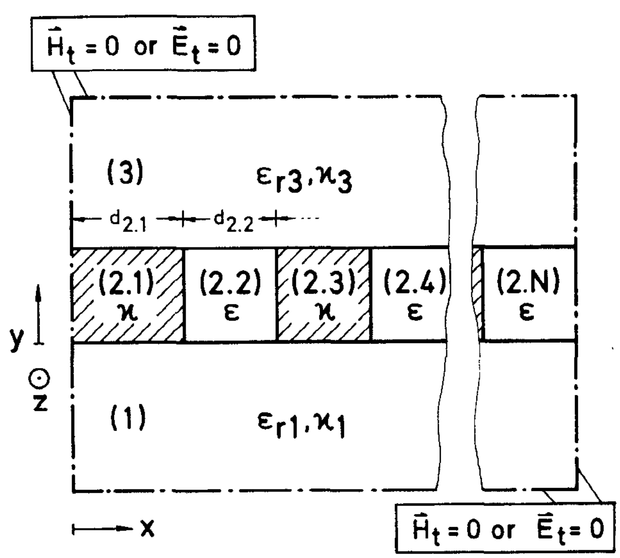



Fig. 1: The waveguide structure analyzed (all regions are characterized by their complex dielectric constant $\varepsilon = \varepsilon_r \varepsilon_0 - j\kappa/\omega$).

As pointed out by Finlay, Jansen et al. [1], for MMIC applications the metallization thicknesses are not always large in comparison with the skin depth. In this case, the common perturbation approach becomes questionable and modified descriptions are to be developed (see [1]).

Moreover, the well-known "incremental inductance rule" of Wheeler [2] requires the evaluation of the line inductance. Hence it is restricted to TEM or quasi-TEM modes and may not be used for slot-line analysis, for instance.

So far, only a few more comprehensive approaches were proposed (e.g. Waldow and Wolff [3]). They treat, however, relatively simple geometries and, hitherto, investigations on detailed structures such as MMIC transmission lines are not known.

The method presented here employs a modified mode-matching technique developed from that used in [4] for Travelling-Wave-FET analysis. The metallic layers are treated in the same way as the remaining waveguide subregions with each of them characterized by its complex dielectric constant. This leads to a fully self-consistent description of the conductor losses offering two principal advantages compared to the usual perturbation methods:

- The approach remains valid also for metallization dimensions in the order of or even smaller than the skin depth.
- Non-TEM waveguide modes can be analyzed for their losses equally.

## METHOD OF ANALYSIS

Fig. 1 shows the model used to analyze the planar transmission lines found in MMIC's such as microstrip, CPW, and slot line. The plane of metallization is described by a series of $N$ regions $(2.1) \ldots (2.N)$ with metallic and dielectric properties, respectively. Regions (1) and (3) can be substituted by several dielectric or conductive layers homogeneous along $x$. This is of interest when incorporating passivation layers or studying the influence of a non-ideally conducting substrate metallization.

According to the common mode-matching procedure the fields in each region are represented by the sum of all the longitudinal-section modes $LSE_{xm}$ and $LSH_{xm}$ with unknown amplitudes.

Regarding the plane of metallization ( i.e. regions $(2.1 \ldots N)$ ), however, these $LS_x$ modes cannot be derived in the usual simple manner, because the boundary conditions at $x = constant$ are not fixed for each region. Thus the separation constants ${k_{xm}}^{(2.1) \ldots (2.N)}$ do not assume the simple form $m\pi/d_i$ (see Fig. 1). As well known from the analysis of layered rectangular waveguides, on the other hand, these $k_{xm}$ eigenvalues may be determined

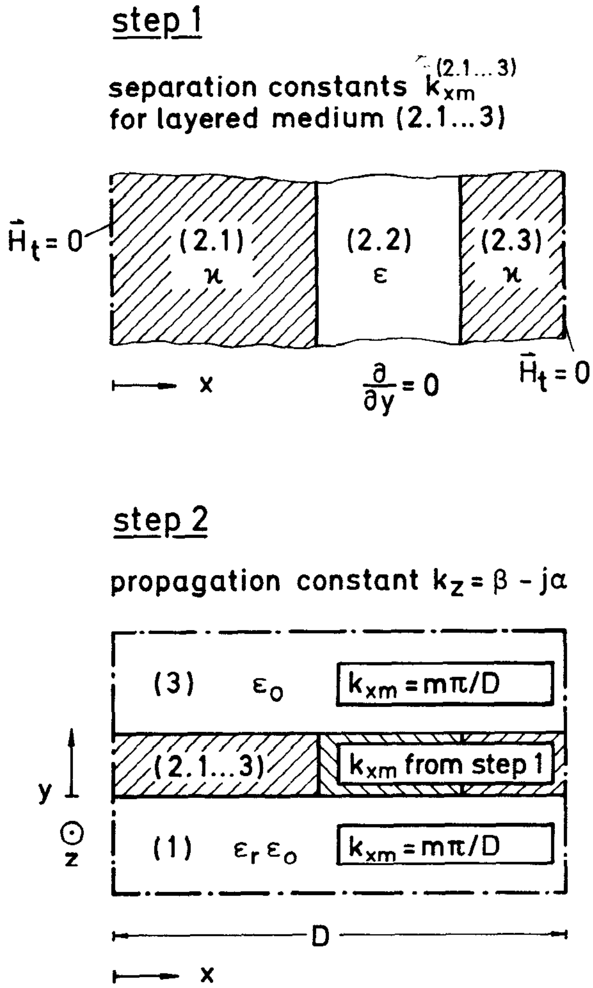



Fig. 2: The two-step mode-matching procedure.

for each $LSE_{xm}$ and $LSH_{xm}$ mode separately employing the continuity conditions at $x = constant$ that connect the fields of neighboured media.

Thus the whole procedure separates into two problems which can be solved separately one after the other (see Fig. 2):

**Step 1 - Eigenvalue problem for $k_{xm}$ :** One determines the (complex) separation constants $k_{xm}$ in regions $(2.1) \ldots (2.3)$ for each $LSE_{xm}$ and $LSH_{xm}$ mode by fullfilling the field continuity at the vertical boundaries. It turns out that these $k_{xm}$ values are identical to those of the equivalent structure with $\partial/\partial y = 0$.

**Step 2 - Eigenvalue problem in $k_z$ :** The whole structure is analyzed employing the continuity conditions at the horizontal planes ($y = constant$) and using the results from step 1.

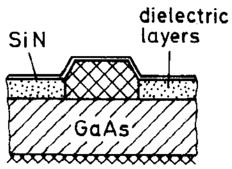
The second step corresponds to the common mode-matching procedure (e.g. [5]) and leads to an homogeneous system of equations. Its eigenvalues represent the resulting complex propagation constants of the waveguide modes.

The procedure described above is similar to that used by Katzier [6] to analyze layered dielectric waveguides. When introducing non-ideal metallic strips, however, the high conductivity values cause numerical problems that require a modified mathematical formulation. Furthermore, regarding the complex root search for $k_{xm}$ (step 1), one has to ensure that all $k_{xm}$ eigenvalues within a given range of Real$\{k_{xm}\}$ are taken into account. Otherwise the field expansion of step 2 would give erroneous results. In order to avoid this, analytical approximations for each $k_{xm}$ were deduced and are now used as starting points for the iterative root search procedure.

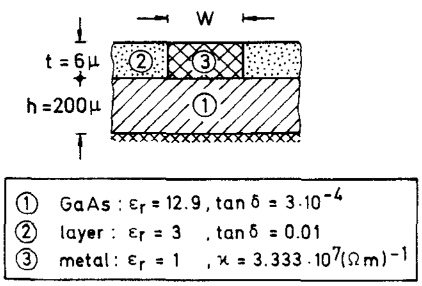
## RESULTS

The Figures 3 and 4 show a comparison to previous work on microstrip [1]. Fig. 3 illustrates the microstrip line considered by Finlay, Jansen et al. [1] and the model analyzed here. Fig. 4 then contains the propagation constants obtained by measurements [1] and the two different theoretical approaches, respectively.

Evaluating the deviations one should bear in mind that the structural data of [1] are not given explicitly but were fitted to the measurement curves. In this work, on the other hand, we applied fixed strip geometries resulting in approximately the impedances of 26Ω and 86Ω, respectively. Furthermore, we did not account for surface roughness effects.




a) structure used in [1].




b) structure analyzed in this work.

Fig. 3: The microstrip geometries under investigation.

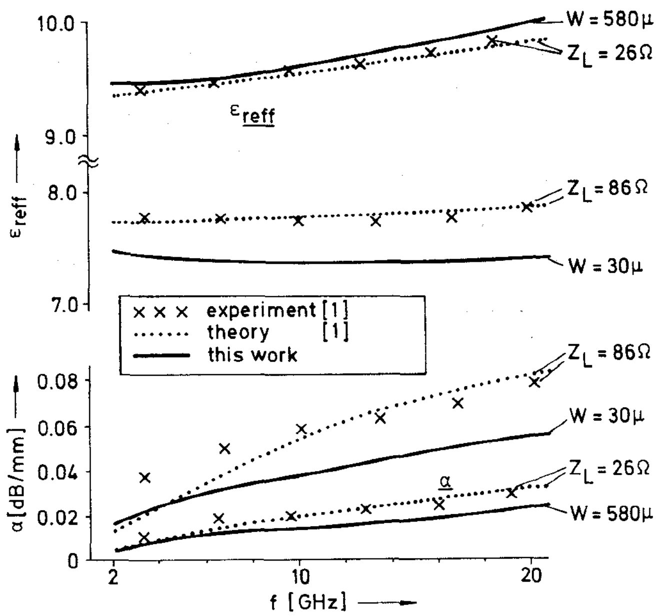



Fig. 4: Effective dielectric constant and loss of a MMIC microstrip line against frequency.

Comparison with measurement data and theory of Finlay, Jansen et al. [1]. The strip width's $W$ assumed for a $26\Omega$ and $86\Omega$ line are $580\mu m$ and $30\mu m$ , respectively. The substrate metallization is described by an infinite region of conductivity $\kappa$ as given.

Altogether, the results agree favourably and thus confirm the validity of the mode-matching approach described above. Naturally, the deviations are larger for the smaller strip width, because in this case the waveguide properties are more sensitive to changes in the structural data.

In particular, one finds excellent agreement with measurements for the *frequency dependence* over the whole band whereas the theoretical approach of [1] leads to discrepancies at the lower frequeny end.

Finally, two further examples for the application of our method will be given: Figures 5 and 6 demonstrate the influence of the metallization thickness on propagation constants for both the microstrip studied before and a slot line as used for hybrid couplers (see [7], for instance). The attenuation constant $\alpha$ behaves as predicted in [1] and remains approximately constant down to strip thicknesses $t$ of double the skin depth $\delta$. As could be expected, $\alpha$ then grows significantly for smaller values of $t$. Despite of its non-TEM nature the slot-line loss characteristics are very similar to the microstrip results.

Regarding Fig. 5 one should note the slight increase of $\varepsilon_{eff}$ for thicknesses $t$ below $0.5\mu m$. It origins from the conductor losses that reduce the phase velocity and thus raise $\varepsilon_{eff}$ compared with the lossless case. Such effects *cannot* be described by perturbation methods but solely when using a self-consistent approach.

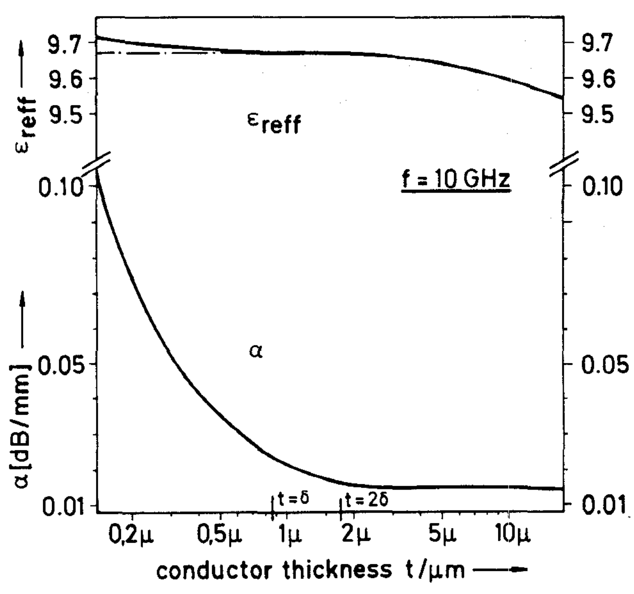



Fig. 5: The propagation characteristics of the microstrip according to Fig. 3(b) as a function of metallization thickness $t$ (frequency $f = 10\,GHz$, strip width $W = 580\mu m$).

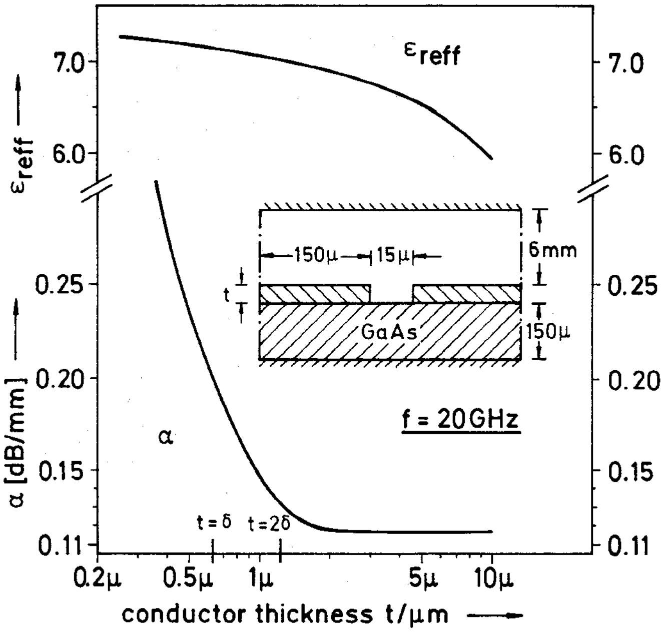



Fig. 6: The propagation constants of a $15\mu m$ slot line against metallization thickness $t$ (for the line geometry see insert, conductivity of the metallizations: $\kappa = 3.333 \cdot 10^7\ [\Omega m]^{-1}$ ).

## CONCLUSIONS

The extended mode-matching method presented in this paper proved its validity and usefulness when compared with previous theoretical and experimental work on GaAs-MMIC transmission-lines. It offers specific advantages against the descriptions known hitherto for line geometries where the metallization thicknesses range in the order of the skin depth or non-TEM modes are studied.

## REFERENCES

[1] H.J. Finlay, R.H. Jansen, J.A. Jenkins, and I.G. Eddison, "Accurate characterization and modeling of transmission lines for GaAs MMIC's", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 961-967, June 1988.

[2] H.A. Wheeler, "Formulas for the skin effect", *Proc. IRE*, vol. 30, pp. 412-424, 1942.

[3] P. Waldow and I. Wolff, "The skin-effect at high frequencies", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 1076-1082, Oct. 1985.

[4] W. Heinrich and H.L. Hartnagel, "Wave propagation on MESFET electrodes and its influence on transistor gain", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1-8, Jan. 1987.

[5] Y. Fukuoka, Y.-C. Shih, and T. Itoh, "Analysis of slow-wave coplanar waveguide for monolithic integrated circuits", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 567-573, July 1983.

[6] Katzier, "Streuverhalten elektromagnetischer Wellen bei sprunghaften Uebergaengen geschirmter dielektrischer Leitungen (Analysis of the scattering of electromagnetic waves at a transition of dielectric waveguides)", *Archiv fuer Elektr. Uebertragung*, vol. 38, pp. 290-296, 1984.

[7] T. Hirota, Y. Tarusawa, and H. Ogawa, "Uniplanar MMIC hybrids – a proposed new MMIC structure", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 576-581, June 1987.

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