# ACCURATE CHARACTERISATION AND MODELLING OF TRANSMISSION LINES FOR GaAs MMICs

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## ABSTRACT

The benefits of the spectral domain hybrid mode approach in the design of multi dielectric media transmission lines is described. Using GaAs ring resonator techniques covering 2 to 24 GHz, accuracies in effective dielectric constant and loss of 1% and 15% respectively are presented. By combining theoretical and experimental techniques a generalised MMIC microstrip design data base is outlined.

## INTRODUCTION

Modern system designs are demanding performance, size, yield and cost specifications which point to the use of GaAs MMIC technology. To meet these complex demands the IC manufacturer must now use improved computer aided design (CAD) tools based on more accurate MMIC component models. This paper describes the use of new CAD tools together with high accuracy microwave measurements to realise improved design data for GaAs MMICs. In particular, this paper details a combined theoretical and experimental approach to the generation of an accurate design database for transmission lines on GaAs MMICs. The theoretical approach is based on an improved transmission line theory which is part of the spectral domain hybrid mode computer program MCLINE (3,4). The program is capable of accurately predicting effective dielectric constant for single and multiple dielectric layers in the presence of lid shielding. Furthermore, it is a generalised multi-conductor strip analysis program and can be applied to other MMIC components such as couplers, interdigital capacitors and spiral inductors. A detailed description is given in reference (4). An extension of this work is now reported and theoretical emphasis has been placed on the treatment of loss mechanisms.

Accurate prediction of transmission line loss in MMICs is complicated by the multi-layered dielectric construction and complex metallisation schemes used in typical GaAs IC technology. The dielectric layers used in addition to the semi-insulating GaAs substrate may exhibit comparatively high dielectric loss factors. Consequently, these thin multi-layer dielectrics can have strong influence on the field distribution of narrow lines and coupled line structures (1). Also, conductors are often composed of different metals whilst the ground metallisation may again be different from the top face metals. Frequently the ground metallisation may consist of a very thin layer deposited on the base of the substrate having relatively high surface roughness. In this complex situation and particularly for frequencies below or in X-band, the usual microwave perturbation approach for the determination of conductor loss (2) fails since skin depth is not small when compared to the metallisation thickness. Therefore, a new, more sophisticated description has to be used. The program has been designed to include loss mechanisms in all dielectric layers and to include conductor and surface roughness loss contributions. The ability to handle such multi-dielectric sandwich structures makes it one of the most suitable CAD tools for GaAs IC lines.

## THEORETICAL APPROACH

The new treatment of loss presented here may be termed a modified microwave perturbation approach. It makes use of the ideal electromagnetic field, evaluated by means of the MCLINE computer program (3) for the lossless case. From the ideal electric field distribution and the dielectric loss factors of the layers involved, the absorbed power per unit length is determined in the conventional way, see for example ref. (2). The validity and high quality of this common approximate type of dielectric loss analysis has been demonstrated by Mirshekar-Syakhal in a comparative study (5). The situation is completely different if conductor loss is considered. For reasons of numerical efficiency the electromagnetic field computation is performed under the assumption of zero strip thickness, ideal conductors, ideal ground and cover metallisation. Here, care has to be taken in the treatment of the magnetic field singularities at the microstrip edges (6,7) and with the presumption that skin depth a is much smaller than metallisation thickness t. The first complication is resolved here assuming merely that the transition from zero to finite thickness essentially changes only the singular field near the conductor edges. This applies to a good approximation if the strip width w is larger than about 5 times the strip thickness t. Accordingly, the transition from t = 0 to



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non-zero values of t implies a modification of only the asymptotic behaviour of the spectral domain magnetic field quantities in the planes below and on top of the conductor metallisation. For both fields this is achieved simply by the introduction of suitable spectral damping factors in conjunction with a spectral threshold beyond which these become effective and make the modified field square-integrable. The criteria defining this modification are discussed and found to yield stable results insensitive with respect to the chosen threshold.

The complication associated with the thickness-to-skin depth ratio t/a is resolved using the modified tangential magnetic field as a boundary condition in a lossy wave problem for each of the metallisations considered, ground and cover. For this case, an approximate analytical solution is derived and discussed. For example, the strip current density is determined approximately as

$$\underline{J}(x,z') = \underline{J}(x,0).\sinh(t'-z')/\sinh(t')$$

$$+ \underline{J}(x,t').\sinh(z')/\sinh(t'),$$

$$\underline{J}(x,b') = (t'/t).(\sinh(t')/(\cosh(t')-1)).$$

$$(\underline{u}_z \times \underline{H}(x,b')) \qquad (1)$$

with $z' = (1+j)z/a$, $t' = (1+j)t/a$ and $b' = 0,t'$ respectively.

Here, $\underline{J}$ and $\underline{H}$ denote current density and magnetic field, respectively. The lower side of the strip is located at $z = 0$ and the top side at $z = t$; x is the co-ordinate transverse to the MMIC transmission line considered, j is the imaginary unit and $\underline{u}_z$ the z-directed unit vector. The analysis for the ground and cover metallisation leads to similar analytical expressions. While eq.(1) describes a homogeneous, single-material metallisation, it can also be extended to composite, layered metallic structures. In any case, the power absorbed per unit length by the non-ideal metallisation is

$$P_c' = 1/2.\iint \rho(z).|\underline{J}(x,z)|^2 \, dx \, dz \qquad (2)$$

where the integration is over the total metallisation cross-section and $\rho(z)$ denotes the piecewise constant resistivity. Surface roughness is taken into account using a well known correction formula. The description given includes interaction of the tangential magnetic fields on both sides of a conductor if the thickness t is not large compared to the skin depth a. In the limit of large normalised thicknesses t/a it results in the usual microwave perturbation solution like that used in (2).

This can be seen clearly in Fig. 1 for a sandwich microstrip structure (polyimide on top of a GaAs substrate) of about 50 ohms characteristic impedance. In this case, the usual perturbation approach is correct only if the respective thicknesses are larger than about 4µm (16 GHz) and 12µm (2 GHz). It has to be expected that the improved theory described here predicts a 1/t law for very small thicknesses independent of frequency and down to DC. The behaviour is less pronounced in Fig. 1(b) since the loss contribution of the ground plane is relatively small for the structure considered.

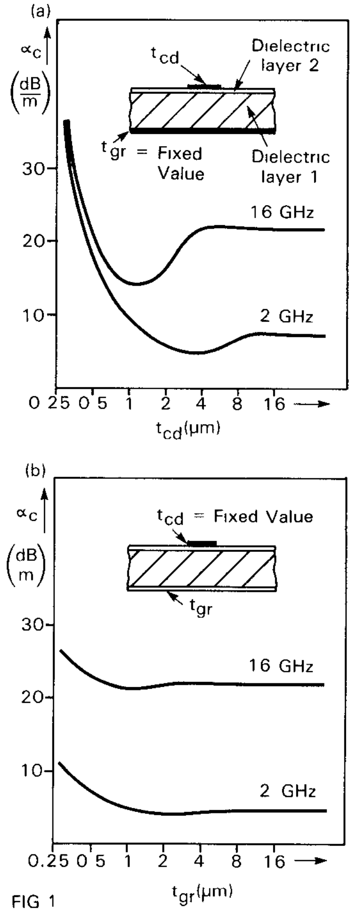


FIG 1
CONDUCTOR LOSS OF MMIC SANDWICH MICROSTRIP vs (a) STRIP THICKNESS $t_{cd}$, (b) GROUND METALLISATION THICKNESS $t_{gr}$

## EXPERIMENTAL VERIFICATION

Having developed an advanced transmission line description capable of dealing with the geometries and structures found on GaAs MMICs then it is clearly necessary to verify the theory's accuracy for practical MMIC circuits.

Of necessity this verification demanded a measurement procedure capable of much greater accuracy than the more usual substitution approach. For this reason, a ring resonator experimental technique was chosen as a proven method of obtaining accurate data on transmission line loss and effective dielectric constant (8). Fig. 2 shows a photograph of a GaAs IC ring resonator chip. Using established design techniques a set of ring resonators were produced with characteristic impedances in the range 20 ohms to 100 ohms. RF coupling to the ring was designed by introducing a 'trident' gap capacitor at either side of a diameter. The gap capacitance was carefully chosen based on established modelled and characterised data for

MMICs. These resonators, 10.03 mm outer diameter, were fabricated on 200 micron thick semi-insulating GaAs wafers. A variety of multi-layer dielectrics were used ranging from GaAs only to complex structures of GaAs, $Si_3N_4$, polyimide and $Si_3N_4$.

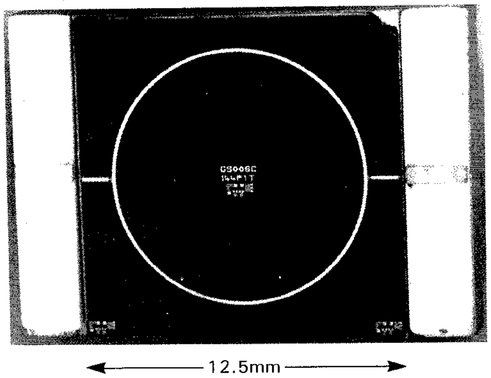


FIG.2 GaAs MMIC RING RESONATOR

This large range of test ring structures were characterised using the latest network analyser techniques (HP8510T) from 2 to 24 GHz. The measured S-parameters around each resonance frequency were optimised to the equivalent circuit model of Fig. 3 using commercially available CAD software. This method took account of the loading effects of the coupling capacitors, effective dielectric constant, loss and ring characteristic impedances with frequency. Estimations of the experimental errors involved, showed effective dielectric constant measurement uncertainties of better than 1%. This high accuracy is due to the excellent frequency resolution of the synthesised output from the HP8510T.

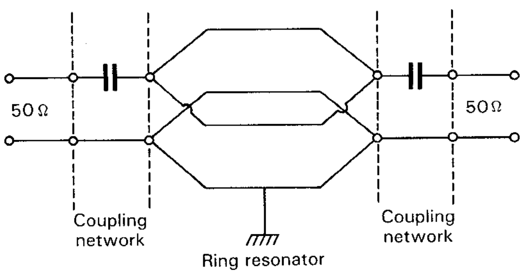


FIG.3 EQUIVALENT CIRCUIT MODEL OF RING RESONATOR

Using the above approach it was possible to identify the optimum low-loss IC technology and to determine the values of crucial material constants. To illustrate this Fig. 4 shows the close agreement between the computed (MCLINES) and measured loss behaviour of various ring resonators mounted on a GaAs substrate only (T1). Note that the top track is a thick composite metal. This close correlation (15% average 2-20 GHz) was achieved using measured metal and dielectric thicknesses, metal resistivities and surface roughness together with a GaAs loss tangent of 0.0003 as the MCLINES input data. Fig. 5 presents a similar correlation for the case of various rings mounted on a $GaAs/Si_3N_4$/polyimide/$Si_3N_4$ dielectric

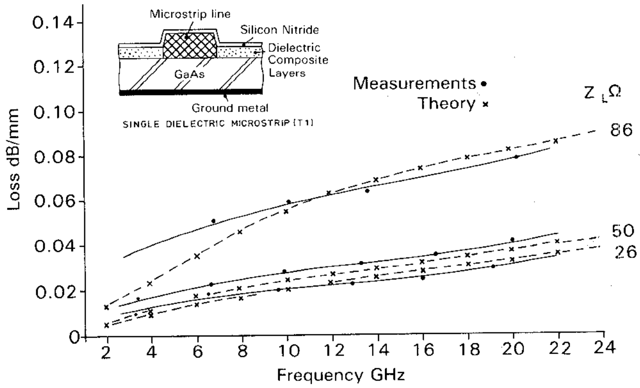


FIG.4(a) PREDICTED AND MEASURED LOSS vs FREQ(TYPE T1)

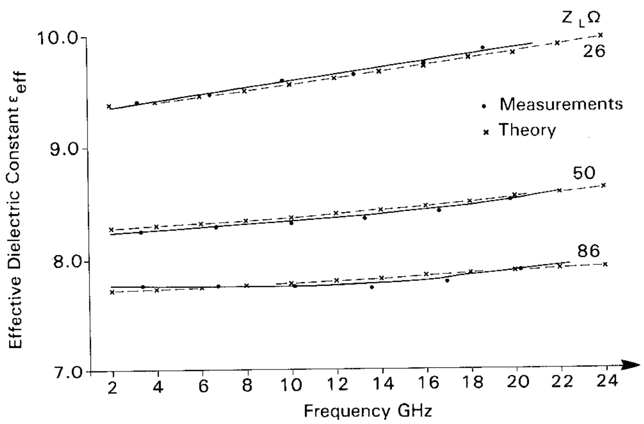


FIG.4(b) PREDICTED AND MEASURED EFFECTIVE DIELECTRIC CONSTANT vs FREQ (TYPE T1)

sandwich structure (T3). Losses in these structures are slightly higher due to reduced track thicknesses and the underlying polyimide layer. In this case the loss tangent for the thin polyimide layer was determined as 0.055 ± 0.005, a value which agrees with subsequent large area MMIC polyimide capacitor measurements (Tan δ = 0.047). Similar results have been obtained for 26 ohm and 94 ohm resonator structures as well as for other GaAs/polyimide sandwich structures (T2). In addition, the measured and predicted effective dielectric constants have been within 1 to 2% for both GaAs ($\varepsilon_r$ = 12.85 ± 0.025) and multi- dielectric topologies. A more comprehensive comparison of the experimental and theoretical results together with details of the crucial material constants will be presented at the conference.

The above detailed measurement and modelling work on several batches of ring resonators clearly established the accuracy and applicability of the improved analysis package. This CAD package combined with further experimental work was then used to develop a comprehensive design database for the realisation of high accuracy, low-loss microstrip lines on GaAs MMICs. Examples of the depth of information produced are presented in Figs. 6 and 7 which show the losses and effective dielectric constants exhibited by transmission lines realised on a commercially available GaAs IC process.

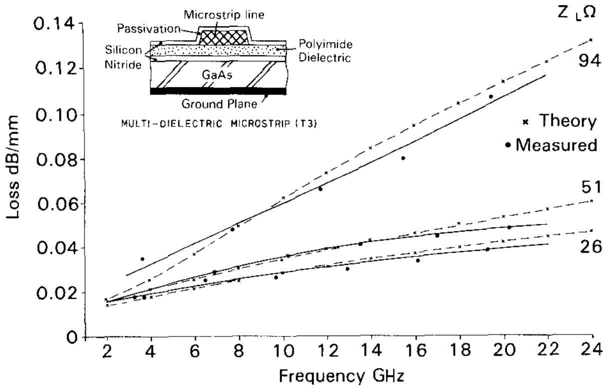


FIG.5(a) PREDICTED AND MEASURED LOSS vs FREQ (TYPE T3).

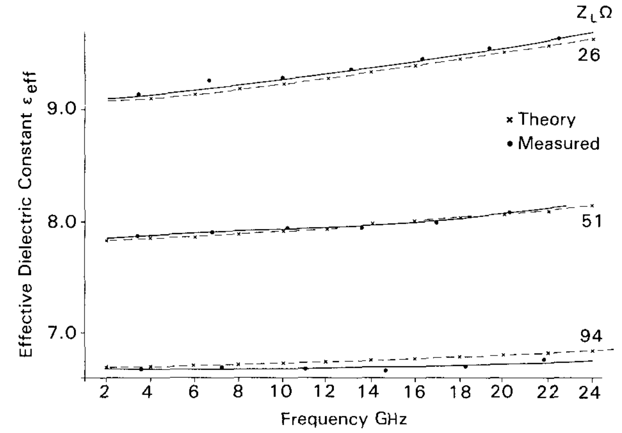


FIG.5(b) PREDICTED AND MEASURED EFFECTIVE DIELECTRIC CONSTANT vs FREQ (TYPE T3).

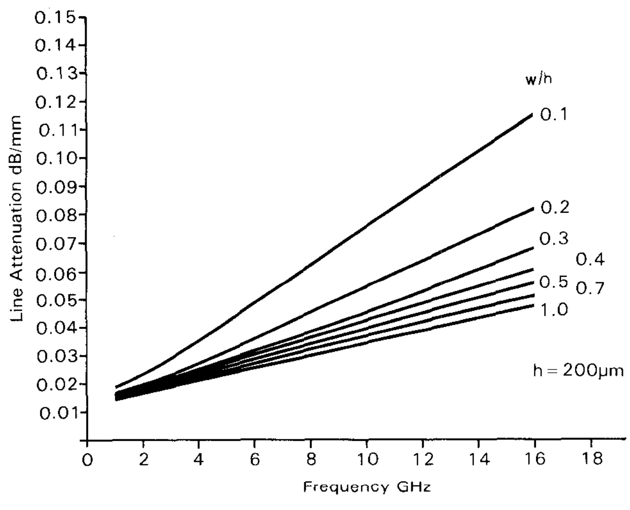


FIG.6 LINE ATTENUATION OF MICROSTRIP (TYPE T3) vs FREQ AND w/h

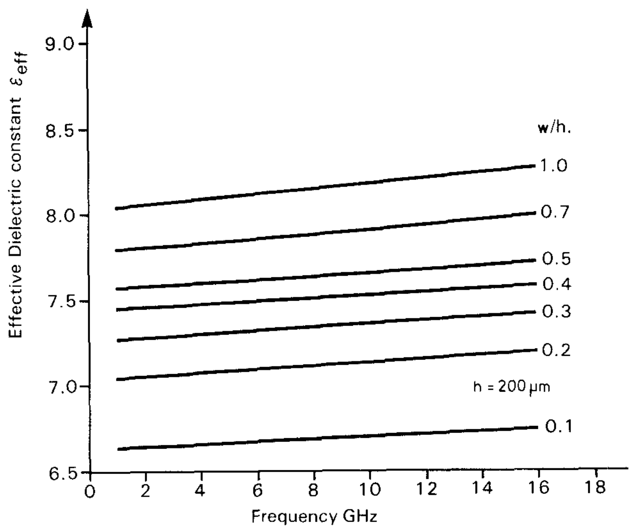


FIG.7 EFFECTIVE DIELECTRIC CONSTANTS OF MICROSTRIP (TYPE T3) vs FREQUENCY AND w/h

## CONCLUSIONS

Using extensive experimental assessments, a powerful hybrid mode CAD package has been validated for multidielectric microstrip in MMICs to 24 GHz. RF loss and phase velocities have been related closely to physical and material parameters resulting in a generalised MMIC microstrip design data base. As such this represents a significant contribution to CAD for MMICs.

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