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Analysis of Lossy Transmission Lines for GaAs MMIC Technology.

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Abstract

Lossy transmission lines for GaAs MMIC technology are analyzed, using an accurate fullwave electromagnetic simulator, based on a Finite Element Method, using edge elements. A complete study of a GaAs coplanar conductor-backed waveguide is presented in a wide frequency range between 5 and 90 GHz, taking into account dielectric as well as conductor losses.

Introduction

The recent widespread use of extremely complex Monolithic Microwave Integrated Circuits (MMIC's) in GaAs technology has increased the need of accurate fullwave electromagnetic (EM) modeling tools.
Especially, the dielectric and conductor losses have to be taken into account to provide precise analysis of such circuits. For this purpose, our paper presents a study of lossy planar transmission lines using a Finite Element Method (FEM) simulation.
Firstly, it briefly explains how a rigorous 2D FE analysis using edge elements can be adapted for characterizing planar lossy transmission lines in GaAs MMIC technology. Then our approach is validated by comparison of our results to those given in previous work using other numerical technique [1] and to those provided by the commercial EM simulator Hewlett Packard (HFSS). Finally, losses as well as propagation characteristic results for a GaAs coplanar conductor-backed waveguide are presented at frequencies of about 60 GHz.

EM analysis of lossy transmission lines

The 2D FEM analysis, using edge elements, is quite suitable for determining propagation characteristics free from parasitic solutions [2] for complex waveguides composed of different dielectric layers and having complex metallization schemes. These waveguides are supposed to be uniform in the propagation direction. Consequently, the EM harmonic vector can be written in the form :

$$\bar{V}(x,y).e^{-j\gamma z}.e^{j\omega t}, \tag{1}$$

where (Oz) is the propagation direction and (xOy) defines the waveguide transverse plane. Also, $\bar{V}(x,y)$ is the tangential vector and γ is the complex propagation constant. The 2D FEM waveguide analysis consists of solving a generalized eigenvalue problem for a given frequency, having the form :

$$\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\begin{bmatrix} Et \\ Bt \end{bmatrix} = \gamma \begin{bmatrix} 0 & X \\ X & 0 \end{bmatrix}\begin{bmatrix} Et \\ Bt \end{bmatrix}, \tag{2}$$

where $\begin{bmatrix} Et \\ Bt \end{bmatrix}$ is the EM tangential vector. γ is expressed as :

$$\gamma = \beta + j\alpha, \tag{3}$$

where α is the attenuation constant and β is the propagation constant of the corresponding waveguide mode.
It is to be noted that the FEM discretization allows a locally fine meshing of zones, where the variations of the EM field are important.
Besides, the inclusion of dielectric and conductor losses calculation in the FEM simulation is quite simple.
A lossy dielectric can be handled by including its loss tangent (tg δ) as an imaginary part of the medium relative permittivity ε_r* :

$$\varepsilon_r^* = \varepsilon_r(1 - j.tg\,\delta) \tag{4}$$

To consider the conductor losses, the conductor is assumed to have a thickness T greater than the skin depth (δ_m) at the frequency of interest, which is a good approximation in most cases. Then the metallic losses are represented by a surface impedance Z_m. This leads to the following relation between tangential electric and magnetic fields on the surface of the lossy conductor :

$$\bar{E} = -Z_m \bar{n} \times \bar{H} \tag{5}$$

with $$Z_m \approx (1+j)\sqrt{\frac{\omega\mu_m}{2\sigma_m}} = \frac{(1+j)}{\sigma_m \delta_m}, \tag{6}$$

where μ_m and σ_m are respectively the permeability and the conductivity of the lossy conductor. $\bar{n}$ is the unit inward normal vector.

Results

Firstly, dielectric losses for a microstrip line (w=0.5 mm, h=0.5 mm, ε_r=10, tgδ=0.0002) are calculated using our approach and compared to those found in literature using the Spectral-Domain Approach [1].

The results given in Table 1 show very good agreement and validate our analysis.

Table 1 : Dielectric losses for microstrip line, (w=0.5 mm, h=0.5 mm, ε_r=10, $tg\delta$=0.0002).

Frequency	5 GHz	10 GHz	15 GHz	20 GHz
α_d (our simulation) dB/m	0.224	0.466	0.723	0.996
α_d (reference [1]) dB/m	0.2	0.45	0.7	1.0

Secondly, both of the attenuation constants α_d and α_c, due to dielectric and conductor losses respectively, are calculated for a GaAs coplanar conductor-backed waveguide (Fig. 1), whose characteristics are :

w=100 µm, s=50 µm, h=100 µm, ε_r=12.9, $tg\delta$=0.006 and $\sigma_m=4.1.10^7\ \Omega^{-1}.m^{-1}$.

As shown in Tables 2a-b-c, our simulation results are compared to those obtained using the Hewlett Packard EM simulator (HFSS).

At a frequency of 60 GHz, the difference between the results for the attenuation constants is less than 5.5 per cent while that between the propagation constants is less than 0.6 per cent. The comparison can be judged to be satisfactory. We note the presence of three propagating modes at the frequency of interest.

Table 2a-b-c : Propagation characteristics taking into account dielectric or/and conductor losses, for coplanar line of Fig. 1, at 60 GHz.

a-with dielectric losses	Our results	HFSS results
α_d mode 1 (Np/m)	14.0	13.9
β mode 1 (rad/m)	3817	3814
α_d mode 2 (Np/m)	13.0	13.4
β mode 2 (rad/m)	3118	3106
α_d mode 3 (Np/m)	16.0	15.9
β mode 3 (rad/m)	2945	2960

b-with conductor losses	Our results	HFSS results
α_c mode 1 (Np/m)	8.0	8.4
β mode 1 (rad/m)	3825	3820
α_c mode 2 (Np/m)	10.3	10.1
β mode 2 (rad/m)	3128	3114
α_c mode 3 (Np/m)	7.0	7.4
β mode 3 (rad/m)	2952	2970

c-with diel.&cond. losses	our results	HFSS results
α_{dc} mode 1 (Np/m)	22.1	22.4
β mode 1 (rad/m)	3825	3822
α_{dc} mode 2 (Np/m)	23.4	23.8
β mode 2 (rad/m)	3128	3115
α_{dc} mode 3 (Np/m)	22.9	23.6
β mode 3 (rad/m)	2952	2967

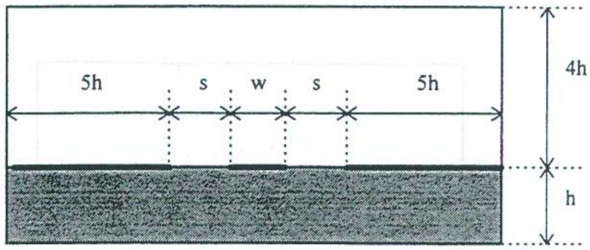
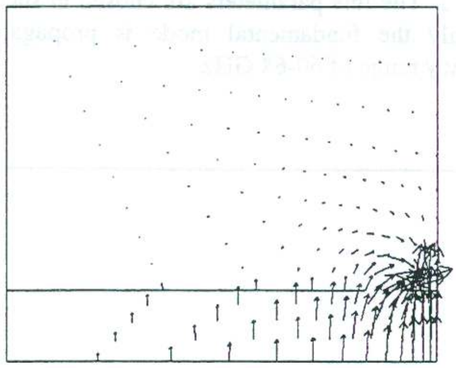


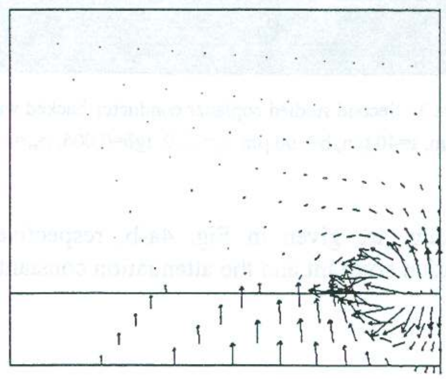
Figure 1 : First studied coplanar conductor-backed waveguide, (w=100 µm, s=50 µm, h=100 µm, ε_r=12.9, $tg\delta$=0.006, σ_m=4.1e7 $\Omega^{-1}.m^{-1}$).

The desired coplanar-like fundamental mode may be coupled to the microstrip-like mode or the dielectric waveguide mode formed by the metallized substrate, depending on the structure geometry. This phenomenon is like the leakage from the laterally infinite conductor-backed coplanar waveguide. Special techniques [3], like the use of shorting pins or the use of extra dielectric layer have to be employed to suppress the mode coupling.

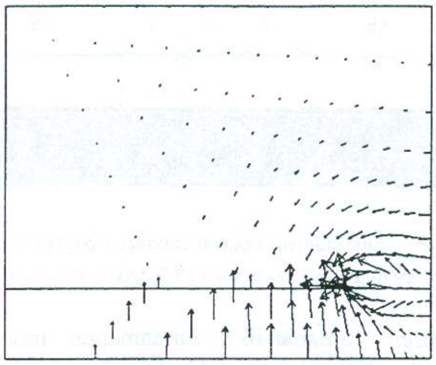
For example, from the electric field patterns given in Fig. 2a-b-c, we recognize each propagating mode and we note that, for this conductor-backed coplanar waveguide, the dominant mode is the microstrip-like one.



2a - First propagating mode.



2b - Second propagating mode.



2c - Third propagating mode.

Figure 2 : Electric field patterns of coplanar line of Fig. 1, at 60 GHz, for half of the symmetric structure.

Finally, the influence of dielectric and/or conductor losses on propagation characteristics is studied for another GaAs conductor-backed coplanar waveguide (w=66 µm, s=40 µm, h=100 µm, ε_r=12.9, tgδ=0.006, $\sigma_m=4.1.10^7\ \Omega^{-1}.m^{-1}$) given in Fig. 3. The line parameters are chosen in such a manner that only the fundamental mode is propagated, in the frequency range of 60-68 GHz.

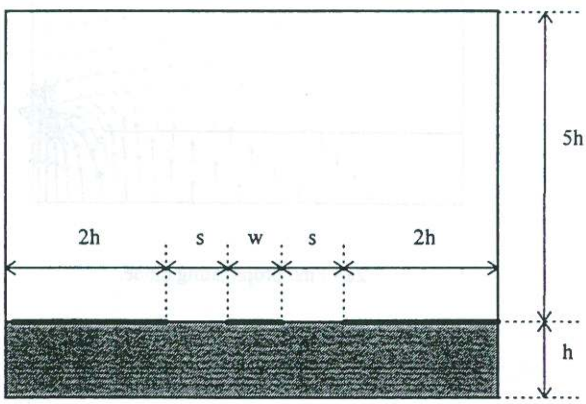
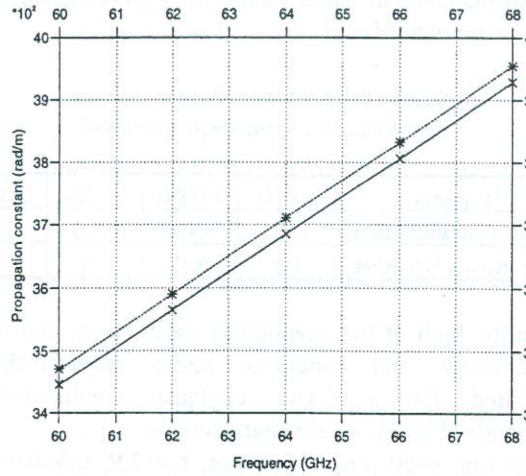
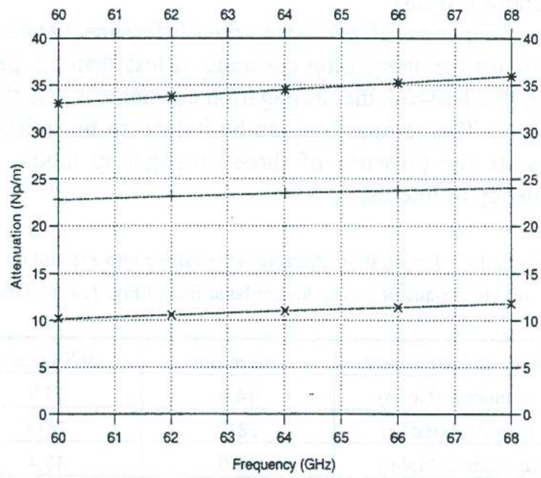


Figure 3 : Second studied coplanar conductor-backed waveguide, (w=66 µm, s=40 µm, h=100 µm, ε_r=12.9, tgδ=0.006, σ_m=4.1e7 $\Omega^{-1}.m^{-1}$)

Our results are given in Fig. 4a-b, respectively for the propagation constant and the attenuation constant.



4a- Propagation constant.



4b- Attenuation constant.

Figure 4a-b : Propagation characteristics for coplanar waveguide of Fig. 3, without losses (continuous line), with losses (dashed line), × : for dielectric losses, + : for metallic losses, ✱ : for dielectric and conductor losses.

It can be seen that the attenuation due to metallic losses is more important than that due to dielectric losses, in the frequency range of 60-68 GHz.

Moreover, only the conductor losses can modify the propagation constant. This variation did not exceed one per cent.

Besides, our simulations give, for a wide frequency range between 5 and 90 GHz, the propagation characteristics (Fig. 5) and the variations of the effective dielectric constant of the fundamental mode (Fig. 6). The results show that the second propagating mode appears at about 85 Ghz.

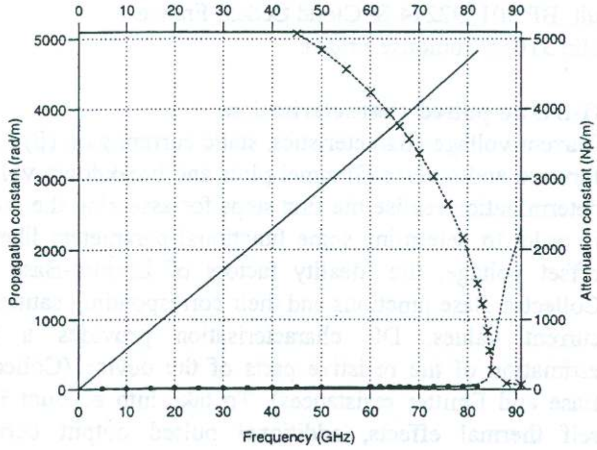


Figure 5 : Propagation characteristics for the coplanar line of Fig. 3. Propagation constant : 1st mode/continuous line, 2nd mode/dashed line, Attenuation constant : 1st mode/o, 2nd mode/×.

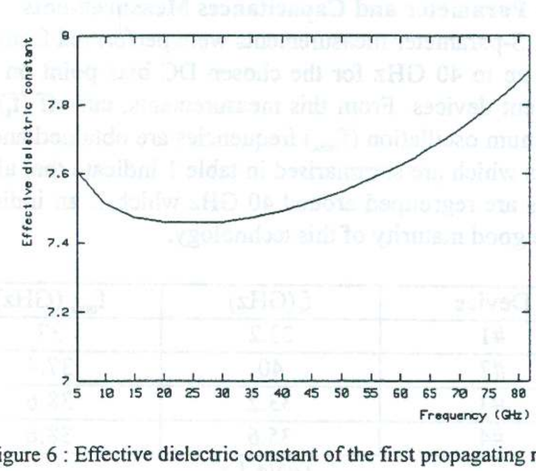
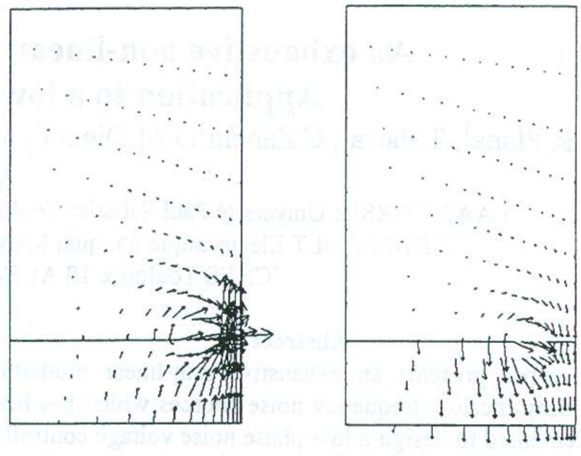


Figure 6 : Effective dielectric constant of the first propagating mode for the coplanar line of Fig. 3.

To complete this study, the electric field patterns of each propagating mode are given at the frequency of 90 GHz in Fig. 7a-b. On Fig. 7a, the coplanar mode is recognized but it is mixed with the microstrip mode. Fig. 7b shows the second propagating mode.



a- First propagating mode. b- Second propagating mode.

Figure 7a-b : Electric field patterns of the propagating modes for the coplanar line of Fig. 3, at a frequency of 90 Ghz.

Conclusion

An efficient 2D FEM electromagnetic simulator has been presented for studying the propagation characteristics of planar waveguides, taking into account dielectric and metallic losses. It has been shown that influence of losses on the propagation constant of GaAS coplanar waveguide is still negligible at frequencies of about 60 Ghz. The study of the conductor-backed coplanar waveguide, especially thanks to the display of the field patterns, shows that these transmission lines have to be used carefully. It is shown that three fundamental modes can propagate along a conductor-backed coplanar waveguide according to line dimensions. Special care must be drawn in choosing line dimensions, including packaging, in order to allow the propagation of only the dominant nearly coplanar waveguide-like mode.

References

[1] D. Mirshekar-Syahkal, J. Brian Davies, « Accurate solution of microstrip and coplanar structures for dispersion and for dielectric and conductor losses », IEEE Trans. MTT, Vol. 27, n°7, July 1979.

[2] M-F. Wong, C. Natu, O. Picon, V. Fouad Hanna, « Finite element of wave-guiding structures using mixed finite elements », URSI, Kyoto, 1993.

[3] N. K. Das « Methods of suppression or avoidance of parallel-plate power leakage from conductor-backed transmission lines », IEEE Trans. MTT, Vol. 44, n°2, February 1996.