Ground Plane Effects in Monolithic Millimeter-Wave Integrated Circuits

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Abstract— **The effect of a lossy ground plane on the propagation parameters of a monolithic millimeter-wave microstrip on semiconductor substrate is studied. The full-wave Spectral-Domain Technique, which can take into account the thickness and conductivity of the ground plane, is used. When considering an ideal ground plane, the losses are very low and quasi-independant on the thickness of the semiconductor. Taking into account the losses of the ground plane, it is shown that the propagation losses are not only dependant on the thickness of the ground plane but also on the thickness of the semiconductor. These losses increase significantly as this thickness is reduced.**

I. Introduction

MODELING millimeter-wave monolithic integrated circuits requires the use of full-wave methods since quasi-static methods are inadequate, in this case. This type of structures exhibits two main types of losses: dielectric losses and metallic losses.

Semiconductors, present even in the simplest monolithic structures, can be treated as dielectric layers with a complex permittivity, where $\tan\delta$ may be dependant on the frequency. Very few studies have been done on the effect of the ground plane and the strip for monolithic millimeter-wave structures. We show that an effective modeling should take into account the real characteristics of the metallizations: thickness and conductivity. As regards the conducting strips, a previous study has already taken their losses into consideration [1]. It revealed that losses due to the conducting strip increase when the strip width decreases and when the strip thickness becomes smaller than the skin depth (we shall show the same point as concerns the ground plane), that is to say when the resistance of the strip increases. We therefore concern ourselves with a comparative theoretical study between losses due to semiconductor layers and those due to lossy ground planes, by means of a full-wave method: The Spectral-Domain Approach. We have applied this analysis to the study of a realistic microstrip structure recently characterized by Wang *et al.* [2].

II. Modeling Principle

Using the well-known spectral-domain approach [3], losses in a semiconductor layer are taken into consideration by means of the complex permittivity, which may or not vary with frequency. The real ground plane (finite conductivity σ and thickness d) is treated as a dielectric layer (σ, d) over an infinite layer of air (Fig. 1).

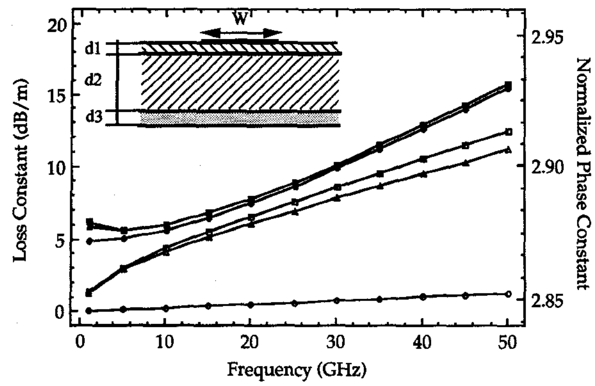

Fig. 1. Propagation parameters as a function of frequency. □ α (dB/m) for structure 1; ○ α (dB/m) for structure 2; △ α (dB/m) for structure 3; ■ $\beta g/\beta 0$ for structure 1; • $\beta g/\beta 0$ for structure 2; ▲ $\beta g/\beta 0$ for structure 3; $W = 70\ \mu$m; $d1 = 0.2\ \mu$m, $\varepsilon r1 = 6.5$; $d3 = 12\ \mu$m, $\varepsilon r2 = 12.9$, $\tan\delta 2 = 10^{-4}$; $d3 = 12\ \mu$m, $\sigma 3 = 4.1\ 10^7$ mho/m.

At a given frequency, once the propagation parameters are calculated, it becomes possible to get the pseudo-characteristic impedance and the electromagnetic fields in the whole structure. As we have a non-TEM propagation line, a precise definition of the characteristic impedance does not exist, but we can define a pseudo-characteristic impedance $Z = \left(P/2|I|^2\right)$, a definition which is the best suited for microstrip lines [4]. For better convergence and accuracy of calculated results, we used trigonometric basis functions corrected with the boundary conditions on metallic edges [5]. We also studied the convergence of calculations as functions of the truncation of the infinite limit of Fourier integrals met in the SDA, in order to have a good accuracy of calculated data.

III. Comparative Study Between the Two Types of Losses

We have studied the MMIC microstrip structure as shown in Fig. 1, with a Au lossy ground plane with $d_3 = 12\mu$m and $\sigma_3 = 4.1\ 10^7$ S/m realized on a semi-insulating semiconductor layer of GaAs with $\tan\delta_2 = 10^{-4}$. This structure is designated as structure 1. In order to compare the two types of losses, we have considered the same structure with an ideal ground plane ($\sigma = \infty, d_3 = 0$), we designate it as structure 2. We consider then the structure 1 but without dielectric losses ($\tan\delta = 0$ in the semiconductor layer), which gives structure 3.

Fig. 1 shows that the losses due to the semiconductor layer (structure 2) are very weak, compared to those due to the

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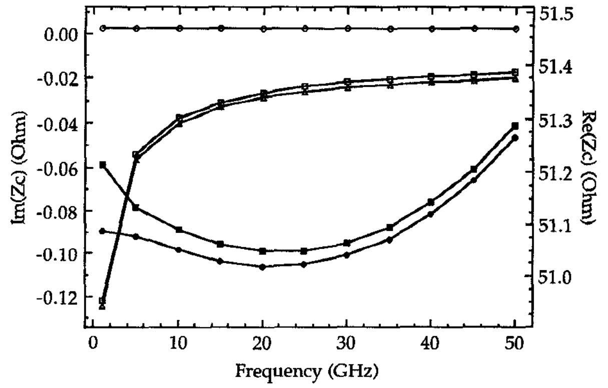

Fig. 2. Characteristic impedance as a function of frequency. □ $\mathrm{Im}(Zc)$ for structure 1; ○ $\mathrm{Im}(Zc)$ for structure 2; △ $\mathrm{Im}(Zc)$ for structure 3; ■ $\mathrm{Re}(Zc)$ for structure 1; • $\mathrm{Re}(Zc)$ for structure 2; ▲ $\mathrm{Re}(Zc)$ for structure 3.

lossy ground plane (structure 3). That is to say that, whether or not the semiconductor losses are taken into consideration, there is little or no change in the calculated propagation parameters. Furthermore, the relative error on the normalized phase constant made when considering an ideal ground plane (structure 2), instead of a real one (structure 1) is less than 0.25% (at 1 GHz), which is acceptable. On the contrary, the effect of the lossy ground plane on the loss constant is more important but the conclusion remains the same: considering the lossy ground plane as an ideal one entails more errors on the calculated constant than considering the semiconductor layer as a perfect dielectric.

The calculation of the characteristic impedance (Fig. 2) leads to the same conclusions. It can be also observed that treating the lossy ground plane as an ideal one leads to the wrong type of the imaginary part of Z_c, which is positive in the case of an ideal ground plane and negative in the case of a real lossy ground plane. This can be explained easily using the (R, L, C, G) parameters. On one hand, in the case of an ideal ground plane, we only have dielectric losses: $R = 0$ and

$$Z_c \approx \sqrt{\frac{L}{C}}\left(1 + \frac{1}{2}j\frac{G}{C\omega}\right),$$

which implies $Im(Zc) > 0$. On the other hand, if we have metallic losses (lossy ground plane) and since dielectric losses are weak (as we have previously shown), $G \approx 0$ and

$$Z_c \approx \sqrt{\frac{L}{C}}\left(1 - \frac{1}{2}j\frac{R}{L}\omega\right),$$

i.e., $\mathrm{Im}(Z_c) < 0$.

Since these two effects are in opposition, we have calculated the ground plane conductivity that cancels $\mathrm{Im}(Z_c)$, for given $\tan\delta$ and thickness d_2 of the semiconductor. For structure 1, this value is 1.210^{11} S/m; which is not realistic in practice. Similarly, we have varied the thickness d_3 of the ground plane in the real structure 1. It can be noticed in Table I that the propagation parameters no longer vary as soon as $d_3 > 2\delta$, where δ is the skin depth of the metal. As an example, for

TABLE I
LOSS CONSTANT (dB/m) AS A FUNCTION OF THE FREQUENCY AND THE LOSSY GROUND PLANE THICKNESS, FOR STRUCTURE 1

f/d_3	0,1 μm	0,5 μm	3 μm	5 μm	12 μm	20 μm
1 GHz	28.3166	6.3928	1.2707	1.2342	1.2976	1.2976
10 GHz	32.7314	6.8592	4.3846	4.3803	4.3803	4.3803
20 GHz	34.2587	7.6479	6.5734	6.5734	6.5734	6.5734
30 GHz	36.0996	8.7154	8.5495	8.5495	8.5495	8.5495
40 GHz	38.1546	10.0356	10.4786	10.4786	10.4786	10.4786
50 GHz	40.3628	11.5861	12.4208	12.4208	12.4208	12.4208

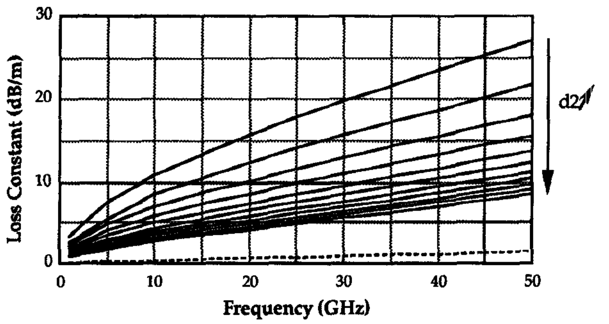

Fig. 3. Loss constant (dB/m) as a function of the frequency and of the semiconductor layer thickness.

$f = 1$ GHz, $\delta = 0.35$ μm and the loss constant no longer varies as soon as $d_3 > 0.7$ μm.

Fig. 3 shows the variation of the loss constant as a function of the semiconductor thickness in the following cases: ideal and imperfect ground plane. It can be noticed that in the case of an ideal ground plane, losses are quasi-independant on the semiconductor thickness d_2. That is why several studies propose to decrease the semiconductor thickness in order to increase the cut-off frequency of the first higher order mode f_c. However, taking the conductivity and thickness of the ground plane into account reveals that the losses increase significantly with the decrease of the semiconductor thickness d_2. For example, as is shown in Fig. 3, at $f = 40$ GHz, $\alpha = 7$ dB/m for $d_2 = 150$ μm, $\alpha = 24$ dB/m for $d_2 = 50$ μm.

We have concerned ourselves with the losses due to the lossy ground plane. However, losses due to the strip can be evaluated by means of the measurements reported by Wang *et al.* [2] which give, for the loss constant, from 10 to 80 dB/m for frequencies ranging from 1 to 40 GHz. The difference with our calculations reveals that the losses due to the conducting strip vary from 10 to 70 dB/m for the same range of frequencies. In this case, losses due to the conducting strip are very important because of the weakness of the strip width. However, when the strip width increases, losses due to the strip and losses due to the ground plane tend towards the same order of magnitude.

IV. Conclusion

We have shown, for the first time, that it is possible to take into account the effect of the ground plane in monolithic millimeter-wave structures, using a rigorous modeling method: the spectral-domain approach.

Our study shows that the ground plane has an important effect, particularly as regards losses. Indeed, in the modeling of the semiconductor based structures, taking the thickness and conductivity of the ground plane into consideration reveals that the losses are strongly dependant on the semiconductor thickness used. This has also an important effect on the cut-off frequency of the first higher order mode, which is inversely proportional to the semiconductor thickness. Thus, it appears that a compromise is needed between the losses on one hand and the cut-off frequency of the first higher order mode, on the other hand.

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