Electromagnetic modelling of conductive or superconductive microstrip lines using spice as electromagnetic solver

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Electromagnetic modelling of conductive or superconductive microstrip lines using spice as electromagnetic solver

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Résumé. — Dans ce papier, une méthode simple et efficace pour calculer les paramètres de propagation d'une ligne microruban et les champs magnétiques qu'elle engendre est présentée ; pour cela, nous simulons un circuit original équivalent à l'aide du simulateur nodal SPICE. Les pertes dans une ligne conductrice (pertes continues et par effet de peau) ainsi que dans une ligne supraconductrice peuvent être considérées. Les solutions électromagnétiques peuvent être intégrées dans les simulateurs de CAO.

Abstract. — This paper presents a simple and efficient method for calculating the propagating line parameters (actually, a microstrip one) and its magnetic fields, by simulating an original equivalent circuit with an electrical nodal simulator (SPICE). The losses in the normal conducting line (due to DC losses and to skin effect losses) and also in the superconducting one can be investigated. This allows us to integrate the electromagnetic solutions to the CAD softwares.

1. Introduction.

Accurate modelling of interconnections and fast circuits is now necessary because of the evolution of fast logic electronics associated with packaging (Multi Chip Module concept). Different methods using a full wave analysis of the system (Spectral Domain Approach, Transmission Line Method..) or static approaches (Moment Method, Finite Element Method...) may be used.

A compromise between reasonable computation time and accurate results in a wide range of frequency must be found. Moreover, the greatest challenge is to interface electromagnetic solvers with CAD software for circuits designers. To accomplish this aim, we present here a method which has two main advantages : a straightforward analyzing concept and the integration of a solver and a circuit simulator in a unique software. Indeed, an original equivalent circuit is analyzed by the nodal well known circuit simulator SPICE.

Our modelling concepts use the Moment Method by means of an equivalent circuit for calculating the microstrip line parameters and the electromagnetic field distributions in the structure. HTc superconductors (HTS) have been very promising for analog and logic circuit applications. In this way, as an application of our method, results on superconductive transmission lines are given ; this allows the analysis of complex superconductive passive circuits and of hybrid circuits populated with cooled semiconductors and HTS.

2. Modelling concepts of a microstrip line.

The main goals of our design are to know on one hand how the characteristic impedance, attenuation constant and phase velocity of microstrip line depend on frequency, on line geometrical factors and on electrical properties of both conductor and dielectric layer. On the other hand, the current density distributions in the line and resulting electromagnetic fields are also to be investigated.

To this aim, the resolution of Maxwell Integral Equations is achieved by applying the Moment Method, with the quasi-TEM propagation mode assumption (2D case). The electric and magnetic fields can then be calculated independently. The whole current flowing through a single microstrip line must be discretized into many parallel elementary currents having different densities. A cross sectional grid division of the strip is realized with an exponential form, so that the current density in each elementary section is assumed constant (Fig. 1). Hence, elementary section dimensions become larger and larger when going towards the center. To obtain accurate results, this grid division must satisfy the condition that the smallest elementary dimension is smaller than the skin depth.

Now, each elementary section has the form of a rectangular bar carrying a uniform elementary longitudinal current. For a unit line length, its self inductance and mutual inductances with the others are calculated using Neumann's formula [1], as the following :

$$M_{ij} = -\frac{\mu_0}{4\pi s_i s_j} \int_{\Delta x_i} \int_{\Delta y_i} \int_{\Delta x_j} \int_{\Delta y_j} G_{\mathrm{m}}(\mathbf{r}_i, \mathbf{r}_j)\, \mathbf{J}_i \, \mathrm{d}x_i \, \mathrm{d}y_i \, \mathrm{d}x_j \, \mathrm{d}y_j$$

where $G_{\mathrm{m}}(\mathbf{r}_i, \mathbf{r}_j)$ is the 2D magnetic Green function, $\mathbf{J}_i$ is the current density of the elementary section $s_i = \Delta x_i \, \Delta y_i$ of the strip.

The self inductance of each elementary bar may be considered as the mutual inductance of the bar duplicated by itself. In addition, the line loss must also be taken into account : the DC resistance and the high frequency resistance due to skin effect are involved. Therefore, the unit line length potential difference on an elementary branch i can be written as :

$$u_i = \frac{i_i}{s_i \sigma} + \frac{j\omega\mu}{4\Pi} \sum_{j=1}^{N} \frac{i_i}{s_i s_j} \iiiint G_{\mathrm{m}}(x_i, y_i, x_j, y_j)\, \mathrm{d}x_i \, \mathrm{d}y_i \, \mathrm{d}x_j \, \mathrm{d}y_j$$

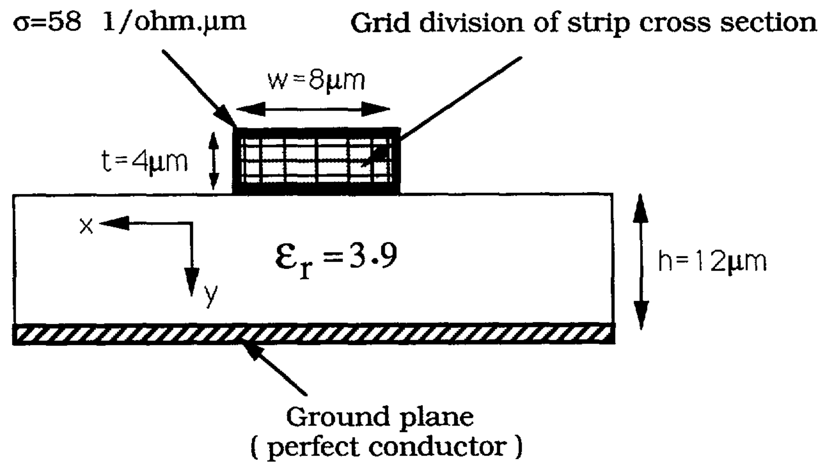

Fig. 1. — Cross section of the microstrip line and its grid division.

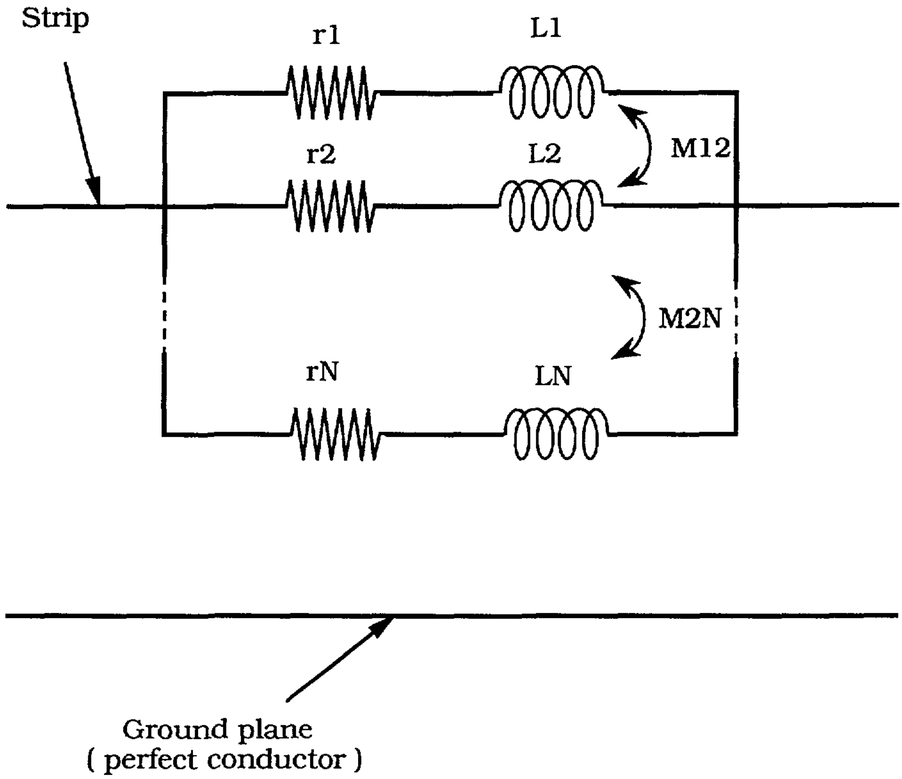

Fig. 2. — Equivalent circuit of the strip.

where σ is the strip conductivity, i_i is the current in the subsection s_i and $\mathbf{r}_i = (x_i, y_i)$, $\mathbf{r}_j = (x_j, y_j)$ are the loaded points and the points of observation respectively in the two-dimensional space. Hence, the electromagnetic equations of the line can be presented in the equivalent circuit form. It is a complex network containing the parallel inductances previously calculated and the resistance added in series with its inductance in each elementary branch. The whole equivalent circuit is presented in figure 2. An analysis by the electrical nodal simulator, e.g. SPICE, is performed on this circuit in frequency domain to obtain the variations of line series impedance $Z(\omega)$ with frequency. The line parameters R and L can be deduced. We can also calculate the current flowing in each parallel branch in complex form so that the magnitude of the current density and its phase distributions may be viewed. This gives an interesting and accurate understanding of skin effect in the line at high frequency.

3. Modelling results.

3.1 CASE OF A CONDUCTIVE MICROSTRIP LINE. — Consider a typical microstrip line whose geometry is given in figure 1. Because of its finite normal conductivity, skin effect will occur above the frequencies where the skin depth is about a half of strip thickness [2]. The associated equivalent circuit is built up for the SPICE analysis in the 1 MHz-10 GHz band.

3.1.1 *Variations of line parameters with frequency.* — The variations of line resistance $R(\omega)$ and inductance $L(\omega)$ *versus* frequency are presented in figures 3a and 3b. At low

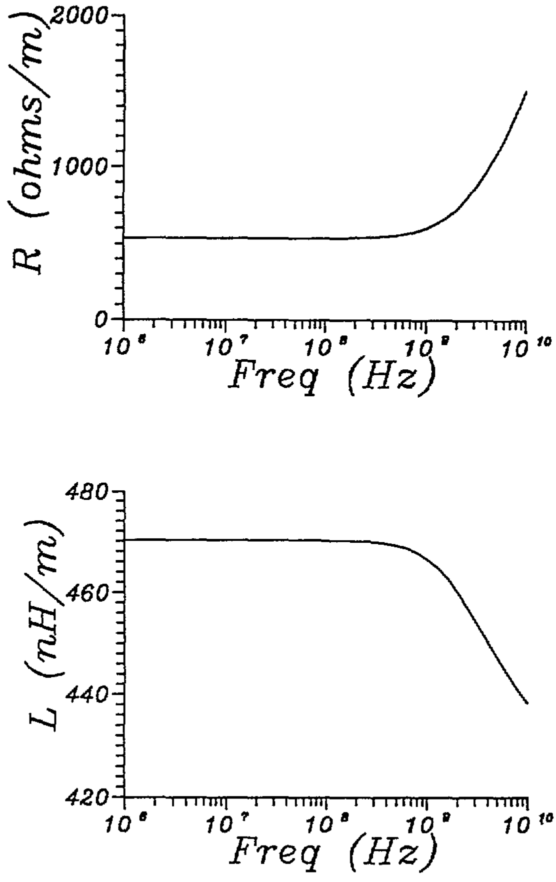

Fig. 3. — The variations of the line resistance $R(\omega)$ and inductance $L(\omega)$ *versus* frequency.

frequencies, $R(\omega)$ remains at its DC value and $L(\omega)$ keeps the inductance value $L_{int} + L_{ext}$ corresponding to a perfect magnetical field penetration. But above the corner frequency ω_c (about 1 GHz), skin effect occurs, $R(\omega)$ increases proportionally to $(\omega)^{1/2}$ and $L(\omega)$ slightly decreases to the asymptotic value L_{ext} of external field. The line attenuation constant can be deduced easily [3].

3.1.2 *Magnetic field distributions.* — As presented in previous section, the current density distributions in the strip can be calculated as being the currents flowing in the branches of the equivalent network. Then, the magnetical fields are obtained by applying the Maxwellian relations :

$$\mathbf{A} = \sum_{i=1}^{N} \int_{s_i} G_m \, \mathbf{J}_i \, ds_i \quad \text{and} \quad \mathbf{H} = \frac{1}{\mu} \operatorname{rot} \mathbf{A}$$

where $\mathbf{J}_i$ is the current density in subsection s_i, N is the total number of subsections.

The space distributions of the vectori potential $\mathbf{A}$ and the magnetic field components H_x and H_y are presented in figure 4 and figures 5a, 5b. With a quasi-TEM mode assumption, $\mathbf{A}$ has only one component A_z which decreases to zero on the reference ground plane (perfect

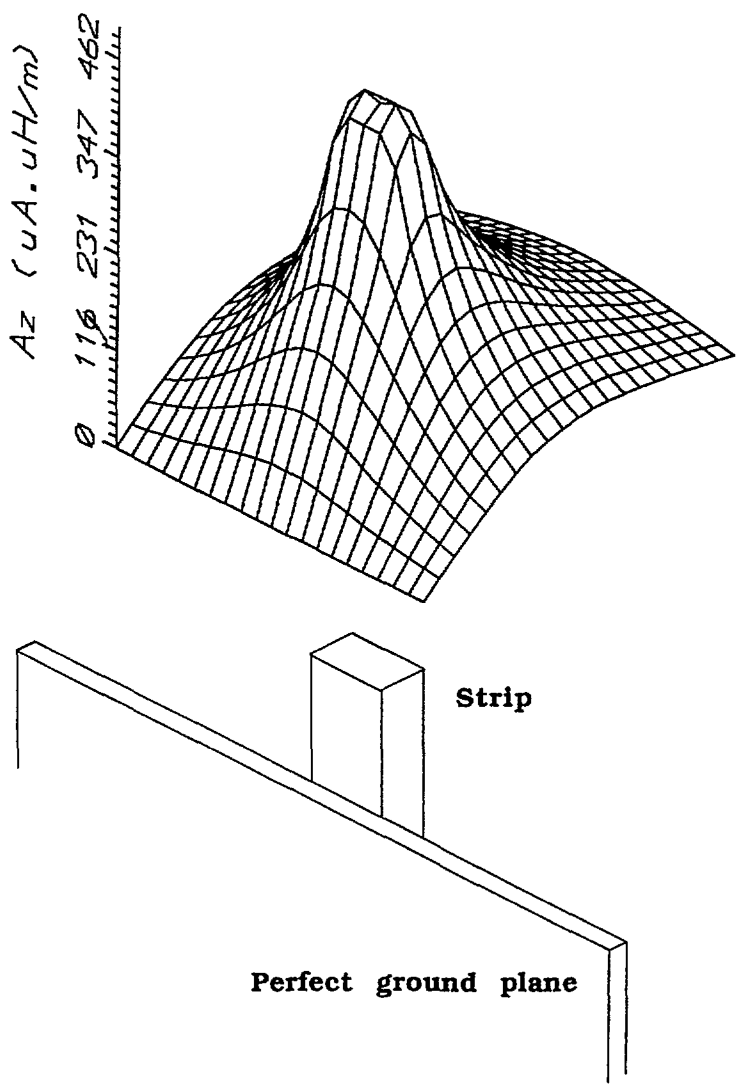

Fig. 4. — Distribution of the potential vector component A_z in the space.

conductor). These results have been successfully compared with those calculated by a Finite Element Method [4].

Notice that for simplicity purposes, the only case of a perfect ground plane has been presented here. But similar analysis have been performed with a conductive ground plane. In this case, losses in the ground plane and proximity effect are taken into account.

3.2 CASE OF A SUPERCONDUCTIVE LINE. — A structure with the same geometry as in the previous case has been simulated, but with both line and ground plane made of HTS material (YBaCuO). For comparison purposes, the cases of a silver ground plane or a perfect ground plane have also been investigated.

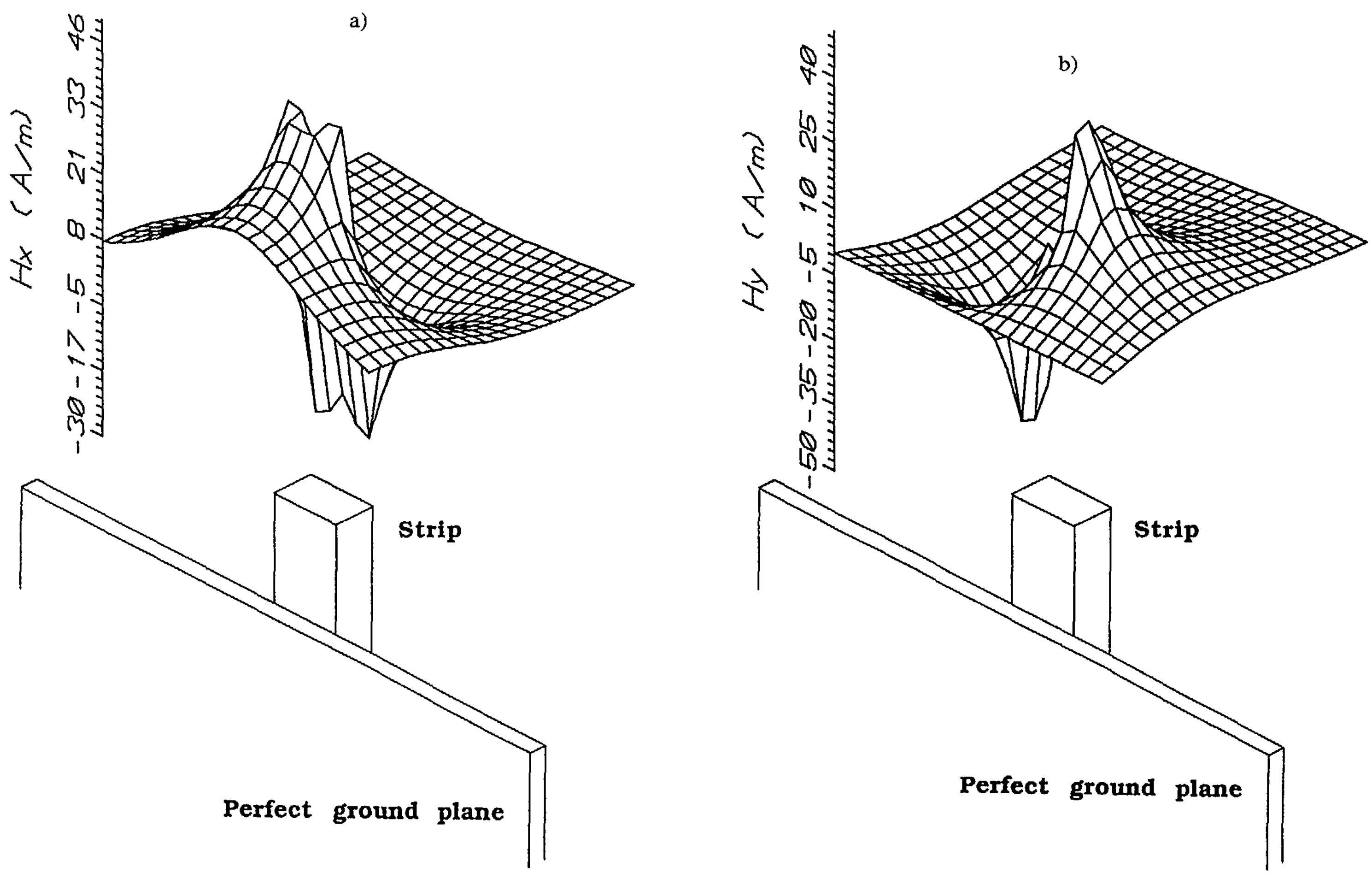

Fig. 5 — Distributions of the magnetical field components H_x and H_y in the space

3.2.1 *Variation of the propagation parameters with frequency. Influence of the nature of the ground plane.* — Using SPICE software, the simulations at 77 K gives us the variations of the attenuation constant of propagation (Fig. 6a) and of phase velocity (Fig. 6b) with frequency, from 100 MHz to 10 GHz. In figure 6a, the attenuation constant of the HTS line is quite similar to that obtained with a perfect ground plane, but this parameter is about 10^3 times lower than that obtained with a silver ground plane. This demonstrates the strong influence of the nature of the ground plane on the total line losses in this frequency range. Hence, because of the very low intrinsic losses of the high temperature superconductive materials, the other peripheral materials such as ground plane, contacts, bondings, .. will play a very important role in the final performances of the HTS transmission line or circuit. In particular, due to the

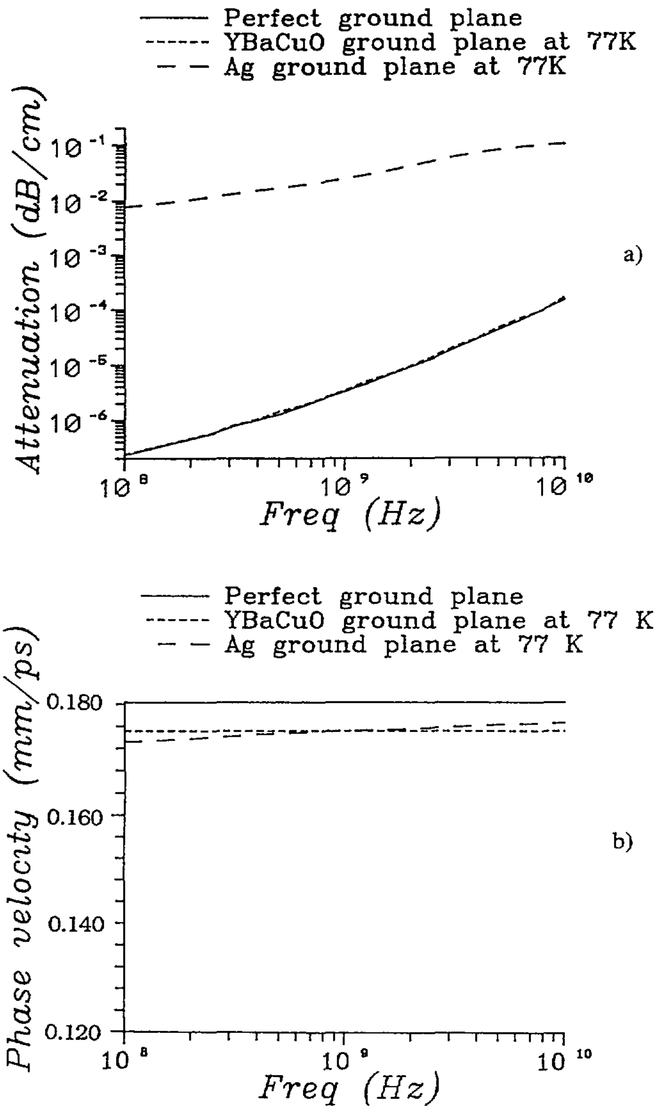

Fig. 6. — Influences of the ground plane on the line attenuation and phase velocity of a superconductive microstrip line.

difficulties in processing double-faced superconductive circuits, one can advantageously use coplanar superconductive lines in order to minimize propagation losses. In figure 6b, the phase velocity of the HTS line (0.175 mm/ps) is a constant, a few lower than that obtained with a perfect ground plane. The values obtained with the use of a silver ground plane is slightly frequency dependent. These variations have been successfully compared with those obtained by the Phenomenological loss Equivalence Method (P.E.M.) [5] : in figure 7 are compared those results, with a line geometry proper to reference [5]. A slight difference is observed, especially towards the lower frequency where the dependence in f^2 (case of the P.E.M. curve) cannot be valid.

Moreover, similar simulations have been performed using a full wave analysis (Spectral Domain Approach) and compared with our results, as shown in figure 7. A good agreement is observed. Consequently, it could be noticed that the TEM approximation in the case presented here is valid up to 10 GHz [6].

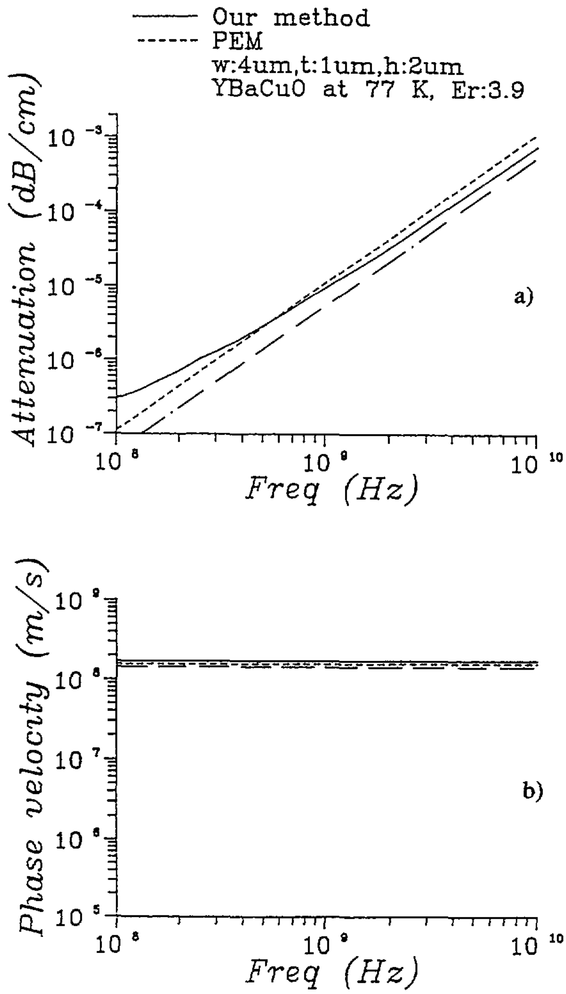

Fig. 7. — Comparison of the variations of attenuation (a) and phase velocity (b) *versus* frequency, calculated with different methods : (---------) Our method. (...) Phenomenological Loss Equivalence method. (—·——·) Spectral Domain Approach.

3.2.2 *Current distributions.* — The current density distributions at 77 K in both the HTS strip and the superconducting ground plane have been calculated. In figure 8 are presented the results related to the strip. The skin effect is at the origine of an inhomogeneity of the current distribution, quasi exponential in the X and the Y directions. Due to the proximity effect of the ground plane, which carries the same current but in the opposite direction, the density on the lower surface of the strip is greater than that of the above one. In addition, a large density accumulation at the above surface of the ground plane facing the strip has been observed. Noticing that the current density values at the edges of the strip can overtake the critical value $J_c = 10^4$ A/cm^2 for the YBaCuO material used, which indicates that the superconductive transition may occur in these regions. Then, the superconductive advantages of the line are no longer kept, since most of the current is flowing there.

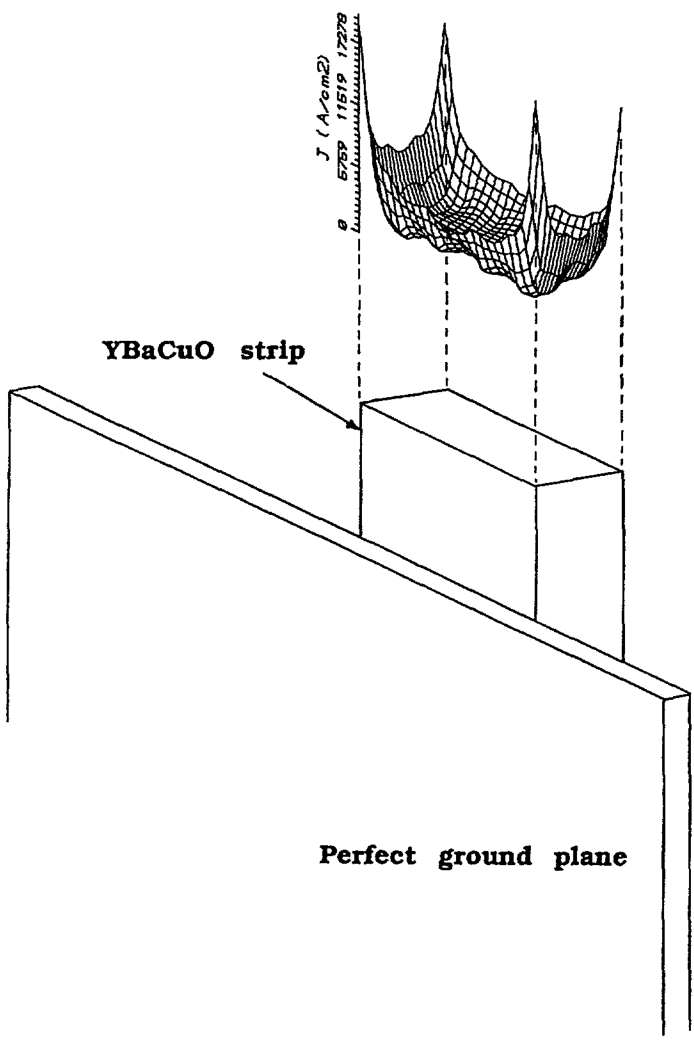

Fig. 8. — Distribution of the current density in the superconductive strip.

4. Conclusions.

A concept of modelling a microstrip propagating line is presented, which is based on the Moment Method and on a new equivalent circuit developed by us. The use of an electrical nodal simulator, e.g. SPICE, allows us to simulate the line in both frequency and time domains, with linear or non-linear loads. In addition, from the current density distributions obtained by the analysis of the equivalent circuit, the magnetic fields can be calculated with the assumption of a quasi-TEM mode propagation ($H_z \ll H_x$, H_y). These concepts can also be extended to a superconductive line allowing the parameters to be obtained. The influences of the lossy ground plane on total line losses can overtake the superconductor advantages. Therefore, a new and innovating technology for producing the homogeneous superconductive microstrip interconnections is required.

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