AN IMPROVED FD–TD FULL WAVE ANALYSIS FOR ARBITRARY GUIDING STRUCTURES USING A TWO–DIMENSIONAL MESH

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ABSTRACT

A new finite–difference time–domain (FD–TD) formulation is proposed for the efficient analysis of arbitrary waveguiding structures. In contrast to the conventional FD–TD eigenvalue formulation, which requires a three–dimensional mesh for adequately formed resonator sections, this method utilizes advantageously a two–dimensional mesh for analyzing the full–wave dispersive characteristic of guided structures. This leads to a significant reduction in cpu time and storage requirements. Numerical examples are presented for bi– and unilateral finlines with finite metallization thickness and for a pair of coupled shielded dielectric guides. The theory is verified by comparison with results obtained by other methods.

INTRODUCTION

The finite–difference time–domain (FD–TD) method [1] is a widely established and versatile numerical tool for solving eigenvalue and scattering problems of a great variety of microwave guiding structures [2] – [6]. The conventional approach for analyzing the dispersion behavior of such waveguides utilizes a three–dimensional mesh for appropriate resonating sections which are obtained by placing shorting planes in halfwave distance along the axis of propagation of the structure under investigation. By repeating the calculation of the resonant frequency of these resonators for different distances of the shorting planes, the dispersion characteristic may be determined step by step. Consequently, the conventional approach requires considerable cpu time, needs a relatively large memory size, and tends to inaccuracies in the near of the cutoff frequencies.

This paper introduces an improved FD–TD full–wave analysis method which is based on a new two–dimensional FD–TD mesh formulation (Fig. 1). Similar to the improved TLM analysis presented recently [7], which applies a phase relationship between TLM node voltages, the new FD–TD formulation in this paper reduces the original three–dimensional Yee's mesh by utilizing the fact that electric and magnetic fields of the wave in the wave propagation direction z of the waveguiding structure are merely related by the phase factor of the waveguiding structure to be investigated. This formulation helps to alleviate the above mentioned shortcomings of the conventional FD–TD approach for the analysis of waveguiding structures since the iteration procedure for the pulse propagation needs only to be carried out in the cross

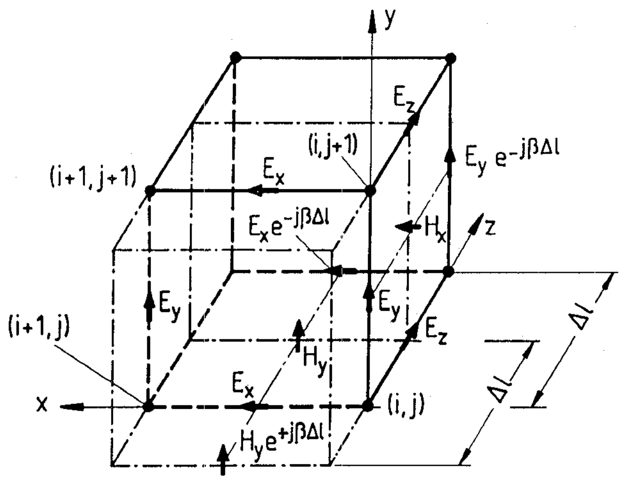

Fig. 1:
New two–dimensional FD–TD mesh (i, j) for solving 2D eigenvalue problems of waveguiding structures

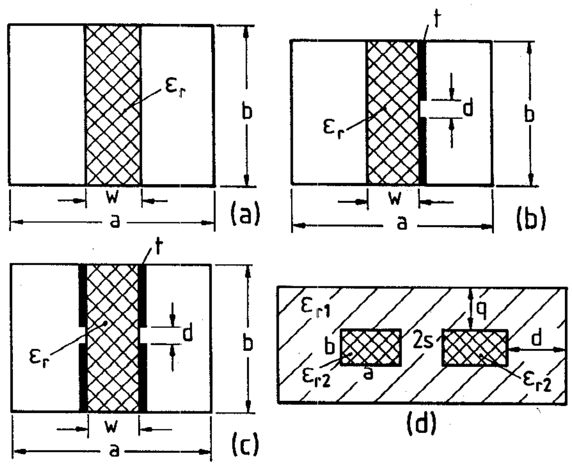

Fig.2:
Investigated mm–wave and optical waveguiding structures.
a) Nonradiative guide b=a/2, ϵ_r=3.75,
b) Unilateral finline, c) Bilateral finline,
d) Shielded coupled dielectric waveguides, dimensions (mm): a=2b=4, s=d=p=1, ϵ_r=2.56.

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section x,y dimension. Consequently, a considerable reduction of both cpu time and memory space required is achieved. Typical numerical results for finline and optical waveguide structures are presented (Fig. 2). The theory is verified by comparison with available results of other methods.

THEORY

The FD–TD method is usually formulated by discretizing Maxwell's curl equations over a finite volume and approximating the derivatives with centered difference approximations [1] – [6]. This leads to the three–dimensional Yee's mesh [1] in various modifications [2] – [6].

Following Yee's notation, we denote (Fig. 1)

$$(i,j,k) = (i\Delta x, j\Delta y, k\Delta l) \, , \qquad (1)$$

where in our case k is only $k = \pm 1$. Utilizing the following relationships between the transverse fields $\vec{E}_t$ and $\vec{H}_t$ of a guided wave travelling in +z direction (Fig.1) of the waveguiding structure to be investigated,

$$\vec{E}_t(z \pm \Delta l) = \vec{E}_t \cdot e^{\mp j\beta\Delta l}$$
$$\vec{H}_t(z \pm \Delta l) = \vec{H}_t \cdot e^{\mp j\beta\Delta l} \, , \qquad (2)$$

and using Yee's formulations e.g. in the form of [2] for anisotropic structures, a new set of FD–TD equations for the six components $\vec{H}$ and $\vec{E}$ is derived. Thus we obtain e.g. for H_x

$$H_x^{n+1/2}(i,j+1/2) = H_x^{n-1/2}(i,j+1/2) + s/[\mu_{xx}(i,j+1/2)\cdot Z_{F0}] \cdot \Big\{ E_y^n(i,j+1/2)\cdot[e^{-j\beta\Delta l} - 1] + E_z^n(i,j) - E_z^n(i,j+1) \Big\} \, , \qquad (3)$$

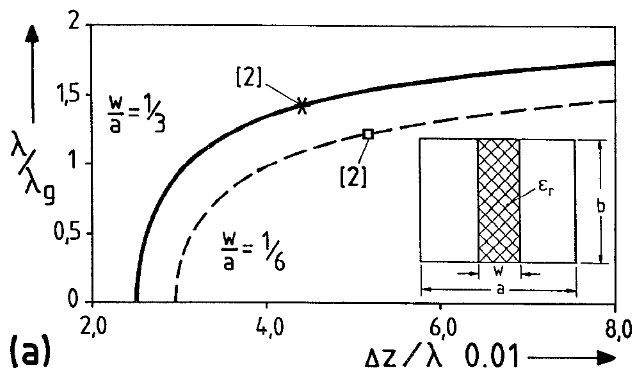
where the stability factor is $s = c\,\Delta t/\Delta l$, c is the velocity of light, Z_{F0} is the characteristic impedance of free space, and μ_{xx} is the diagonal element of the relative permeability tensor. The condition for stability in free space is $s \leq 1/\sqrt{3}$ [2].

The remaining finite difference equations related to the other five field equations can be similarly calculated. Note that the FD–TD equations in (3) only depend on $i\Delta x$ and $j\Delta y$, i.e. the mesh for the pulse propagation iteration needs only to be built up in the cross section x,y dimension, the number of nodes in z direction is reduced to ±1. Also it should be emphasized that the amplitudes of all field components in the new formulation are complex quantities.

The principal numerical calculation steps are similar to those in the conventional FD–TD approach with the exception that a propagation factor β has to be selected first. After launching an excitation pulse, waiting until the distribution of the pulse is stable and performing the Fourier transformation, the modal frequencies related to the selected propagation factor are obtained.

RESULTS

Fig. 2 shows some typical mm–wave and optical waveguiding structure examples which have been investigated by our improved FD–TD method. Normalized and actual resonant frequencies of nonradiative guide (Fig. 2a) and unilateral finline (Fig. 2b) resonators of finite length c are reported in [2] which are calculated by the transverse resonance method (TRM), the spectral domain method (SDM), the transmission line method (TLM), and the conventional three–dimensional FD–TD method. A comparison with these results is particularly indicated, therefore. In order to verify our results with the calculations of [2], the related fundamental mode dispersion curves obtained by our two–dimensional FD–TD method are plotted in Fig. 3. The dimensions of the nonradiative guide (Fig. 3a) resonator in [2] are $a = 12\Delta z$, $b = 6\Delta z$, $c = 8\Delta z$, and the data of the unilateral finline (Fig. 3b) resonator [2] are given by a = 20mm, b = 10mm, c = 15mm, w = 1mm, d = 4mm, $\epsilon_r = 2.22$. Although the discretization in our 2D



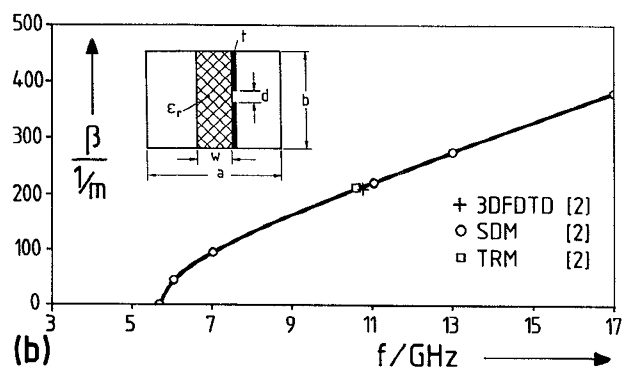


Fig. 3:
Fundamental mode dispersion curves obtained by our two–dimensional FD–TD method.
Comparison with the conventional 3D FD–TD method [2] for resonators of finite lengths c.
a) Nonradiative guide.
Discretization 2D FD–TD: 12 × 6.
b) Unilateral finline.
Discretization 2D FD–TD: 80 × 20.

FD–TD method was relatively wide–meshed (12 × 6 for Fig. 3a, 80 × 20 for Fig. 3b), very good agreement may be stated. The number of time iterations used was 2000 in both cases.

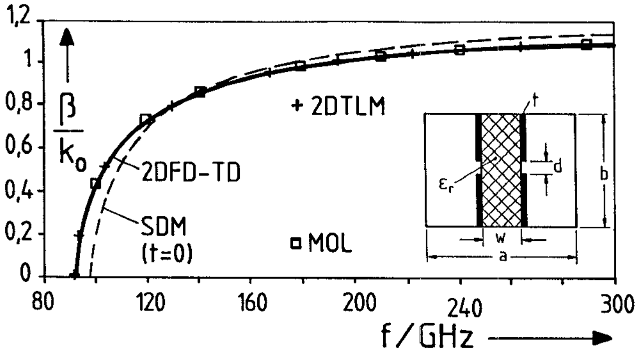


Fig. 4:
Fundamental mode dispersion curves for a bilateral finline obtained by our two–dimensional FD–TD method. Comparison with own calculations using the 2D TLM, SDM, and MOL methods.
WR–3 housing, $\epsilon_r = 2.2$, w = 0.1mm, s = 0.124mm, t = 54 μm. Number of time iterations: 2000.
Discretization: 32 × 16.

The great advantage of the 2D FD–TD method reported in this paper as compared with the classical 3D FD–TD method is that the whole set of dispersion curves of waveguide structures can be obtained in one computational run and with the same degree of accuracy. Fig. 4 presents the dispersion curve for the fundamental mode in a bilateral finline. The analysis has been verified by own calculations applying the method of lines (MOL), the spectral domain method (SDM), and a modified 2D TLM algorithm which is based on similar formulations like those used for the 2D FD–TD method. Good agreement with the results of the MOL and TLM methods may be observed. Compared with the SDM (for t = 0), however, there are some discrepancies which are due to the finite thickness of the metallization (t = 54μm) which has been taken into account in our 2D FD–TD, MOL, and TLM calculations.

A unilateral finline is investigated in Fig. 5. Here, good agreement with the SDM may be stated since the influence of the finite thickness of t = 17μm on the fundamental mode propagation behavior for this kind of structure has been taken into account in the SDM calculation used which is based on a new spectral domain formulation taking the finite metallization thickness into account. Fig. 5 presents the dispersion curves for the even and odd E^y_{11e} and E^y_{11o} modes of a shielded coupled dielectric waveguide. The agreement with results calculated by our own 2D TLM method as well with mode–matching results reported in [7] is very good although the discretization is only 24 × 16.

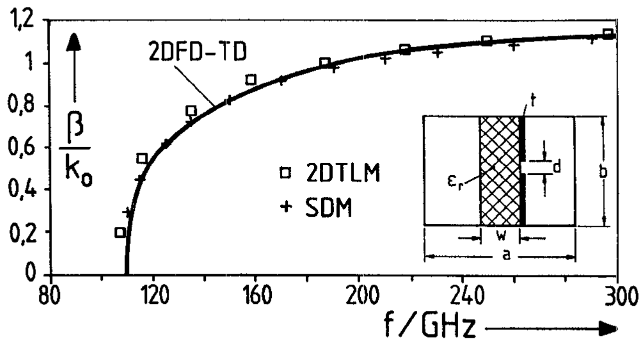


Fig. 5:
Fundamental mode dispersion curve for a unilateral finline obtained by our two–dimensional FD–TD method. Comparison with own calculations using the 2D TLM, and SDM methods.
WR–3 housing, $\epsilon_r = 2.2$, w = 0.1mm, s = 0.127mm, t = 17 μm. Number of time iterations: 2000.
Discretization: 152 × 38.

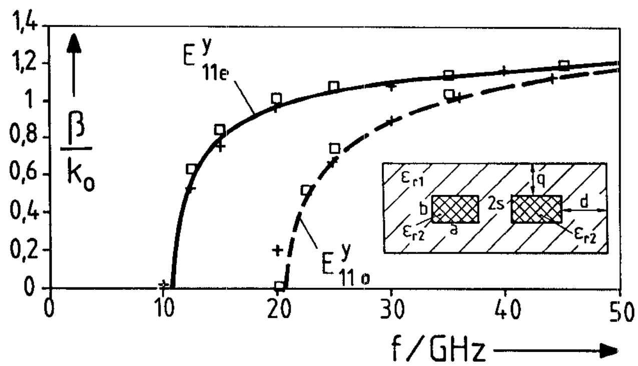


Fig. 6
Dispersion curves for the even and odd E^y_{11} modes of a shielded coupled dielectric waveguide obtained by our two–dimensional FD–TD method. Comparison with own calculations using the 2D TLM method, and by mode–matching (MM) results reported in [7].
Dimensions: a = b = 2mm, s = d = q = 1mm, $\epsilon_{r1} = 1.0$, $\epsilon_{r2} = 2.56$,
Number of time iterations: 2000.
Discretization: 24 × 16.

CONCLUSION

A new finite–difference time–domain formulation is presented for the full–wave analysis of arbitrary waveguiding structures. This method utilizes advantageously a two–dimensional mesh instead of the original three–dimensional Yee's mesh. Consequently a significant reduction in cpu time and storage requirements is achieved. Moreover, the whole dispersion curve can be obtained with the same degree of mesh discretization, and hence with the same accuracy. Typical numerical examples demonstrate the applicability of the 2D FD–TD method. The theory is verified by comparison with results obtained by other methods.

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