NUMERICAL ANALYSIS OF UNSHIELDED STRIP LINES FOR MICROWAVE MEASUREMENTS

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This paper reports the results of numerical analysis of coplanar and slot-line when a sample of dielectric material with limited dimensions is added as an outer medium. The main purpose of the analysis is to demonstrate how the unshielded field of the line could be used for measurement of the dielectric constant of the sample material. FDTD method is used to calculate the electromagnetic field in and outside the line. As a result, the effective dielectric constant of the line and the voltage standing wave ratio are obtained. The numerical results were compared to and were found to be in very good agreement with the analytical predictions as well as with previous experimental results.

1. INTRODUCTION

The development of microwave devices with strip lines in the last decade shows a trend towards constructions where the conducting strips are situated in one plane. The coplanar and slot-lines become preferred to asymmetric and microstrip line for a number of advantages: they are technologically more convenient and cheaper; they allow easy mounting of electronic elements and junctions to other lines; the possibility of obtaining greater characteristic impedance allows easier contact with the environment and matching to other standard lines.

The coplanar and the slot-line have relatively larger unshielded field which usually is a disadvantage if the line is used as a transmission system. This field, however, could turn to be an advantage when the line is used for measurement of the outer medium parameters which is the purpose of the current research.

The analysis of the processes in the coplanar and the slot-line in their frequency range of use (1 - 8 GHz) is carried out assuming a quasi-TEM approximation although the real wave is a hybrid TE wave. In this case another advantage is the relatively low dispersion which allows multifrequency measurements when several parameters of the medium are to be determined.

The purpose of the current work is to estimate the influence of the outer medium on the line parameters. By means of the Finite Difference Time Domain (FDTD) method wave propagation through the line and reflection from a dielectric sample placed upon the line are simulated. As a result, the effective dielectric constant and the voltage standing wave ratio are calculated. The numerical experiment demonstrates how a coplanar or a strip line can be used for measurement of the properties of dielectric materials.

2. FDTD FORMULATION OF THE PROBLEM

2.1 On the FDTD method

The Finite Difference Time Domain method (FDTD), first introduced by K.Yee in 1966, provides a direct solution of the time-dependent Maxwell's equations. The space is divided into small cubes (Fig.1a), on which walls and edges the six field vectors are placed (Fig.1b). Based on second-order accurate central difference, FDTD implements the space derivatives of the curl operators from the Maxwell's equations via finite differences in the Cartesian mesh [6]. The solution for the electromagnetic field is obtained as a function of time.

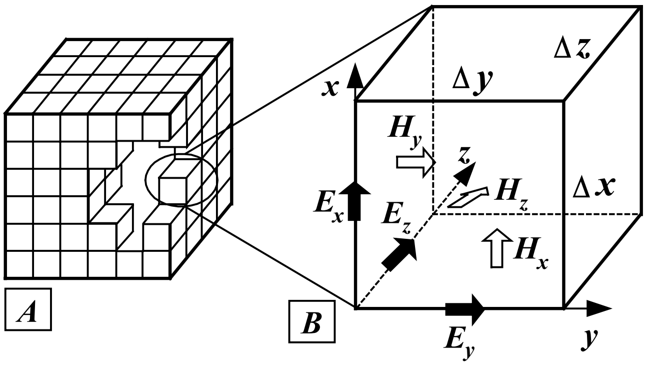

Fig.1. Space discretization in FDTD method

FDTD has been found to be one of the most popular computational techniques in the modeling the microwave circuits. The method is highly robust and computationally efficient and has a number of significant advantages over traditional frequency domain techniques. Specially, as the fields are computed from the Maxwell's equations, the development of the processes in time can be observed.

2.2 Description of the General Simulation Setup

The simulated structure is shown in Figure 2. A sample of a dielectric material with relative dielectric permittivity ε_{diel} is placed upon a coplanar line starting from the middle of the computational domain (the same simulation has been carried out with slot-line as well but as the principle of calculations and the results are the same, here only the simulation with a coplanar line will be discussed). The thickness of the substrate is h = 3.5 mm. The slot width is G = 0.7 mm and the width of the central conducting strip is W = 4 mm. All the walls of the computational domain are terminated by Mur's first order absorbing boundary conditions (ABC) providing that there will be no reflections back into the computational domain [3,6]. The Absorbing

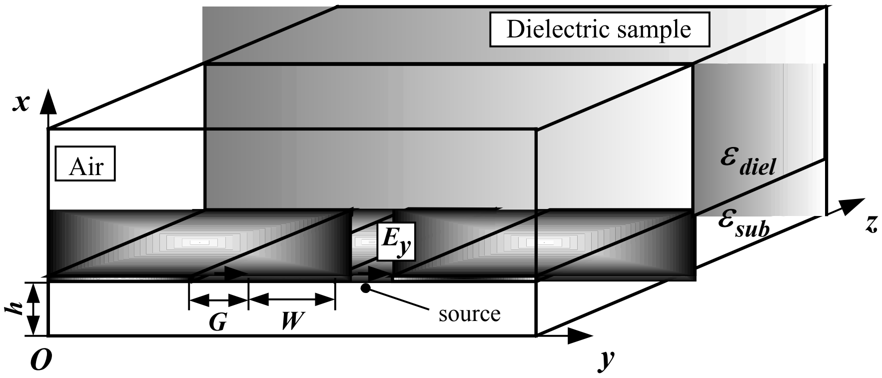

Fig.2. Schematics of the simulation setup.

Boundary Conditions simulate unlimited space in all directions. This automatically means that the line is perfectly matched at both ends. A sinusoidal wave is launched to travel in z-direction by applying electric field E_y as shown in Figure 2.

The simulation is carried out at 2 GHz. The spatial steps are: Δx = 1.667 mm, Δy = 0.233 mm, Δz = 0.233 mm. The corresponding time step according to the Courant condition is: Δt = 0.5449 ps. The simulation is carried out until a steady state is reached - for the frequency of 2 GHz approximately 2000 iterations were performed which is equal to 1.1 ns. The spatial steps are chosen in such way that each slot in the coplanar line is three cells wide and there are at least 25 cells per wavelength. These conditions provide good accuracy of the algorithm.

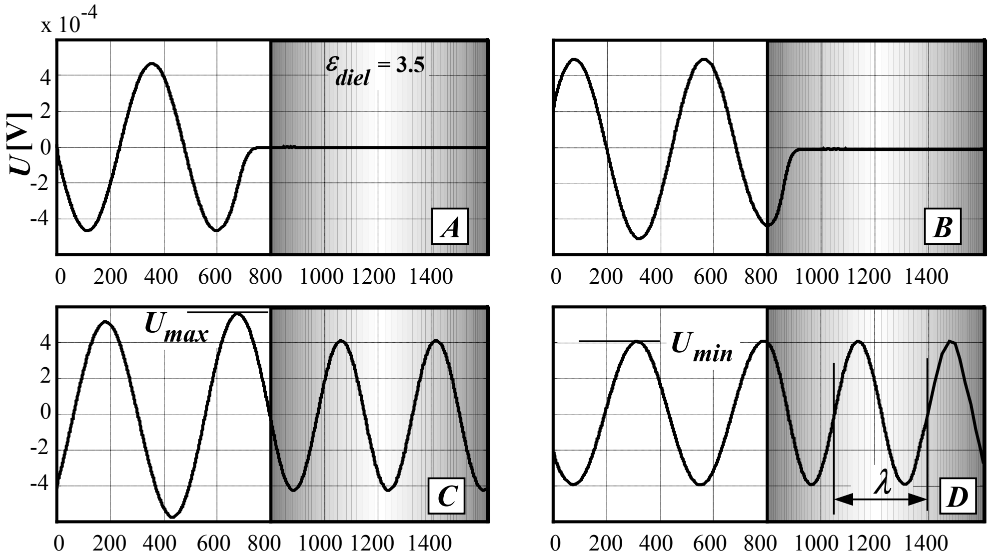

Fig.3. Voltage distribution along the line. The values on the x-axis indicate the number of spatial steps from the source, each step is equal to 0.2333 mm. In A only the incident wave is shown, in B reflection begins, C and D show the field pulses.

To find the voltage along the line, line integrals over E_y have been calculated inside the slots, along the line connecting the central and side conducting strips (Figure 2). In Figure 3 four snapshots of the voltage distribution along the line are shown. As the wave travels in z-direction, some of the energy is reflected back from the sample. Therefore, the total field (the sum of the incident and reflected wave) in front of the reflecting surface pulses, varying from a minimum (U_{min}) to a maximum value (U_{max}) as shown in Figure 3c,d. The ratio of these values gives the voltage standing wave ratio ($VSWR$):

$$VSWR = \frac{|U_{\max}|}{|U_{\min}|}. \quad (1)$$

To determine the effective dielectric constant of the line, the wavelength is measured for the part of the line with the dielectric sample material (Figure 3). Following the quasi-TEM approximation the wavelength in the coplanar line is:

$$\lambda = \lambda_0 / \sqrt{\varepsilon_{eff}\ \mu}\ , \tag{2}$$

where λ_0 is the wavelength in free space (for 2 GHz $\lambda_0 = 0.1499$ m) and ε_{eff} is the relative effective dielectric constant.

As all materials in the experiment are non-magnetic:

$$\varepsilon_{eff} = (\lambda_o / \lambda)^2\ . \tag{3}$$

3. SOME THEORETICAL CONSIDERATIONS

The main idea of the numerical experiment was to compare the results with analytical ones. The analytical solution for the effective dielectric constant and the *VSWR* is found according to the following considerations:

The ratio of the voltage and the current of the traveling wave in a TEM-wave line is equal to the line's characteristic impedance:

$$Z_c = 1/(\upsilon_{\varepsilon\mu}\ C_l), \tag{4}$$

where $\upsilon_{\varepsilon\mu}$ is the phase velocity in an unlimited medium with parameters ε and μ and C_l is the capacity between the conductors per unit length of the line. As C_l is proportional to the effective dielectric constant ε_{eff}, Z_c is inversely proportional to $\sqrt{\varepsilon_{eff}}$. It is easy to show, via integrating the energy in the substrate and the outer medium, for example, or finding the electrostatic capacity C_l, that ε_{eff} is equal to the average of the dielectric permittivities of the substrate and the outer medium [1]. So, the characteristic impedance of the part of the line without the dielectric sample is:

$$Z_{c_1} \sim 1/\sqrt{(1+\varepsilon_{sub})/2}, \tag{5}$$

where $\varepsilon_{sub} = 2.56$ is the relative dielectric permittivity of the substrate and

$$Z_{c_2} \sim 1/\sqrt{(\varepsilon_{sub}+\varepsilon_{diel})/2}\ , \tag{6}$$

where ε_{diel} is the relative dielectric permittivity of the dielectric sample.

As the wave passes through the interface between the air and the dielectric sample, the difference of the characteristic impedances causes reflection to occur. The reflection factor is:

$$R = \frac{Z_{c_2} - Z_{c_1}}{Z_{c_2} + Z_{c_1}}. \tag{7}$$

Using the Z_{c_1}/Z_{c_2} ratio found from (5) and (6), the reflection factor module is:

$$|R| = \frac{\sqrt{\varepsilon_{sub} + \varepsilon_{diel}} - \sqrt{1+\varepsilon_{sub}}}{\sqrt{\varepsilon_{sub} + \varepsilon_{diel}} + \sqrt{1+\varepsilon_{sub}}}. \qquad (8)$$

Hence, in front of the air/dielectric sample interface a standing wave will be observed with voltage standing wave ratio:

$$VSWR = \sqrt{\frac{\varepsilon_{sub} + \varepsilon_{diel}}{\varepsilon_{sub} + 1}}. \qquad (9)$$

The *VSWR* could be measured easily. When the dielectric sample material is homogeneous, its dielectric permittivity could be found from (9):

$$\varepsilon_{diel} = \varepsilon_{sub}(VSWR - 1) + VSWR^2. \qquad (10)$$

4. RESULTS

The FDTD algorithm was implemented in a *C* language program which was used to perform a number of simulations with different dielectric samples. The quantities measured were the effective dielectric constant and the *VSWR*. The simulations were carried out at 2 GHz. In Table 1 the numerical results are compared to analytical predictions.

Table 1

ε_{diel}	1	1.5	2	2.5	3	3.5	4	5
$\varepsilon_{eff\,analytical}$	1.78	2.03	2.28	2.53	2.78	3.03	3.28	3.78
$\varepsilon_{eff\,FDTD}$	1.7802	2.0311	2.2803	2.5285	2.7842	3.0309	3.2747	3.7941
$VSWR_{analytical}$	1	1.0679	1.1318	1.1922	1.2497	1.3047	1.3575	1.4573
$VSWR_{FDTD}$	1	1.0707	1.1288	1.1829	1.2509	1.3289	1.3543	1.45

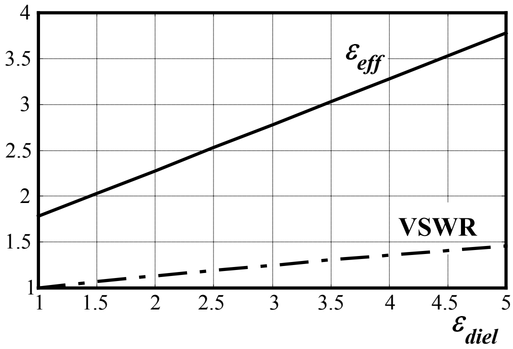

Fig.4. The effective dielectric constant and VSWR versus the dielectric constant of the sample material.

As it could be seen from Table 1 the numerical results are in very good agreement with the theoretical ones. Thus, the integral formula for ε_{eff} as averaged value of the dielectric permittivity of the substrate and the outer medium is proved by a differential method (FDTD method). In Figure 4 the effective dielectric permittivity and the voltage standing wave ratio is plotted versus the dielectric constant of the sample material.

5. CONCLUSIONS

This paper presented a numerical approach based on FDTD for modeling wave propagation along a coplanar and a slot-line and reflection from a dielectric sample placed upon the line. The numerical experiment was performed very much like a real experiment in the sense that voltages were measured and the voltage standing wave ratio was determined. Moreover, the numerical solution for the field allowed the wavelength for the part of the line with the sample to be directly measured and so was the effective dielectric constant determined. The results were found to be in very good agreement with the analytical relations according to the transmission line theory.

The numerical approach proved that the coplanar and the slot-line can be used for material parameters measurement as the dependence of the effective dielectric constant on the dielectric permittivity of the material upon the line is well known. Furthermore, the FDTD method allows complex inhomogeneous materials with random permittivity distribution to be analyzed.

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