Numerical Analyze of Waveguide Transmission Coefficient with Non-uniform Dielectric Slab

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Abstract— Propagation in the time domain of electromagnetic waves in a rectangular waveguide with a non-uniform dielectric slab is considered. Electromagnetic field components are computed and investigation of energy transport in the guide is performed by using Finite Difference Time Domain (FDTD) method in different frequency ranges. Parallel high performance FDTD solver, based on Maxwell equations approximation in integral form on Yee lattice and developed by the paper authors is used. A method for calculating the transmission coefficient with respect to all the problem parameters is proposed. The method is based on the analysis of the amplitude of the scattered wave derived from FDTD numerical solution. The pure scattered field method is proposed to specify the waveguide mode with respect to numerical dispersion. Computations for nonstationary Maxwell equations system are performed for the H_{10}-mode scattering from a dielectric slab placed in the waveguide. Multiple numerical computations for the corresponding large-scale problems have been performed on Lomonosov Moscow State University IBM BlueGene/P supercomputer. Using the methods described above, we compute the values of the waveguide transmission, attenuation and propagation factors in a wide range of permittivity and different positions of the dielectric slab inclusions. Continuous curves on the complex plane describing the dependence of the transmission coefficient on the dielectric constant are obtained. The comparison of the transmission coefficient calculated by the present approach and the volume integral equation method is performed.

1. INTRODUCTION

Investigation of electromagnetic waves scattering on dielectric bodies that have complicated geometry or structure is an important problem when composite or artificial materials and media are used as elements of various devices. However, the solution usually cannot be obtained directly, because of composite character of the material and small size of samples, which leads to the necessity of applying methods of mathematical modeling and numerical solution of the corresponding electromagnetic problems [1].

In this work we are using 3-dimensional FDTD solver EMWSolver3D [2]. Based on Maxwell equations approximation in integral form on Yee lattice, it provides numerical solution in time domain. EMWSolver3D supports multi-core single processors machines and provides hybrid MPI/OpenMP support for IBM BlueGene/P series.

Pure scattered field method is used to specify waveguide mode with respect to numerical dispersion [3].

This work aims at propagation factors estimation of filters created on the basis of single-layered parallel-plane dielectric diaphragms in waveguides of rectangular cross section with dielectric inclusions. This topic is interesting for the possibility of design of specific frequency selective filters. For instance, such filters can suppress a desired band of frequencies. The proposed method can be used for benchmark problems where electromagnetic parameters of materials obtained analytically or numerically reconstructed from inverse problem [5].

2. INHOMOGENEOUS ONE-SECTIONAL DIAPHRAGM

Lets consider geometry of the problem at Figure 1. Assume that a waveguide $P = \{x : 0 < x < a,\ 0 < y < b,\ -\infty < z < \infty\}$ of rectangular cross-section with the perfectly conducting boundary surface ∂P is given in the Cartesian coordinate system (see figure).

A three-dimensional body Q ($Q \subset P$ is a domain) with a constant magnetic permeability μ_0 and variable permittivity $\varepsilon_r(\vec{r})$ is placed in the waveguide. Function $\varepsilon(\vec{r})$ is bounded in $\bar{Q}$, $\varepsilon_r \in L_\infty(Q)$, and $\varepsilon_r^{-1} \in L_\infty(Q)$. The boundary ∂Q of domain Q is piecewise smooth. In the provided numerical experiment electric permittivity $\varepsilon_r(\vec{r})$ was set constant.

We assume that the electromagnetic field $\mathbf{E_t} = \mathbf{E_s} + \mathbf{E_{inc}}$, $\mathbf{H_t} = \mathbf{H_s} + \mathbf{H_{inc}}$ in the waveguide is excited by an external field with E_{inc}, H_{inc} the time dependence functions $e^{-i\omega t}$ and where E_s and H_s are scattered field components obtained from FDTD numerical scheme [1].

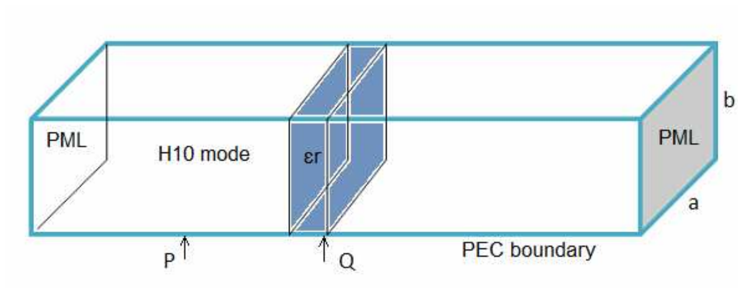

Figure 1: Geometry of the problem.

Choose the waveguide parameters so that $\pi/a < k_0 < \pi/b$, where k_0 is the free-space wave number, $k_0^2 = \omega^2\varepsilon_0\mu_0$, and ω is the circular frequency. In this case, only one mode propagates in the waveguide (namely, the principal $\mathbf{H}_{10}$ mode), and all other modes are evanescent (decaying).So let $a = 2b = 0,625\lambda$. It suits the condition that $\Lambda < \frac{2}{\sqrt{\frac{1}{a^2}+\frac{1}{b^2}}}$, where λ wavelength in cubic waveguide.

According to the work [3] transmission coefficient F can be obtained from exact solution of finite-difference problem and E_ω field in frequency domain that is calculated using Fourier transform from time domain solution.

3. NUMERICAL MODELLING

Lets consider domain Q ($Q \subset P$ — domain) with constant magnetic permeability μ_0 and varying permittivity $\varepsilon_r(\vec{r})$ located inside waveguide. Function $\varepsilon_r(\vec{r})$ is bounded in $\bar{Q}$, $\varepsilon_r \in L_\infty(Q)$, and $\varepsilon_r^{-1} \in L_\infty(Q)$. Boundary ∂Q of domain Q is piecewise smooth. Dielectric permittivity $\varepsilon_r(\vec{r})$ is piecewise function, that describes Q_1 ($Q1 \subset Q$ — domain, which have cube shape ($Q_1 = \{x : 0 < x_1 \le x \le x_2 < a,\ 0 < y_1 \le y \le y_2 < b,\ z_1 \le z \le z_2\}$) located inside Q (see Figure 2).

The thickness of diaphragm Q $l_1 = \lambda$. The numerical FDTD parameters: $\Delta x = \Delta y = \Delta z = \lambda/120$. The size of inhomogeneity $x_2 - x_1 = y_2 - y_1 = z_2 - z_1 = \lambda/10$. Simulation is performed for three locations $d = z_2 - z_0 = \lambda/12$, $\lambda/2$, λ of inhomogeneity $Q1$ related to z-axis. Dielectric permittivity $\varepsilon_1 = 1.9$ of diaphragm Q is constant, while permittivity of inhomogeneity is varying $\varepsilon_2 = 1.9\ldots15.9$ with step 1. For each simulation transmission coefficient F is calculated. Figure 3 illustrates graph of transmission coefficient F on complex plane. Dielectric permittivity can be uniquely determined from the transmission coefficient F relying on the absence of the curves intersection on in the graph.

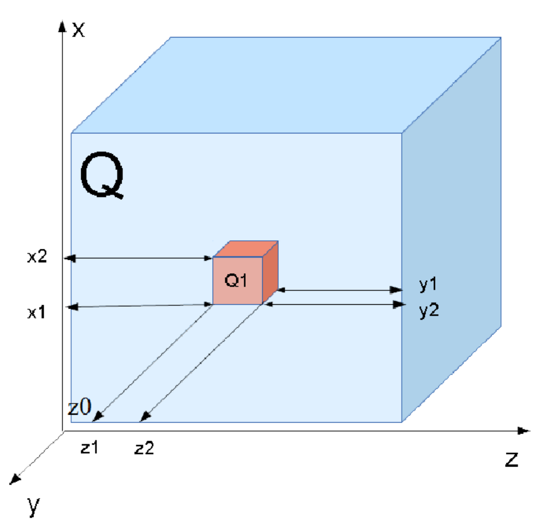

Figure 2: Geometry and location of inhomogeneity Q_1 inside dielectric diaphragm Q.

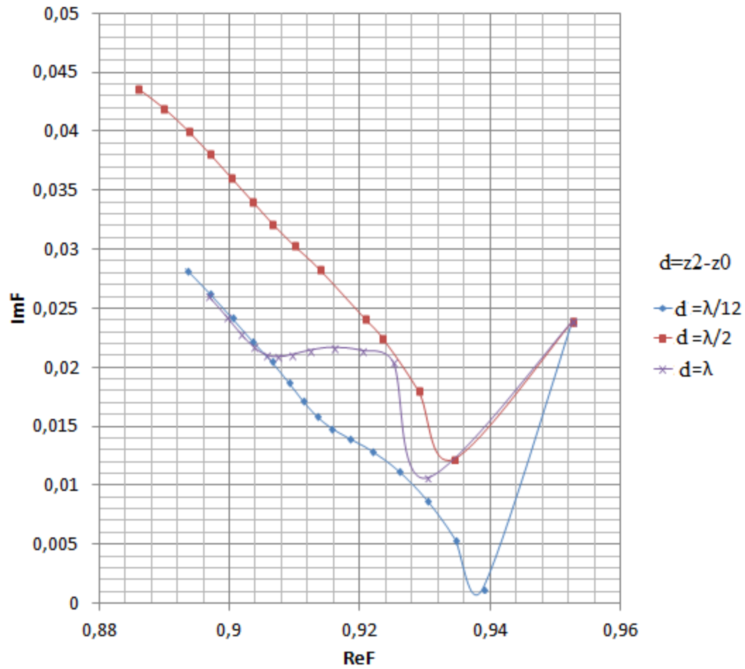

Figure 3: Transmission coefficient F on complex plane for three locations $d = z_2 - z_0 = \lambda/12$, $\lambda/2$, λ of inhomogeneity $Q1$ related to z-axis for $\varepsilon_2 = 1.9 \ldots 15.9$ with step 1.

4. CONCLUSION

Scattering in the time domain of electromagnetic waves in the waveguide of rectangular cross section with inhomogeneous single-layered parallel-plane dielectric diaphragm is considered. Electromagnetic field components are computed and investigation of energy transport in the guide is effected by using Finite Difference Time Domain (FDTD) method for different positions of cubic inhomogeneity. Computation for the nonstationary Maxwell equation system is performed by efficient 3D FDTD solver EMWSolver3D created by authors of this paper. Simulation is performed for the H10-mode scattering from dielectric slab inclusions. Numerical computations for solving large-scale problems have been implemented on IBM BlueGene/P. Continuous curves on the complex plane describing the dependence of the transmission coefficient on the dielectric constant are obtained.

ACKNOWLEDGMENT

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