Interactive Electromagnetic Simulation for Optimizing Photonic Crystal Waveguides Using GPU

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We propose an interactive electromagnetic simulation technique based on the finite-difference time-domain (FDTD) method. Our technique enables users to modify material parameters during FDTD simulation and the interaction is designed for optimization of photonic crystal waveguides. For appropriate FDTD computation with interactively varying material parameters, we introduce a stabilizer that restrains unnaturally disturbed waves of electromagnetic fields caused by discontinuous change of material parameters. The FDTD computation is performed on GPU in parallel for fast computation. We provide a scheme that combine user interaction, FDTD and visualization with efficient data transfer.

Index Terms— **Electromagnetic propagation, Finite difference method, Numerical simulation, Optical waveguides, Photonic crystals**

I. INTRODUCTION

PHOTONIC CRYSTALS are optical material consisting of periodically arranged dielectric microstructures with different permittivity and are used as optical waveguides for electronic devices [1]. The structure prevent light to penetrate the material if the light frequency is in specific ranges called photonic band gaps. The arrangement of the dielectric material determines the band gaps and needs to be suitably determined so that the device behaves as a waveguide according to requirements of specific applications.

The finite-difference time-domain method (FDTD) has been widely used to investigate the optical wave propagation through photonic crystals [2]. This method well reflects the property of the photonic band gaps and helps us to identify the range specific to a given crystal arrangement corresponding to source frequencies. Another requirement is to identify the optimal arrangement of the dielectric material that acts as a waveguide along a user specific path and a source frequency. Given an arrangement of dielectric materials, it is possible to investigate the performance as a waveguide by the FDTD-based simulation. In order to find the optimal arrangement, the simulation needs to be performed repeatedly with different parameters for the arrangement and the performance as a waveguide needs to be evaluated every time. This scheme often forces users to spend time and effort.

The purpose of this study is to develop a method of interactive FDTD-based simulation with user interaction. We aim to design the interaction to help users to determine optimal arrangement of dielectric material for optical waveguides. In this study, we assume that the crystals consist of two-dimensionally arranged dielectric cylinders [1]. The interface is designed so that users can modify parameters that determine the structure like the spatial interval of periodically located dielectric cylinders, size of each cylinder and add/delete operation of cylinders. In addition, we assume that FDTD is performed in parallel on GPU for fast computation.

There are mainly two difficulties to achieve the goal: how to change material and geometric parameters appropriately during simulation and how to combine user interaction, FDTD simulation and visualization appropriately for optimizing photonic crystal waveguides. For the former difficulty, we introduce a kind of stabilizer so that the change of parameters smoothly affects to electromagnetic fields in FDTD. For the latter difficulty, we design the algorithm based on the technique of CUDA/GL interoperation so that the communication loss between CPU (host) and GPU (device) can be kept to a minimum.

II. INTERACTIVE FDTD FOR PHOTONIC CRYSTALS

We assume that photonic crystals are constructed as a set of two-dimensionally arranged dielectric cylinders and electromagnetic waves propagate through the material based on the transverse magnetic mode:

$$\begin{cases} \dfrac{\partial E_z}{\partial t} = \dfrac{1}{\varepsilon}\left(\dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y}\right) \\ \left[\dfrac{\partial H_x}{\partial t}, \dfrac{\partial H_y}{\partial t}\right] = -\dfrac{1}{\mu}\left[\dfrac{\partial E_z}{\partial y}, -\dfrac{\partial E_z}{\partial x}\right] \end{cases}$$

where H_x, H_y and E_z are x-, y- and z-components of magnetic and electric fields, ε is permittivity and μ is permeability. All the variables are assumed to be defined as functions of two-dimensional space and the permittivity behaves as an indicator of material, i.e., the permittivity is ε_1 at the dielectric cylinders and ε_0 at the background free space. In our case, the permittivity ε_1 is set to $11.9\varepsilon_0$.

For interactive simulation, we allow users to edit the permittivity according to the following three operations: add/delete each dielectric cylinder, increase/decrease the radii of them and widen/tighten the interval of periodical arrangement. These operations are required to find appropriate arrangement of cylinders for photonic crystal waveguides. In this work, we assume that the centers of cylinders are restricted to grid points (id, jd) with an interval d, where i and j are integers and r is the radius of the cylinders. The cylinders exist at some of the grid points and this existence information determines the paths of waveguides. The three operations are performed by changing the existence information of cylinders, the radius and the interval. Fig. 1 shows the modification of the radius and the interval. Note that users can control these parameters independently.

Although the above operations help users to design waveguides, a rapid change of permittivity can cause largely disturbed noise to electromagnetic fields in FDTD which results in inappropriate simulation as shown in Fig. 2 (a). In order to overcome this problem, we introduce two techniques: temporally and spatially continuous change of permittivity and antialiasing of the binary valued permittivity.

The first technique is to prevent abrupt change of permittivity. Assuming that a user is going to change the radius r_0 to r_1, our stabilizer works by increasing the radius gradually as the time step of FDTD proceeds. The same is true of the interval d. In case of adding a new dielectric cylinder to an empty grid point, the initial radius is set to zero and is gradually increases as the FDTD computation proceeds. This contributes to prevent large noise of electromagnetic fields.

The second technique, antialiasing, is another approach to prevent discontinuous change of permittivity. Antialiasing is a technique used in image processing to reduce visual artifacts along borders of differently colored regions. As a result of interactive modification of permittivity, the permittivity at each discrete point can be changed from ε_0 to ε_1 discontinuously after a time interval Δt which causes noisy waves in electromagnetic fields. In order to suppress this effect, we apply the antialiasing technique to the permittivity at the border of the cylinders. Specifically, if the permittivity at a discrete point (x, y) is required, we generate super-sampling points in the square centered at the discrete point and set the anti-aliased permittivity as the average of the permittivity $\varepsilon(x, y)$ at the super-sampling points. This process acts as a kind of stabilizer to restrain the fluctuation. As a result, the largely disturbed waves caused by the discontinuous change of the permittivity as shown in Fig. 2 (a) can be reduced by introducing the two stabilizing techniques as shown in Fig. 2 (b).

III. FDTD and Visualization on GPU

The computation of the FDTD-based simulation of photonic crystals mainly consists of three stages: user interaction to change geometric structure of photonic crystals, FDTD simulation and visualization of electromagnetic fields. In addition, data transfer is required. All the processes following with data transfer are performed at every time step of FDTD and they should be fast enough in order for interactive simulation.

One approach for the fast computation is to perform parallel computation on GPU. The stage of FDTD can be effectively accelerated by the parallelization and the visualization stage is efficiently performed using the GPU. The challenge is to design the algorithm so that only a small amount of data transfer is required between host (CPU) and device (GPU). The dominant part of the data transfer is the set of results of FDTD, i.e., the discrete electromagnetic fields computed in the second stage should be efficiently passed to the third stage.

In our implementation, the two stages, FDTD simulation and visualization, are implemented based on CUDA (compute unified device architecture [3]) and OpenGL. The simplest design of data transfer is to copy the results from device to host and run OpenGL commands to display the results to the screen. However, this approach is inefficient and time consuming because data transfer from device to host is required at every time step. In order to avoid this situation, we make use of the interoperability between CUDA and OpenGL [3]. The data for visualization are passed, converted to RGB bitmap called texture and displayed as a textured square on the screen. This approach enables us to perform interactive simulation without data transfer from device to host.

IV. Conclusion

We have developed an interactive electromagnetic FDTD method for optimizing photonic crystal waveguides. Two types of stabilizers have been introduced and the algorithm is designed so that the amount of data transfer is kept low.

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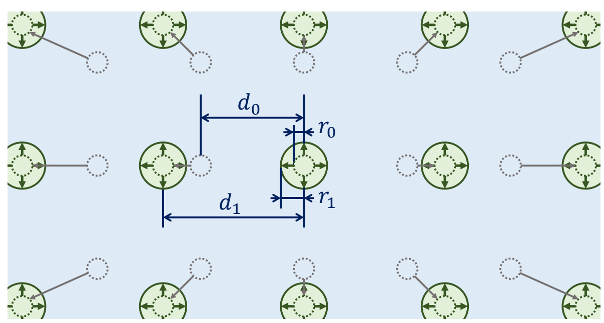
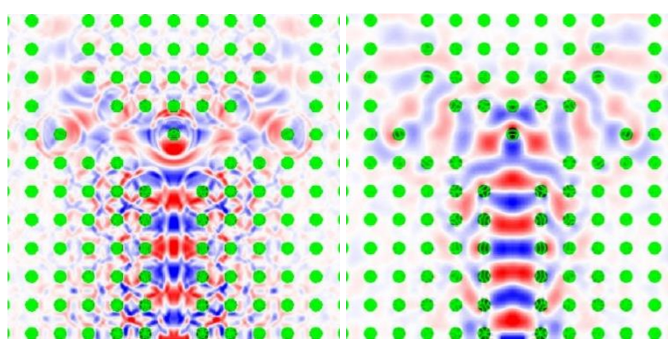


Fig. 1. Modification of radius from r_0 to r_1 and interval from d_0 to d_1.



(a) (b)

Fig. 2. Interactive FDTD. Left: without stabilizer and Right: with continuous radius change and antialiasing.