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Fast analysis for electromagnetic band gap waveguides using compact finite-difference-time-domain method

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ABSTRACT

A fast analysis method, cell modified compact finite-difference time-domain method (CMC-FDTD), is presented to analyze the performance of electromagnetic band gap waveguides. The method calculates band diagrams in orthogonal coordinate system by translating nonorthogonal lattice to orthogonal lattice. It has highly stability for calculating dielectric and metallic material, either TE or TM mode, and reduces the requirement for memory. The comparisons are made among two numerical results and experimental one to validate the method.

1. Introduction

Electromagnetic band gap (EBG) structures [1], which can control electromagnetic wave at wavelength scale, have attracted much attention in the fields of optical communications, terahertz devices, and microwave devices [2–4]. As well known, it is important a distinctive feature of one or more band diagrams should be properly designed for the applications of EBG structures. A variety of numerical techniques have been presented to make a study of band gaps and defect modes in the EBG structures based on metallic or medium materials, including modified plane-wave expand (M-PWE) method [5], full wave modal techniques [6], transfer matrix method (TMM) [7], finite element method [8,9], transmission line method (TLM) [10], finite difference method (FDM) [11] and finite-difference time-domain (FDTD) method [12–16]. Among the methods mentioned above, FDTD method is essentially proportional for the CPU time and memory to the number of the representative points of the spatial mesh used for the discretization of Maxwell's equations, others consume a great lot of resources proportional to the cube of the number used.

As well knowing, it is convenient for calculating band diagrams in orthogonal Cartesian system, in which the calculation domain can be subdivided into small orthogonal grid. However, most of EBG structures has nonorthogonal lattice which should be solved band diagrams in nonorthogonal systems. It also should be claimed attention to study the off plane propagation for photonics crystal fibers or other EBG based waveguides, because the propagation constant exists out of the plane in two dimensional (2D) EBG structures. To overcome these problems, a compact FDTD scheme to compute the in plane and off plane global bands of nonorthogonal lattice EBG structures has been presented [14]. However, a split-field formula should be adopted in [14], which induces more computational resources required. Therefore, this method is not suitable to obtain the off plane bands of EBG structures with nonorthogonal lattice.

In this paper, a cell modified method combined with compact FDTD (CMC-FDTD) is presented to calculate the in plane and off plane band diagrams of 2D nonorthogonal lattice EBG structures. This method calculates band diagrams in orthogonal coordinate system by translate nonorthogonal lattice to orthogonal lattice. It has highly stability for calculating dielectric and metallic material, either TE or TM mode, and reduces the memory requirement. Finally, a metallic EBG waveguide is designed and fabricated. The simulation results are agreed well with experimental ones.

2. CMC-FDTD method

2D EBGs can be modeled efficiently by studying a few unit cells (or one unit cell) and applying proper periodic boundary condition (PBC). For the perfect EBG structure, the unit cell, shown in Fig. 1(a), can be obtained in nonorthogonal coordinate system whose directions are labeled as ζ and η. In this nonorthogonal coordinate system, the lattice angle is labeled as θ, and the lattice length is a_ζ and a_η, respectively. Moving the right triangle area (red area) to the left (blue area), we can obtain a modified unit cell in orthogonal coordinate system which is shown in Fig. 1(b). The boundaries of the modified cell can be divided to three PBCs, which are labeled as PBC1, PBC2 and PBC3. The modified unit cell obeys the PBCs at

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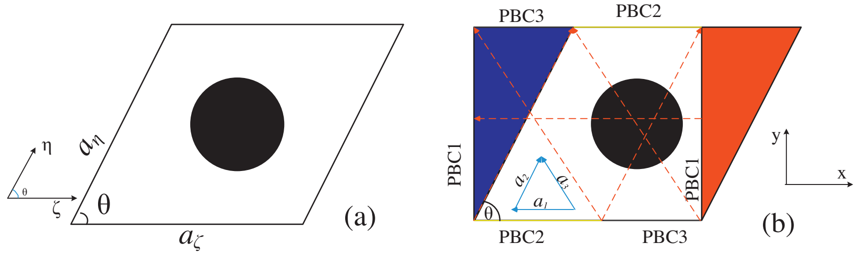

Fig. 1. (a) The unit cell of nonorthogonal lattice EBG in nonorthogonal coordinate system, where a_ζ and a_η is the lattice distance in each direction. (b) The modified unit cell in orthogonal coordinate system.

its boundaries, which is indicated as the vector triangular inserted in Fig. 1(b), where $a_1 = -a_\zeta$, $a_2 = a_\eta$ and $a_3 = -(a_\zeta - a_\eta)$. Obviously, PBC1 represents period vector a_1, PBC2 represents period vector a_2 and PBC3 represents period vector a_3, respectively. For any lattice angle of θ, we only need to transform the nonorthogonal cell to the orthogonal cell as shown in Fig. 1(b). Since the modified cell occupies a rectangular area, it is easier to be fitted by the rectangular mesh.

Fig. 2 gives the schematic of modified cell in a defect EBG. In nonorthogonal coordinate system, the 3×3 supercell is given in Fig. 2(a). Move the left area (red) to right area (blue), we can get the modified 3×3 supercell in orthogonal coordinate system, which is shown in Fig. 2(b).

Generally, the PBCs can be expressed as:

$$\mathrm{PBC1}: \Phi[(x, y) + a_1] = \Phi(x + a_\xi, y) = \Phi(x, y)\exp(-ik_x a_\xi) \quad (1a)$$

$$\begin{aligned}\mathrm{PBC2}: \Phi[(x, y) + a_2] &= \Phi(x + a_\eta \cos\theta, y + a_\eta \sin\theta) \\ &= \Phi(x, y)\exp[-i(k_x a_\eta \cos\theta + k_y a_\eta \sin\theta)]\end{aligned} \quad (1b)$$

$$\begin{aligned}\mathrm{PBC3}: \Phi[(x, y) + a_3] &= \Phi[x - (a_\xi - a_\eta \cos\theta), y + a_\eta \sin\theta] \\ &= \Phi(x, y)\exp\{-i[-k_x(a_\xi - a_\eta \cos\theta) \\ &\quad + k_y a_\eta \sin\theta]\}\end{aligned} \quad (1c)$$

where Φ presents the vector field (electric or magnetic field) in the unit cell, k_x and k_y are the wavenumbers in x and y direction, respectively.

Since the 2D EBG structures are uniform along the z direction and periodic in the transverse plane, we can discretized the Maxwell equations in space domain and time domain using Yee's mesh by compact FDTD method with $\Delta z \to 0$.

$$E_z\big|_{i,j}^{n+1} = \frac{2\varepsilon_{i,j} - \sigma_{i,j}\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} E_z\big|_{i,j}^{n} + \frac{2\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} \times \left(\frac{H_y\big|_{i,j}^{n+1/2} - H_y\big|_{i-1,j}^{n+1/2}}{\Delta x} - \frac{H_x\big|_{i,j}^{n+1/2} - H_x\big|_{i,j-1}^{n+1/2}}{\Delta y} \right) \quad (2a)$$

$$H_x\big|_{i,j}^{n+1/2} = H_x\big|_{i,j}^{n-1/2} - \frac{\Delta t}{\mu}\left(\frac{E_z\big|_{i,j+1}^{n} - E_z\big|_{i,j}^{n}}{\Delta y} - i\beta E_y\big|_{i,j}^{n} \right) \quad (2b)$$

$$H_y\big|_{i,j}^{n+1/2} = H_y\big|_{i,j}^{n-1/2} + \frac{\Delta t}{\mu}\left(\frac{E_z\big|_{i+1,j}^{n} - E_z\big|_{i,j}^{n}}{\Delta x} - i\beta E_x\big|_{i,j}^{n} \right) \quad (2c)$$

$$H_z\big|_{i,j}^{n+1/2} = H_z\big|_{i,j}^{n-1/2} + \frac{\Delta t}{\mu}\left(\frac{E_x\big|_{i,j+1}^{n} - E_x\big|_{i,j}^{n}}{\Delta y} - \frac{E_y\big|_{i+1,j}^{n} - E_y\big|_{i,j}^{n}}{\Delta x} \right) \quad (2d)$$

$$E_x\big|_{i,j}^{n+1} = \frac{2\varepsilon_{i,j} - \sigma_{i,j}\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} E_x\big|_{i,j}^{n} + \frac{2\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} \times \left(\frac{H_z\big|_{i,j}^{n+1/2} - H_z\big|_{i,j-1}^{n+1/2}}{\Delta y} - i\beta H_y\big|_{i,j}^{n+1/2} \right) \quad (2e)$$

$$E_y\big|_{i,j}^{n+1} = \frac{2\varepsilon_{i,j} - \sigma_{i,j}\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} E_y\big|_{i,j}^{n} - \frac{2\Delta t}{2\varepsilon_{i,j} + \sigma_{i,j}\Delta t} \times \left(\frac{H_z\big|_{i,j}^{n+1/2} - H_z\big|_{i-1,j}^{n+1/2}}{\Delta x} - i\beta H_x\big|_{i,j}^{n+1/2} \right) \quad (2f)$$

Eq. (2) gives compact 2D mesh FDTD algorithm in an x–y plane, where μ, ε and σ are the permeability, permittivity and conductivity of the medium, respectively, and Δt is the FDTD time step, β is the off-plane wave number. The boundary condition is given by Eq. (1) and all the fields are obtained in the time domain. In order to obtain the spectral information, one needs to transform from time domain to frequency domain by a Fourier transform, such as FFTW which is used in our computation.

3. Numerical analysis and results

3.1. Validation of CMC-FDTD

A nonorthogonal lattice EBG structure with θ equals to 45° is considered firstly. This structure is formed by parallel rods with relative permittivity $\varepsilon_r = 6.5536$ and radius $r = 0.3P$ in the air, where P is the lattice period length. Each point along the boundary of the first Brillouin zone is shown as the insert part in Fig. 3(a) which determines k_x and k_y in the PBCs with Eq. (2). The grid distance of Yee's mesh in our computation is $dx = P/60$ and $dy = [(2^{1/2}/2) \times P]/60$. In other words, we have 60×60 grids in the computational domain. The total number of the time steps is 65,536 with each time step $\Delta t = 0.95/(c \times [\Delta x^{-2} + \Delta y^{-2} + (\beta/2)^2]^{1/2})$, where c is the speed of the light. When β equals to zero, it can be decoupled into TE mode (magnetic field is in the EBG plane) and TM mode (electric field is in the EBG plane). The band diagrams of the TE mode and TM mode are plotted in Fig. 3(a) and (b), respectively. The circular dots are the results obtained using our method and the solid lines are obtained using the PWE method with 128×128 resolution. It can be seen that the circular dots match quite well with the solid lines for TE/TM mode and hybrid mode.