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Numerical simulation for photonic bandgap of cuboid structure

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ABSTRACT

Detailed numerical simulations are carried out to envisage the band structure of silicon cuboid (3D) photonic crystal structure is presented in this paper. Photonic bandgap of above cuboid structure are simulated by employing plane wave expansion method. Simulation result revealed that both radius of air holes and lattice spacing of crystal play vital role to realize the photonic bandgap of the cuboid structure. Also present simulation result showed that photonic bandgaps of silicon cuboid structure exist for certain values of lattice spacing; for an example bandgap is observed, if lattice spacing along *x*-axis varies from 0.7 μm to 1.4 μm and lattice spacing along *y* and *z* axis is 1 μm each. Similarly photonic bandgap is found if lattice spacing along *y*-axis varies from 0.7 μm to 1.1 μm and lattice spacing along *x* and *z* axis is 1 μm each. Also, the photonic bandgap is found if the lattice spacing along *z*-axis varies from 0.8 μm to 2.1 μm and the lattice spacing of *x* and *y* axis are taken of 1 μm. Apart from this it is also seen that variation of lower and upper edges of the photonic bandgap is non-linear with respect to aforementioned lattice spacing of cuboid crystal structure.

1. Introduction

The parameter photonic bandgap in photonic crystal structure play vital role to realize various applications in the field of optical technology. Photonic bandgap is also an important parameter to discuss one, two and three dimensional photonic crystal structure. Without the cogitation of bandgap, the photonic crystal structure is insignificant. As far as different types of photonic crystal structures are concerned, one dimensional photonic crystal structures have reached almost in mature stage with respect to fabrication and commercial application [1]. Similarly, though two dimensional photonic crystal structures have been used for various purposes, it is at young stage and not attained the heap of mature stage so far [2]. As far as fabrication and commercial application of three dimensional photonic crystal structures is concerned, it stands with its infant stage at the present research scenario[3]. Though the progress of 3D photonic crystal is slow, few papers related to 3D photonic crystal structure have been appeared in literature, out of which recently two papers have been published by Palai et al. for sensing application using cubic photonic crystal structure [4,5], But here, this paper deals with photonic bandgap of cuboid silicon photonic crystal structure having air holes.

2. Structure analysis

Since this paper investigates the photonic bandgap of cuboid structure, Fig. 1 represents silicon cuboid structure showing incident and reflected light.

Fig. 1 represents, 3D photonic crystal structure having silicon as background material which consists of air holes. From this figure it is seen that lattice spacing of *a*, *b* and *c* are chosen along *x*, *y* and *z* direction respectively. To understand the cuboid structure,we have chosen different set values of *a*, *b* and *c* in such a way that, for first set, the values of 'a' is not same with *b* and *c* (where 'b' and 'c' are same and 1 μm each). Similarly for the second set, the values of 'b' is not same with *a* and *c* (where 'a' and 'c' are same and 1 μm each). Again for third set, the values 'c' is not same with the values of *a* and *b* (where 'a' and 'b' are same and 1 μm each). Here diameter of hole is taken of 130 nm. Apart from this it is also seen that light having certain range of wavelength incident on said photonic crystal structure and then light having particular range of wavelength cannot propagate through it, which is nothing but photonic bandgap. As per definition, photonic bandgap is nothing but the amount of electromagnetic wave reflected from such structure. We in this paper realize the photonic bandgap of the silicon cuboid

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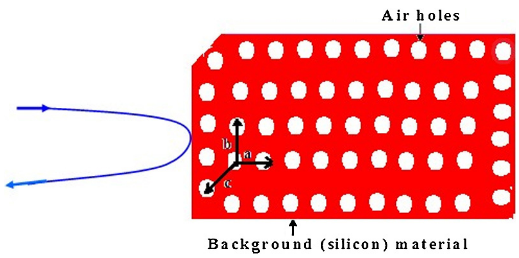

Fig. 1. schematic diagram of silicon cuboid photonic crystal structure.

photonic crystal structure using plane wave expansion method. The photonic bandgap is found with varying different values of lattice spacing (a, b and c).

3. Numerical analysis

3D photonic crystal structure possesses air holes periodically in three directions and their band structure computations are made using Helmholtz equation, which is given by

$$\frac{1}{\in(r)}\nabla\times\left\{\nabla\times E(r)\right\}=\frac{\omega^2}{c^2} \quad (1)$$

where $\in(r)$ is permittivity and 'r' is a 3D vector in coordinate system

To search the Eigen state of infinite periodic structure, spatial distributions of electric field components represented in form of Bloch function. The plane wave is multiplied by periodic functions with the periodicity of lattice is given by

$$E(r)=E_{k,n}(r)e^{ik,r} \quad (2)$$

where $E_{k,n}$ are the periodic functions with periodicity of lattice. In cuboids structure lattice constants are differed from different directions. Choosing a, b and c are lattice vectors along x, y and z directions, the periodic function along three directions are

$$E_{k,n}(r)=E_{k,n}(r+a) \quad (3a)$$

$$E_{k,n}(r)=E_{k,n}(r+b) \quad (3b)$$

$$E_{k,n}(r)=E_{k,n}(r+c) \quad (3c)$$

The periodicity of wave function in Eq. (3) lead to possibilities of their Fourier expansion over reciprocal lattice vector. So wave function in the wave vectors space is represented as

$$E_{k,n}(r)=\sum_{a_1}E'_{k,n}(r)e^{i(k+a_1)r} \quad (4a)$$

$$E_{k,n}(r)=\sum_{b_1}E'_{k,n}(r)e^{i(k+b_1)r} \quad (4b)$$

$$E_{k,n}(r)=\sum_{c_1}E'_{k,n}(r)e^{i(k+c_1)r} \quad (4c)$$

where a_1, b_1 and c_1 are reciprocal lattice vectors along x, y and z directions respectively.

Taking the above concept the dielectric function is also expanded to the Fourier series in different directions as

$$\frac{1}{\in(r)}=\sum_{a_1}\chi(a_1)e^{ia_1,r} \quad (5a)$$

$$\frac{1}{\in(r)}=\sum_{b_1}\chi(b_1)e^{ib_1,r} \quad (5b)$$

$$\frac{1}{\in(r)}=\sum_{c_1}\chi(c_1)e^{ic_1,r} \quad (5c)$$

here 5(a)–5(c) are Fourier expansion along x, y and z axis respectively.

Where $\chi(a_1)$, $\chi(b_1)$ and $\chi(c)$ are Fourier expansion coefficient, which depend on the reciprocal lattice vector.

Substituting Eqs. ((4a)–(4c)) and ((5a)–(5c)) in to (1) and after simplification, we obtained Eigen-value equations for Fourier expansion coefficient of electric field, which is given by

$$\sum_{a_1}\chi\left(a_1-a'_1\right)\times\left(k+a'_1\right)\times\left(k+a'_1\right)\times E'_{k,n}(a_1)=\sum_{a_1}E'_{k,n}(a_1)e^{i(k+a_1)\times r} \quad (6a)$$

$$\sum_{b_1}\chi\left(b_1-b'_1\right)\times\left(k+b'_1\right)\times\left(k+b'_1\right)\times E'_{k,n}(b_1)=\sum_{b_1}E'_{k,n}(b_1)e^{i(k+b_1)\times r} \quad (6b)$$

$$\sum_{c_1}\chi\left(c_1-c'_1\right)\times\left(k+c'_1\right)\times\left(k+c'_1\right)\times E'_{k,n}(c_1)=\sum_{c_1}E'_{k,n}(c_1)e^{i(k+c_1)\times r} \quad (6c)$$

Using Eqs. 6(a)–6(c), different wave vectors of 3D band structures are computed.

4. Simulation results and discussion

Since photonic bandgap play a key role to realize the properties of photonic crystal structure, we in this paper, plane wave expansion method is used to carry out simulation to obtain photonic bandgap of three dimensional photonic crystal structure [6]. The photonic bandgap depends on structure parameter such as lattice spacing, radius of air holes, including the nature and configuration of structures. To obtain photonic bandgap of silicon cuboid structure, here we have considered three sets of parameters. In first set, lattice spacing along x-axis (a) varies from 0.8 μm to 1.4 μm, where lattice spacing along y axis (b) and z axis (c) is chosen of 1 μm each. Similarly, in second set of parameter, lattice spacing along y-axis (b) varies from 0.7 μm to 1.1 μm, where lattice spacing along x axis (a) and z axis(c) is taken of 1 μm each. Again for third set the lattice spacing along z axis (c) varies from 0.8 μm to 2.1 μm, where lattice spacing along x axis (a) and y axis (b) is considered as 1 μm each. The reason for choosing such thickness ranges of different lattice spacing is that photonic bandgap is observed only in these ranges of lattice spacing. No photonic bandgap is found either above or below of these ranges. The dispersion diagrams for second set of parameters are shown in Fig. 2(a) and (b). Simulation for photonic bandgap with respect to other values of a, b and c are done but not shown here.

Fig. 2(a) and (b) represent dispersion diagram of 3D photonic crystal structure for a = 1 μm, b = 0.6 μm, c = 1 μm and a = 1 μm, b = 0.7 μm, c = 1 μm, respectively. In these figures, it is seen that normalized frequency is taken along vertical axis, where wave vector is taken along horizontal axis. In Fig. 2(a), it is seen that no gap is found between the two consecutive normalized frequency lines. It is inferred that no photonic band exists in Fig. 2(a). However a gap is seen in Fig. 2(b) where pink coloured band is drawn. In this figure the upper (U) and lower (L) band edges are indicated by