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Study on the anisotropic photonic band gaps in three-dimensional tunable photonic crystals containing the epsilon-negative materials and uniaxial materials

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HIGHLIGHTS

- Introducing the uniaxial materials into 3D PCs containing the ENG materials can obtain the larger PBGs.
- Introduced type-1 uniaxial materials into 3D PCs, have largest PBGs compared to another two types of uniaxial materials.
- The anisotropic PBGs can be modulated by ϵ_b, ω_p, f, n_e and n_0, respectively.
- Damping factor of ENG material has no effect on the anisotropic PBGs.

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ABSTRACT

In this paper, the properties of anisotropic photonic band gaps (PBGs) for three-dimensional (3D) photonic crystals (PCs) composed of the anisotropic positive-index materials (the uniaxial materials) and the epsilon-negative (ENG) materials with body-centered-cubic (bcc) lattices are theoretically studied by a modified plane wave expansion (PWE) method, which are the uniaxial materials spheres inserted in the epsilon-negative materials background. The anisotropic photonic band gaps (PBGs) and one flatbands region can be achieved in first irreducible Brillouin zone. The influences of the ordinary-refractive index, extraordinary-refractive index, filling factor, the electronic plasma frequency, the

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dielectric constant of ENG materials and the damping factor on the properties of anisotropic PBGs for such 3D PCs are studied in detail, respectively, and some corresponding physical explanations are also given. The numerical results show that the anisotropy can open partial band gaps in such 3D PCs with bcc lattices composed of the ENG materials and uniaxial materials, and the complete PBGs can be obtained compared to the conventional 3D PCs containing the isotropic materials. The calculated results also show that the anisotropic PBGs can be manipulated by the parameters as mentioned above except for the damping factor. Introducing the uniaxial materials into 3D PCs containing the ENG materials can obtain the larger complete PBGs as such 3D PCs with high symmetry, and also provides a way to design the tunable devices.

1. Introduction

Since the first proposed by Yablonovitch [1] and John [2], the photonic crystals (PCs) have been attracted much attention both experimentally and theoretically. The conventional PCs are artificial materials, in which the different dielectrics are periodically arranged in one-, two- or three-dimensions (3D). The PCs can exhibit spectral regions named photonic band gaps (PBGs) originating from the interface of Bragg scattering [3,4]. If the frequencies of electromagnetic wave (EM wave) are in the PBGs, EM wave cannot propagate through the PCs. The PCs have been potentially used to design various applications due to their ability to control the propagation of light, such as defect cavities [5], waveguide [6], defect-mode PCs lasers [7], filter [8], and omnidirectional reflector [9,10]. However, the PBGs of conventional PCs are highly sensitive to the lattices and randomness. To overcome this limit, the researchers have introduced the metamaterials into the PCs to form tunable PBGs [11] and zero-$\bar{n}$ PBGs [12]. The metamaterials are firstly proposed by Veselago in 1967 [13], and can exhibit a negative index of refraction in some frequency ranges. Due to this, the metamaterials can exhibit some unusual physical properties, such as inverse Snell's law, Cherenkov effects and reversed Doppler effect. The metamaterials can be divided into two categories. One is named double-negative metamaterials whose permittivity ε and permeability μ are simultaneously negative [14], the other is called single-negative metamaterials [15]. The single-negative metamaterials also can be divided into two types. One configuration, in which the permittivity is negative but the permeability is positive, gives rise to so-called the epsilon-negative (ENG) materials. The other is that the permittivity is positive but the permeability is negative. In this case, the mu-negative (MNG) materials can be obtained. It has been reported that stacking alternating layers of ENG materials and MNG materials can obtain the zero-$\bar{n}$ PBGs and zero-effective-phase PBGs [16], which can help us to design some novel tunable PCs devices, such as omnidirectional mirrors [17], omnidirectional filter [18], multiple-channeled filter [19] and omnidirectional reflector [20]. Moreover, the double-negative metamaterials hardly can be found in nature but the ENG materials always can be found easily in practical applications, such as plasma [21–23], superconductors [24–26], semiconductors [27] and metals [28]. The PCs composed of ENG materials not only can form tunable PBGs but also can be realized. Compared to the conventional PCs, the PCs containing the ENG materials display strong spatial dispersion [29]. Thus, the PCs containing the ENG materials become a new research focus, and have been extremely investigated. The most extensive works to date on such kind of PCs are reported on the 1D or 2D structures. There are few reports on the 3D structures compared to 1D and 2D cases. For example, the 3D PCs containing the metals have been investigated in theory and experiment [30–32]. It has been shown that such kind of metal PCs is a good candidate to obtained complete PBGs in visible. The dispersive properties of 3D plasma PCs also have been reported recently, and the research results [33–35] showed that the tunable complete PBGs can be obtained and the bandwidths of PBGs can be enlarged by the external