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Adjustable band gaps structures and semi-Dirac points in two-dimensional linear function photonic crystals

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ABSTRACT

We have proposed a new two-dimensional function photonic crystals, which the dielectric constants of medium columns are the function of space coordinates $\vec{r}$. The photorefractive nonlinear optical effect or electro-optic effect can turn the dielectric constants of medium column into the function of space coordinates. In this paper, we studied the dielectric constants of medium columns are the linear function of space coordinates, i.e., $\varepsilon(\vec{r}) = kr + b$, and calculated the band gaps structures of *TE* and *TM* waves. We have found there are absolute band gaps and semi-Dirac points in the two-dimensional function photonic crystals. When the parameters k, b and the medium column radius r_a change, the band gaps number, location and width, the absolute band gaps and semi-Dirac points should be changed, which can realize the adjustability of band gaps structures. The two-dimensional function photonic crystals should provide a new method for designing optical device.

1. Introduction

Photonic crystals (PCs) have generated a surge of interest in the last decades because they offer the possibility to control the propagation of light to an unprecedented level [1–4]. In its simplest form, a photonic crystal is an engineered inhomogeneous periodic structure made of two or more materials with very different dielectric constants. PCs important characteristics are: photon band gap, defect states, light localization and so on. The photon band gap prevents light from propagating in certain directions at specific frequencies. On the other hand, engineering the photonic bang gap to achieve a type of gapless band structure, namely the Dirac and Dirac-like cone dispersion relation, has been the focus of much recent work [5–9]. Various theoretical approaches, such as multiple scattering [10], tight binding [11], and perturbation [12–14], have also been developed to analyze the properties of Dirac cones in PhCs. A unique band structure was discovered in a VO_2/TiO_2 structure: near a point Fermi surface in the two-dimensional Brillouin zone, the dispersion relation is linear along the perpendicular direction, which is called a semi-Dirac cone and the associated point is called a semi-Dirac point [15]. It was reported that such a point is associated with the topological phase transition between a semi-metallic phase and a band insulator [16] in a two-dimensional PhC with anisotropic scatterers, it is indeed to achieve a semi-Dirac type dispersion relation in the Brillouin zone center, which is associated with a semi-Dirac point.

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Owing to the PCs periodicity, the plane-wave expansion (PWE) method is conventional for calculating PCs modes and photonic band structures. Its essence is the Fourier expansion of electromagnetic fields and material parameters, which is not only a counterpart of the PWE method for electronic crystals, but it also advantageously follows the classical coupled-wave theory developed for diffraction gratings [17–19].

In Refs. [20–26], we have proposed one-dimensional function photonic crystals, which is constituted by two media A and B, their refractive indexes are the functions of space position. Unlike conventional photonic crystal (PCs), which is constituted by the constant refractive index media A and B. We have studied the transmissivity and the electric field distribution with and without defect layer. In this paper, we have proposed two-dimensional function photonic crystals, which the dielectric constants of medium columns are the function of space coordinates $\vec{r}$. The photorefractive nonlinear optical effect or electro-optic effect can turn the dielectric constants of medium column into the function of space coordinates. In the following, we shall study the dielectric constants of medium columns are the linear function of space coordinates, i.e., $\varepsilon(\vec{r}) = kr + b$. By the Fourier transform, we obtained the Fourier transform form $\varepsilon(G)$ of the dielectric constant function $\varepsilon(r)$ for the two-dimensional function photonic crystals, which is more complicated than the Fourier transform in the two-dimensional conventional photonic crystals, which the dielectric constants of medium columns are the constant. The calculation results indicate that when the dielectric constant of medium columns is a constant, the Fourier transforms for both of them are same, which implies that the two-dimensional conventional photonic crystals is a special case for the two-dimensional function photonic crystals. We calculated the band gaps structures of TE and TM waves and found there are absolute band gaps and semi-Dirac points in the two-dimensional function photonic crystals. The absolute band gap can be designed into the polarization selection device. At the corresponding frequency of this semi-Dirac point, the structure of the equivalent dielectric constant and equivalent permeability will be zero. The photonic crystal including the semi-Dirac point can be used to achieve zero refractive index materials, which has wide application potential. When the parameters k, b and the medium column radius r_a change, the band gaps number, location and width, the absolute band gaps and semi-Dirac points should be changed, which can realize the adjustability of band gaps structures. The two-dimensional function photonic crystals should provide a new method for designing optical device.

2. The Fourier transform of dielectric constant for two-dimensional function photonic crystals

For the two-dimensional function photonic crystals, the medium column dielectric constants are the function of space coordinates $\vec{r}$, it is different from the two-dimensional conventional photonic crystals, which dielectric constants are constant. The medium column dielectric constants become the function of space coordinates $\vec{r}$, which can be came true easily in physics. We know that the external electric field can cause the change of medium refractive index, it is called the electro-optical effect [27], i.e., $n(E) = n_0 + aE + bE^2$, where E is the external electric field intensity, n_0 is the medium refractive index without external electric field, $n(E)$ is the medium refractive index with external electric field, a and b are the electro-optical coefficients. When the external electric field $E = E(x, y, z)$, the medium refractive index $n(E) = n(x, y, z)$. Moreover, in nonlinear optics, the medium refractive index is the linear function of external light intensity I, which is called the optical Kerr effect [28], it is $n(I) = n_0 + n_2 I$, where n_0 represents the usual, weak-field refractive index, the optical Kerr coefficient $n_2 = \frac{3}{4n_0^2\epsilon_0 c}\chi^{(3)}$, and $\chi^{(3)}$ is the third-order nonlinear optical susceptibility. When the external pump light intensity $I = I(x, y, z)$, the medium refractive index $n(I) = n(x, y, z)$. So, the medium column dielectric constants can become the function of space coordinates $\vec{r}$, i.e., $\varepsilon = \varepsilon(x, y, z)$, where $\varepsilon(x, y, z) = n^2(x, y, z)$, when the medium columns are imposed the external electric field $E = E(x, y, z)$ or external pump light intensity $I = I(x, y, z)$.

The dielectric constant of cylindrical medium column can be written as

$$\varepsilon(\vec{r}) = \begin{cases} \varepsilon_a(\vec{r}) & r \le r_a, \\ \varepsilon_b & r > r_a, \end{cases} \tag{1}$$

or

$$\frac{1}{\varepsilon(\vec{r})} = \begin{cases} \dfrac{1}{\varepsilon_a(\vec{r})} & r \le r_a, \\ \dfrac{1}{\varepsilon_b} & r > r_a. \end{cases} \tag{2}$$

Eq. (2) can be written as

$$\frac{1}{\varepsilon(\vec{r})} = \frac{1}{\varepsilon_b} + \left(\frac{1}{\varepsilon_a(\vec{r})} - \frac{1}{\varepsilon_b}\right) s(r) \tag{3}$$

where

$$s(r) = \begin{cases} 1 & r \le r_a, \\ 0 & r > r_a. \end{cases} \tag{4}$$