Physica E 45 (2012) 166–172

Contents lists available at SciVerse ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Transmission character of general function photonic crystals

Xiang-Yao Wu [a,*], Bo-Jun Zhang [a], Jing-Hai Yang [a], Si-Qi Zhang [a], Xiao-Jing Liu [a], Jing Wang [a], Nuo Ba [a], Zhong Hua [a], Xin-Guo Yin [b]

[a] Institute of Physics, Jilin Normal University, Siping 136000, China
[b] Institute of Physics, Huaibei Normal University, Huaibei 235000, China

HIGHLIGHTS

- ► The peak value of transmission intensity T can be much larger or smaller than 1.
- ► When $T>1$, the optical thickness increases, the number of band gaps increases, and the width becomes narrow.
- ► When $T<1$, the optical thickness increases, the number of band gaps increases, and the width becomes narrow.
- ► When $T>1$, as the incident angles increase, the transmissivity increases, and the band gaps red shift.
- ► We study the effect of incident angles and periods number on the transmissivity.

ARTICLE INFO

Article history:
Received 30 April 2012
Received in revised form
24 June 2012
Accepted 21 July 2012
Available online 31 July 2012

ABSTRACT

In the paper, we present a new general function photonic crystals (GFPCs), whose refractive index of medium is a arbitrary function of space position. Unlike conventional photonic crystals (PCs), whose structure grows from two mediums A and B, with different constant refractive indexes n_a and n_b. Based on the Fermat principle, we give the motion equations of light in one-dimensional GFPCs, and calculate its transfer matrix, which is different from the conventional PCs. We choose the linearity refractive index function for two mediums A and B, and find the transmissivity of one-dimensional GFPCs can be much larger or smaller than 1 for different slope linearity refractive index functions, which are different from the transmissivity of conventional PCs (its transmissivity is in the range of 0 and 1). Otherwise, we study the effect of different incident angles, the number of periods and optical thickness on the transmissivity, and obtain some new results different from the conventional PCs.

1. Introduction

Photonic crystals (PCs) are composite structures with a periodic arrangement of materials with different refractive indices in one-dimension (1D), two-dimension (2D) or three-dimension (3D). Due to the introduced periodicity, multiple Bragg scatterings from each unit cell may open a photonic band gaps (PBGs), analogous to the electronic band gaps in semiconductors, within which the propagation of electromagnetic (EM) waves is completely forbidden. The existence of PBGs will lead to many interesting phenomena, e.g., modification of spontaneous emission [1–5] and photon localization [6–10]. Thus numerous applications of photonic crystals have been proposed in improving the performance of optoelectronic and microwave devices such as high-efficiency semiconductor lasers, right emitting diodes, wave guides, optical filters, high-Q resonators, antennas, frequency-selective surface, optical limiters and amplifiers [11–14]. These applications would be significantly enhanced if the band structure of the photonic crystal could be tuned.

For the conventional PCs, the photonic band gaps remain fixed once the PCs have been fabricated. If the band gaps of the photonic crystals could be tuned the applications would be significantly enhanced. A practical scheme for tuning the band gap was proposed by Busch and John [15]. It has been demonstrated theoretically and experimentally that PCs with liquid crystal infiltration exhibit tunability on applying an external electric field [15] or changing the temperature [16–20]. If the constituent materials of PCs have magnetic permeabilities dependent on the external magnetic field, the photonic band gaps [PBGs] can be altered by changing the external magnetic field [21–28]. An electric or magnetic field changes the PBGs easily than the temperature.

In Ref. [29], we have proposed special function photonic crystals, in which the medium refractive index is the function of

* Corresponding author.
E-mail address: wuxy2066@163.com (X.-Y. Wu).

1386-9477/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physe.2012.07.024

space position, but the function value of refractive index is equal at two endpoints of every medium A and B, and obtain some new results different from the conventional PCs. In this paper, we present a new general function photonic crystals (GFPCs), whose refractive index is an arbitrary function of space position (needless refractive index same at two endpoint). Unlike conventional photonic crystals (PCs), whose structure grows from two materials, A and B, with different dielectric constants ε_A and ε_B. Firstly, we give the motion equation of light in one-dimensional GFPCs according to the Fermat principle. Secondly, we calculate the transfer matrix for the one-dimensional GFPCs, which is different from the transfer matrix of the conventional PCs. Finally, we give the dispersion relation, band gap structure and transmissivity. We choose the linearity refractive index function for two medium A and B, and find that the transmissivity of GFPCs can be much larger or smaller than 1 for the different slope linearity refractive index functions, which is different from the transmissivity of conventional PCs (its transmissivity is in the range of 0 and 1). Otherwise, we study the effect of different incident angles, the number of periods and optical thickness on the transmissivity, and obtain some new results. By the calculation, we find that the conventional PCs is the special case of the GFPCs.

2. The light motion equation in general function photonic crystals

For the general function photonic crystals, the medium refractive index is a periodic function of the space position, which can be written as $n(z)$, $n(x,z)$ and $n(x,y,z)$ corresponding to one-dimensional, two-dimensional and three-dimensional function photonic crystals. In the following, we shall deduce the light motion equations of the one-dimensional general function photonic crystals, i.e., the refractive index function is $n=n(z)$, meanwhile motion path is on the xz plane. The incident light wave strikes plane interface point A, the curves AB and BC are the path of incident and reflected light respectively, and they are shown in Fig. 1.

The light motion equation can be obtained by the Fermat principle, it is

$$\delta\int_A^B n(z)\,ds=0. \tag{1}$$

In the two-dimensional transmission space, the line element ds is

$$ds=\sqrt{(dx)^2+(dz)^2}=\sqrt{1+\dot{z}^2}\,dx, \tag{2}$$

where $\dot{z}=dz/dx$, then Eq. (1) becomes

$$\delta\int_A^B n(z)\sqrt{1+(\dot{z})^2}\,dx=0. \tag{3}$$

Eq. (3) changes to

$$\int_A^B\left(\frac{\partial(n(z)\sqrt{1+\dot{z}^2})}{\partial z}\delta z+\frac{\partial(n(z)\sqrt{1+\dot{z}^2})}{\partial\dot{z}}\delta\dot{z}\right)dx=0. \tag{4}$$

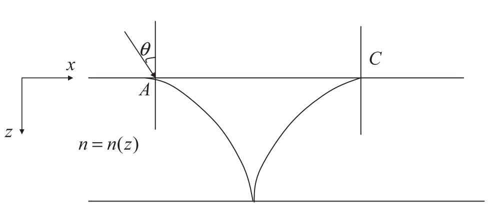

Fig. 1. The motion path of light in the medium of refractive index $n(z)$.

At the two end points A and B, their variation is zero, i.e., $\delta z(A)=\delta z(B)=0$. For arbitrary variation δz, Eq. (4) becomes

$$\frac{dn(z)}{dz}\sqrt{1+\dot{z}^2}-\frac{dn(z)}{dz}\dot{z}^2(1+\dot{z}^2)^{-1/2}-n(z)\frac{\ddot{z}\sqrt{1+\dot{z}^2}-\dot{z}^2\ddot{z}(1+\dot{z}^2)^{-1/2}}{1+\dot{z}^2}=0, \tag{5}$$

simplify Eq. (5), we have

$$\frac{dn(z)}{n(z)}=\frac{\dot{z}d\dot{z}}{1+\dot{z}^2}. \tag{6}$$

Eq. (6) is light motion equation in one-dimensional function photonic crystals.

3. The transfer matrix of one-dimensional general function photonic crystals

In this section, we should calculate the transfer matrix of one-dimensional general function photonic crystals. In fact, there is the reflection and refraction of light at a plane surface of two media with different dielectric properties. The dynamic properties of the electric field and magnetic field are contained in the boundary conditions: normal components of D and B are continuous; tangential components of E and H are continuous. We consider the electric field perpendicular to the plane of incidence, and the coordinate system and symbols as shown in Fig. 2.

On the two sides of interface I, the tangential components of electric field E and magnetic field H are continuous, they are

$$\begin{cases}E_0=E_I=E_{t1}+E'_{r2},\\ H_0=H_I=H_{t1}\cos\theta_t^I-H'_{r2}\cos\theta_t^I.\end{cases} \tag{7}$$

On the two sides of interface II, the tangential components of electric field E and magnetic field H are continuous and give

$$\begin{cases}E_{II}=E'_I=E_{i2}+E_{r2},\\ H_{II}=H'_I=H_{i2}\cos\theta_i^I-H_{r2}\cos\theta_i^I,\end{cases} \tag{8}$$

the electric field E_{t1} is

$$E_{t1}=E_{t10}e^{i(k_x x_A+k_z z)}\big|_{z=0}=E_{t10}e^{i(\omega/c)n(0)\sin\theta_t^I x_A}, \tag{9}$$

and the electric field E_{i2} is

$$E_{i2}=E_{t10}e^{i(k'_x x_B+k'_z z)}\big|_{z=b}=E_{t10}e^{i(\omega/c)n(b)(\sin\theta_i^I x_B+\cos\theta_i^I b)}, \tag{10}$$

where x_A and x_B are the x component coordinates corresponding to points A and B. We should give the relation between E_{i2} and E_{t1}. By integrating the two sides of Eq. (6), we can obtain the coordinate component x_B of point B

$$\int_{n(0)}^{n(z)}\frac{dn(z)}{n(z)}=\int_{k_0}^{k_z}\frac{\dot{z}\,d\dot{z}}{1+\dot{z}^2}, \tag{11}$$

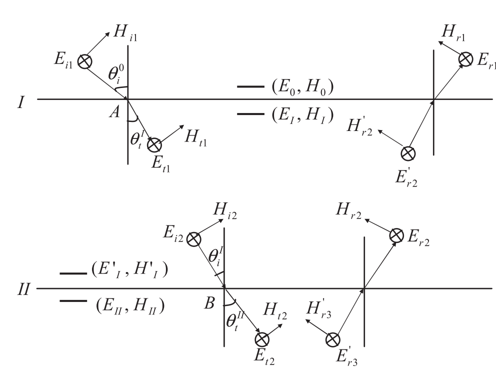

Fig. 2. The light transmission and electric magnetic field distribution figure in Fig. 1 medium.