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The optimal design of photonic crystal optical devices with step-wise linear refractive index

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ABSTRACT

In the paper, we have studied one-dimensional step-wise linear photonic crystal with and without defect layer, and analyzed the effect of defect layer position, thickness, refractive index real part and imaginary part on the transmissivity, electric field distribution and output electric field intensity. By calculation, we have obtained a set of optimal parameters, which can be optimally designed optical device, such as optical amplifier, attenuator, optical diode by the step-wise linear photonic crystal.

1. Introduction

Photonic crystal are artificial materials with periodic distribution of refractive index, which are designed to affect the propagation of light [1–4]. An important feature of the photonic crystal is that there are allowed and forbidden ranges of frequencies at which light propagates in the direction of index periodicity. Due to the forbidden frequency range, known as photonic band gap (PBG) [5,6]. The existence of PBGs will lead to many interesting phenomena, e.g., modification of spontaneous emission [7–10] and photon localization [11–14]. Thus numerous applications of photonic crystal 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 [15–18]. These applications would be significantly enhanced if the band structure of the photonic crystal could be tuned.

In Refs. [19–22], we have proposed a step-wise photonic crystal $(AB)^N$, which is constituted by two media A and B, their refractive indexes are arbitrary 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.

We know the Airy functions is the solution of Airy equation $y'' = xy$. For the one-dimensional linearity function photonic crystals, the medium refractive index is the linearity function of space position, i.e., the refractive index $n(x) = ax + b$, corresponding one-dimensional Helmhltz equation is not the Airy equation. If the permittivity ε is the linearity function of space position, i.e., $\varepsilon(x) = ax$, we can obtain the Airy equation and should use the Airy functions to study the problem.

In this paper, we should study the one-dimensional photonic crystal with a spatially linearly varying refractive index, i.e., the media A and B refractive indexes are the linearity functions of space position, which is called step-wise linear photonic crystal. We systematically study the transmissivity, electric field distribution and output electric field intensity for the step-wise linear photonic crystal. We analyzed the effect of defect layer position, thickness, refractive index real part and imaginary part on the transmissivity, the electric field distribution and the output electric field intensity, and studied the electric field distributions of light positive incident and negative incident. By calculation, we have obtained a set of optimal parameters of the larger output electric field intensity, which are useful to optimally design optical device, such as optical amplifier, attenuator, optical diode by the one-dimensional step-wise linear photonic crystal.

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2. The transmissivity and electric field distribution of one-dimensional step-wise linear photonic crystal

In Refs. [19–22], we have given the step-wise photonic crystal transfer matrices M_B and M_A for the media B and A, they are

$$M_B=\begin{pmatrix}\cos\delta_b & \dfrac{-i\sin\delta_b}{\sqrt{\frac{\varepsilon_0}{\mu_0}}n_b(b)\cos\theta_i^I}\\ -in_b(0)\sqrt{\frac{\varepsilon_0}{\mu_o}}\cos\theta_t^I\sin\delta_b & \dfrac{n_b(0)\cos\theta_t^I\cos\delta_b}{n_b(b)\cos\theta_i^I}\end{pmatrix}, \tag{1}$$

$$M_A=\begin{pmatrix}\cos\delta_a & -\dfrac{i\sin\delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}}n_a(a)\cos\theta_i^{II}}\\ -in_a(0)\sqrt{\frac{\varepsilon_0}{\mu_o}}\cos\theta_t^{II}\sin\delta_a & \dfrac{n_a(0)\cos\theta_t^{II}\cos\delta_a}{n_a(a)\cos\theta_i^{II}}\end{pmatrix}, \tag{2}$$

where

$$\delta_b=\frac{\omega}{c}n_b(b)\left[\cos\theta_i^I\cdot b+\sin\theta_i^I\int_0^b\frac{dz}{\sqrt{\frac{n_b^2(z)}{n_0^2\sin^2\theta_i^0}-1}}\right], \tag{3}$$

$$\delta_a=\frac{\omega}{c}n_a(a)\left[\cos\theta_i^{II}\cdot a+\sin\theta_i^{II}\int_0^a\frac{dz}{\sqrt{\frac{n_a^2(z)}{n_0^2\sin^2\theta_i^0}-1}}\right], \tag{4}$$

$$\sin\theta_i^I=\frac{n_0}{n_b(b)}\sin\theta_i^0, \tag{5}$$

$$\cos\theta_i^I=\sqrt{1-\frac{n_0^2}{n_b^2(b)}\sin^2\theta_i^0}, \tag{6}$$

$$\cos\theta_t^I=\sqrt{1-\frac{n_0^2}{n_b^2(0)}\sin^2\theta_i^0}, \tag{7}$$

and

$$\sin\theta_i^{II}=\frac{n_0}{n_a(a)}\sin\theta_i^0, \tag{8}$$

$$\cos\theta_i^{II}=\sqrt{1-\frac{n_0^2}{n_a^2(a)}\sin^2\theta_i^0}, \tag{9}$$

$$\cos\theta_t^{II}=\sqrt{1-\frac{n_0^2}{n_a^2(0)}\sin^2\theta_i^0}. \tag{10}$$

In one period, the transfer matrix M is

$$\begin{aligned}M&=M_B\cdot M_A\\ &=\begin{pmatrix}\cos\delta_b & \dfrac{-i\sin\delta_b}{\sqrt{\frac{\varepsilon_0}{\mu_0}}n_b(b)\cos\theta_i^I}\\ -in_b(0)\sqrt{\frac{\varepsilon_0}{\mu_o}}\cos\theta_t^I\sin\delta_b & \dfrac{n_b(0)\cos\theta_t^I\cos\delta_b}{n_b(b)\cos\theta_i^I}\end{pmatrix}\\ &\quad\begin{pmatrix}\cos\delta_a & \dfrac{-i\sin\delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}}n_a(a)\cos\theta_i^{II}}\\ -in_a(0)\sqrt{\frac{\varepsilon_0}{\mu_o}}\cos\theta_t^{II}\sin\delta_a & \dfrac{n_a(0)\cos\theta_t^{II}\cos\delta_a}{n_a(a)\cos\theta_i^{II}}\end{pmatrix},\end{aligned} \tag{11}$$

where $n_b(0)$, $n_b(b)$, $n_a(0)$ and $n_a(a)$ are the endpoint values of refractive index for media B and A, b and a are the thickness of media B and A, θ_i^0 is incident angle, n_0 is air refractive index, and the angles θ_t^I, θ_i^I, θ_t^{II} and θ_i^{II} are shown in Fig. 1.

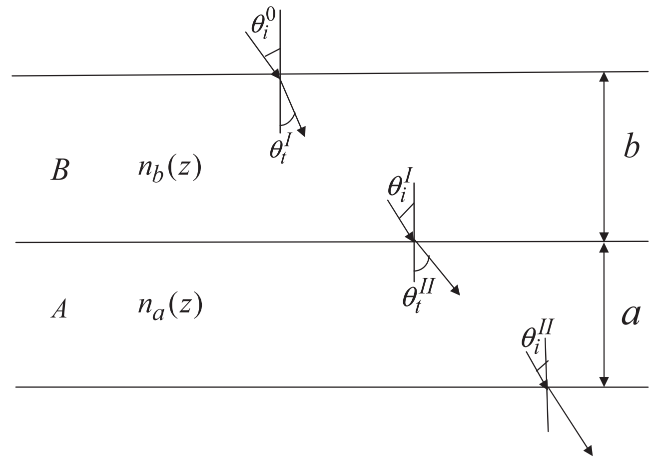

Fig. 1. The light transmission figure in media B and A of step-wise linear photonic crystal.

For defect layer medium D, its refractive index is complex number $n_d=n_{d0}+ik$, where n_{d0} and k are the real part and imaginary part of refractive index, its transfer matrix M_D is

$$M_D=\begin{pmatrix}\cos\delta_d & -\frac{i}{\eta_d}\sin\delta_d\\ -i\eta_d\sin\delta_d & \cos\delta_d\end{pmatrix}, \tag{12}$$

where $\eta_d=\sqrt{\frac{\varepsilon_0}{\mu_0}}n_d\cos\theta_d^0$, $\delta_d=\frac{\omega}{c}n_d d\cos\theta_d^0$, the θ_d^0 is the incident angle of medium D, when $\theta_i^0=0$, $\theta_d^0=0$.

We can find the transfer matrix M of the step-wise linear photonic crystal is more complex than the conventional PCs. For the structure $(BA)^N D(BA)^M$ step-wise linear photonic crystal, which is shown in Fig. 2, its characteristic equation is

$$\begin{aligned}\begin{pmatrix}E_1\\ H_1\end{pmatrix}&=M_BM_AM_BM_A\cdots M_D\cdots M_BM_A\begin{pmatrix}E_{N+1}\\ H_{N+1}\end{pmatrix}\\ &=M\begin{pmatrix}E_{N+1}\\ H_{N+1}\end{pmatrix}=\begin{pmatrix}A & B\\ C & D\end{pmatrix}\begin{pmatrix}E_{N+1}\\ H_{N+1}\end{pmatrix}.\end{aligned} \tag{13}$$

With the total transfer matrix M, we can obtain the transmission and reflection coefficients t and r, and the transmissivity T and reflectivity R, they are

$$t=\frac{E_{tN+1}}{E_{i1}}=\frac{2\eta_0}{A\eta_0+B\eta_0\eta_{N+1}+C+D\eta_{N+1}}, \tag{14}$$

$$r=\frac{E_{r1}}{E_{i1}}=\frac{A\eta_0+B\eta_0\eta_{N+1}-C-D\eta_0}{A\eta_0+B\eta_0\eta_{N+1}+C+D\eta_0}, \tag{15}$$

and

$$T=t\cdot t^*, \tag{16}$$

$$R=r\cdot r^*, \tag{17}$$

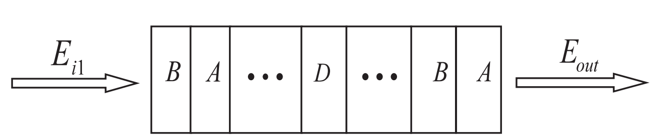

Fig. 2. The structure of the step-wise linear photonic crystal $(BA)^N D(BA)^M$, E_{i1} is input electric field and E_{out} is output electric field.