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PHOTONIC CRYSTAL NARROW FILTERS WITH NEGATIVE REFRACTIVE INDEX STRUCTURAL DEFECTS

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Abstract—This paper presents a proposal of taking the left-handed material as the structural defects of one-dimensional photonic crystals and uses the transfer matrix method to analyze the band-gap of that structure. The simulation result shows that the structure investigated can be considered as a narrow pass band optical filter. By tuning the refractive index of the left-handed material, the ideal transmission rate in the pass band is as higher as 99.99%, while in the band-gap is lower than 0.01%. In addition, we show that the bandwidth can be increased by reducing the cycle number of the photonic crystals.

1. INTRODUCTION

Photonic crystals (PhCs) which were firstly introduced by Yablonovich [1] and John [2] in 1987, are periodic or metallic structure that are artificially designed to control the propagation of wave. For PhC contains two or more different materials, the large refractive index contrast gives rise to a photonic band-gap within which light wave can't propagate. The behavior of light propagating in a PhC has a strong formal similarity to that of electrons in semiconductor, this result in the formation of pass bands and forbidden bands over a range of frequency, and therefore the PhCs have many interesting characteristics, such as abnormal Lamb shift and super-refraction effect [3–5].

Throughout these years, the PhCs have been attracted much attention [6–10], at the same time, the research about another new medium, the left-handed material (LHM), has also received many people's interest. In 1968 the former Soviet Union scientist Veselago [11] investigated the case that if the dielectric permittivity and magnetic conductivity are both negative, some interesting phenomenon will raised, such as the negative refraction, reverse Doppler shift, reverse Cerenkov radiation, and so on. Veselago's study hasn't gotten people's interest until recently, based on Pendry's theoretical work [12, 13], Smith [14] synthesized the LHM in the RF-band and experimental confirmed the existence of the left-handed material. After that, a great publications on this topic is raised [15–24] and the left-handed material becomes a hot research topic in scientific area.

The spontaneous decay of atomic radiation depends on the distribution of atoms in the PhC, the periodic structure will be destroyed if defects are imported. Therefore it is possible to create pass bands within the photonic band-gap by introducing point defects or line defects. The PhC with band-gap is expected to be a new material that can control the propagation of light in a micronsized scale. Due to the property that the photonic band gap can prohibit any propagation of light in the forbidden bands while allow other wavelengths to penetrate through freely, it can be used to realize band-pass filter.

The current research about the PhCs with defects is mainly focused on the area of adding a different right-hand material film into the crystal to break the periodicity. This paper studies a different case, which introduces the LHM as a defect material and designs a new type of band-pass filter. Simulation result shows that in the pass bands the transmission rate is more than 99.99% while in the forbidden bands it is less than 0.01%, which shows better performance than conventional PhCs.

2. THEORETICAL MODELS

We suppose a layered medium realized by two conventional homogenous medium with different dielectric constant. We call the two layers as layer A and B, with the thickness of d_1 and d_2, respectively. The indices of refraction of the two layers are n_1 and n_2. These four parameters satisfy the formula: $d_1 \cdot n_1 = d_2 \cdot n_2 = \lambda/4$. The structure of this one-dimension PhC transforms from $(AB)_k$ to $(AB)_m C(BA)_n$, after adding the layer C realized with LHM, whose refraction index is n_3 ($n_3 < 0$), as show in Fig. 1, where m and n are the cycle number on both sides of the defect.

We can analyze the characteristics of band-gap by transfer matrix

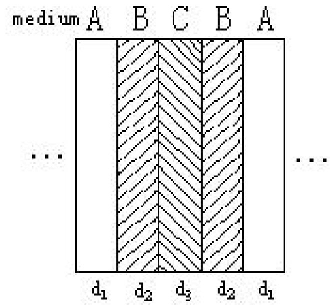

Figure 1. The structure of 1-d photonic crystal narrow-band filter with left-hand medium defect.

method [17, 18], in no-defect state, the transfer matrix of $(AB)_k$ is:

$$M = (M_A M_B)^k$$

where M_A, M_B are the transfer matrix of layer A and B, respectively, and was defined by

$$M_A = \begin{bmatrix} \cos\delta_A & -\dfrac{i}{\eta_A}\sin\delta_A \\ -i\eta_A\sin\delta_A & \cos\delta_A \end{bmatrix} \tag{1}$$

$$M_B = \begin{bmatrix} \cos\delta_B & -\dfrac{i}{\eta_B}\sin\delta_B \\ -i\eta_B\sin\delta_B & \cos\delta_B \end{bmatrix} \tag{2}$$

When the incident wave is in TE mode, we have $\eta_A = \sqrt{\frac{\varepsilon}{\mu}}\cos\theta_{i2}$, $\delta_A = \frac{2\pi}{\lambda} n_1 d_1 \cos\theta_{i2}$, $\eta_B = \sqrt{\frac{\varepsilon}{\mu}}\cos\theta_{i3}$, $\delta_A = \frac{2\pi}{\lambda} n_2 d_2 \cos\theta_{i3}$.

After adding the LHM defect, based on the Bloch-Floquet theorem, we can get the dispersion relation equation as below:

$$\cos[k(\omega)d] = \cos(k_B d_2)\cos(k_C d_3) + \frac{1}{2}\left(\frac{k_B}{k_C} + \frac{k_C}{k_B}\right)\sin(k_B d_2)\sin(k_C d_3) \tag{3}$$

The transfer matrix from normal medium to LHM is [27]

$$M_C = \begin{bmatrix} \dfrac{1}{t_{TE}} & \dfrac{r^*_{TE}}{t^*_{TE}} \\ \dfrac{r_{TE}}{t_{TE}} & \dfrac{1}{t_{TE}} \end{bmatrix} \tag{4}$$

The parameter r_{TE}, t_{TE} are respectively the reflectance and transmission rate at the interface.

The final transfer matrix is $M = (M_A M_B)^m M_{BC} M_{CB} (M_B M_A)^n$ after adding the layer made by LHM. From quantum physics, we can get a way to produce a pass band in the band-gap of the PhC by putting a LHM layer into it to break the periodic structure, so that the defect state is formed.

The phonic band-gap is determined by the transfer matrix M [28, 29], from $M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$, the total reflectance and transmission rate can be obtained.

$$r = \frac{E_{r1}}{E_{i1}} = \frac{m_{11}\eta_0 + m_{12}\eta_0^2 - m_{21} - m_{22}\eta_0}{m_{11}\eta_0 + m_{12}\eta_0^2 + m_{21} + m_{22}\eta_0} \tag{5}$$

$$t = \frac{E_{tN+1}}{E_{i1}} = \frac{2\eta_0}{m_{11}\eta_0 + m_{12}\eta_0^2 + m_{21} + m_{22}\eta_0} \tag{6}$$

3. SIMULATION RESULT AND DISCUSSION

Based on the theoretical model described above, we can calculate the transmission properties of the PhC. We consider the case of TE wave normally incidence from the free space onto the PhC. We choose ZnSe ($n_1 = 2.58$) and Na_3AlF_6 ($n_2 = 1.35$) as high refractive index material and low refractive index material. By changing the negative reflection coefficient and the periodicity number of PhC, we exam the filtering properties of the structure with defect.

First we set the periodicity number as $m = n = 8$ and compare the filtering performance under the influence of different negative refractive index. We plot in Fig. 2(a) the transmission coefficient when n_3 is -2. It can be seen that the phonic band gap ranges from $0.76\lambda_o$ to $1.43\lambda_o$, where λ_o is central wavelength. At the forbidden gap, the attenuation is more than 40 dB; but at the central wavelength, due to the existence of defect layer C, there is a very narrow pass band whose transmission peak is about 93%, therefore, only the wave within the very narrow band can pass through PhC filter. If we decrease the negative refractive index to $n_3 = -2.5$, the transmission curve is shown in Fig. 2(b), from which we see that the location of the band gap and the center defect states hasn't changed much, but the maximum value of transmission rate increased to 99.9%; however, if we decrease n_3 further, for instance, letting $n_3 = -4$, the maximum of transmission level of defect states declined to 83%, as shown in Fig. 2(c).

Therefore, the transmission coefficient will not increase to 1 as the refractive index decrease. The relationship between them is shown in

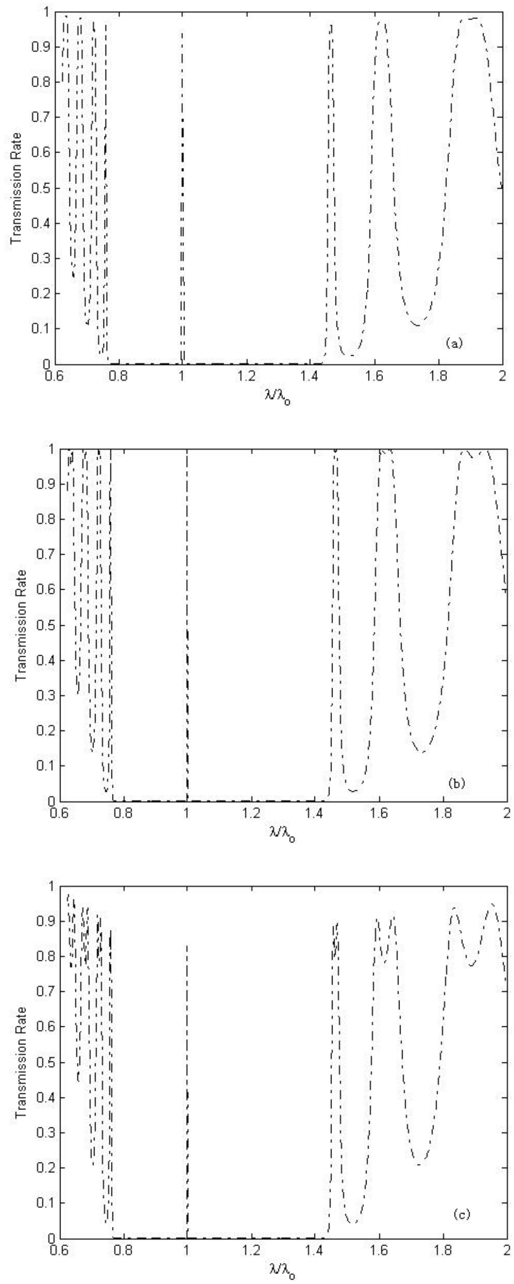

Figure 2. The transmission rate of 1-d photonic crystals with a negative refractive defect.

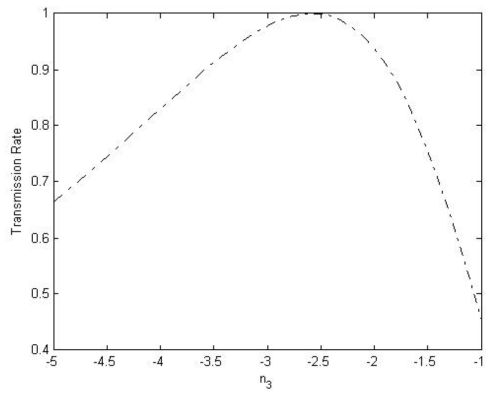

Figure 3. The influence of refractive index of the defect on the transmission rate.

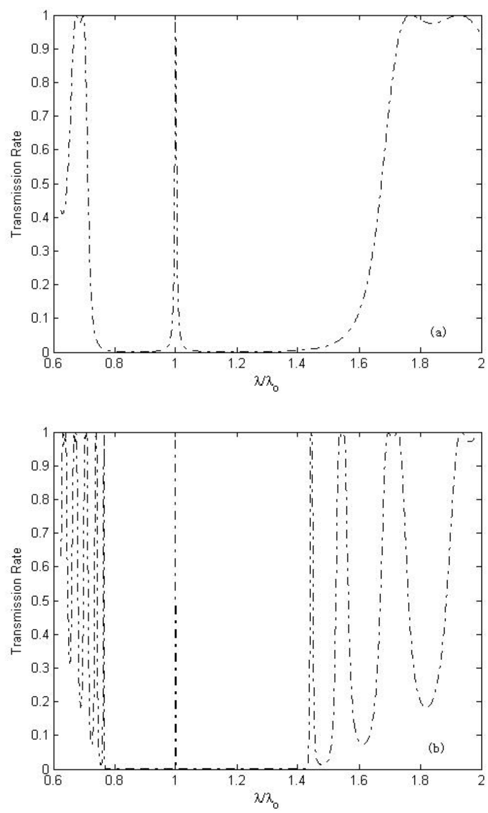

Figure 4. The influence of the number of structure periods on narrow pass filtering.

Fig. 3. Only when n_3 has reached the value of -2.6, the structure has the maximum transmission rate of 99.99%, which indicates that the wave penetrates the structure almost without any attenuation.

When the refractive index of LHM is $n_3 = -2.5$, we decrease the number of periodicity and let $n = m = 3$, the result is shown as Fig. 4(a), the position of narrow pass band is still unchanged, but the width of the band increase obviously, so as the width of side lobe band; on the contrast, when the number of periodicity is increased and $n = m = 10$, the position of narrow pass band isn't changed yet, but the width of the pass band and side lobe band decrease notablely, the result is shown on Fig. 4(b). This indicates that we can adopt the appropriate number of cycles to adjust bandwidth. In addition, because the distance between the narrow pass band and the side lobe band is far enough, the influence of the side lobe band to the performance of the filter is relatively small.

4. CONCLUSION

We have presented a new type of one-dimensional PhC, using the LHM as the material of defect. This new structure could have a narrow pass band in the centre of the band-gap. By tuning the negative refractive index, the transmission coefficient at the pass band could reach as high as 99.99%, while at the forbidden band it is no more than 0.01%. Besides, we show that by changing the number of layers, the bandwidth of the pass band could be tuned. This structure can be realized as a narrow-band filter with good performance. The excellent feature of this filter, encourages us to concentrate on this new structure for its application in photovoltaic device.

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