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Narrow Band Longitude Mode Selector of Laser Based on Conjugated Photonic Crystals *

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Properties of transmission spectra of multi-layers consisting of two conjugated photonic crystals are investigated. It is found that, in the case of a small amount of time, the mode density at the interface mode is much larger than that at the band edge. Under certain conditions, the transmission can reach the unity, and the bandwidth can reach the order of picometer. Based on this property, a longitude mode selector of laser consisting of two conjugated photonic crystals made with gain materials is suggested. The effects of the impedance contrast of materials and the refractive index of the environment on the bandwidth are studied.

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Many applications of lasers require the extreme monochromaticity of laser. Many techniques for selecting single longitude mode have been developed, such as dispersion method, short cavity method, F-P etalon method, multi-cavity method and so on. However, the requirement on monochromaticity in some applications can still not be satisfied. Moreover, there exist energy losses in those techniques.

In the past 20 years, the study about photonic crystals (PCs)[1,2] was developed rapidly for their potential applications.[3,4] There exists the ferromagnetic material and metamaterial[5−7] which are transparent in certain frequency ranges. PCs consisting of these materials[8−12] show some particular characteristics. Especially, omnidirectional band gaps can be easily obtained in a PC made with two kinds of materials with the same refractive indices and different impedances.[10] Magnetic photonic crystals attract much attention. Alternatively, in a multi-lattice structure consisting of two or more PCs, there exist some surface modes at interfaces. Under some conditions, there will appear several extra narrow transmitted peaks in its transmission spectrum which can be used as extra narrow band filters. It should be emphasized that these modes were first mentioned by Turner and Baumeister,[13] but they took them as a nuisance and did not study their potential applications. Later, in a patent, Russell *et al.*[14] considered this kind of multi-lattice structures as a conjugated filter. Recently, Villa[15] analyzed the behavior of the wave at the interface between two PCs and imaged to fabricate narrow band filters. However, the abrupt raising of mode density at the peak wavelength of the extra narrow transmission has not been considered in the above-mentioned studies (this kind of abrupt raising can be used to design filter and/or mode selector with selective gain). Also, the influence on the line width of the extreme narrow transmission has not been considered. However, it should be pointed out that these factors are very important for designing narrow band filters and mode selector of a laser. In this Letter, mode selector of a laser formed by conjugated magnetic photonic crystals is discussed, and its emitting characteristics and optimization is analyzed.

In our study, we consider a structure in the form of $((AB)^m(BA)^n)$, this is our definition of a conjugated PCs. Here $(AB)^m$ is the first PC (described as PC1) and $(BA)^n$ represents the PC2 which is conjugated with the PC1 (see Fig. 1). A and B represent two different kinds of materials with the thicknesses a and b, the permittivity ε_a and ε_b, the permeability μ_a and μ_b, respectively, m and n are the periodic numbers of PC1 and PC2. The lattice period of each PC is $\Lambda = a + b$. We assume that the structure is put in the symmetric environment[16] and the surrounding medium is material G with the permittivity ε_g and permeability μ_g respectively. A monochromatic light beam with a frequency ω is incident normally on the complex structure.

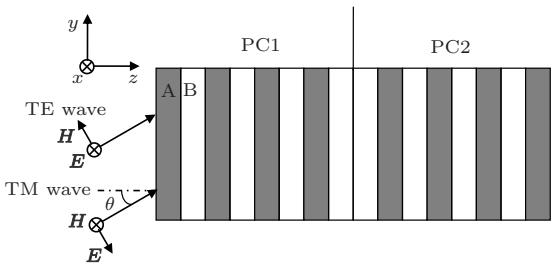


Fig. 1. Complex structure consisting of two conjugated photonic crystals.

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In the formalism of the characteristic matrix method of propagation of light through multilayers,[17] any simple thin film has an associated 2×2 matrix that relates the total electric and magnetic fields between the boundaries of one medium. This matrix is a function of the parameters of the corresponding jth film:

$$M_j = \begin{bmatrix} \cos\delta_j & (i/\eta_j)\sin\delta_j, \\ i\eta_j \sin\delta_j & \cos\delta_j \end{bmatrix}, \tag{1}$$

$$\eta_j = \begin{cases} 1/Z_j \cos\theta_j, & \text{for TM}, \\ \cos\theta_j/Z_j, & \text{for TE}, \end{cases} \tag{2}$$

where $\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos\theta_j$ is the phase delay of light in jth layer, $n_j = \sqrt{\varepsilon_j}\sqrt{\mu_j}$ is the refractive index of the jth layer, θ_j is the refractive angle with which the light beam enters into the jth layer, η_j is the optical admittance of the jth layer, $Z_j = \sqrt{\mu_j/\varepsilon_j}$ is the optical impedance of the jth layer. The total transmission of the stack can also be achieved.

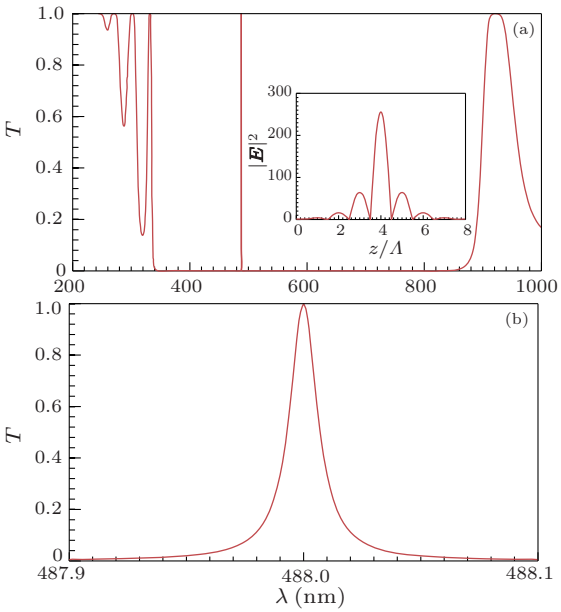


Fig. 2. (a) Transmission of the two conjugated photonic crystals on the same substrate change with the wavelength of the incident waves, with the inset picture showing the amplitude of the electric field for $\lambda = 488$ nm. (b) Transmission of the interface mode.

In our calculations, the parameters of materials A and B are assumed to satisfy $\varepsilon_a \mu_a = \varepsilon_b \mu_b$. Considering the matching of the optical length, we assume that layer A and layer B have the same thickness, i.e. $a = b$. According to Ref. [10], we can know that PC1 and PC2 have omnidirectional band gaps. TE waves and TM waves have the same dispersion relation at band edge. That is to say, TE waves and TM waves have the same band gaps. Figure 2 shows the transmission spectrum of the multi-layers with $\varepsilon_a = 4$, $\mu_a = 1$, $\varepsilon_b = 1$, $\mu_b = 4$, $a = b = \lambda_0/8$, $\lambda_0 = 488$ nm, $m = n = 4$, $\varepsilon_g = \mu_g = 1$. In Fig. 2, the x axis is the wavelength of the incidence wave, and the y axis represents the corresponding transmission efficiency. It can be seen that there exists the gap in the whole visible range, and in the gap there is an interface mode (see Fig. 2(a)). This interface mode possesses an extreme narrow band width (about the pm order of magnitude), and its transmission reaches unity (see Fig. 2(b)). We also plot the amplitude of the electric field for $\lambda_0 = 488$ nm (in the inset picture of Fig. 2(a)). It is obvious that the intensity of the field at the interface of the two PCs increases abruptly, and it will decrease exponentially when light is away from the interface in the perpendicular direction. We can affirm it has a surface mode according to this characteristic. It is induced by the finite property of the PC.

The mode density of these kinds of conjugated structures are also given in Fig. 3, where the x axis is the relative frequency (ω/ω_0, $\omega_0 = 2\pi c/\lambda_0$) and the y axis is the mode density normalized by $\rho_0 = c/2(1/n_a + 1/n_b)$. It is obvious that the mode density of the local mode is much higher than that at the band edges. In Fig. 3, in order to compare the values of normalized mode density at the local mode and at the band edges, the maximum value of the vertical axis is 60. However, actually the normalized mode density at the interface mode is about 2700 and almost equals the mode density of the PC in the form of $G(AB)^{210}G$. The corresponding group velocity is $1.8 \times 10^{-4}c$, the effective gain can be increased 10^4 times.[18] This means that we can obtain excellent characteristics with less layers, beneficial to achieve them easily. Therefore, these characteristics can be used to design a new kind of mode selector of laser, it can achieve increasing output power of laser while ensure excellent monochromaticity.

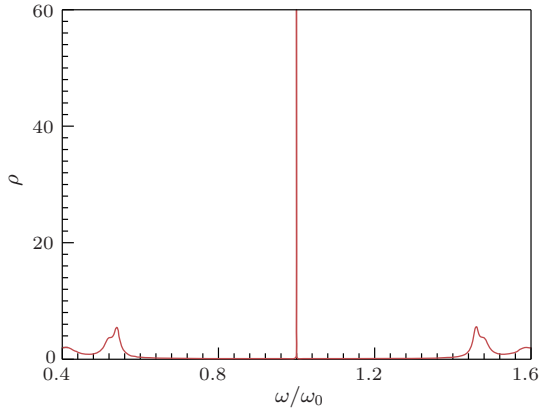


Fig. 3. Normalized mode density changes with the relative frequency.

It is well known that the transmission of the narrow band-pass peak decreases rapidly with the increase of the period number (m and n) of the conjugated PCs,[13] even disappears. Also, the line width of the narrow transmission peak is related to the re-

fractive index of the environment where the PC is put in. We assume that the stack discussed here is put in a symmetric environment, and let $\varepsilon_a = 4$, $\mu_a = 1$, $\varepsilon_b = 1$, $\mu_b = 4$, $a = b = \lambda_0/8$, $\lambda_0 = 488\,\text{nm}$, $m = n = 4$, $\mu_0 = \mu_g = 1$. Figure 4 shows the relation of the line width $\Delta\lambda$ of the transmission peak vs the refractive index n_g (or permittivity ε_g) of the surrounding medium. It is clear that the line width $\Delta\lambda$ increases linearly with the increase of n_g. Thus, in order to obtain good monochromatic laser, the mode selector should be put in air.

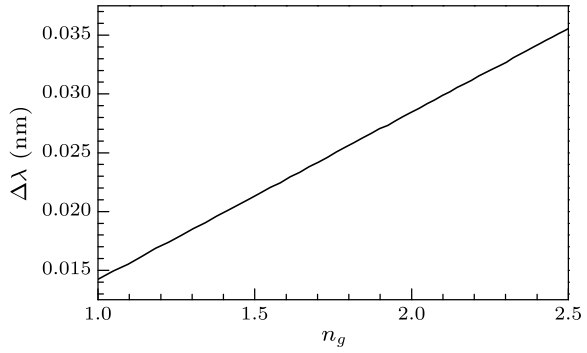


Fig. 4. Width of the narrow transmission changing with the refractive index of the surrounding medium.

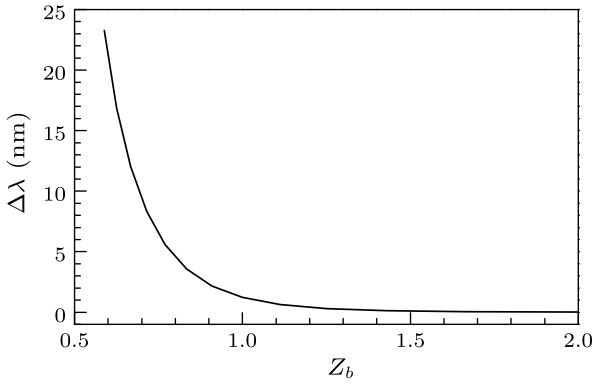


Fig. 5. Width of the narrow transmission changing with the impedance of medium B.

At the same time, the effects of the wave impedance contrast on the line width and the peak values are also considered. By changing ε_b under the condition of $\varepsilon_a = 4$, $\mu_a = 1$, $m = n = 4$, $a = b = \lambda_0/8$, $\lambda_0 = 488\,\text{nm}$, $\varepsilon_g = \mu_g = 1$, $\varepsilon_b\mu_b = \varepsilon_a\mu_a = 4$, the calculated results as shown in Fig. 5 are obtained. It can be seen that the band-width of the transmission peak decreases exponentially with the increase of the wave impedance Z_b, and the change becomes very slow when value of Z_b is larger than one. It should be pointed out that the transmission of the peak with a narrow band keeps unity when the wave impedance is less than 32. Considering feasibility of manufacturing, in the following discussions, only the value of the wave impedance less than 2 is considered so that the peak has high and narrow transmission.

Assuming $\varepsilon_a = 4$, $\mu_a = 1$, $\varepsilon_b = 1$, $\mu_b = 4$, $a = b = \lambda_0/8$, $\lambda_0 = 488\,\text{nm}$, $m = n = 4$, $\varepsilon_g = \mu_g = 1$, when the light beam is incident obliquely on the conjugated PCs, we can obtain the change curve of the central position of the interface mode with the incidental angle of the light beam as shown in Fig. 6. It should be pointed out that TE wave and TM wave have the same behavior in Fig. 6. This is because the components of PC have the same thickness and the same refraction index.[10] One can find that the central position of the interface mode changes monotonously with the change of the incidental angle. That is to say, we can control the output wavelength of the laser by changing the incidental angle. This suggests a way for the mode selector tuning. We can also change the refractive index of the components of PCs by changing the temperature or using the photosensitive mediums to achieve the tune property of the mode selector.

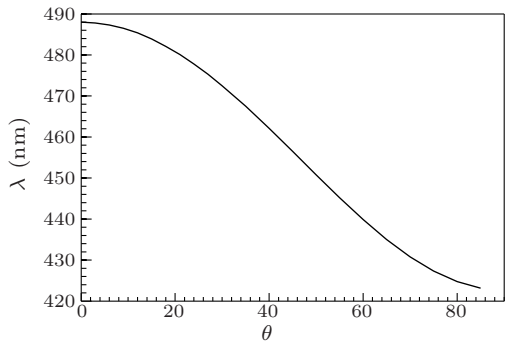


Fig. 6. Center position of the interface mode changing with the incidental angle for TE or TM wave.

According to the above analysis, we know that a stack made of two conjugated PCs consisting of gain materials can reflect the visible light except the localized mode. Thus it can be used as a novel mode-selector. This kind of mode selector has the following advantages: (1) There is only one mode in the band gap of the PC in overall visible frequency. It makes a single longitude mode oscillate in a laser, even in the solid state laser with wide fluorescence line width. (2) The mode at the middle frequency of the transmission peak can penetrate into the selector with little energy loss, while the other modes will be almost reflected. Thus one can select an appropriate angle to obtain a useful mode and to remove other modes. (3) The group velocity of the selected mode in the conjugate PCs is much smaller than that in the air; the effective gain at this frequency is so high in the stack that the mode can be amplified greatly while the other modes can not exist. Therefore, a powerful laser beam with very narrow band width can be obtained. (4) The high gain can be achieved using a few lattice layers, it makes fabrication easy. (5) The band-width of laser beam can be optimized by choosing suitable materials, layer numbers of PCs and environment media.

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