Multi-channel and sharp angular spatial filters based on one-dimensional photonic crystals

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Received May 10, 2006

A photonic heterostructure with multi-channel and sharp angular defect modes by combining two different one-dimensional defective photonic crystals is proposed. The filters designed on the basis of this heterostructure possess both functions of multi-channel narrow band filtering and sharp angular filtering. The channels, channel interval, and number of channels can be tuned by adjusting the geometric and physical parameters of the heterostuctures. This kind of filters will benefit the development of multi-channel interstellar or atmosphere optical communication.

OCIS codes: 120.2440, 330.6110, 350.2460, 310.6860, 230.4170.

Since the pioneering work of Yablonovitch[1] and John[2], photonic crystals (PCs) have attracted considerable attention in recent years owing to their unique characteristics in physics as well as important potential applications in devices[3−7]. PCs potentially possess the ability to control spontaneous emission and propagation of light, as they exhibit photonic band structures due to multiple Bragg scatterings. When the periodicity is broken by introducing structural defects in the photonic band gap (PBG) of the constituent PCs, localized defect modes will appear inside the Bragg gap because of the change of the interference behavior of light, which leads to an unprecedented flexibility in the ability to control and manipulate light.

Recently, much attention has been paid to one-dimensional (1D) defective PCs[6−13] because of their well-known properties as well as easy fabrication. Defective PCs, which possess narrow pass band with high transmittance, are usually used as narrow bandwidth filters. Also, multiple-channeled phenomena of 1D periodic structures have attracted extensive interests[14−16]. However, in such structures, the frequencies of defect modes will blue-shift with the increase of the incident angle, i.e., some higher frequencies will transmit at oblique incidence, as shown in Fig. 1. This means that light of unwanted frequencies cannot be cut off at some incident angles, which will restrict the application of these multi-channel filters. In other words, such filters only have a function of frequency filtering at perpendicular incidence, while at oblique incidence they do not work. It makes many weak optical signals difficult to be detected as the result of the intense ambient light from other directions. For some outdoors detections, people usually use a long tube to serve as a spatial filter. But in certain cases, it is necessary to limit the weight of the filter, such as the interstellar or atmosphere optical communication, and the anti-jam system of missile weapon. In these applications, the narrow bandwidth filters in common use can serve for filtering perpendicular incidence light, but they cannot play the role of spatial filters. For some applications, such as multi-channel interstellar or atmosphere optical communication, the filters with both functions of multi-channel narrow frequency filtering and sharp angular spatial filtering are in urgent need.

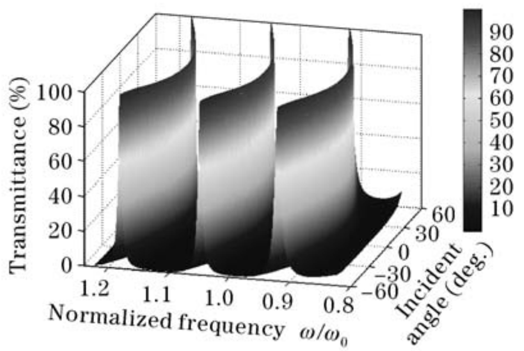

Fig. 1. Transmission spectrum of conventional heterostructure $(\mathrm{HL})^2 14\mathrm{H}(\mathrm{LH})^2$, $n_{\mathrm{H}} = 3.4$, $n_{\mathrm{L}} = 1.45$.

In this research, based on combining two PCs with different defects, a new filter is proposed to function multi-channel filtering and sharp angular spatial filtering simultaneously. The 1D defective structures in this present work can be expressed as $(\mathrm{HL})^S\mathrm{C}(\mathrm{LH})^S$, where L and H denote the dielectric layers of two materials; C=mA represents the defect layer, A denotes the dielectric material, m determines the optical thickness of the defect; S is the number of the period. The frequency of the defect mode in this structure is determined by[17]

$$\frac{\varphi_1 + \varphi_2 + 2\delta_c}{2} = k\pi \qquad (k = 0, \pm 1, \pm 2, \cdots), \tag{1}$$

where φ_1 and φ_2 are the phase shifts of the reflection for two sides of the defect layer; $\delta_c = (mg\pi)/2$ denotes the phase thickness of defect layer, g is the wave number. As to k order of interference, Eq. (1) can be written as

$$\varphi_1(g_k) + \varphi_2(g_k) + m \cdot \frac{\pi}{2} g_k = 2k\pi \quad (k = 0, \pm 1, \pm 2, \cdots). \tag{2}$$

It shows that the order of interference changes with the different value of m, that is, the frequency of the defect modes can be modulated by adjusting the optical thickness of the defect. At normal incidence, the width of the

PBG of PCs is expressed as[17]

$$2\Delta g_0 = \frac{4}{\pi}\arcsin\frac{n_{\mathrm{H}} - n_{\mathrm{L}}}{n_{\mathrm{H}} + n_{\mathrm{L}}}. \tag{3}$$

It is well known that if the channel interval of defect modes satisfies with the condition of $|g_1 - g_0| < \Delta g_0$, these defect modes g_k ($k = 0, \pm 1, \pm 2, \cdots, \pm i$) will appear within the PBG of PCs. The number of defect modes is $N = 2i$ or $N = 2i+1$, or the channel interval of adjacent defect modes $\Delta g_k = |g_{k\pm 1} - g_k|$ is determined by the thickness and refractive index of the defect.

The different defect layers in two 1D PCs with the same structure will result in different defect frequencies at oblique incidence. If the defect modes of the two 1D PCs have the same defect frequency at normal incidence (θ_0), they will be different at oblique incidence. Combining these two defective PCs to form a photonic heterostructure, i.e., $(\mathrm{HL})^S\mathrm{C}_1(\mathrm{LH})^S(\mathrm{LH})^S\mathrm{C}_2(\mathrm{HL})^S$, as shown schematically in Fig. 2, the result will be that only light with one channel at normal incidence can propagate through the combined structure, whereas lights with any channel are blocked at oblique incidence[6,7]. Here, the optical thicknesses are $\mathrm{H} = \mathrm{L} = n_{\mathrm{H}}d_{\mathrm{H}} = n_{\mathrm{L}}d_{\mathrm{L}} = \lambda_0/4$, $\mathrm{C}_1 = m\mathrm{H}$ and $\mathrm{C}_2 = m\mathrm{L}$. When m is large enough, every sub-PCs have multi-defect modes. As an example, we figure out the angle-dependent band gaps and defect modes of two types of defective PCs (type I: $(\mathrm{HL})^4 9\mathrm{H}(\mathrm{LH})^4$, type II: $(\mathrm{LH})^4 9\mathrm{L}(\mathrm{HL})^4$, $n_{\mathrm{H}} = 3.4$, and $n_{\mathrm{L}} = 1.45$), as shown in Fig. 3. It is shown that two defect modes fall into the band gap of the photonic structure in all incident angles. Next, it will be demonstrated that these multi-defect modes can transmit at normal incidence simultaneously, and are blocked in other directions, i.e., multi-channel sharp angular spatial filters are realized.

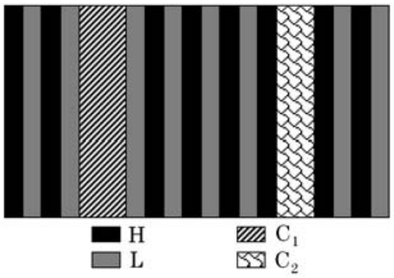

Fig. 2. Schematic sketch of the photonic structure.

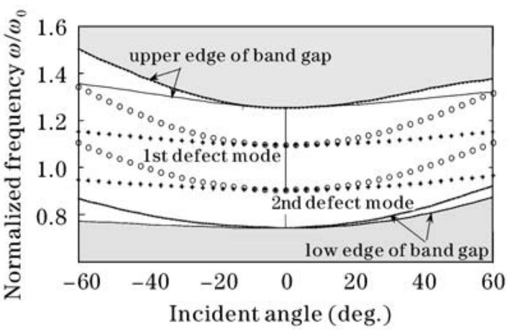

Fig. 3. Angle-dependent band gaps and defect modes of two types of defective PCs (type I: $(\mathrm{HL})^4 9\mathrm{H}(\mathrm{LH})^4$, type II: $(\mathrm{LH})^4 9\mathrm{L}(\mathrm{HL})^4$, $n_{\mathrm{H}} = 3.4$, $n_{\mathrm{L}} = 1.45$). The crossed and circled curves in the band gaps represent the photonic structures (type I and type II), and the solid and dashed lines represent the gap-edge of photonic structures (type I and type II), respectively.

The choice of the design parameter for the multi-channel sharp angular spatial filters is depicted as follows. Firstly, the design structure must be an omnidirectional reflector (ODR), which can exihibit high reflectivity for all incident angles, in which the larger the S, the broader the omnidirectional bandwidth and the sharper the defect band are. Secondly, the choice of the value of m depends on the required parameters of the filter, such as frequency and frequency space. Generally, the larger the m is, the more modes within ODR will appear. Thirdly, we select the quarter-wavelength stacks as the underlying periodic structure, which approximately reaches the maximum range of omnidirectional reflection of 1D PCs. Moreover, the higher the ratio of the high refractive index to the low one is, the broader the ODR band is[17].

On the basis of the above analysis, Si and $\mathrm{SiO_2}$ are chosen as high and low refractive index meterials for design, and their refractive indices are supposed to be $n_{\mathrm{H}} = 3.4$ and $n_{\mathrm{L}} = 1.45$, respectively. As example, filters with both spatial and multi-channel functions, including two channels, three channels, and eight channels, are studied by selecting the relevant values of m and S. The transmittance curves of these heterostructures, which are theoretically calculated by the transfer matrix method[17], are shown in Figs. 4—6, respectively.

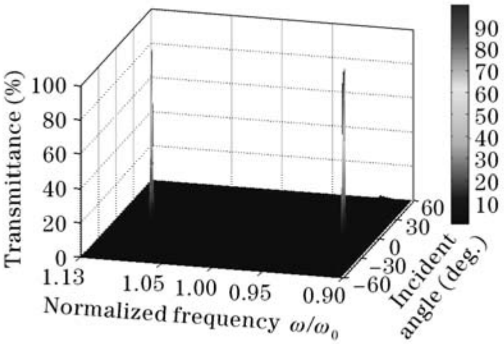

Fig. 4. Theoretical calculation results of frequencies and incident angle-dependent transmittance of structure $(\mathrm{HL})^4\mathrm{C}_1(\mathrm{LH})^4(\mathrm{LH})^4\mathrm{C}_2(\mathrm{HL})^4$ ($\mathrm{C}_1 = 9\mathrm{H}$, $\mathrm{C}_2 = 9\mathrm{L}$, $n_{\mathrm{H}} = 3.4$, $n_{\mathrm{L}} = 1.45$).

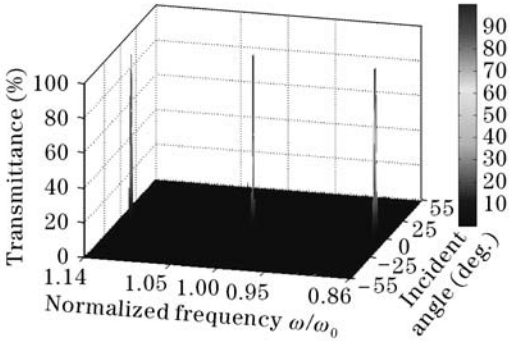

Fig. 5. Theoretical calculation results of frequencies and incident angle-dependent transmittance of structure $(\mathrm{HL})^4\mathrm{C}_1(\mathrm{LH})^4(\mathrm{LH})^4\mathrm{C}_2(\mathrm{HL})^4$ ($\mathrm{C}_1 = 14\mathrm{H}$, $\mathrm{C}_2 = 14\mathrm{L}$, $n_{\mathrm{H}} = 3.4$, $n_{\mathrm{L}} = 1.45$).

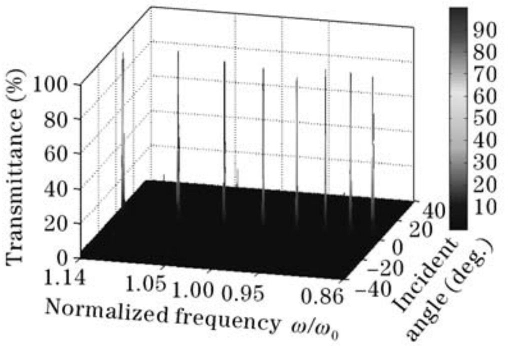

Fig. 6. Theoretical calculation results of frequencies and incident angle-dependent transmittance of structure $(\mathrm{HL})^4\mathrm{C}_1(\mathrm{LH})^4(\mathrm{LH})^4\mathrm{C}_2(\mathrm{HL})^4$ (C_1 = 51H, C_2 = 51L, $n_\mathrm{H} = 3.4$, $n_\mathrm{L} = 1.45$).

For two-channel filter, it is designed that C_1 = 9H, C_2 = 9L, and $S = 4$. As shown in Fig. 4, in the channel range of $0.87\omega_0 - 1.13\omega_0$ and in all incident angles, only two channels of light with narrow pass bands of $(0.91 \pm 0.0001)\omega_0$ and $(1.10 \pm 0.0001)\omega_0$, respectively, are allowed to pass within sharp incident angle breadth of $(0° \pm 3°)$.

For the three-channel filter, C_1 = 14H, C_2 = 14L, and the period number $S = 4$ are chosen. Figure 5 shows three defect modes within narrow frequency pass band of $(0.87\pm0.0001)\omega_0$, $(1.00\pm0.0001)\omega_0$, and $(1.13\pm0.0001)\omega_0$ in the channel range of $0.86\omega_0 - 1.14\omega_0$ and with sharp pass angle breadth of $(0° \pm 3°)$ in all incident angles.

More defect modes will be formed with the increase value of m when we select the parameter C_1 = 51H, C_2 = 51L, and $S = 4$. From the results illustrated in Fig. 6, it can be seen that in the range of $0.86\omega_0 - 1.14\omega_0$ and all incident angles, eight defect modes appear within the narrow frequency pass band and sharp incident angle breadth of $(0° \pm 3°)$.

This kind of structure has a shortcoming that the error of the defect layers should be within 1% of its optical thickness, therefore it can be fabricated only with coating machines of high precision, such as that for dense wavelength division multiplexing (DWDM). These structures with multi-channel and sharp angular defect modes provide an excellent way to select useful optical signals at the desired incident angles from a broader band frequency.

The filters based on these structures can be utilized in the detections of weak outdoor optical signals. The outdoor ambient light is always very intense, and the traditional narrow frequency Fabry-Perot (F-P) filters in common use will allow shorter wavelength ambient light to enter the detector at oblique incidence. The ambient light can be much more intense than the signals. For some outdoor detections, people usually use a long tube to serve as a spatial filter. But in certain cases, it is necessary to limit the weight of the filter, such as multi-channel interstellar or atmosphere optical communication. In these applications, this new type of filters will receive more attention.

Filters with the functions of narrow frequency multi-channel pass band and sharp angular pass breadth in visible and near infrared regions are designed by combining two different 1D defective PCs. The channels, channel interval, and number of channels can be tuned by adjusting the geometric and physical parameters of the heterostuctures, and both the defects and the periodic structure are integral times of quarter-wavelength layers. The ambient light of both out of the signal frequency and out of the signal incident direction will be cut off by this type of filters. The development of multi-channel interstellar or atmosphere optical communication is potential to be activized by such filters.

This work was supported by the National Natural Science Foundation of China (No. 10274108), the National "973" Project of China (No. 2004CB719804), the National "863" Project of China (No. 2003AA311022), and the Natural Science Foundation of Guangdong Province of China. H. Wang is the author to whom the correspondence should be addressed,his e-mail address is stswhz@zsu.edu.cn.

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