Broadening of Non-Transmission Band of Ultra-Narrow Band-Pass Filters Using Heterostructures *

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Transmission characteristics are studied for the hybrid structures combining defect and multiple heterostructures. It is shown that the non-transmission frequency range can be substantially enlarged and the phenomenon of narrow band-pass filter can be realized by adjusting the number, position and size of the defect. The theoretical and experimental results on heterostructures containing Ta_2O_5/SiO_2 multilayer films are presented. With perfect non-transmission frequency range and high peak transmissivity, this structure opens a promising way to fabricate ultra-narrow band-pass filters with wide non-transmission frequency range.

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Photonic crystals (PCs) exhibiting photonic band structures due to multiple Bragg scatterings, have received considerable attention in recent years because of their intrinsic physical properties as well as important potential applications in devices.[1−5] In the PCs, there may exist photonic band gaps, in which the propagation of electromagnetic waves is strongly inhibited. If the photonic band gaps of the constituent PCs are aligned properly, quantum wells will appear and the number of confined states can be tuned, leading to the phenomenon of narrow band-pass filtering. Narrow band-pass filtering phenomena of one-dimensional periodic structures have been studied extensively.[6−8] However, in such structures, the non-transmission sideband is limited by the material properties. With certain materials, the forbidden band becomes deeper with increasing layer numbers, whereas the sidebands cannot be confined. Thus the application of the narrow band-pass filters is restricted. The periodic structures can, however, be optimized by introducing defects in multiple heterostructures.[11−13]

If several one-dimensional PCs with different layer thickness are combined, multiple heterostructures are formed. Since different crystals have different band gap widths, multiple heterostructures can show many characteristics, for example the non-transmission frequency range can be enlarged in contrast to that without using heterostructures.[9] If defects are introduced in multiple heterostructures, some isolated modes in the whole band gap can be modulated in an analogous way to semiconductors, so band-pass filtering phenomena can be produced. The transmission spectra are calculated by using the transfer matrix method.[10]

The heterostructures containing defect is schematically shown in Fig. 1, where A, B, and E etc. are different PCs with different periodic thicknesses, D is the defect introduced in the heterostructures. In the experiment, Ta_2O_5 and SiO_2 are chosen as high and low refractive index media, and their refractive indices are supposed to be $n_H = 2.11$ and $n_L = 1.48$ respectively. The optical thickness is $1\,H = 1\,L = n_H d_H = n_L d_L = \lambda_0/4$, where d_H and d_L are the physical thickness of Ta_2O_5 and SiO_2 respectively, $\lambda_0 = 494\,nm$. The incident medium and substrate are air and Crown glass ($n = 1.52$), respectively. The incident angle is 0°.



Fig. 1. Schematic of the calculated heterostructures containing defect. A, B and E are three different one-dimensional crystals with different thicknesses, respectively. D is a defect layer.

The calculated transmission spectrum shown in Fig. 2 is for the heterostructure inserted with defect, $(0.6H0.6L)_3$ $(0.7H0.7L)_4$ $(0.8H0.8L)_6$ $(0.9H0.9L)_9$ $(1H1L)_{13}$ $(1.2H1.2L)_{10}$ $(3.6H5.4L)_1$ $(1.3H1.3L)_4$ $(1.4H1.4L)_6$ $(1.5H1.5L)_3$ $(1.6H1.6L)_4$, where the subscript symbols are the period number in the structure, respectively. The transmissivity peak is 98.4% at the wavelength 633 nm and the non-transmission wavelength range is 400–750 nm. It is shown that the heterostructure containing defect forms a wide forbidden band beside the transmission peak compared

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to the Fabry–Perot structure, owing to the overlap of the forbidden band of the PCs which are properly arranged. It is obvious that the non-transmission frequency range can be enlarged as desired by choosing proper multiple heterostructures.[11,12] Different band structures are thus obtained by introducing defects in the heterostructures shown in Fig. 1 and the defects energy level can be shifted among the band structure.

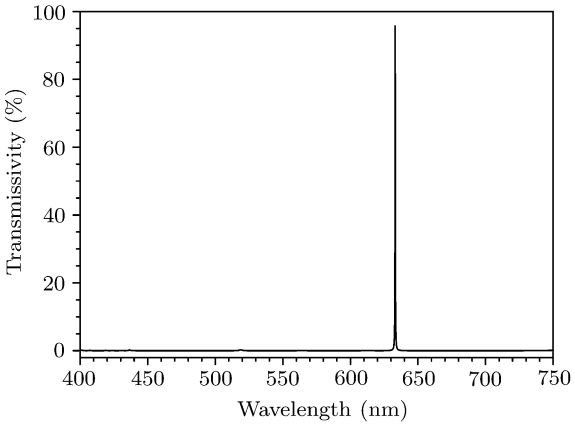


Fig. 2. Calculated transmission spectra for the designed structure.

The structure discussed here is similar to the periodic one-dimensional crystals containing cavities. By introducing defects into the PCs, it is possible to obtain highly localized cavity modes inside the photonic forbidden band, which is analogous to the impurity states inside the semiconductor band gap.[4] Because of the existence of the defects, the localized cavity modes will transmit as resonant tunnelling and it is possible to obtain highly resonant modes inside the photonic band gap. The sidebands of the periodic structures can be restricted by adopting the heterostructures. Since the isolated modes in the forbidden band are modulated by the defects, we can adjust the geometric and physical parameters of the defects in order to reach a resonant tunnelling mode for certain resonant electromagnetic wave and heterostructures, which enhances light transmission. The symmetrical characteristic and energy of the potential barrier mainly influence the transmission band and peak value. Thus these structures provide an excellent way to select useful optical signal from a broader band frequency.

The film was fabricated on a crown glass substrate by using a Veeco dual ion-beam sputtering system. Before deposition, the vacuum chamber was evacuated to lower than 2.0×10^{-6} Torr. The physical thickness of layers was controlled by time-power method. The transmission spectra of the films were measured by using a Lambda-900 spectrophotometer in the wavelength range from 200 to 2000 nm.

From the theoretical result, we can see that the half width of transmission peak is ultra-narrow, approximately 0.2 nm. In order to measure the non-transmission wavelength range of the sample, the slit width and scan speed of the spectrophotometer were adjusted to 2 nm and 5 nm/min, respectively. The measured and calculated transmission spectra are shown in Fig. 3. Figure 3(a) exhibits the result in quite good agreement with the theoretical values, except for the low transmission peak, which is mainly caused by the large slit width of the spectrophotometer. We narrowed the slit width to 0.05 nm but the scan speed was unchanged, the measured spectrum is shown in Fig. 4. It is shown that the transmission is 95.6% at the wavelength 633 nm, though the measured transmission band is wider than the theoretical value, which may be caused by the difference of material dispersive property between calculation and experiment. This condition can be improved by modifying the experiment parameters. In this study, we obtain the result better than that reported in Ref. [12]. It can be seen from Figs. 3 and 4 that the structure we fabricated owns broad non-transmission band and ultra-narrow transmission band.

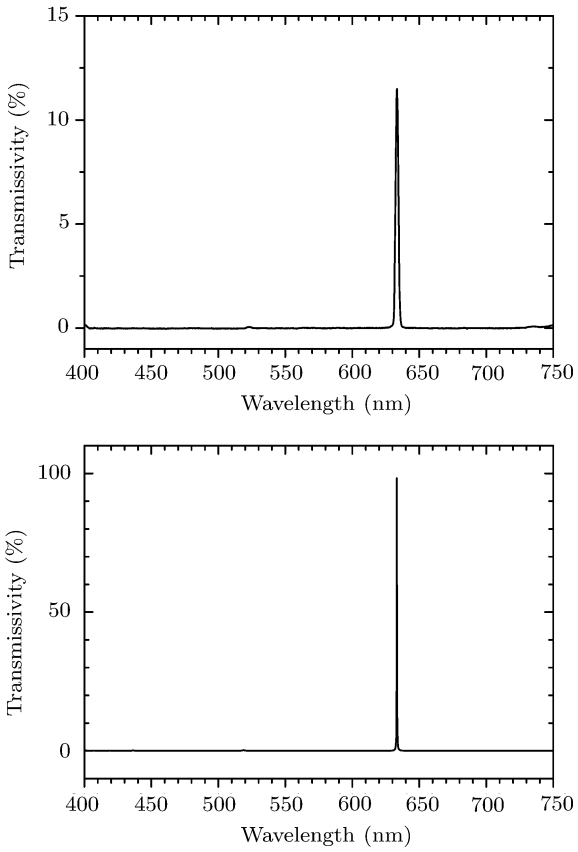


Fig. 3. (a) Measured transmission spectrum and (b) calculated transmission spectra. Here the slit width is 2 nm and the scan speed is 5 nm/min.

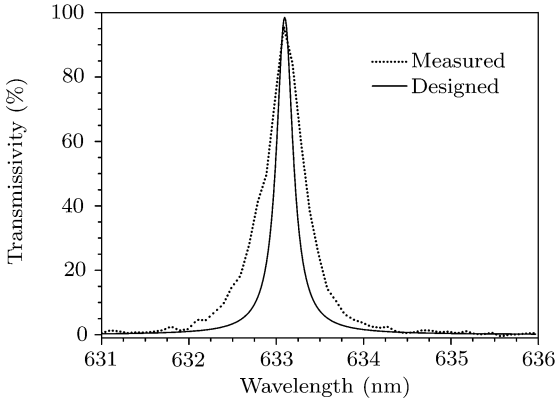


Fig. 4. Measured transmission spectrum and calculated transmission spectra for the slit width 0.05 nm.

Ultra-narrow band-pass filtering with wide non-transmission frequency range and high transmissivity, which cannot be obtained by using metal-dielectric Fabry–Perot structure, has been investigated. It is shown that the non-transmission frequency range beside the transmission peak can be restricted by adopting multiple heterostructures, and the position of the transmission peak can be changed by adjusting the geometric and physical parameters of the defects. This structure opens a promising way to design and fabricate ultra-narrow band-pass filters with wide non-transmission frequency range.

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