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Selectable-frequency and tunable-*Q* perfect transmissions of electromagnetic waves in dielectric heterostructures

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Multiple perfect transmissions of electromagnetic waves are found in the photonic band gap of the symmetric dielectric heterostructures (SDH) constructed as $(AB)^nB^m(BA)^n$, where A and B stand for different dielectric materials, and m and n are the repeating numbers of the units. The photonic frequency and the mode number of resonant transmissions therein can be manipulated by varying m, and the quality factor Q of the perfect transmission peak increases exponentially with increasing n. These features are experimentally demonstrated in a SDH of TiO_2/SiO_2 for visible and near infrared light. The possible applications of SDH for the wavelength division multiplexing system are discussed. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1748848]

The propagation of electromagnetic waves in dielectric multilayers has been studied for a long time.[1] Recently, the interest is rekindled due to the concept of photonic crystals (PCs) proposed by Yablonovitch[2] and John[3] in 1987. Essentially photonic crystals are the periodic arrays of dielectric materials with a sufficiently strong contrast of refractive indexes. The PCs forbid the propagation of photons with a certain range of energies known as the photonic band gap (PBG). This feature makes PCs a potentially important material for optoelectronics and optical communications.[4,5] To fabricate three-dimensional photonic crystals, however, remains a formidable task. Yet fabrication of dielectric multilayer films, which can be regarded as one-dimensional (1D) PCs in some cases, is much easier. Recently, it has been recognized that a 1D PC can achieve an omnidirectional PBG under proper conditions[6] and it is possible to realize the tunable PBG devices in a 1D case.[7] This makes the studies on dielectric multilayer films even more interesting.

In this letter, we present the resonant transmission of electromagnetic wave in the symmetric dielectric heterostructure (SDH) as

$$S(n,m)=(AB)^nB^m(BA)^n, \tag{1}$$

where A and B are two kinds of dielectric materials, and m and n are the repeating numbers of the units. We found that multiple perfect transmissions occur in the PBG of this SDH. The perfect transmission originates from the internal symmetry of heterostructure and the modulation of optical thickness. The mode number, the photonic frequency, and the quality factor Q of the resonant transmissions are related to the structural setting, which can be described with a ''phase diagram.'' To demonstrate this, multilayers of TiO_2/SiO_2 have been fabricated according to the structural requirement of the SDH. Optical measurements are in agreement with theoretical predictions. It is noteworthy that by designing the SDH purposely, resonant transmissions can appear at any desired wavelength range of electromagnetic waves. Here we show that with SDH $S(7,7)$, resonant modes may appear within the same photonic band gap on the wavelengths of 1.55 and 1.3 μm, which are the wavelengths currently used for telecommunication. We therefore suggest that we have found a method to create controllable multifrequency outputs with high transmission and high Q.

In order to tune perfect transmissions in the PBG, we design a structure of SDH as $S(n,m)$ [shown in Eq. (1)]. There are several advantages in this aperiodic symmetric multilayer. (i) The PBG occurs because of the substructures of $(AB)^n$ and $(BA)^n$, and the width of the PBG depends on the ratio of refractive indices n_A/n_B. (ii) An internal symmetry exists in the structure, which is expected to induce the perfect transmission peaks.[8,9] (iii) The central part B^m controls the number and the wavelength of the perfect transmission peaks in the PBG according to the optical thickness modulation. (iv) The quality factor Q of perfect transmission peak depends on the size of substructures, i.e., ''$(AB)^n$'' and ''$(BA)^n$.''

The propagation of electromagnetic wave through SDH obeys Maxwell equations and satisfies the boundary condition at the interface. With the transfer matrix method,[10] the optical transmission through the SDH can be calculated numerically. As an example, we choose dielectric materials titanium dioxide (TiO_2) and silicon dioxide (SiO_2) as A and B, respectively. The indices of refraction are $n_A=2.30$ for TiO_2 and $n_B=1.46$ for SiO_2. The layer thicknesses of A and B are designed to satisfy $n_Ad_A=n_Bd_B$, therefore the optical phase shift through each dielectric layer is the same, i.e., $\delta_A=\delta_B=\delta$. In the case of normal incidence and polarization parallel to the multilayer surfaces, we have calculated the transmission coefficient of the SDH $S(4,m)$ for different m. We find that in the case of even m, there are odd peaks of perfect transmission in the PBG. Figures 1(a)–1(d) give the transmission coefficient T as a function of the optical phase δ in the interval $[0,\pi]$ for the SDH of $S(4,m)$, and m is selected as $m=2$, 10, 20, 30, respectively. Corresponding to these scenarios, there exist $2i+1$ ($i=0,1,2,3$) peaks within the PBG [as shown in Figs. 1(a)–1(d)]. Whereas in the case of odd m, an even number of perfect transmissions occur in the PBG. For example, when the SDH has $m=5$, 15, 23, 31,

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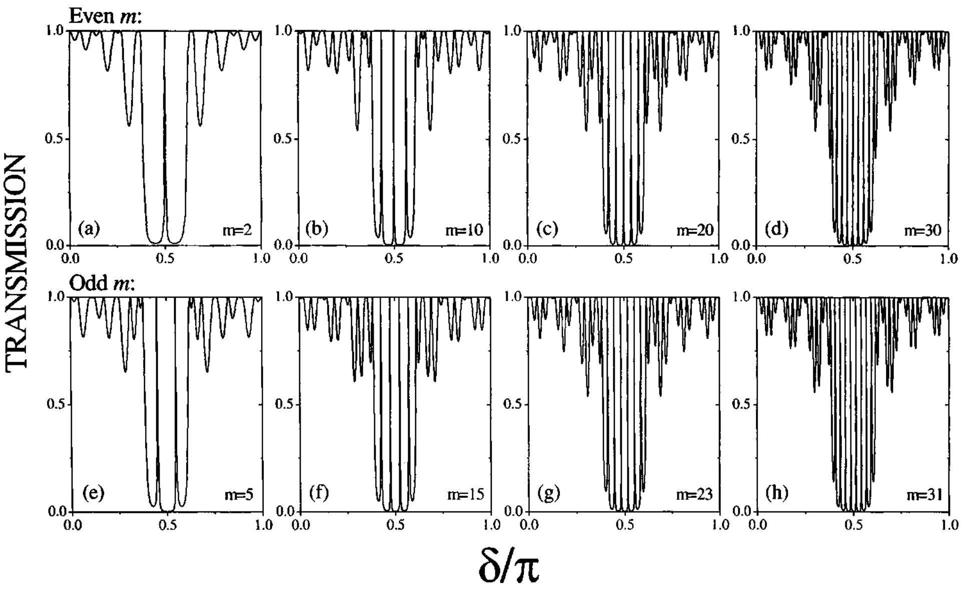

FIG. 1. Calculated transmission coefficient T as a function of the optical phase δ/π for the SDH with $S(4,m)$. For even m (a) $m=2$, (b) $m=10$, (c) $m=20$, (d) $m=30$, respectively. For odd m (e) $m=5$, (f) $m=15$, (g) $m=23$, (h) $m=31$, respectively. The refractive indices of the two materials are chosen as $n_A=2.3$ and $n_B=1.46$, respectively.

correspondingly $2i$ ($i=1,2,3,4$) peaks appear in the PBG in Figs. 1(e)–1(h). Therefore, we conclude that by increasing m, more and more perfect transmission peaks appear in the 1D PBG of the SDH, and the density of peaks in the PBG increases. Now we define the optical phase of the nearest peak to $\delta_0=\pi/2$ as δ_1. Figure 2(a) illustrates the relation between δ_1 and m in the SDH $(AB)^nB^m(BA)^n$ with $n=3$, 4, and 8, respectively. Obviously, the nearest peak to $\delta_0=\pi/2$ gradually approaches the center of the PBG when m increases. For example, in the SDH of $S(4,m)$, the nearest peaks to $\delta_0=\pi/2$ locate approximately at $\delta_1\cong\delta_0+0.014\pi+0.067\pi\exp(-m/7.72)$, where m (even) is the number of B in central part of the SDH with $n=4$. By increasing n, the number of peaks in the PBG does not change and the peak position only shift slightly [as shown in Fig. 2(a)]. However, increasing n may lead to a significant change of the quality factor Q of the peak, which is defined as $Q=\Delta\lambda/\lambda_0$, and λ_0 is the wavelength of the peak and $\Delta\lambda$ is the half width of the peak, respectively. Figure 2(b) shows the relation between the quality factor Q of the peak in the PBG and n in the SDH $S(n,10)$. It is obvious that the quality factor of peak increases exponentially by increasing n in the SDH. Accordingly, Fig. 2 can be regarded as a "phase diagram" which presents the modes of perfect transmissions and the corresponding structure in the family of SDH $[S(n,m)]$. Therefore, the perfect transmissions with high-Q can be manipulated at the specific wavelengths by structural design of the SDH.

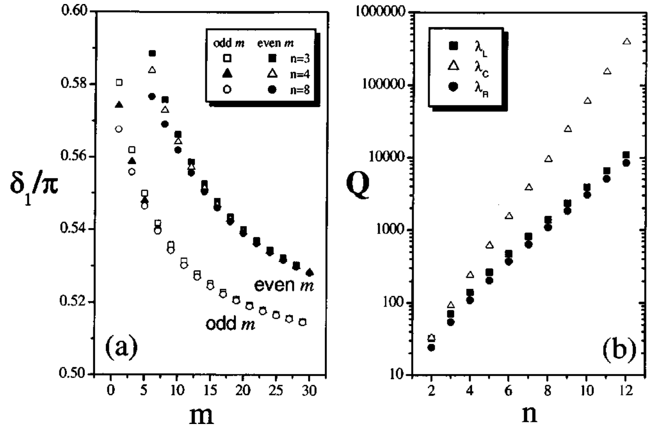

FIG. 2. (a) The relation between δ_1 and m in the SDH $(AB)^nB^m(BA)^n$ with $n=3$, 4, and 8, respectively. δ_1 is the optical phase of the nearest peak to $\delta_0=\pi/2$ and we focus on the peak with $\delta_1>\delta_0$. (b) The relation between the quality factor Q of the peak in the PBG and n in the SDH with $S(n,10)$, where the central wavelength is set to be $\lambda_C=700$ nm. The wavelengths of the three peaks in the PBG of $S(n,10)$ are $\lambda_L\cong622$ nm, λ_C, $\lambda_R\cong800$ nm, respectively.

In the experiments, titanium dioxide and silicon dioxide are used as dielectric materials A and B, respectively. Their refractive indices are $n_A=2.30$ and $n_B=1.46$ for the wavelength of 700 nm. By the electron-gun evaporation method, SDH TiO_2/SiO_2 films were fabricated on the glass substrate. Before evaporation, vacuum of the chamber was better than 2×10^{-5} Torr. The film was formed under an oxygen atmosphere. The pressure was 0.8×10^{-4} Torr for SiO_2 deposition and 2×10^{-4} Torr for TiO_2. The thickness of the film was controlled by quartz-crystal monitoring at a frequency of 5.0 MHz, and also the quarter-wave and half-wave optical thicknesses were optically monitored. The thicknesses of two materials in the film were chosen to satisfy $n_Ad_A=n_Bd_B$, which gives the same phase shift in the two materials, i.e., $\delta_A=\delta_B=\delta$. The central wavelength was set to 720 nm which gives $d_A\approx(720\text{ nm})/4n_A\approx78.3$ nm, and $d_B\approx(720\text{ nm})/4n_B\approx123.3$ nm.

Optical transmission spectra were measured by PerkinElmer Lambda 900 spectrophotometer in the range of wavelength from 175 to 3000 nm. Figure 3 shows the measured and calculated transmission coefficients as a function of wavelength in the SDH of $S(4,m)$ in the photonic band gap. In the SDH with an even number of m, for example, $m=2$, 10, 20, an odd number of transmission peaks (1, 3, and 5) occur in the PBG [shown in Figs. 3(a)–3(c)]. For the SDH with an odd number of m ($m=5,15,23$), there are 2, 4, 6 transmission peaks in the PBG, respectively, as shown in Figs. 3(d)–3(f). The experimental results are in good agreement with the numerical calculations. For example, the resonant modes of the SDH with $S(4,10)$ are located at 641.3, 721.3, and 820.6 nm in the PBG, respectively, [shown in Fig. 3(b)]. The transmission coefficients are observed as 77.7%, 80.0%, and 96.4%, respectively. Their quality factors Q are

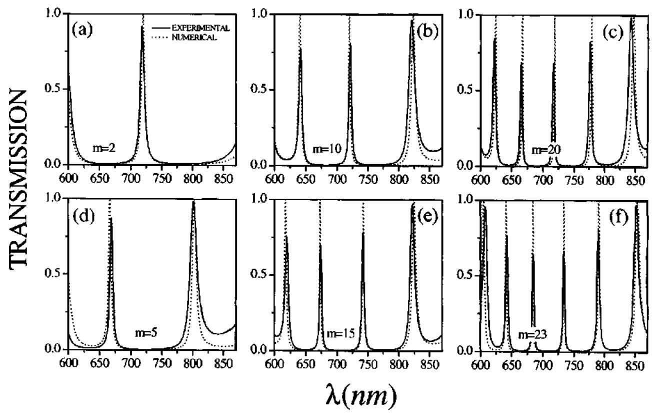

FIG. 3. Measured and calculated transmission coefficient T as a function of the wavelength λ in the photonic band gap for the TiO_2/SiO_2 SDH films. The SDH of $S(4,m)$ with even m (a) $m=2$, (b) $m=10$, and (c) $m=20$, respectively. The SDH of $S(4,m)$ with odd m (d) $m=5$, (e) $m=15$, and (f) $m=23$, respectively.

measured as 110, 150, 73, respectively. These Q values are reasonably comparable with the numerically calculated $Q=146$, 248, 112. The quality factor of the transmission peak exponentially increases if we increase the value of n in the SDH with $S(n,10)$ [as shown in Fig. 2(b)]. The resonant transmissions in the PBG may originate from the mirror symmetry in internal structure[9] and the modulation of optical thickness[11] in the SDH.

It is enlightening that resonant transmissions can be tuned to the specific wavelengths. Consider a SDH with $S(7,7)$, in which the refractive indices of dielectric material A and B are $n_A=2.70$ and $n_B=1.45$, and the layer thickness of A and B are $d_A=130.9$ nm and $d_B=243.8$ nm, respectively. Numerical calculation shows that the perfect transmission takes place on wavelength 1.55 and 1.30 μm, respectively, within the same photonic band gap (shown in Fig. 4). These two wavelengths are exactly the ones that are used for telecommunication. The quality factors Q are as high as 14 968 and 12 511 according to the calculation of the transfer-matrix method. By increasing n in the SDH $S(n,7)$, Q will increase exponentially. The experimental realization of this interesting numerical prediction is currently in progress.

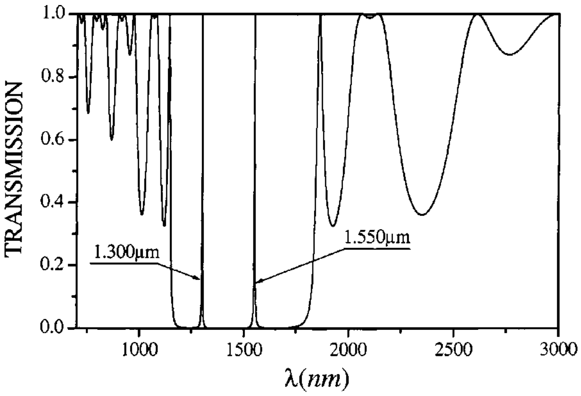

FIG. 4. Calculated transmission coefficient T as a function of the wavelength λ for the SDH with $S(7,7)$, where the refractive indices of dielectric material A and B are $n_A=2.7$ and $n_B=1.45$, and the layer thickness of A and B are $d_A=130.9$ nm and $d_B=243.8$ nm, respectively. The perfect transmissions are found at two telecom wavelengths of 1.55 and 1.30 μm in the same photonic band gap.

To summarize, the SDH structured as $(AB)^n B^m (BA)^n$ has been designed and fabricated, which has tunable perfect transmissions in the photonic band gap. With the SDH films of TiO_2/SiO_2 we demonstrate that this type of structure possesses perfect transmissions in the photonic band gap with selectable frequency and tunable Q. Meanwhile, the perfect transmission occurs in the visible and near infrared regions of electromagnetic waves. By select proper structure and material, we suggest that the perfect transmission may take place at any region of the electromagnetic wave. To demonstrate this, we show numerically that the resonant modes can be obtained within the same photonic band gap of the SDH on the wavelengths of 1.55 and 1.3 μm, which are exactly the wavelengths for telecommunications. Our work presents a way to control high-transmission and high-Q multifrequency outputs, and has potential applications in the wavelength division multiplexing system, photonic integrated circuits, and the multiwavelength narrow-band optical filters.

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