Large frequency range of negligible transmission in 1D photonic quantum well structures

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We show that it is possible to enlarge the range of low transmission in 1D photonic crystals by using photonic quantum well structures. If a defect is introduced in the photonic quantum well structures, defect modes with a very high quality factor may appear. The transmission of the defect mode is due to the coupling between the eigenmodes of the defect and those at the band edges of the constituent photonic crystals.

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Since the work of Yablonovitch[1] and John[2] photonic band-gap (PBG) materials have received considerable attention for fundamental physics study as well as for potential applications in photonic devices. In PBG materials with any number of dimensions, the dispersion relations (frequency versus wave-vector) possess a number of branches. These branches form bands that might be separated by frequency gaps owing to the periodic dielectric modulation, analogous to the electronic band-gaps in semiconductors due to the periodic potentials. Within a frequency gap electromagnetic (EM) waves cannot propagate. The idea that 1D, 2D, and 3D periodic dielectric lattices can be designed to possess PBGs has attracted wide interest, both theoretically and experimentally. The absence of EM waves inside a PBG can lead to some unusual features, which have many potential applications and novel physics. By adjusting the geometric and dielectric parameters of a photonic crystal, we can tailor the optic properties at will, the same way as in semiconductor technology.

It is well known that many novel features for electronic properties appear when two semiconductors form superlattice (SL) or quantum well (QW) structures. In this letter, a transfer matrix method is used to study the band structures of 1D periodic photonic structures and transmission of photonic multilayers. We show that a large frequency range of very low transmission exists in 1D photonic QW structures. By introducing a defect, defect modes with very large quality factor may appear. The physical meaning of the two matrices is that \( P \) propagates the electric field a distance \( \Delta x \) in a uniform medium, whereas \( Q \) makes the electric field from one side of an interface to the other. It is easy to show that for an \( AB \) SL the band structures can be obtained by applying the Bloch theorem

\[
T(0,d)E(x|\omega) = E(x+d|\omega) = e^{ikd}E(x|\omega),
\]

where \( d \) and \( k \) are the period and wave-vector of the SL, respectively. The eigenfrequency is then obtained from

\[
\cos(kd) = |T_{11}(0,d) + T_{22}(0,d)|/2,
\]

where \( T_{ij} \) is the element of the \( 2 \times 2 \) transfer matrix. The transfer matrix for an \( AB \) SL is given by

\[
T(0,d) = Q_{BA}P_{B}(d_B)Q_{AB}P_{A}(d_A),
\]

where \( d_A \) and \( d_B \) are the width of \( A \) and \( B \) layer, respectively and \( d = d_A + d_B \). After some algebra, it is easy to obtain the relation

\[
E(x|\omega) = \left( \begin{array}{c} E_{11}e^{ik_1x} \\ E_{12}e^{-ik_1x} \end{array} \right).
\]
\[
\cos(kd) = \cos(k_A d_A) \cos(k_B d_B) - \\
\frac{1}{2} \left( \eta_{A,B} + \frac{1}{\eta_{A,B}} \right) \sin(k_A d_A) \sin(k_B d_B). \tag{10}
\]

From the above relation, photonic band structures can be obtained.

For a multilayer dielectric structure, the total transfer matrix is given by

\[
T^{(N)} = Q_{N,N+1} \prod_{l=N}^{1} P_l(d_l)Q_{l-1,l},
\]

where \( N \) is the number of dielectric layers and \( d_l \) is the width of the \( l \)th layer. When one encounters \( N + 1 \) or \( 0 \) in the subscript of the matrices, the layer is treated as an air layer. From the total transfer matrix, the transmissivity \( t \) and reflectivity \( r \) are given by

\[
t = \left| \frac{T_{11}^{(N)} - T_{12}^{(N)}}{T_{21}^{(N)}} T_{22}^{(N)} \right|^2,
\]
\[
r = \left| \frac{T_{21}^{(N)}}{T_{22}^{(N)}} \right|^2. \tag{11}
\]

For lossless dielectrics, the condition \( t + r = 1 \) must be satisfied.

In Fig. 2, the band structures of photonic SLs, calculated by Eq. (10), is given. The SLs consist of an air and a dielectric layer alternatingly. PBGs appear in SLs due to the periodic modulation of the dielectric constant. The two SLs given in the figure consist of the same dielectric layers. The only difference is the filling factor, one (solid lines) 0.5 and the other one 0.32. The second and third band of the \( AB \) SL is just inside the first and second PBG of the \( CD \) SL, while the second band of the \( CD \) SL is just inside the second PBG of \( AB \) SL. The propagation of EM waves is forbidden in the PBGs. Therefore, we can use \( AB \) and \( CD \) multilayers to produce a QW structure, which may lead to a large frequency range with very small transmission.

We display in Fig. 2 the transmission of photonic QW structures \((AB)_n/(CD)_n/(AB)_m\), where \((AB)_m\) means that this multilayer consists of \( m \) sublayers of \( AB \). The transmission was calculated by Eq. (11). The \( CD \) layers play a role of well or barrier depending on the frequency of the EM wave. In the absence of \( CD \) layers (Fig. 2b) the second and third bands of \( AB \) multilayers have large transmission. With the introduction of a well or barrier layer \( CD \), the transmission of these bands is suppressed owing to the fact that these two bands are just inside the second and third PBGs of \( CD \) multilayer. For a small number of \( CD \) multilayers, there is still some transmission for the second and third band of the \( AB \) multilayer. With the increase in number of \( CD \) layers, the transmission of these bands is reduced rapidly. When the number of \( CD \) layers is greater than 10, the transmission is very small and can be neglected. In this case, a large forbidden gap for transmission exists with a very large range in reduced frequency from 0.16 to 0.72. With the photonic QW structures, by properly choosing the geometric and dielectric parameters, a large forbidden gap for transmission can be achieved, which may have potential applications. For instance, this structure can be used as a nearly perfect mirror that can reflect all visible light.

By introducing some defects in the photonic QW structures, defect modes can be induced, as shown in Fig. 3. It can be seen from the figure that the defect peak is very sharp with the quality factor as high as several thousands. This defect QW structure can be used as a microcavity or as a high quality filter. The very sharp transmissivities of the defect modes are due to the coupling between the eigenmodes in defect layers and those at the band edges of the \( AB \) or \( CD \) layers. Normally, the coupling between the eigenmodes of defects and those away from the band edges is very small. Therefore, in some cases, the transmission of a defect mode is very small if the coupling is small. This behavior is somewhat different from that in the usual dielectric multilayers.

In summary, 1D photonic QW structures have been suggested. By properly choosing the geometric and dielectric parameters of the photonic constituents, a large frequency range of negligible transmission of EM waves is possible, which may have potential applications. By introducing some defects in the photonic QW structures, defect modes with very large quality factors may appear. The sharp defect transmission peaks are due to the coupling between the eigenmodes of defect layer and those at the band edges of the constituents.

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FIG. 1. Photonic band structures of photonic SLs. The periodicity of the SLs is \( a \). Solid lines are for an \( AB \) SL with sublayer width \( d_A = d_B = 0.5a \) and dielectric constant \( \epsilon_A = 1, \epsilon_B = 13 \). Dashed lines are for an \( CD \) SL with \( d_A = 0.68a, d_B = 0.32a \) and \( \epsilon_C = 1, \epsilon_D = 13 \).

FIG. 2. Transmission of photonic QW structures \((AB)_n/(CD)_n/(AB)_m\). (a) \( n = 0 \), (b) \( n = 1 \), (c) \( n = 2 \), (d) \( n = 5 \), (e) \( n = 10 \).
FIG. 3. Transmission for photonic QW structures with defects. The QW structure is $(AB)_{10}/(CD)_{10}/(AB)_{10}$ and the defect is inserted in the middle of the $CD$ multilayers. (a) The defect is an $EF$ layer with $d_E = 0.6a$, $d_F = 0.4a$ and $\epsilon_E = 1$, $\epsilon_F = 13$. (b) The defect is a single layer with $d = 0.5a$ and $\epsilon = 1$. 
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