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TUNABLE MULTI-CHANNEL FILTERING USING 1-D PHOTONIC QUANTUM WELL STRUCTURES

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Abstract—In the present study, we show that it is possible to achieve multi-channel filters in one-dimensional photonic crystals using photonic quantum well structures. The photonic quantum well structure consists of different 1-D photonic structures. We use $(\mathrm{AB})_8/\mathrm{C}_n/(\mathrm{BA})_8$ structure, where A, B and C are different materials. The number of defect layers (C) can be utilized to tune the multi-channel filtering. The filter range can be tuned for desired wavelength with the change in angle of incidence for multi-channel filtering.

1. INTRODUCTION

During the last two decades, studies on photonic crystals (PCs) have drawn the interest of many researchers as the propagation of electromagnetic waves can be hugely modified by such structures [1, 2]. PCs are periodic array(s) of dielectric materials, generally, exhibiting characteristic electromagnetic stop bands known as photonic band gaps (PBGs). That is, the PCs can prohibit the propagation of electromagnetic waves whose frequencies lie within the PBGs. One-dimensional PC structures have many interesting applications such as dielectric reflecting mirrors, low-loss waveguides, optical switches, filters, optical limiters etc. It has been demonstrated theoretically and experimentally that specifically designed one-dimensional PCs exhibit absolute omnidirectional PBGs [3–10, 11].

Recently, tunable photonic filters [12–14] have attracted wide attention due to their applications in optical communication and ultra-fast optical processing. The quantity of information carried by an N channel filter is N times that of a single channel filter. Both semiconductor [15–17] and metal [18–20] quantum well (QW)

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structures have attracted tremendous attention in fundamental studies as well as possible technological applications. Thus, it is expected that their photonic counterparts, photonic quantum well (PQW) structure, are also attractive materials for intensive research [21–22]. Qiao et al. [22] proposed a kind of PQW structure by assembling different photonic crystals (PCs) with positive-index materials (PIMs). Through these structures, the photonic bandgaps (PBGs) can be enlarged effectively, and narrow multichannel filters can be obtained when the constituent PBGs are designed properly [23, 24]. For these structures, however, the resonance modes as well as the PBGs vary noticeably with different incident angles and polarizations.

In the present work, we show theoretically that it is possible to achieve multi-channel filters in 1-D photonic crystal using photonic quantum well structures. These multi-channel filters depend on the defects and the angle of incident light.

2. THEORETICAL MODELS

The multilayered structure consists of alternate layers of high and low refractive indices along the x-axis and placed between semi-infinite media of refractive indices n_i (refractive index of the incident medium) and n_s (refractive index of the substrate), as shown in Figure 1.

Applying the transfer matrix method (TMM), the characteristic matrices for the TE and TM waves have the form [25, 26]

$$M_j = \begin{bmatrix} \cos\beta_j & -\frac{i\cdot\sin\beta_j}{q_j} \\ -iq_j\sin\beta_j & \cos\beta_j \end{bmatrix} \tag{1}$$

where coefficients $q_j = n_j \cos\theta_j$, $(j = 1,\ 2)$ for the TE polarization

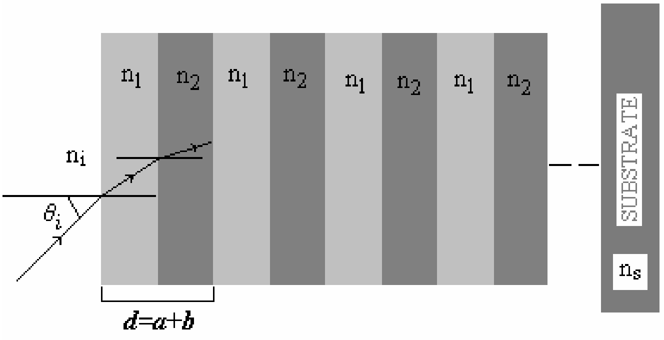

Figure 1. Schematic representation of multilayered structure.

and coefficients $q_j = \cos\theta_j/n_j$ for the TM polarization, $\beta_j = (2\pi/\lambda)n_j d_j \cos\theta_j$, θ_j is the ray angle inside the layer of refractive index n_j and λ is the wavelength of light in the medium of incidence. The total characteristics matrix for the N periods of the structure is given by

$$M = (M_j)^N = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{2}$$

The transmission coefficient of the structure for the TE and TM polarizations are given by

$$t = \frac{2q_i}{(M_{11} + q_s M_{12})q_i + (M_{21} + q_s M_{22})} \tag{3}$$

where coefficients $q_{i,s} = n_{i,s}\cos\theta_{j,s}$ for the TE wave and coefficients $q_{i,s} = \cos\theta_{j,s}/n_{i,s}$ for the TM wave, where the subscripts i, j and s correspond to the quantities in the incident medium, periodic medium of photonic crystal and substrate respectively. The transmission of the structure is given by

$$T = |t|^2 \tag{4}$$

The schematic representation of the proposed structure is shown in Figure 2. We consider a PQW structure having the following sequence — $(\mathrm{AB})_8/\mathrm{C}_n/(\mathrm{BA})_8$. For AB stack, we choose the thicknesses a and b for A and B materials, respectively. The thickness of the defect layer C is taken as d. The proposed structure leads to conventional PC for defect layer C as A in the present structure.

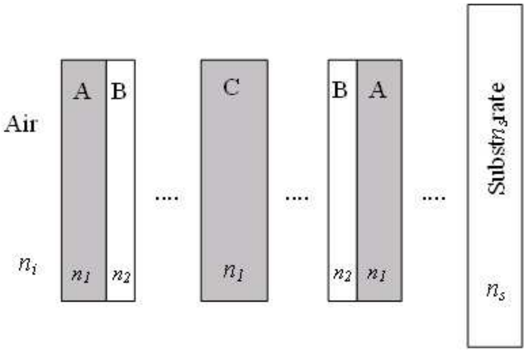

Figure 2. Schematic representation of PQW structure.

3. RESULTS AND DISCUSSION

In this section, numerical calculations on the transmission properties of the one-dimensional photonic crystals using Equation (4) have been presented. In the present work, we use $(AB)_8/(C)_n/(BA)_8$ structure, where $(AB)_8$ is the periodic multilayered structure consists of eight sub-layers of AB and $(C)_n$ consist of n sub-layers of C. For AB stack, we choose the material of layer A as TiO_2 and the material of layer B as SiO_2 having refractive indices 2.41 and 1.5 respectively. The incident medium is taken as air while the substrate is taken as glass. The substrate has been used to define the actual coupling of photonic filter device with other devices as per requirement. The thicknesses of the alternate layers are taken as $a = 182\,\text{nm}$ and $b = 291\,\text{nm}$ according to the quarter wave stack condition $a = \lambda_c/4n_1$ and $b = \lambda_c/4n_2$, while $\lambda_c = 1750\,\text{nm}$ is the critical wavelength which is the mid-wavelength of the wavelength range considered in our numerical computation. While

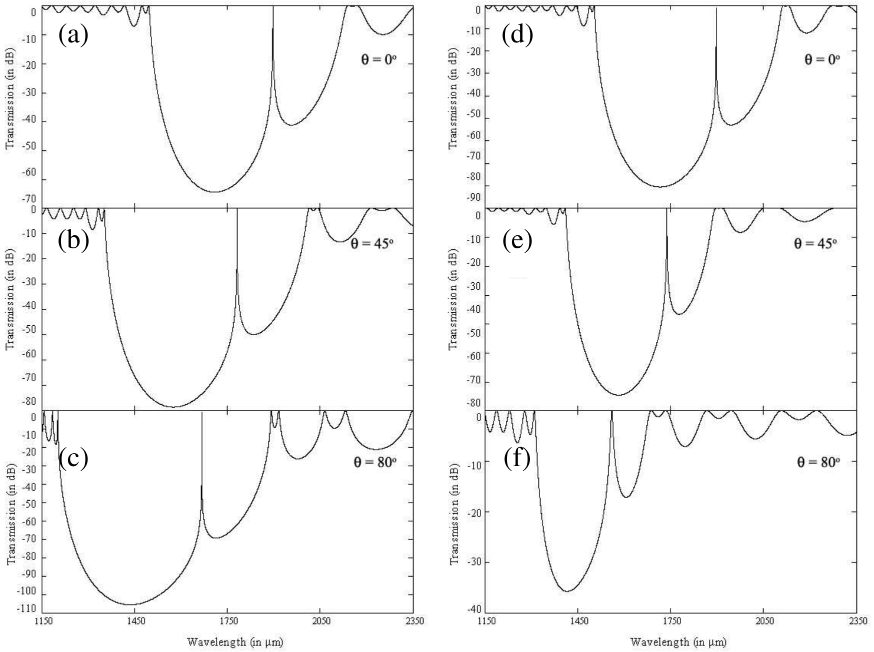

Figure 3. Transmission of PQW structure $(AB)_8C(BA)_8$, for TE mode with angle of incidence (a) $\theta = 0°$, (b) $\theta = 45°$, (c) $\theta = 80°$ and for TM mode with angle of incidence (d) $\theta = 0°$, (e) $\theta = 45°$, (f) $\theta = 80°$.

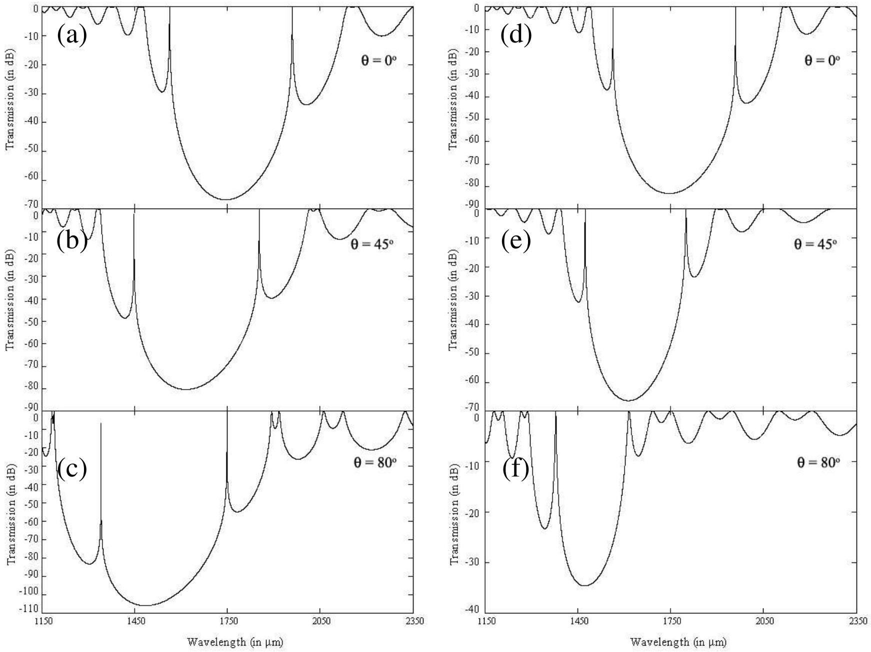

Figure 4. Transmission of PQW structure $(AB)_8C_2(BA)_8$, for TE mode with angle of incidence (a) $\theta = 0°$, (b) $\theta = 45°$, (c) $\theta = 80°$ and for TM mode with angle of incidence (d) $\theta = 0°$, (e) $\theta = 45°$, (f) $\theta = 80°$.

for the defect layers C, we choose the material of layer C same as layer A (TiO_2) with the thickness of layer taken as $d = 450\,\text{nm}$. Here, all the regions are assumed to be linear, homogeneous and non-absorbing. Also, the refractive indices of both the materials are considered to be constant for incident wavelength region. The defect stack C_n is a cavity stack whose spectral response overlaps with the spectrum of the primary stack. The defect C_n layers play a role of a refractive index well or cavity depending on the wavelength of electromagnetic waves.

Figures 3, 4 and 5 depict the transmission spectra of photonic quantum well structures $(AB)_8/(C)_n/(BA)_8$. The transmission was calculated using Equation (4). From Figures 3, 4 and 5, it is clearly seen that there are photonic band gaps (PBGs) near the lower wavelength or higher frequency region with some defect modes. This PBG region along with the defect filter mode shifts towards higher frequency with angle of incidence, while the defect filter mode increases with the number of defect layers. It can be predicted from above

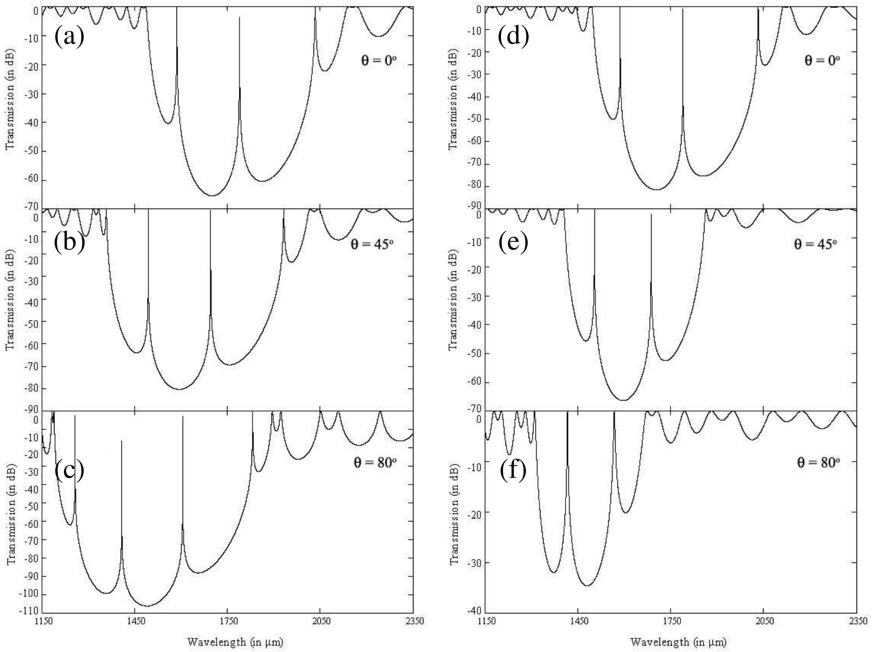

Figure 5. Transmission of PQW structure $(AB)_8C_5(BA)_8$, for TE mode with angle of incidence (a) $\theta = 0°$, (b) $\theta = 45°$, (c) $\theta = 80°$ and for TM mode with angle of incidence (d) $\theta = 0°$, (e) $\theta = 45°$, (f) $\theta = 80°$.

figures that no waves can transmit in the low-frequency range while nearly all the high-frequency waves can pass through for the TE modes. Contrasting the TM modes with the TE modes, the only discrimination is that two striking TM defect modes come out in the low-frequency range which gradually shifts left with increasing number of defect layers (n). It is similar to results obtained for multilayer photonic structure with increase in the thickness of defect layer [11]. This device can be used to filter a narrow wavelength or frequency out of the incident radiation within the PBG region.

The C_n layers play a role as well or cavity to capture a resonance frequency or wavelength corresponding to thickness and number of defect layers C_n as reported in an earlier work [11]. This defect layer also introduces the filter channel into the PBG region. In Figures 3, 4 and 5, the number of defect layer C_n is chosen as 1, 2 and 5 respectively. From Figure 3, it is clearly seen that a single layer of C introduces a single channel filter which varies with the angle of incidence of light.

In the case of normal incidence ($\theta = 0°$), both TE and TM modes have the same values, so the filter channel modes are also at same wavelength. While at the other (non-zero) angle of incidence, both TE and TM modes present separate patterns of transmission spectra and band gap region as shown in above figures. As the angle of incidence increases, the filter channel mode moves towards the lower wavelength or higher frequency range with the PBG region.

As the number of layers C_n increases, the number of filter channels also increases, as shown in Figures 4 and 5. As the number of defect layers C_n increases from 1 to 5, the corresponding resonant frequency modes will also be increased, leading to an increase in the number of filter channels into the PBG region. These multi-channel filters can be tuned with the angle of incidence of light along with the PBG region to obtain the desired result. With the PQW structures, by properly choosing the geometric and dielectric parameters, a large number of multi-channel filter mode can be achieved, which may have potential application as narrow band filters. For instance, this structure can be used as a multi-channel filter that can transmit multi wavelength or frequency singles with a single device in infrared region.

4. CONCLUSION

These results show that the PQW structures have been used to achieve multi-channel filter modes in the photonic band gap region. The PQW structure can be used to design multi-channel filter of 1-D PQW structure. These multi-channel filters can also be tuned with the angle of incidence of light. Also, such structures can be used for the design of optical devices like multi-channel filter, resonators, etc.

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