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COMPUTING TRANSMISSIVITY OF ONE-DIMENSIONAL DEFECTED PHOTONIC CRYSTAL UNDER POLARIZED INCIDENCE FOR BAND-PASS FILTER APPLICATIONS

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ABSTRACT

Transmissivity of 1D defected photonic crystal is computed using transfer-matrix technique as function of wavelength for TM and TE mode of propagations. Layer dimensions and incidence angle are varied within practical range to study the change in wave propagation characteristics computed around 1.55 μm. Normalized defect density is varied within acceptable limit to observe the variation of transmission, which plays key role for application of the structure as band-pass filter. Results revel that defected crystal can be implemented in designing photonic b.p.f with acceptable passband width and confinement at the cut-off frequencies for optical communication.

Keywords: Transmissivity, Defect density, Polarized incidence, 1D photonic crystal, Band-pass filter

I. INTRODUCTION

Propagation of electromagnetic wave through one-dimensional periodic crystal is studied for the last two decades by theoretical [1-2] and experimental [3-4] researchers. Study reveals the novel possible feature of the structure about restricting electromagnetic wave in specified frequency range due to the formation of photonic bandgap [5], and thus the structure may be realized as photonic filter [6]. Suitable choice of structural parameters add the flexibility of tuning the property of photonic filter [7], and choice of material composition play the vital role for performance estimation [8]. This may replace the conventional optical fiber due to its highly improved performance from communication point-of-view [9].

Semiconductor heterostructure based photonic crystal has already been the choice of researchers [10] due to its potential for design of high frequency tunneling devices. Rudziński [11] first used transfer matrix technique to analyze the polarized wave propagation inside photonic crystal. The property is also utilized for image processing applications [12] using multiband optical filter. Effect of material property on transmission spectra [13] is also recently investigated for designing multi-narrow channel band filter.

In this paper, transmittivity of 1D defected photonic crystal for different structural parameters and also for a given range of incidence angle for TM and TE mode of propagation. Normalized effect density is varied within practical range (2% - 4%) to study its utility for bandpass filter application. Simulation studies suggested remarkable performance for the filter in optical communication spectrum with proper choice of design parameters.

II. Mathematical Modeling

Consider the smallest unit of 1D photonic crystal structure comprising of SiO_2/Air material composition where forward and backward propagating waves are given by-

$$a_2 = t_{21}a_1 + r_{12}b_2 \quad (1)$$

$$b_1 = t_{12}b_2 + r_{21}a_1 \quad (2)$$

where r_{ij} and t_{ij} are reflectivity and transmissivity in passing from layer *i* to layer *j*.

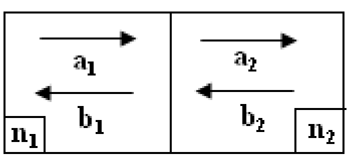

Fig. 1: Schematic picture of forward and backward waves in smallest unit of 1D photonic crystal

For p-polarized incident wave (TM mode) at angle θ_1, interface reflectivities are given by

$$r_{12} = -r_{21} = \frac{n_2\cos(\theta_1) - n_1\cos(\theta_2)}{n_2\cos(\theta_1) + n_1\cos(\theta_2)} . \quad (3)$$

For s-polarized incident wave (TE mode) at angle θ_1, interface reflectivities are given by

$$r_{12} = -r_{21} = \frac{n_1\cos(\theta_1) - n_2\cos(\theta_2)}{n_1\cos(\theta_1) + n_2\cos(\theta_2)} . \quad (4)$$

From the wave equations, transfer matrix corresponding to the interface can be obtained as

$$M^T_{1,2} = \frac{1}{t}\begin{pmatrix} 1 & r_{21,12} \\ r_{21,12} & 1 \end{pmatrix} . \quad (5)$$

Considering the phase factor of the field propagating through uniform medium, propagation matrix is given as

$$P_{1,2} = \begin{pmatrix} exp[jk_{1,2}d_{1,2}] & 0 \\ 0 & -exp[jk_{1,2}d_{1,2}] \end{pmatrix} . \quad (6)$$

Considering '*f*' as defect density, propagation matrix in presence of defect, is given as

$$P_{1,2\ defect} = \begin{pmatrix} exp[jk_{1,2}d_{1,2}]f & 0 \\ 0 & -exp[jk_{1,2}d_{1,2}]f \end{pmatrix} \quad (7)$$

where d_i is the propagation length in i^{th} layer, and k_i is the wave vector in that layer. Thus, transfer matrix for the elementary cell is

$$M = M^T_1 P_1 M^T_2 P_2 . \quad (8)$$

Transfer matrix for the elementary cell in presence of defect in second layer (well)

$$M_{defect} = M^T_1 P_1 M^T_2 P_{2defect} . \quad (9)$$

For a perfectly periodic medium composed of N such elementary cells, the total transfer matrix for such a structure is

$$M_{tot} = M_N . \quad (10)$$

For a defected periodic medium composed of N such elementary cells, the total transfer matrix for such a structure is

$$M_{tot} = (M_{defect})_N \quad (11)$$

Transmission coefficient is given by

$$T = \frac{1}{M^2_{11}(tot)} . \quad (12)$$

III. RESULTS

Using Eq. (12), transmissivity inside one-dimension photonic crystal is computed for TE and TM mode propagation. Structural parameters are tuned to observe the effect on transmission in presence and absence of defect. Fig 2 shows the transmittivity profile w.r.t wavelength for normal incidence with different defect density. From the plot, it may be concluded that with increase of defect density up to a particular range, better filter characteristics can be obtained, which is only possible with suitable choice of design parameters. Further introduction of defect degrades the filter performance. For the different magnitudes of normalized defect density as shown in the plot, it is observed that generation of unwanted ripple in the passband region can be prevented with increase of normalized defect density up to 3%, and it also enhances the passband width. But if defect density further increases (4% as depicted in the plot), passband width reduces along with generation of unwanted ripple. Thus suitable introduction of defect in otherwise ideal photonic crystal can tune its filter property for application in optical communication.

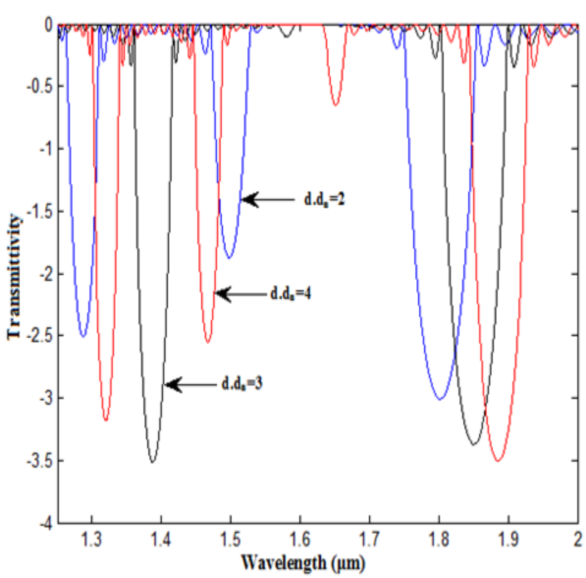

Fig. 2: Transmittivity with wavelength for normal incidence of TM mode in presence of defect for different defect density

Fig 3 shows the transmittivity profile w.r.t wavelength for oblique incidence with different defect density. For specified angle of incidence, it may be noted that with increase of normalized defect, first passband width is enhanced, and then starts decreasing.

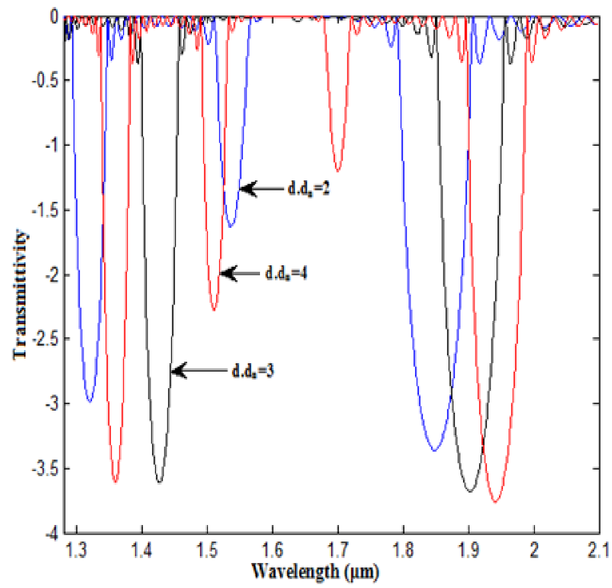

Fig. 3.1: Transmittivity with wavelength for oblique incidence of TM mode in presence of defect for different defect density

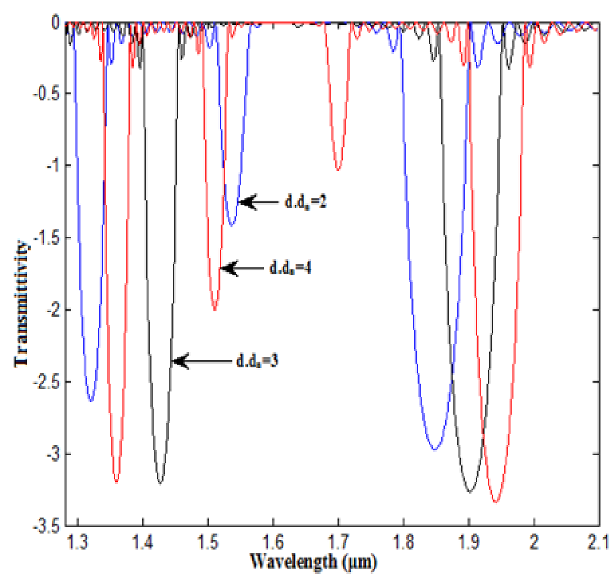

Fig. 3.2: Transmittivity with wavelength for oblique incidence of TE mode in presence of defect for different defect density

For TE mode propagation, ripple is reduced in passband, which speaks in favor of better Butterworth characteristics as shown in Fig 3.2. From Fig 3.1, it is observed that width of notch (in wavelength scale) is higher for TM wave which reduces width of passband. Again, length of notch (in transmittance scale) is higher for TM wave which speaks about better passband characteristics.

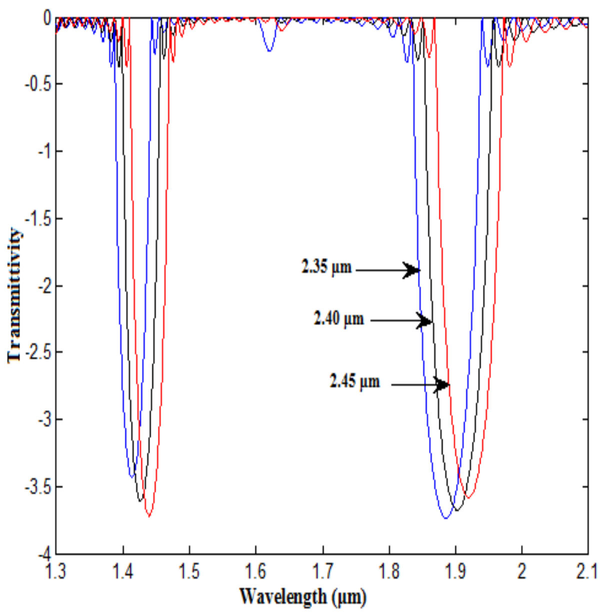

Fig. 4.1: Transmittivity with wavelength for oblique incidence of TM mode in presence of defect for different propagation length of barrier layer

Fig 4 shows the transmittivity profile w.r.t wavelength for oblique incidence of TE and TM mode propagation for different propagation length of barrier layer (layer with lower refractive index). In Fig 4.1 & Fig 4.2, it is seen that transmittance is decreased at the notches in the range 1.3 μm-1.45 μm and is also decreased at 1.8 μm-2.0 μm when propagation length of barrier layer is increased, which reveals the fact that suitable introduction of propagation length in alternative single layer enhances the filter characteristics. It may also be noted that ripple is reduced in passband, which speaks in favor of better Butterworth characteristics. Comparing the Fig 4.1 and Fig 4.2, width of notch (in wavelength scale) is higher for TM wave which reduces width of passband. Length of notch (in transmittance scale) is higher for TM wave which speaks about better passband characteristics. Hence for designing efficient filter, a trade-off is necessary.

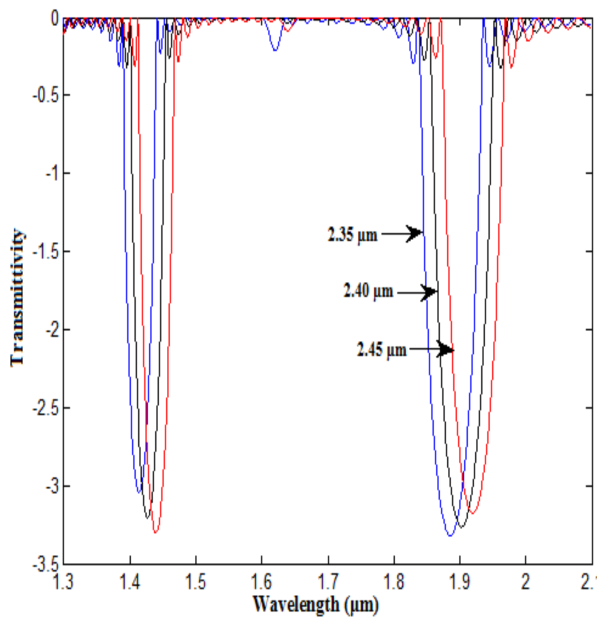

Fig. 4.2: Transmittivity with wavelength for oblique incidence of TE mode in presence of defect for different propagation length of barrier layer

Fig 5 shows the transmittivity profile w.r.t wavelength for oblique incidence of TE and TM mode propagation for different propagation length of well layer (layer with higher refractive index) in defected structure. Similar to Fig 5, here we can also observe that tuning of the well layer also tailor the notch length and width, which, in turn, modifies filter bandwidth and notch at either side. The result reveals the fact that suitable introduction of propagation length in alternative single layer enhances the filter characteristics. Also for TE wave, ripple is reduced in passband, which speaks in favor of better Butterworth characteristics as shown in Fig 5.2. Comparative analysis between Fig 5.1 and Fig 5.2 shows that width of notch (in wavelength scale) is higher for TM wave, but again width of passband is reduced.

Fig 6 shows the transmittivity profile w.r.t wavelength for oblique incidence of TM and TE mode propagation for different angle of incidence. From the plot, it is seen that with increase of incident angle, bandwidth in the passband region slowly increases, along with generation of unwanted ripple in passband. This phenomenon is observed for both TE and TM mode propagation.

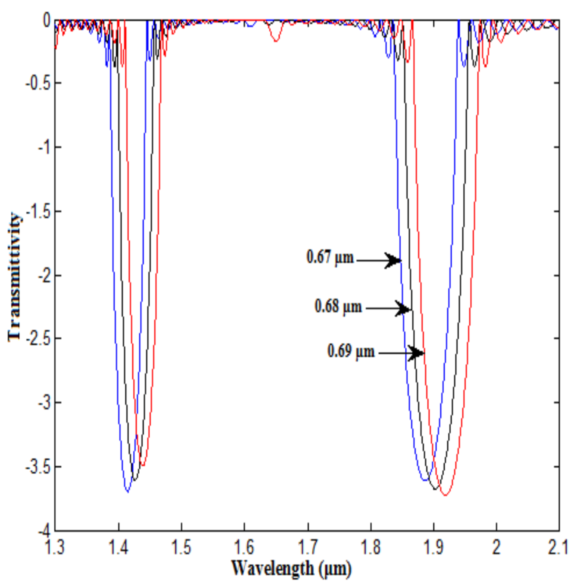

Fig. 5.1: Transmittivity with wavelength for oblique incidence of TM mode in presence of defect for different propagation length of well layer

One interesting feature may be noted in this context that the length of the first notch becomes almost independent with incidence angle when TM mode of propagation is considered, whereas it varies for TE mode. Thus confinement inside bandpass filter heavily depends on the incidence angle and also of mode of propagation.

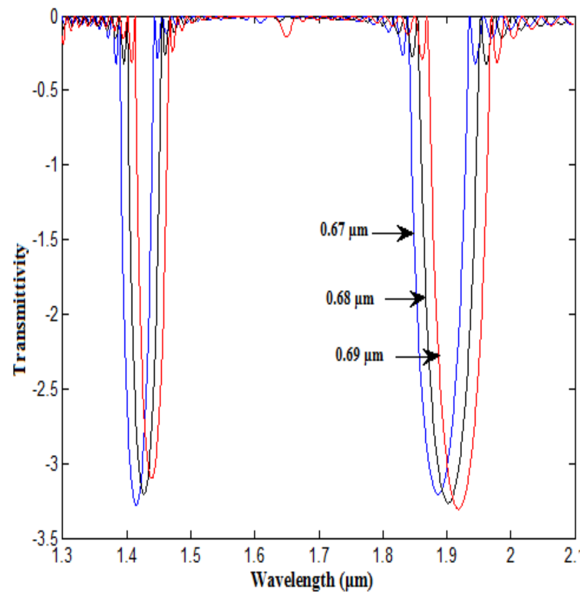

Fig. 5.2: Transmittivity with wavelength for oblique incidence of TE mode in presence of defect for different propagation length of second layer

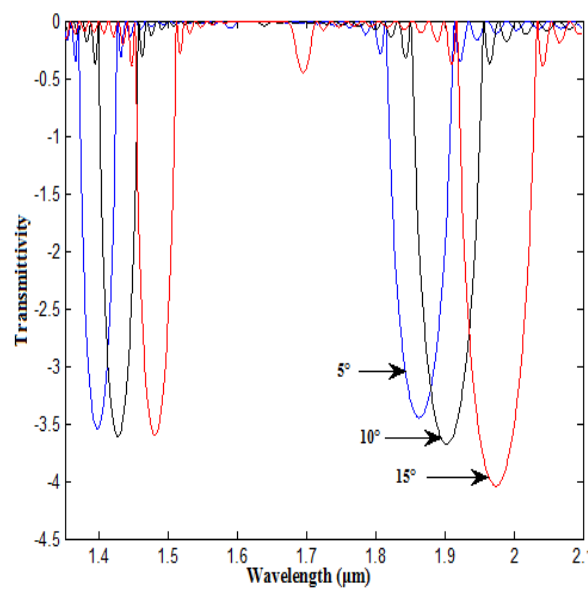

Fig. 6.1: Transmittivity with wavelength for oblique incidence of TM mode in presence of defect for different incident angle

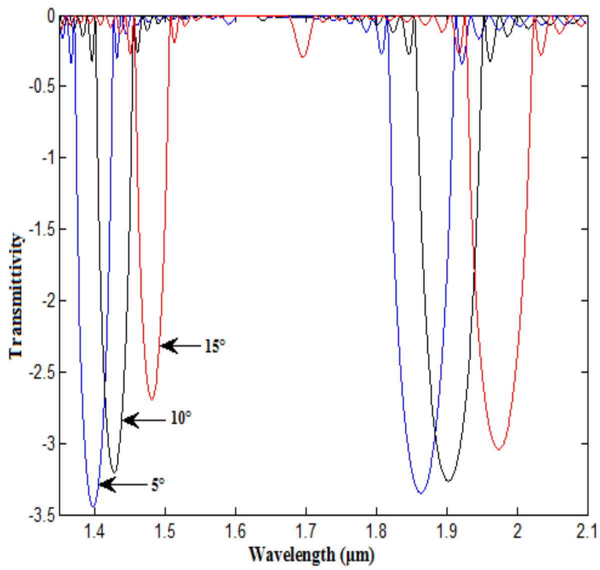

Fig. 6.2: Transmittivity with wavelength for oblique incidence of TE wave in presence of defect for different incident angle

IV. CONCLUSION

Performance study of one-dimensional photonic crystal based bandpass filter shows that suitable introduction of defect may enhance filter performance in terms of bandwidth and confinement. In case of oblique incidence for TM mode, notch length (in transmittance scale) increases compared to that of TE mode for various propagation length of different layers different defect density and different incident angle of e.m wave. It also depends on the angle of incidence of e.m wave. Hence suitable choice of structural parameters along with incidence angle may provide bandpass filter in the range of optical communication in defected structure, provided the defect density lies within acceptable range.

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