Effect of Optical Gain Factor on Transmittivity of SiO_2-Air 1D Photonic Crystal under Polarized and Normal Incidence

Rajashree Khan, Arpan Deyasi

***Abstract*— In this paper, transmittivity of photonic crystal-based bandpass filter is numerically simulated for both normal and oblique incidence of electromagnetic wave considering the effect of optical gain factor. Results are compared with that obtained for normal incidence, and both positive and negative gain (loss) factors are considered. Conventional SiO2-air system is taken for simulation purpose, and it has also shown that slight tuning of structural parameters makes a large shift of passband position from the desired spectrum, both for unpolarized and polarized conditions. The extent of shift is large when layer dimensions are smaller. Results are important for optical communication applications at 1.55 µm.**

***Index Terms*— One-dimensional photonic crystal, Transmittivity, Optical gain factor, Polarized incidence**

I. Introduction

One-dimensional photonic crystal is a special periodic arrangement of dielectric/ semiconducting/ metallic /combination of materials [1-3] which exhibits the novel property of photonic bandgap [4]. By virtue of this property, selected wavelength bands of the incident electromagnetic wave on photonic crystal is restricted to propagate, whereas other spectra are allowed to free [5]; thus demonstrated the property of optical filter, passband of which depends on the structural parameters and material composition [6], and tuning of incident angles can also modify the filter performance [7]. This novel structure can be used for photonic integrated circuit [8], optical transmitter [9], optical receiver [10], photonic crystal fiber [11-12], quantum information processing applications [13]. Conventional optical fiber is now-a-days replaced by photonic crystal fiber due to very low attenuation and dispersion [14], thus providing excellent efficiency for high-speed communication [15].

Work on 1D photonic crystal has attracted several researchers due to its potential advantage for communication point-of-view, and also due to ease of fabrication processes, thanks to the rapid advancement of microelectronics technology. Mekis etc. [16] obtained high transmission in presence of sharp bends in photonic crystal-based optical waveguides. Chen [17] demonstrated optical filter by making air-gap in otherwise solid photonic crystal structure. Szczepański [18] proposed distributed feedback laser using photonic crystal, whereas Hansyrd [19] made parametric amplifiers in optical range. In this paper, transmittance of one-dimensional conventional photonic crystal using SiO_2-air is calculated incorporating the effect of optical gain factor for filter applications. Dimensions of periodic layers are varied to observe the effect on pass bandwidth, and incidence angles are also tuned for studying the effect of different polarization conditions. Structural parameters are tuned to observe the shift the passband position from the desired zone. Results are important for 1550 nm based optical communication applications.

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II. Mathematical Modeling

Consider the smallest unit of 1D photonic crystal structure where forward and backward propagating waves are given by-

$$a_2 = t_{21}a_1 + r_{12}b_2 \tag{1}$$

$$b_1 = t_{12}b_2 + r_{21}a_1 \tag{2}$$

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

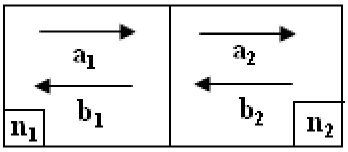

Fig 1: Schematic picture of forward and backward waves in smallest unit of 1D photonic crystal

For p-polarized incident wave at angle θ_1, interface reflectivities are given by

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

For s-polarized incident wave at angle θ_1, interface reflectivities are given by

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

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

$$M^T{}_{1,2} = \frac{1}{t}\begin{pmatrix} 1 & r_{21,12} \\ r_{21,12} & 1 \end{pmatrix} \tag{5}$$

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

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

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

$$M = M^T{}_1 P_1 M^T{}_2 P_2 \tag{7}$$

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

$$M_{tot} = M_N \tag{8}$$

Transmission coefficient is given by

$$T = \frac{1}{M_{11}{}^2(tot)} \tag{9}$$

Optical gain factor (γ) may be written as a function of effective refractive index as

$$n_{eff} = n + j\gamma \tag{10}$$

III. Results and Discussion

Using Eq. (10), transmittivity of the one dimensional finite photonic crystal is computed and plotted for SiO_2/air material composition considering normal and oblique incidences. Optical gain/loss factors are included in the calculations to observe the effect on transmittance. Fig 2.1 shows the transmittivity profile with and without gain for normal incidence. It may be seen from the plot that transmittance increases with addition of gain factor [0.0001 dB] keeping the nature of profile unchanged, i.e., extent of photonic bandgap remains same. If optical loss factor is included, then similar downward fall of transmittance is observed, as depicted in Fig 2.2. By decreasing the layer dimensions, it is seen that the passband position largely deviates from its original and bandwidth also largely increases, plotted in Fig 2.3. Hence only narrowband optical filter design is possible at 1.55 μm .

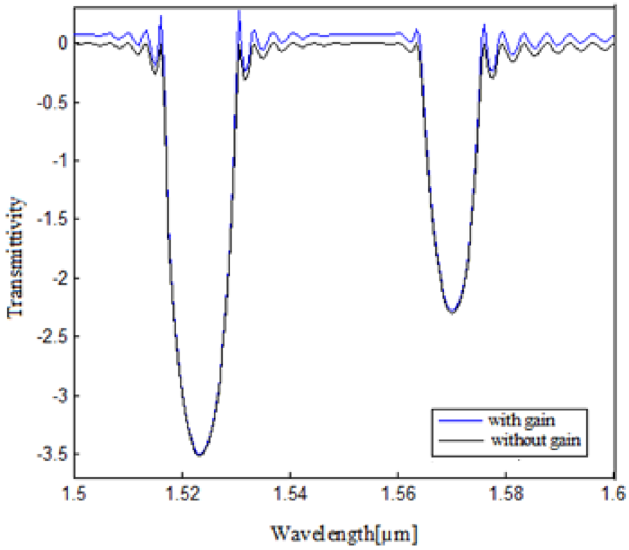

Fig 2.1: Transmittivity with wavelength for with and without gain under normal incidence of light

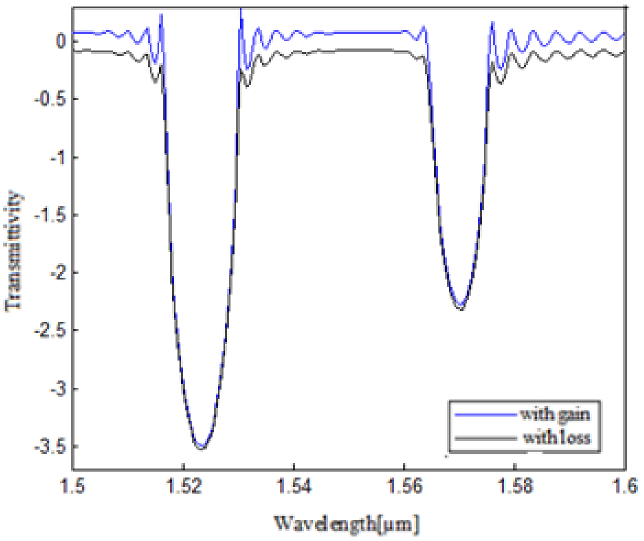

Fig 2.2: Transmittivity with wavelength for with gain and loss under normal incidence of light

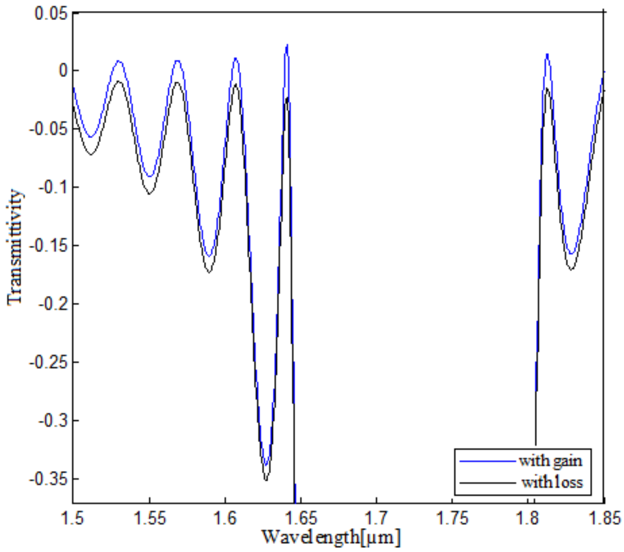

Fig 2.3: Transmittivity with wavelength for with gain and loss under normal incidence of light with smaller layer dimensions

Fig 3.1 shows that effect of oblique incidence on transmittance considering p-polarization. With increase in incidence angle, it is observed that the graph makes a right shift keeping the magnitude of the photonic bandgap unchanged. This ensures the fact that suitable tailoring of incidence angle controls the choice of operating frequency region. Also oblique incidence reduces the extent of stopband which deviates the filter characteristics. In Fig 3.2, similar computation is made by introducing loss factor. In this case, also reduction of transmittance is seen with oblique incidence. For smaller layer dimensions, the polarization effect is less dominant, as observed from Fig 3.3.

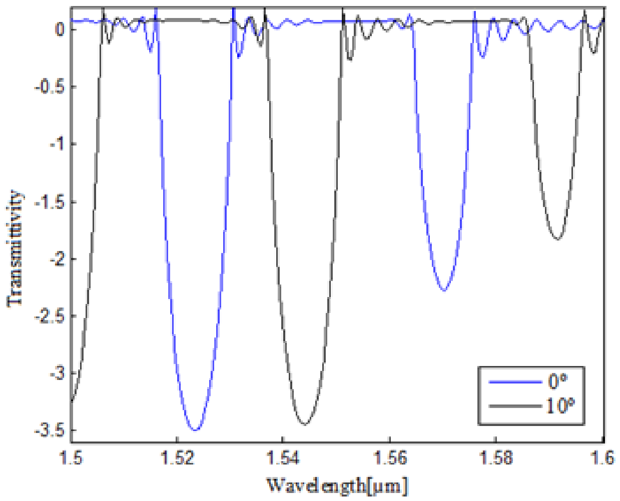

Fig 3.1: Transmittivity with wavelength for with gain under normal and oblique incidences(10º) of light considering p-polarization

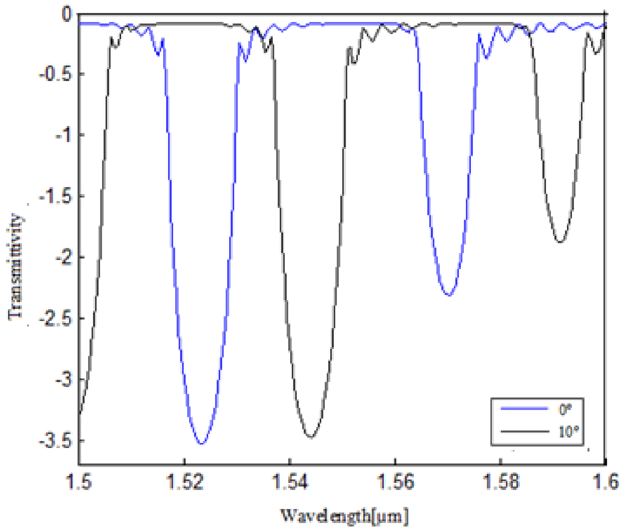

Fig 3.2:Transmittivity with wavelength for with loss under normal and oblique incidence(10º) of light considering p-polarization

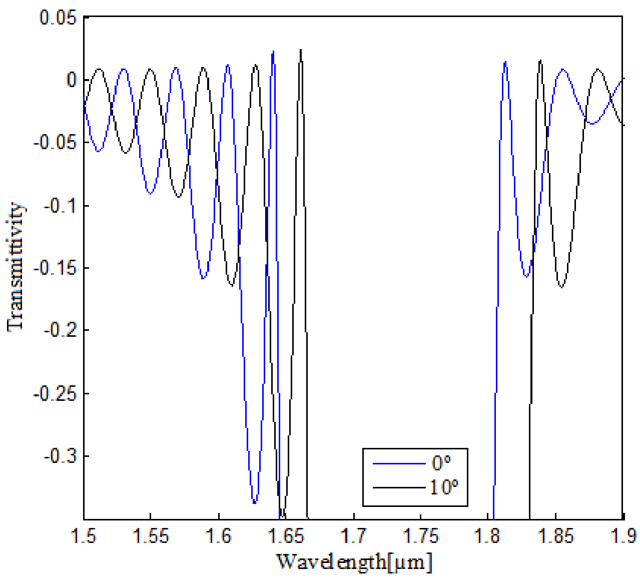

Fig 3.3: Transmittivity with wavelength for with loss under normal and oblique incidence(10º) of light considering p-polarization for smaller layer dimensions

Fig 4.1 shows that effect of oblique incidence on transmittance considering s-polarization. With increase in incidence angle, similar type of variations is observed. Here also the magnitude of photonic bandgap remains unchanged. One interesting feature may be noted in this context that the nature of profile is almost identical when compared with the profiles obtained for p-polarized wave incidence, about for the smaller dimensions, the deviation is noticeable. This is plotted in Fig 4.3.

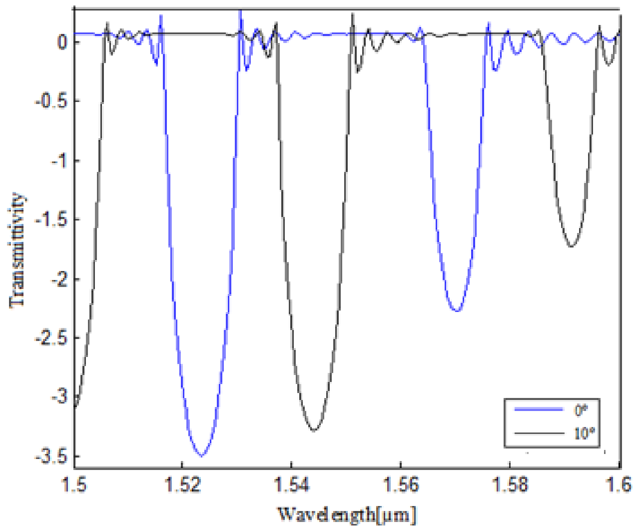

Fig 4.1: Transmittivity with wavelength for with gain under normal and oblique incidences(10º) of light considering s-polarization

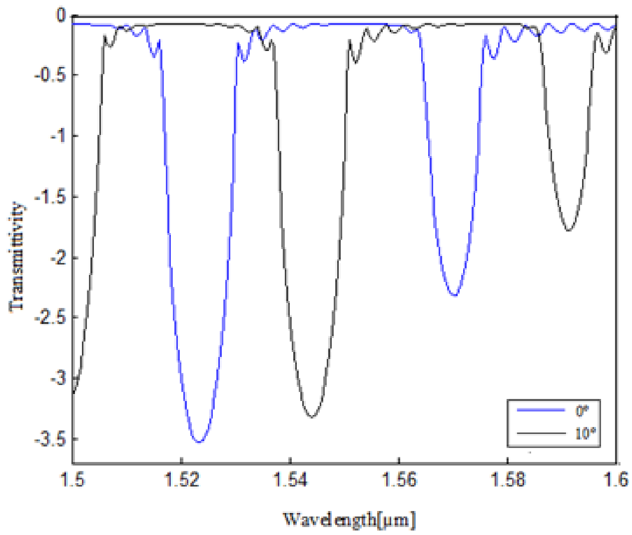

Fig 4.2: Transmittivity with wavelength for with loss under normal and oblique incidence(10º) of light considering s-polarization

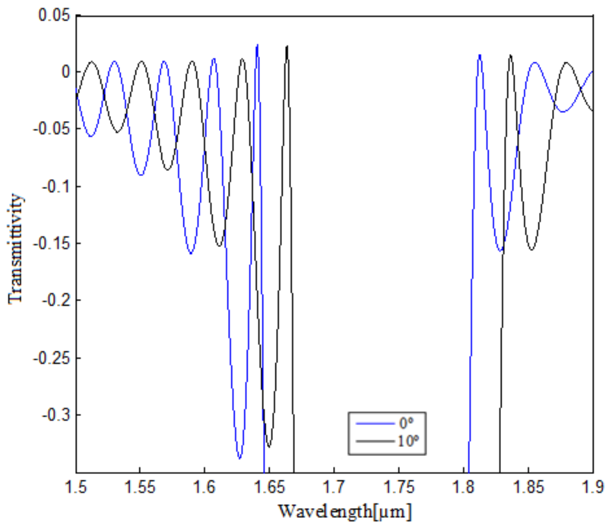

Fig 4.3: Transmittivity with wavelength for with loss under normal and oblique incidence(10º) of light considering s-polarization for smaller dimensions

IV. Conclusion

Present analysis showed that conventional one-dimensional photonic crystal can be used as photonic bandpass filter with limited bandwidth at 1.55 μm, and both s and p-type polarized wave incidence makes a large tuning of passband from its original position, obtained for normal wave incidence. Also tuning of structural parameters makes a huge impact on the central wavelength, which makes a deviation of filter bandwidth. Optical gain factor increases the magnitude of transmittance, which is required for communication application.

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