Nature & Environment
Vol. 20 (1), 2015: 102--106
Website: www.natureandenvironment.com

ISSN (Print) : 2321-810X
ISSN (Online) : 2321-8738

RESEARCH ARTICLE

TM-Polarized Narrowband Filtering Characteristics in One-Dimensional Dielectric Photonic Crystal Structures

Hitender Kumar Tyagi[1], Vipin Kumar[2] and Kh. S. Singh[2]
[1]Deptt. of Electronics, University College, Kurukshetra University, Kurukshetra, Haryana
[2]Deptt. of Physics, D.J. College, Baraut, Dist.- Baghpat, Uttar Pradesh
Corresponding author's Email: hitender.tyagi@gmail.com

Received: 4th Nov. 2014, Revised: 21st Dec. 2014, Accepted: 28th Dec. 2014

ABSTRACT

An analytical investigation of a one-dimensional photonic crystal composed of alternating layers of TiO_2 and SiO_2 has been carried out. The reflectivity characteristics for both TE and TM polarization modes of the proposed structure were theoretically analyzed using the Transfer Matrix Method (TMM). The results reveal that, at the communication wavelength of 1550 nm and an incidence angle of 78°, the reflectivity for the TE mode attains unity, while that for the TM mode approaches zero. This distinct polarization-dependent behavior can be effectively utilized for the design of an optical TE/TM mode selective filter.

Keywords: *Photonic crystal, Optical filter, Transfer matrix method*

INTRODUCTION

Extensive research on periodic optical structures has been conducted throughout the last century, focusing on their unique light–matter interaction properties. The concept of *photonic crystals* emerged in the late 1980s, following the pioneering works of Yablonovitch [1] and John [2], which marked the beginning of a new era in photonics. Photonic crystals are periodic arrangements of dielectric materials that give rise to energy band structures for electromagnetic waves propagating through them. A key feature of these structures is the *photonic band gap (PBG)*-a frequency range in which the density of electromagnetic states is zero, thereby prohibiting wave propagation within that range. The existence of such band gaps enables the design of highly efficient, low-loss dielectric reflectors capable of confining light within optical channels (waveguides) or localized defects (resonators) with dimensions comparable to the wavelength of light.

The concept of an optical band-pass filter operating in the near- and far-infrared regions using one-dimensional photonic crystals was first proposed by Ojha *et al.* [3] in 1992. Subsequently, Chen *et al.* [4] presented significant findings on photonic filters employing air-bridge structures. D'Orazio *et al.* [5] successfully fabricated photonic band gap filters suitable for wavelength division multiplexing applications, while Singh *et al.* [6] demonstrated a broad omnidirectional reflection range by overlapping two photonic crystals. Villar *et al.* [7] analyzed one-dimensional photonic band gap structures incorporating a liquid crystal defect layer for tunable fiber-optic filters. More recently, Kumar *et al.* [8] proposed a simple cascaded photonic band gap filter design operating in the ultraviolet region. Qiao *et al.* [9] introduced a novel class of photonic crystals-termed *Photonic Quantum Wells (PQWs)*-composed of alternating positive-index materials, which allow for enlarged band gaps and the realization of narrow multi-channel filters [10–12].

In the present work, we investigate a one-dimensional photonic crystal consisting of alternating layers of TiO_2 and SiO_2. Fused silica (SiO_2) is particularly suitable for optical applications due to its extremely low coefficient of thermal expansion (5.5×10^{-7} mm^{-1}), making it ideal for optical flats, mirrors, furnace windows, and other precision optical components. Titanium dioxide (TiO_2), on the other hand, has attracted considerable attention because of its promising applications in photocatalysis, sensing, and solar energy conversion. TiO_2 possesses a high refractive index sufficient to induce a pronounced photonic band gap in dielectric multilayers, while exhibiting optical absorption losses approximately ten times lower than silicon at the optical communication wavelength of 1.55 µm. Additionally, its small thermal expansion coefficient ensures high structural stability-making TiO_2/SiO_2 multilayer systems excellent candidates for photonic crystal–based optical filters.

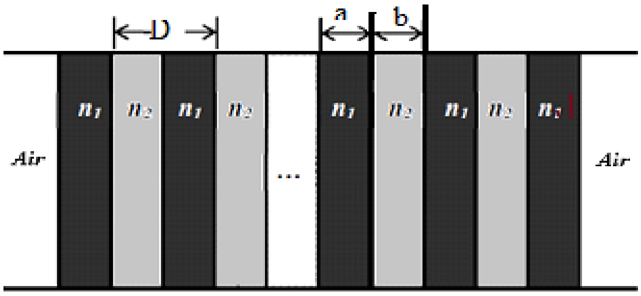

Fig.1: Periodic variation of one-dimensional photonic band gap structure.

THEORY:

The Transfer Matrix Method (TMM), which is widely employed to describe the optical properties of multilayered structures, is utilized here to determine the reflectivity and transmittance of the proposed one-dimensional photonic crystal.

Let us consider a stack of N dielectric layers arranged perpendicular to the -axis, as illustrated in Fig. 1. The refractive index profile, exhibiting a rectangular periodic symmetry, can be expressed as

$$n(z) = \begin{cases} n_1, & 0 < z < d_1 \\ n_2, & d_1 < z < d_1 + d_2 \end{cases} \quad \text{....(1)}$$

where n_1 and n_2 are the refractive indices of the alternating layers, and $d = d_1 + d_2$ denotes the lattice period.

To determine the electric field distribution, the following system of equations is solved to relate the field amplitudes A_0, B_0, A_s, and B_s:

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = M \begin{bmatrix} A_s \\ B_s \end{bmatrix}, \quad \text{....(2)}$$

where M is the overall transfer matrix of the multilayer structure and can be written as

$$M = \prod_{l=1}^{2N} \begin{bmatrix} \cos(\delta_l) & \frac{i}{q_l}\sin(\delta_l) \\ iq_l\sin(\delta_l) & \cos(\delta_l) \end{bmatrix}, \quad \text{....(3)}$$

With $\delta_l = \frac{2\pi}{\lambda} n_l d_l \cos\theta_l, q_l = \begin{cases} n_l \cos\theta_l, & \text{for TE polarization} \\ \frac{\cos\theta_l}{n_l}, & \text{for TM polarization.} \end{cases}$

Here, $l = 1,2$ corresponds to the first and second layers of the unit cell, and N denotes the total number of periods in the structure.

The reflectance R and transmittance T of the multilayer system for TE and TM polarizations can be obtained from the elements of the matrix M as follows:

$$R = \left| \frac{M_{21}}{M_{11}} \right|^2, T = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} \left| \frac{1}{M_{11}} \right|^2 \quad \text{....(4)}$$

where $n_0$and $n_s$denote the refractive indices of the incident and substrate media, respectively.

According to Bloch's theorem, the Bloch wave vector K satisfies the eigenvalue condition derived from the periodicity of the structure. The dispersion relation between K and the angular frequency ω for the Bloch waves is given by

$$\cos(Kd) = \cos(\delta_1)\cos(\delta_2) - \frac{1}{2}\left(\frac{q_1}{q_2} + \frac{q_2}{q_1}\right)\sin(\delta_1)\sin(\delta_2) \qquad \text{....(5)}$$

where d is the lattice period. This dispersion relation defines the photonic band gap regions, corresponding to frequency ranges where $|\cos(Kd)| > 1$and wave propagation is forbidden.

AIM OF THE STUDY

Photonic crystals represent a class of advanced optical materials capable of precisely controlling and manipulating the propagation of light. In the present study, a TM-polarized optical filter has been investigated. The proposed filter permits the transmission of TM-polarized waves while effectively blocking TE-polarized waves, thereby functioning as a TM-polarized selective filter. Such structures hold significant potential for implementation in optical switches, dense wavelength division multiplexing (DWDM) systems, optical sensors, and other photonic devices requiring polarization-dependent control.

RESULT AND DISCUSSION

In this section, the reflection and transmission characteristics of the one-dimensional photonic crystal are evaluated using Eq. (3). For numerical analysis, a multilayer structure of the form Air/$(AB)_{16}$/Air is considered, where $(AB)_{16}$ denotes a periodic arrangement of 16 unit cells, each consisting of two alternating layers A and B. In the AB periodic stack, TiO_2 is selected as material A and SiO_2 as material B, with refractive indices of 2.65 and 1.45, respectively. Both the incident and exit media are assumed to be air. The thicknesses of layers A and B are chosen as $a = 465$nm and $b = 255$nm, respectively, to achieve the desired photonic band gap characteristics near the telecommunication wavelength.

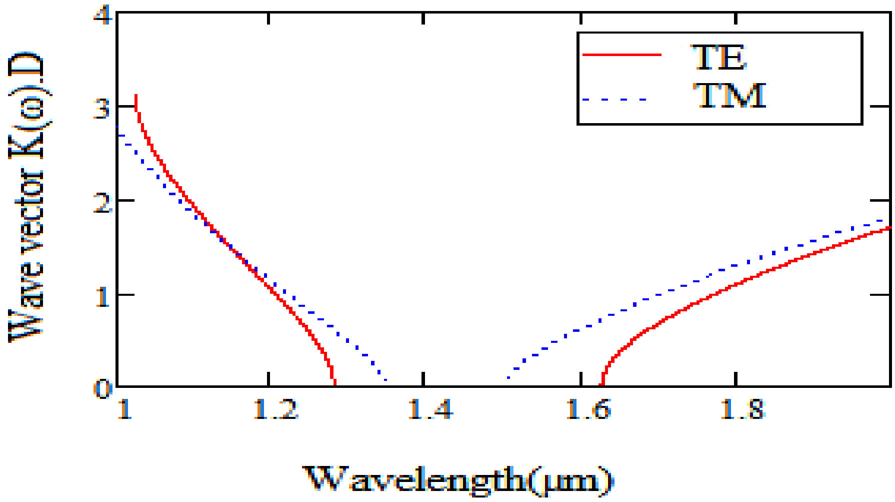

Fig. 2: Dispersion spectra of TiO_2 /SiO_2 1DPC at angle of incidence at 78^0.

Figure 2 illustrates the dispersion spectra of the photonic structure Air/$(AB)_{16}$/Air. It is evident from the figure that distinct photonic band gaps (PBGs) appear for both TE and TM polarizations. Specifically, the PBG for the TE mode lies within the wavelength range of 1.280–1.626 μm, while that for the TM mode occurs between 1.347–1.504 μm at an incidence angle of 78°. It is noteworthy that at the telecommunication wavelength of 1.55 μm, the TE mode exhibits a pronounced band gap, whereas the TM mode does not. In other words, TE-polarized waves are completely reflected and fail to propagate through the crystal, while TM-polarized waves demonstrate the opposite behaviour. This polarization-dependent phenomenon is further analysed and visualized in Figures 3, 4, and 5.

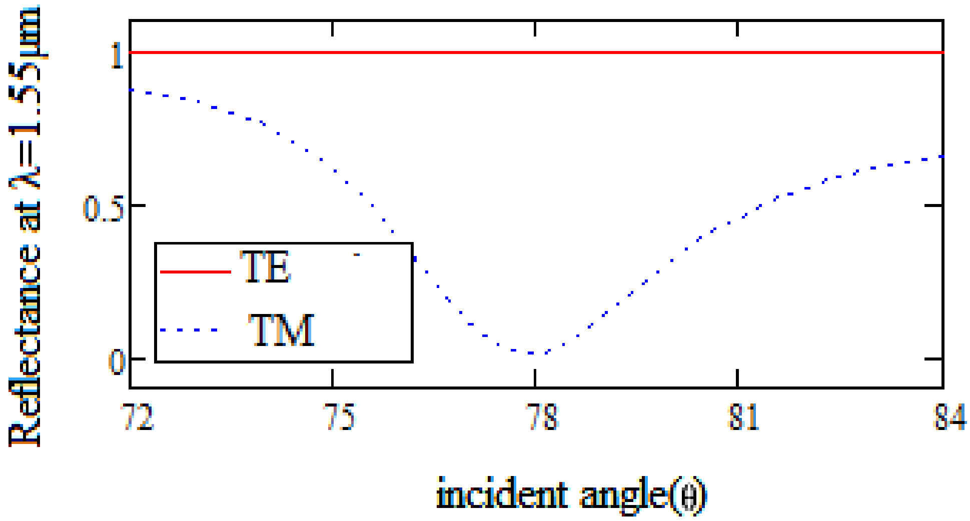

Fig. 3: Reflectance vs incident angle at λ=1.55μm.

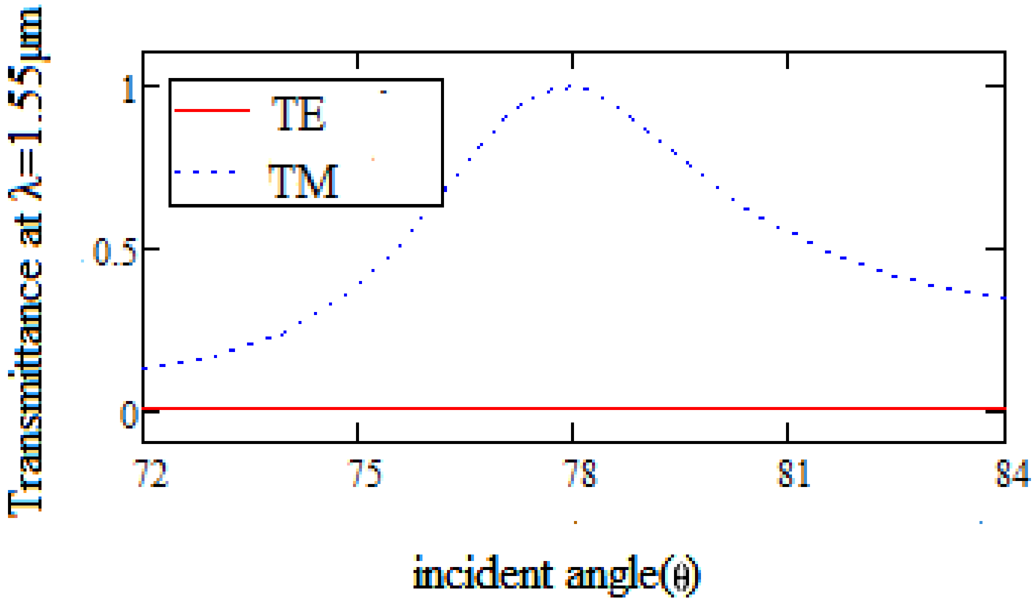

Fig. 4: Transmittance vs incident angle at λ=1.55μm.

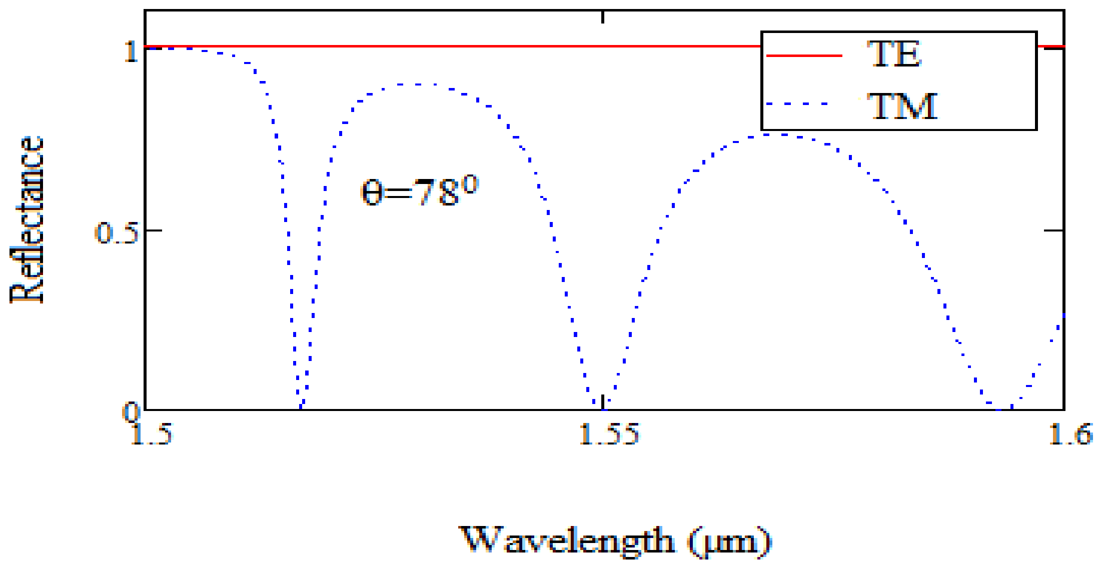

Fig. 5: Reflectance spectra at oblique angle of incidence78^{0} of TiO_2/SiO_2 Structure.

Figures 3 and 4 illustrate the reflectivity and transmittivity spectra of the proposed one-dimensional photonic crystal for TE and TM polarizations at different angles of incidence. Figure 5 presents the variation of reflectivity with wavelength. From these figures, it is evident that both TE and TM modes exhibit distinct polarization-dependent behaviours at specific wavelength and angle combinations. Notably, at an incidence angle of 78° and wavelength $\lambda = 1.55\,\mu$m-which corresponds to the mean wavelength of the optical communication window-the reflectivity of the TE mode attains unity while its transmittivity becomes zero. Conversely, the TM mode exhibits the opposite behaviour, showing nearly complete transmission and negligible reflection. This selective polarization response demonstrates the potential of the designed structure for TE/TM mode filtering applications in fiber-optic communication systems.

CONCLUSION

It can be concluded that the proposed photonic crystal structure can effectively function as a TE/TM mode filter based on its polarization-selective properties. Owing to this characteristic, it can also operate as an optical demultiplexer, thereby enhancing the data-carrying capacity of optical communication lines. Consequently, the designed structure can serve as a tunable demultiplexer for wavelength-selective applications in fiber-optic communication systems. Furthermore, the proposed device may be utilized as a single-channel drop filter, offering potential applications across various integrated optical and photonic systems.

REFERENCES

1. E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", *Phys. Rev. Lett.* 58, pp. 2059-2062, May 1987.
2. S. John, "Strong localization of photon in certain disordered dielectric superlattice", *Phys. Rev. Lett.* 58, pp. 2486-2489, May 1987.
3. S. P. Ojha, P. K. Chaudhary, P. Khastgir and O. N. Singh, "Operating characteristics of an optical filter with a linearly periodic refractive index pattern in the filter material", *Jpn. J. Appl. Phys.* 31, pp. 281–285, 1992.
4. J. C. Chen, A. Haus, S. Fan, P. R. Villeneuve and J. D. Joannopoulos, "Optical filters from photonic band gap air bridges", *IEEE: J. Lightwave Technol.* 14, pp. 2575–2580, 1996.
5. D'Orazio, M. De Sario, V. Petruzzelli and F. Prudenzano, "Photonic band gap filter for wavelength division multiplexer", *Opt. Exp.* 11, pp. 230-239, 2003.
6. S. K. Singh, Khem B. Thapa and S. P. Ojha, "Large Frequency Range of Omnidirectional Reflection in Si-based One-Dimensional Photonic Crystals", *Int. J. Micro. Opt. Technol.* 1(2), pp. 686-690, 2006.
7. I. Del Villar, I. R. Matias, F. J. Arregui and R. O. Claus, "Analysis of one-dimensional photonic band gap structures with a liquid crystal defect toward development of fiber-optic tunable wavelength filters", *Opt. Exp.* 11(5), pp.430-436, 2003.
8. Vipin Kumar, Kh. S. Singh and S. P. Ojha, "A Simple Design of a Monochromator by cascading photonic band gap Filters", *Int. J. Micro. Opt. Technol.* 5(3), pp. 162-165, 2010.
9. F. Qiao, C. Zhang, J. Wan and J. Zi, "Photonic quantum-wellstructures: Multiple channeled filtering phenomena", *Appl. Phys. Lett.* 77, pp. 3698-3700, 2000.
10. Y. Xiang, X. Dai, S. Wen and D. Fan, "Omnidirectional and multiple-channeled high-quality filters of photonic heterostructures containing single-negative materials", *J. Opt. Soc. Am. A* 24, pp. A28-A32, 2007.
11. Y. H. Chen, "Frequency response of resonance modes in heterostructures composed of single-negative materials", *J. Opt. Soc. Am. B* 25, pp. 1794-1799, 2008.
12. A. Kumar, V. Kumar, B. Suthar, M. Ojha, Kh.S. Singh and S.P. Ojha, IEEE: Photon. Technol. Lett. 25(3), 279 (2013).