Design and Analysis of a 1D Ternary Photonic Crystal for Multichannel Filtering Applications

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Abstract

In this paper, we theoretically investigate the optical characteristics of a one-dimensional ternary photonic crystal (1D-TPC) structure designed for tunable multichannel filtering applications in visible region. The structure consists of a periodic arrangement of three dielectric layers—Ta_2O_5, SiO_2, and TiO_2. The optical characteristics of 1D-TPC are investigated using the Transfer Matrix Method (TMM) in the visible wavelength range (400–800 nm), which gave few transmission peaks. The number of unit cells influenced the number of transmission peaks and spectral sharpness too. Furthermore, the effect of incident angle on transmission is explored for both TE and TM polarizations. A blue shift and narrowing of transmission peaks are observed at higher angles, particularly for TE mode. These results confirm the suitability of the proposed 1D-TPC as a compact, tunable multichannel filter for photonic and optical communication systems.

Keywords: Ternary Photonic Crystal, Multichannel Filter, Transfer Matrix Method.
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Introduction

Photonic crystals (PCs) are artificial multilayered structures on the nano- or microscale, characterized by periodic variations in refractive index. This periodic modulation leads to the formation of forbidden frequency ranges, known as photonic bandgaps (PBGs), where the propagation of electromagnetic waves is prohibited [1-3]. These bandgaps block the transmission of specific wavelengths, making PCs highly attractive for a wide range of applications, including optical filtering, waveguiding, and sensing [4-11]. Among the various configurations, one-dimensional photonic crystals (1D-PCs) have gained considerable attention due to their structural simplicity, ease of fabrication, and tunable optical properties [12-14].

Ternary photonic crystals (TPCs), composed of three distinct dielectric layers per unit cell, offer enhanced design flexibility and richer spectral features compared to binary systems. By appropriately selecting material combinations and layer thicknesses, TPCs can support multiple transmission resonances within the PBG, making them suitable for multichannel filtering applications [15-17].

In this work, we propose a 1D ternary photonic crystal (1D-TPC) structure composed of Ta_2O_5, SiO_2, and TiO_2 layers. The optical transmission properties are analyzed using the Transfer Matrix Method (TMM), with particular attention given to the effects of unit cell number and angle of incidence. Our results demonstrate that the proposed structure exhibits multiple, sharp, and tunable transmission peaks, confirming its potential for compact, high-resolution optical filtering in photonic communication and sensing systems.

Theoretical Model and Method

In this section, we consider a one-dimensional ternary photonic crystal (1D-TPC), which composed of a periodic structure of three layers labeled as A, B, and C, with refractive indices n_A, n_B, and n_C, while the thicknesses are defined as d_A, d_B, and d_C, respectively. The unit cell of the structure is defined as the sequence ABC, and the whole structure is formed by repeating this unit cell N times, resulting in a structure of the form $(ABC)^N$ as shown in Figure 1. For simplicity, each layer is assumed to be homogeneous, isotropic, and non-magnetic ($\mu=\mu_0$). The refractive index contrast and periodic arrangement of the layers lead to the formation of photonic band gaps (PBGs), where electromagnetic waves of certain frequencies are prohibited from propagating through the structure.

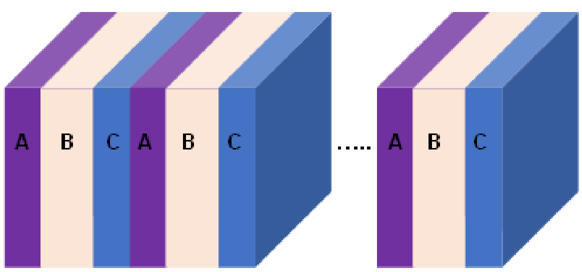

Figure 1: Schematic diagram of 1-D TPC as $(ABC)^N$

The optical characteristics of the 1D-TPC may be analysed using the Transfer Matrix Method (TMM), a well-known theoretical approach for calculating the transmission spectra of layered media with finite sized. For each layer j, the propagation of an electromagnetic wave is described by the characteristic matrix [18]

$$M_j = \begin{bmatrix} \cos(\delta_j) & i\gamma_j \sin(\delta_j) \\ \frac{i}{\gamma_j}\sin(\delta_j) & \cos(\delta_j) \end{bmatrix}$$

where $\delta_j=(2\pi/\lambda)n_j d_j \sin(\varphi_j)$ is phase angle in j^{th} layer and λ is wavelength and $\gamma_j = n_j \cos(\varphi_j)$ for TE mode and $\gamma_j = \cos(\varphi_j)/n_j$ for TM mode.

The total transfer matrix for the complete structure consisting of N unit cells is given as:

$$M=(M_A M_B M_C)^N$$

The transmission coefficient can be obtained as [18]

$$T = \left|\frac{2p_0}{M_{11}p_0 + M_{12} + M_{11}p_0p_s + M_{22}p_s}\right|^2$$

Results and Discussion

In this study, we investigate the optical characteristics of the proposed one-dimensional ternary photonic crystal (1D-TPC) structure, as illustrated in Figure 1. The structure consists of three alternating dielectric layers: A (Ta_2O_5), B (SiO_2), and C (TiO_2), with respective refractive indices n_A = 2.15, n_B = 1.46 and n_C = 2.42 [19-21]. The thicknesses of the layers are determined using the quarter-wave optical thickness condition at a central wavelength of 550 nm, resulting in d_A = 64, d_B = 94 nm, and d_C = 56 nm, respectively. For this analysis, the number of unit cells N is chosen as 4 to observe the initial formation of photonic band structures. Using the Transfer Matrix Method, we compute the transmission spectra for normal incidence in the visible wavelength range from 400 nm to 800 nm as illustrated in Figure 2.

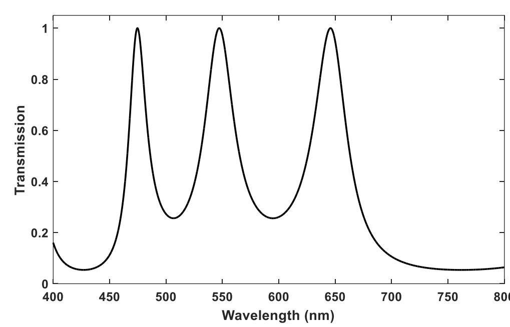

Figure 2: Transmission spectra for 1D-TPC as $(ABC)^4$

As shown in Figure 2, three distinct transmission peaks appear between two photonic bandgap regions. These peaks are located at wavelengths of 474.67 nm, 547.16 nm, and 645.82 nm. The corresponding full width at half maximum (FWHM) values are 15.45 nm, 33.15 nm, and 28.43 nm, respectively, indicating well-defined resonance modes within the bandgap structure.

Now, we focused our aim to explore the optical characteristics of 1D-TPC with the number of unit cells (N). The transmission spectra are computed and plotted for different values of unit cells for N = 2, 4, 6, 8, 10 and 12 as illustrated in Figure 3 (a-e). As observed from the Figure 3, increasing the number of unit cells leads to the emergence of additional transmission peaks in between photonic bandgaps. Notably, the number of transmission peaks observed is consistently one less than the number of unit cells, i.e., for N unit cells, $N-1$ peaks appear.

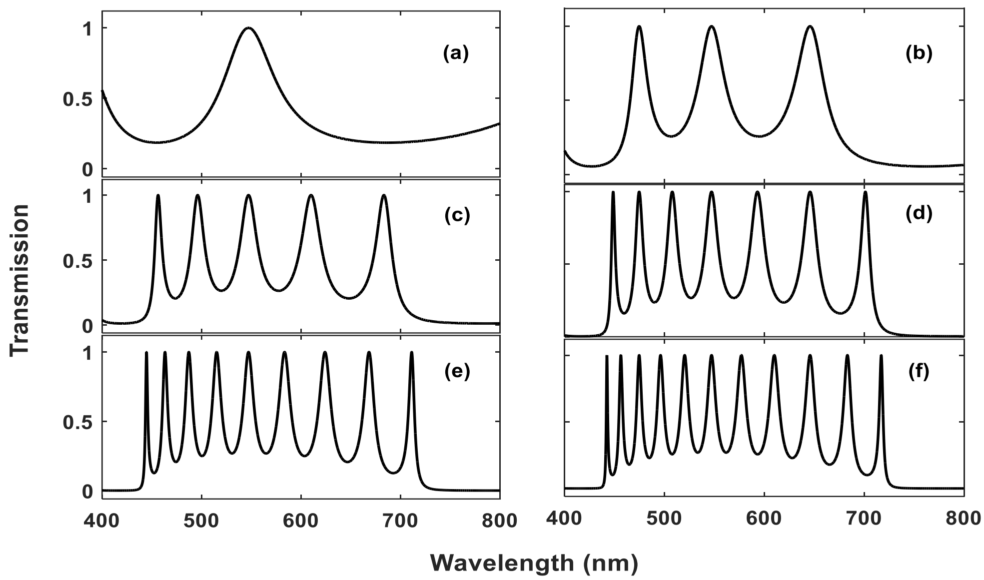

Figure 3: Transmission spectra for unit cells (a) N = 2, (b) N = 4, (c) N = 6, (d) N = 8, (e) N = 10 and (f) N = 12

In addition to the increase in the number of peaks, we also observe a significant narrowing of the transmission bandwidth. Specifically, the full width at half maximum (FWHM) of the central peak at 547.16 nm decreases from 56.53 nm for N = 2 to just 8.81 nm for N = 12. Furthermore, in all cases, the central transmission peaks exhibit broader FWHM values compared to those near the spectral edges, indicating stronger confinement and resonance at the centre.

Next, we focused our investigation on the influence of the angle of incidence on the transmission characteristics of the one-dimensional ternary photonic crystal (1D-TPC) for both TE and TM polarized modes. In this context, we first calculated and plotted the transmission spectra for TM polarization at various angles of incidence φ = 0°, 30°, 45 °, 60 °, 70 °, 80 ° as illustrated in Figure 4 (a-e).

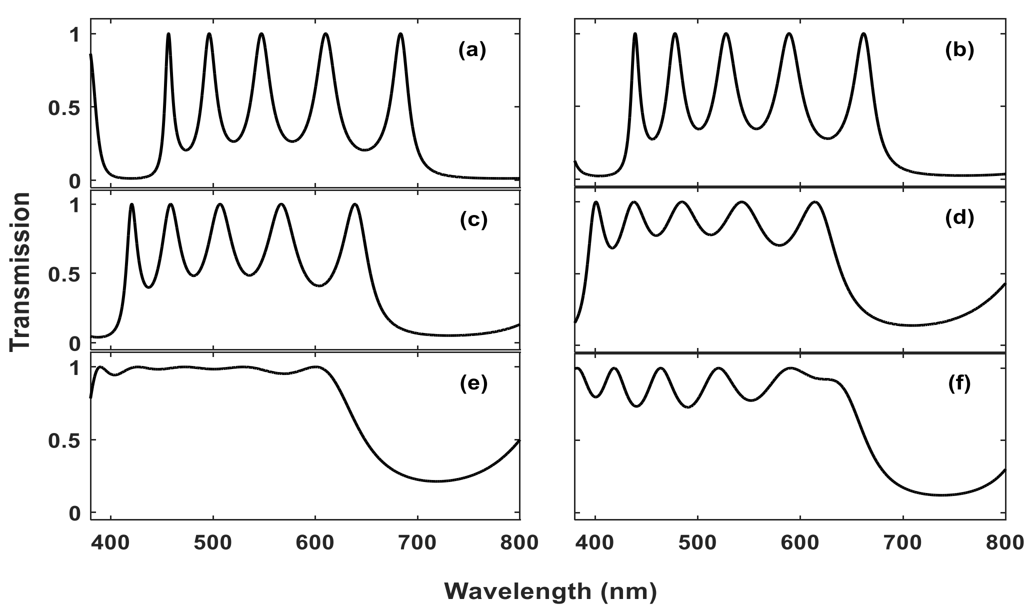

Figure 4: Transmission spectra for TM mode at (a) φ = 0°, (b) φ = 30°, (c) φ = 45°, (d) φ = 60°, (e) φ = 70° and (f) φ = 80°

As evident from the Figure 4, the transmission peaks systematically shift towards shorter wavelengths with increasing angle of incidence. This blue shift is attributed to the change in the optical path difference within the multilayer structure due to the angular dependence of the effective refractive index. Additionally, we observed that the lower edges of the transmission peaks rise with increasing angle, leading to a gradual transformation of the transmission window. At φ = 70°, the structure exhibits a broad band-pass region, which then transitions back to discrete peaks at higher angles (e.g., φ = 80°). At lower angles of incidence, the 1D-TPC functions effectively as a multichannel filter due to the presence of sharp transmission peaks. However, as the incident angle increases, noise or overlap between filter channels also increases, making the structure more suitable for wide band-pass applications at higher angles rather than precise filtering.

At last, we turned our focus to investigate the angular dependence of transmission spectra for the TE mode in the 1D-TPC structure. Transmission spectra were calculated and plotted for various angles of incidence: φ = 0°, 30°, 45°, 60°, 70°, and 80°, as shown in Figures 5(a–e). Similar to the TM mode, the transmission peaks for TE polarization also exhibit a noticeable blue shift with increasing incident angle, indicating that the photonic structure's response is strongly angle-dependent in both polarization modes.

At last, we turned our focus to investigate the angular dependence for TE mode on the transmission spectra of 1D-TPC. The transmission spectra are calculated and plotted for TE polarization at various angles of incidence φ = 0°, 30°, 45 °, 60 °, 70 °, 80 ° as illustrated in Figure 5 (a-e). As can be seen from Figure 5 that the transmission peaks shifted towards shorter wavelength region with as increase in incident angle similar to TM mode. But the transmission peaks became more sharper with an increase in angle of incidence. The FWHM obtained as 17.43 nm for the central transmission peaks for φ = 0°, which reduced up to 2.57 nm at φ = 80°. Such decrease in FWHM shows sharpness of transmission peaks, which can be useful for multichannel filter application with narrow signal.

However, unlike the TM mode, the transmission peaks in the TE mode became significantly sharper with increasing angle of incidence. At normal incidence (φ = 0°), the full width at half maximum (FWHM) of the central transmission peak was measured to be 17.43 nm. This width gradually decreased and reached as low as 2.57 nm at φ = 80°, demonstrating a high degree of spectral selectivity at oblique incidence.

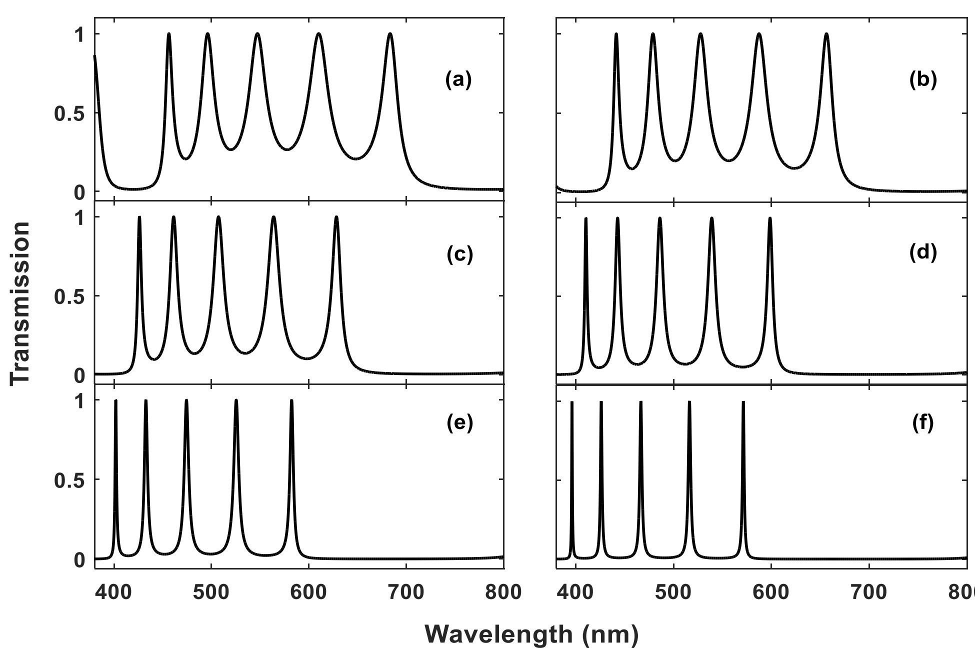

Figure 5: Transmission spectra for TE mode at (a) φ = 0°, (b) φ = 30°, (c) φ = 45°, (d) φ = 60°, (e) φ = 70° and (f) φ = 80°

The pronounced narrowing of the transmission peaks with angle suggests the 1D-TPC's strong potential for high-resolution multichannel filtering. These results make the structure highly suitable for integrated optical systems where compact, angle-tunable narrow-band filters are needed. Applications include wavelength division multiplexing (WDM), optical sensing, and precision spectral filtering in photonic communication and detection systems.

Conclusion

In this work, we have theoretically designed and analyzed a one-dimensional ternary photonic crystal (1D-TPC) based on a periodic $(ABC)^N$ structure comprising Ta_2O_5, SiO_2, and TiO_2 layers. The optical characteristics were evaluated using the Transfer Matrix Method for normal and oblique incidences. The structure exhibits multiple sharp transmission peaks within the visible range, effectively functioning as a multichannel filter. We found that increasing the number of unit cells N increases the number of transmission peaks while significantly narrowing the full width at half maximum (FWHM), demonstrating enhanced spectral resolution. Additionally, the angular dependence of the transmission spectra was explored for both TE and TM polarizations. In both cases, a blue shift in the transmission peaks was observed with increasing angle of incidence. Notably, TE polarization exhibited a substantial narrowing of FWHM—from 17.43 nm at 0° to 2.57 nm at 80°—highlighting the structure's suitability for angle-tunable, high-resolution filtering. These findings suggest that the proposed 1D-TPC structure holds significant potential for use in tunable multichannel optical filters, particularly in applications such as wavelength division multiplexing (WDM), optical sensing, and integrated photonic circuits, where compact and efficient spectral control is essential.

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