



Near Infrared -Visible Photonic Bandgap in One-Dimensional Periodic Photonic Crystal Structure Composed of Tio₂/Te Layers

Shalaw Saman Khalid*

Department of Physics, College of Science, University of Halabja, Halabja, IRAQ

Sarkew Salah Abdulkareem

Department of Physics, College of Science, University of Halabja, Halabja, IRAQ

Sana Latif Ahmed

Department of Physics, College of Science, University of Halabja, Halabja, IRAQ

Sana Dishad Talib

Department of Physics, College of Science, University of Halabja, Halabja, IRAQ

Shahla Ahmed Ghidan

Department of Physics, College of Science, University of Halabja, Halabja, IRAQ

Article Info

Article history:

Received: April 21, 2023

Revised: June 4, 2023

Accepted: June 28, 2023

Keywords:

Tellurium;
Photonic bandgap;
Photonic crystal;
Titanium dioxide;
Transfer matrix method.

Abstract

This paper considers some features of the states of one-dimensional photonic crystals. Based on the numerical results performed by the transfer matrix method in a periodic multilayer structure made of titanium dioxide and tellurium material, the structure possesses a photonic band gap. The structure was determined to have a photonic band gap in the borderline visible and infrared spectral region. Our predictions were in good agreement with the photonic bandgap tuning. Our simple model can also predict and explain the effect of incidence angle and wavelength and the number of layers on the photonic bandgap. The band gap of TiO₂/Te, which has an increase in layers up to 64 layers by the periodic sequence and is sensitive to the angle of radiation and the wavelength of the incoming light, is in the range of 700 nm to 900 nm. We expect such structures to play an important role in micromechanical tunable optical sensors and filters.

To cite this article: S. S. Khalid, S. S. Abdulkareem, S. L. Ahmed, S. D. Talib, and S. A. Ghidan, "Near Infrared -Visible Photonic Bandgap in One-Dimensional Periodic Photonic Crystal Structure Composed of Tio₂/Te Layers," *Int. J. Electron. Commun. Syst.*, vol. 3, no. 1, pp. 1-10, 2023.

INTRODUCTION

Photonic crystals (PCs), which Yablonoitch and John first proposed as analogs to electronic semiconductors, have been the subject of much attention over the past decade due to their laser technology, optical telecommunications, computing, and potential applications in optoelectronics. A photonic crystal is a formation in which the refractive index is varied regularly, as well the resulting photonic dispersion has a band nature similar to the electrical band structure in a solid [1]–[5]. It can produce strong light, reduces light, is easy to enlarge, and has a small size [6], [7]. Photonic crystals are electromagnetic

media that are periodically organized and generally possess photonic band gaps (PBGs). The presence of photonic band gaps (PBGs) brought about unprecedented forces to regulate and control as well as tamper with the propagation of electromagnetic (EM) waves [8]–[11]. One of the main features of PC photonic band gaps (PBGs) is in the wave dispersion and transmission spectrum. It is the frequency range over which electromagnetic waves (EMWs) cannot be carried periodically [12]–[14].

The periodic structure of various refractive index materials influences photon propagation owing to varying PBG, and such PBG is

• **Corresponding author:**

The address of each author's institution, COUNTRY. ✉ shalaw.Khalid@uoh.edu.iq

© 2023 The Author(s). **Open Access.** This article is under the CC BY SA license (<https://creativecommons.org/licenses/by-sa/4.0/>)

important in optical applications [15]–[19]. The transfer matrix method is a popular technique used to analyze photon crystals. Using a transfer matrix, the electric field's amplitude and its slope (the magnetic field) can be related from one layer to another. Due to their simplicity in fabrication and wide range of uses in optic engineering, photonic equipment, optic filters, resonant spaces, and the application of lasers, 1D-photonic crystals are the most prevalent and well-known type of thin film technology [14], [20]–[23]. The simple structure of one-dimensional photonic crystals (1D-PCs) can be easily made [24]. Gondek et al. proves that the selective back reflectors based on 1D PCs have the potential as sunlight concentrators that can be applied to improve photovoltaic systems [25].

In previous experiments on synthetic crystals and thin films, $\text{TiO}_2/\text{SiO}_2$, and $\text{TiO}_2/\text{Al}_2\text{O}_3$, were used to fabricate these thin films. Mbakop et al. used a $\text{TiO}_2/\text{SiO}_2$ 1D-PhCs multilayer structure to observe the frequency variation and transmission of final light [26], [27]. The period and incident angle are different. The optical characteristics of one-dimension (1D) photonic crystals (PCs) were examined experimentally and theoretically. The 1D PCs were essentially multilayer films made of high and low indexes (TiO_2 and Al_2O_3) materials. $\text{TiO}_2/\text{SiO}_2$ has also been generated utilizing dc magnetic sputtering with successive TiO_2 dipoles and radio frequency magnetic sputtering to make SiO_2 with a broad visible photonic bandwidth [19], [28], [29]. Although TiO_2 has been treated as the main layer because of its optical properties, trillium is also used in some studies, such as ODR in alternating fullerene-tellurium photonic crystal (PC) systems in one dimension (Te). The proposed structures produce 100% reflection over a fairly large wavelength range in the visible and a comparatively small percentage of the EM spectra near the IR region [28]–[30].

In this paper, we use the combination of Te and TiO_2 . Each one-dimensional photonic crystal in the two analyzed structures is composed of two dielectric layers with different refractive indices that are repeated very accurately and are theoretically studied using the transition matrix method (TMM). The uses of TiO_2/Te are purely scientific. They were studied recently in the field of nanotechnology. After that, we present work on 1D photonic

crystals to fabricate a spectrum filter capable of transmitting and reflecting light in the infrared band centered from 700 nm to 900 nm. Begin the Introduction by providing a concise background account of the problem studied.

METHODS

We have been inspired by the use of the transmission matrix method (TMM) to calculate the theory of reflection and the transmission spectrum [31]–[33]. There are basic deterministic laws that describe periodic photonic structures and cause them to form is periodic. In this paper, titanium dioxide (TiO_2) and tellurium (Te) material-based one-dimensional periodic crystal has been taken into consideration. The periodic photonic crystal with layers of TiO_2 and Te may be created deterministically by stacking the two building blocks of A and B, where $S(\Delta z) = (AB)^N$: where A and B represent the layers of TiO_2 and Te, respectively, and N denotes the number of lattice periods, as shown in Figure 1. The generating rule is executed repeatedly to produce: $S_1=AB$, $S_2=ABAB$, $S_3=ABABABAB$, et [34]. Figure 1 depicts the periodic multilayer construction that is implanted in the air. In this multilayer-containing (periodic) structure, layers A and B are anticipated to have thicknesses of d_A and d_B , respectively. Consequently, the A and B layers are regarded to be positive-index isotropic materials.

The 1D periodic component in the air is composed of identical dielectric layers A and B, stacked according to the periodic array. A schematic sketch of the one-dimensional periodic structure embedded in the air can be seen in Figure 1.

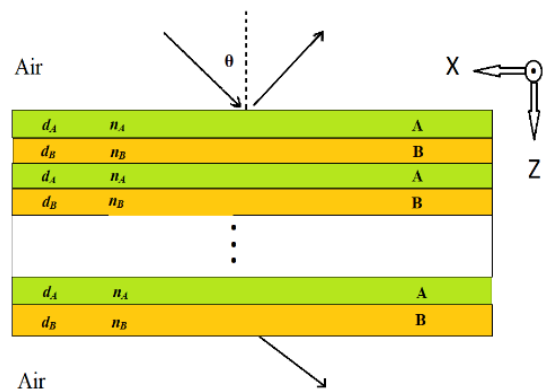


Figure.1 Schematic sketch of the one-dimensional periodic structure embedded in air. A (TiO_2) and B (Te) thicknesses are supposed to be d_A and d_B , respectively.

Along the z direction, we assume that the A layers are Titanium dioxide (TiO₂) films with a refractive index of 2.6 and the B layers are Tellurium (Te) with a refractive index of 4.8. We use the transfer matrix method to compute the transmission spectrum of the layered structure for an electromagnetic wave on the structure from the air at an angle of incident θ . For transverse magnetic (TM) and transverse electric (TE) waves, it is assumed that the electric field E and magnetic field H are in the x direction (the dielectric layers are in the xy plane). We can show the transfer matrix.

$$(\Delta z, \omega) = \begin{pmatrix} \cos(k_z^j \Delta z) & \frac{i}{\beta_j} \sin(k_z^j \Delta z) \\ i\beta_j \sin(k_z^j \Delta z) & \cos(k_z^j \Delta z) \end{pmatrix}, \quad (1)$$

connects the tangential components of the electromagnetic fields at the beginning of the jth layer to those at the end [35]. Here, $k_z^j = (\omega/c) \sqrt{\epsilon_j} \sqrt{\mu_j} \sqrt{1 - \sin^2 \theta / \epsilon_j \mu_j}$ is the component of the wave vector along the z-axis in the jth layer, $\beta_j = (k_z^j / \omega \epsilon_0 \epsilon_j)$ for transverse magnetic field (TM) wave, where ϵ_0 is the permittivity of the vacuum, and $\beta_j = (k_z^j / \omega \mu_0 \mu_j)$ for transverse electric field (TE) wave where μ_0 is the permeability of vacuum, c is the speed of light in vacuum. The total TMM for the 1D photonic crystal is given by

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \quad (2)$$

Can be solved for the reflection and transmission coefficients in terms of the transfer matrix elements to give

$$r = \frac{\gamma_0 M_{11} + \gamma_0 \gamma_s M_{12} - M_{21} - \gamma_s M_{22}}{\gamma_0 M_{11} + \gamma_0 \gamma_s M_{12} - M_{21} + \gamma_s M_{22}}$$

$$t = \frac{2\gamma_0}{\gamma_0 M_{11} + \gamma_0 \gamma_s M_{12} - M_{21} + \gamma_s M_{22}}$$

where we have writing

$$\gamma_0 = n_0 \sqrt{\epsilon_0 \mu_0} \cos \theta_0$$

$$\gamma_s = n_s \sqrt{\epsilon_0 \mu_0} \cos \theta_s$$

and the total reflectance and transmittance

$$T = |t|^2$$

$$R = |r|^2$$

The treatment of TE waves is similar to that of TM waves.

RESULTS AND DISCUSSION

This section shows the reflection bands in all directions for TE and TM waves and the numerical analysis of the proposed computer settings. The transmission matrix method is used to model the transmission and reflection

through this multilayer thin film. Two different materials with different refractive indices are used: titanium dioxide (TiO₂) a refractive index of 2.6 and tellurium (Te) with a refractive index of 4.8, which are periodically arranged. In this analysis, we presented some R reflectance and T transmittance properties as different TiO₂/Te parameters in homogeneous media with thin films at different wavelengths. Periodic (1D) structure does not consider the number of layers, refractive index contrast, or whether the electrical parameters are homogeneous [36]. Let us now consider a 1D periodic multilayer. It consists of two building blocks named A and B. In our simulation findings, medium A is titanium dioxide with a refractive index of 2.6, and medium B is tellurium (Te) with a refractive index of 4.8. The thickness of the bilayers ($d_A = 40$ nm and $d_B = 60$ nm) and the arrangement of the number of different layers in TiO₂ and Te.

Figures 2, 3, and 4 illustrate the reflectance and transmittance coefficients for various layer numbers and wavelengths at various angles. The photonic crystal's unique structure and features determine the relationship between reflectance and transmittance against the angle of incidence in a photonic crystal at a wavelength of (500 nm, 800 nm, and 1000 nm). The reflectance and transmittance of a photonic crystal can be calculated at normal incidence (i.e., when the light is perpendicular to the surface) using the Bragg condition, which states that the wavelength of light reflected or transmitted by a photonic crystal must be equal to twice the crystal's lattice constant times the size of the angle of incidence. The photonic band gap of a one-dimensional (1D) thin film can disappear in the Bragg situation at the time of TM [37]. The constructive interference of waves reflected or transmitted by the crystal is the basis for this state. The connection between reflectance and transmittance grows increasingly complicated as the angle of incidence increases. This is because the interior structure of the crystal influences light wave propagation in a way that is dependent on the angle of incidence. The band structure of the crystal, which characterizes the allowed and prohibited wavelengths of light, changes with the angle of incidence, affecting reflectance and transmittance qualities. A photonic crystal can be built up of many layers of alternating materials with different refractive indices, and

the number of layers can affect the crystal's band structure and optical properties. Increasing the number of layers in a photonic crystal may result in smaller band gaps or wavelength ranges that cannot pass through the crystal. This might result in higher reflection and poorer transmittance at specific incidence angles and wavelengths within the band gap region.

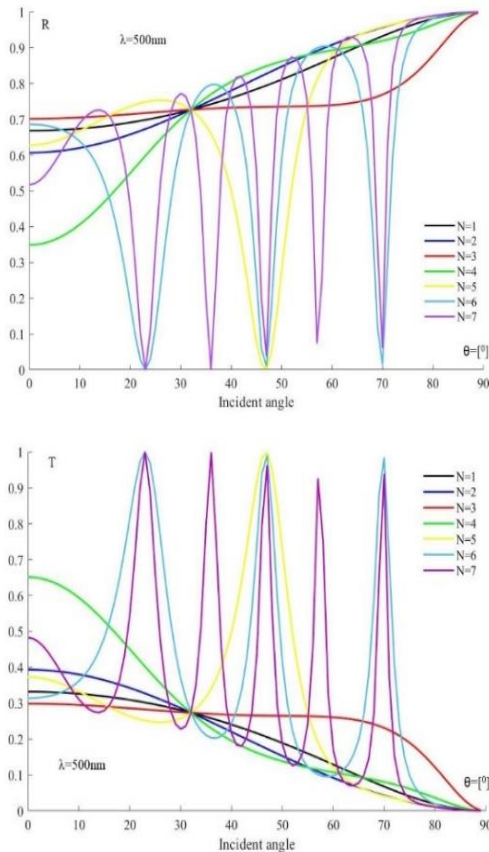


Figure 2 Reflectance and Transmittance vs. the incident angle for different values of the number of lattice periods is N at wavelength =500nm.

To start our work, we used a photonic crystal structure, which is arranged periodically, as we mentioned above, made of titanium dioxide and trillium, and we periodically increased the number of layers. We want to know the state of the reflection and transmission coefficients. The light we use with our structure is from the visible and infrared spectral regions. The first wavelength we used is in the green light region, which is 500 nm, shown in Figure 2. It has been found that with the increase of the numeral of lattices, periods are the N, the coefficients of reflection and transmission are more affected, in the

continuation of a certain angle which is 33 degrees, they give the same result in transmission and reflection.

At a wavelength of 800 nm (see Fig. 3), which lies at the interface of the visible and infrared spectra, it is unexpected to observe that the reflection coefficient attains its highest value, and the transmission coefficient reaches its lowest value with an increase in the number of layers. This means that as the number of layers increases, the material reflects lighter, allowing less light to pass through at this specific wavelength. Here we claim that it takes us toward the stop band because when we increase the number of layers, the reflection coefficient reaches its peak, which is one of the optical properties of photonic crystals.

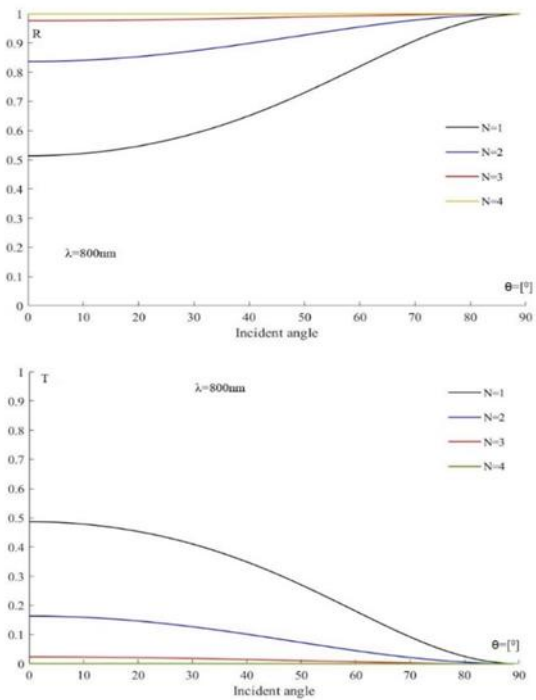


Figure 3 Reflectance and Transmittance vs. the incident angle for different values of the number of lattice periods is N at wavelength =800nm.

The last wavelength of our desired light with our structure is 1000 nm, which is in the near-infrared region as shown in Figure 4. We expect that our structure will show itself in a way. Whenever we increase the number of layers, the reflection and transmission coefficient will be complex. show, at an angle of 39 degrees for N=3 to N=7, the maximum amount of incident light passes, unlike the reflection coefficient, which reaches its lowest value at that angle, no light is reflected.

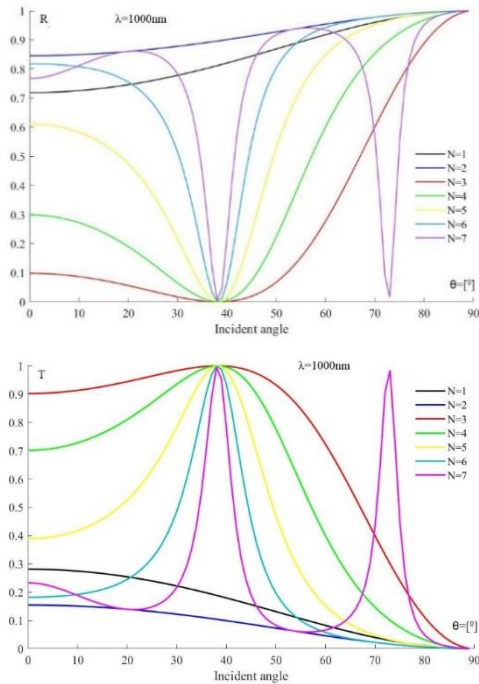
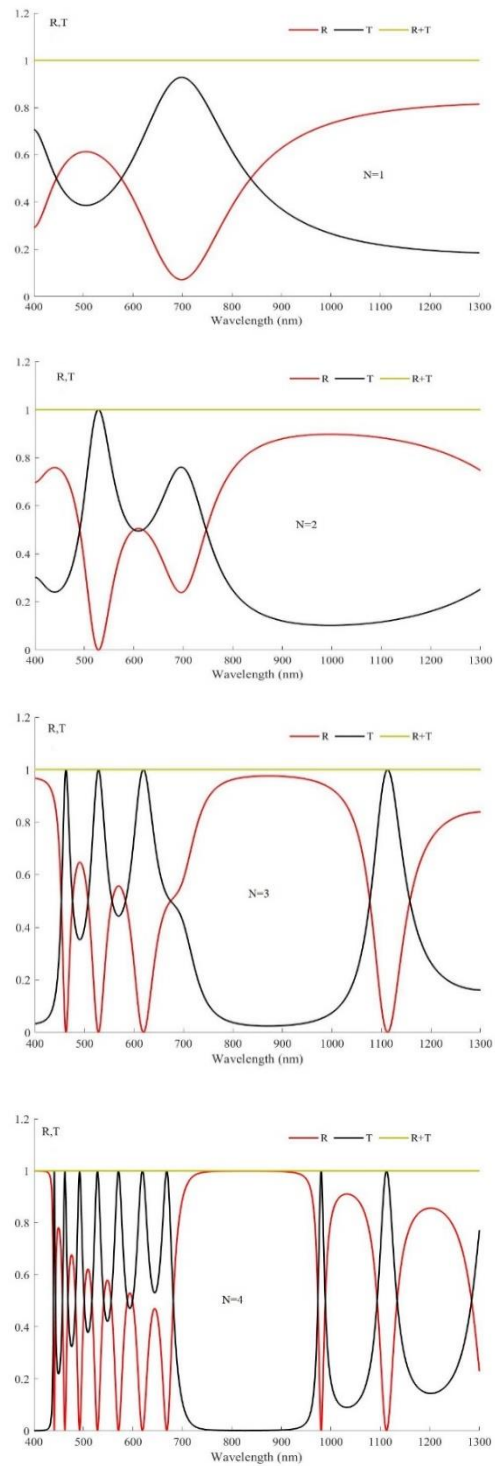


Figure 3 Reflectance and Transmittance vs. the incident angle for different values of the number of lattice periods is N at wavelength = 1000nm.

Calculated transmission and reflectance spectra of the photonic crystal formed in the period $N=1-6$ are shown in Fig. (5). Photonic crystals have a narrow photonic band gap in the near IR region. The narrow photonic band gap is attributed to slight differences in the refractive index of the constituent substance (TiO_3/Te). Matsushita et al. discover that The refractive index of TiO_2 using 2D-PBG band gap width from the refractive index map point of view is very helpful for real applications of TiO_2 structure [38]. A photonic crystal's reflection (R) and transmission (T) properties could be tuned by changing the numeral of layers in the crystal structure. As the numeral of layers increases, the photonic crystal becomes thicker, which can lead to changes in the reflectance and transmittance spectra. At normal incidence (i.e., when the light is incident perpendicular to the surface of the photonic crystal), the reflectance and transmittance spectra of a photonic crystal will typically exhibit a series of peaks and valleys, known as photonic stop bands or band gaps. These stop bands arise from the interference between the waves that are reflected and transmitted at each layer interface within the crystal structure. By increasing the number of layers in the photonic crystal, the width and position of these stop

bands can be tuned specifically as the number of layers is increased.



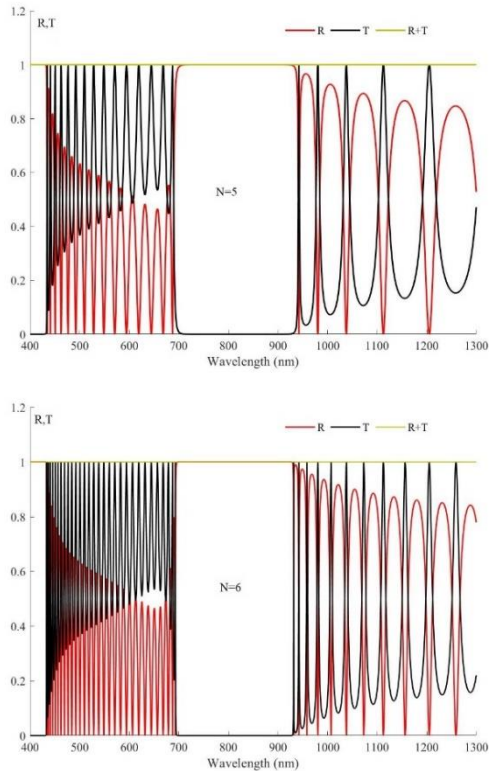


Figure 4 Photonic bandgap structure of periodic structure consisting of TiO₂/Te photonic crystal in terms of wavelength considering normal incident angle for light reflection and transmission.

The width of the stop bands will typically decrease, while the position of the stop bands will shift to higher energies (shorter wavelengths) due to the increased path length of the light through the crystal. Additionally, increasing the number of layers in a photonic crystal can enhance its reflectance properties. This is because more interfaces between layers in the crystal structure can lead to a more efficient reflection of incident light. As a result, photonic crystals with more layers and specific wavelengths can show higher reflection and lower transmittance than crystals with fewer layers. Therefore, the design of a photonic crystal with a specific number of layers must be carefully considered to achieve the desired optical properties while maintaining its structural integrity.

Effect of the incident angle, the photonic band gaps originating from the structure are shifted to shorter wavelengths with increasing the incidence angle. This behavior is not a surprise. Figure 6 presents the reflection and transmission vs. the wavelength of light for different values of the incident angle. We deal with this problem to see if the angle of

incidence of light affects the position of our stop band. Considering our target structure which is composed of titanium, which is arranged together with a period, we used a 64-layer structure for this work. Where $n=5$, the number of titanium layers is equal to the number of trillium layers. It is very clear in Figure 6 that when we increase the angle of incidence, the position of the band gap has shifted from the wavelength of our spectrum to shorter wavelengths.

The last Figure 7 shows the transmittance spectra of 1D Titanium dioxide -Tellurium periodic multilayer sequence for both TE (see figure. 7(a), (c), (e) and TM (Figure. 7(b), (d), (f)) polarizations versus visible- near-infrared wavelength range at different angles of the incident as 0° (black solid line), 30° (blue dashed line) and 60° (red dotted line). It is clear from these figures that in the transmission spectra TiO₂/Te, there is a band gap for both TE and TM waves started in the visible wavelength region nearly 700nm to 900 nm, based on the same graph, as the angle of incidence increases for both TE and TM polarizations, the upper and lower sides of the gap shift to longer wavelengths. Conversely, Mbakop et al. argue that TiO₂/SiO₂ structure has a small band gap caused by its high refractive index [39]. The varying angle behavior makes TM polarization more sensitive than Te.

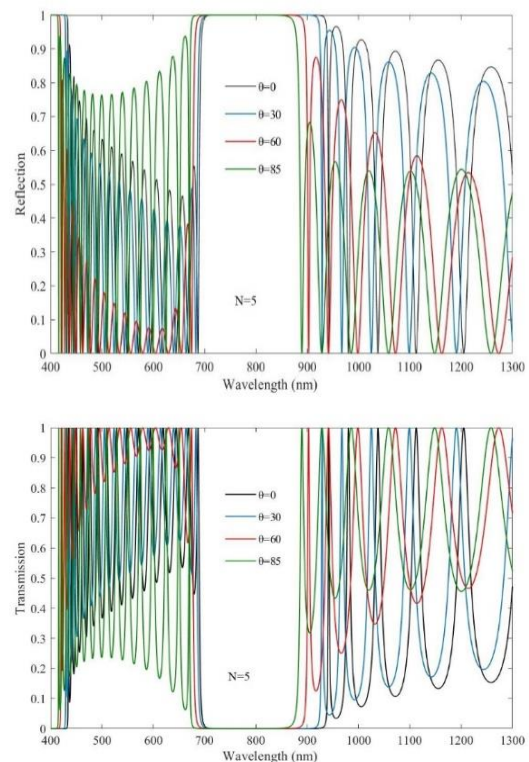


Figure 5 Photonic band gap structure of periodic TiO₂/Te photonic crystal in terms of wavelength and incident angle for both reflection and transmission of light. Simulated reflection spectra of the 1DPC at two different angles (0°, 30°, 60° 85°)

The bandwidth and reflectance spectra of the one-dimensional periodic photonic crystal multilayer structure consisting of titanium dioxide (TiO₂) and trillium (Te) material have the same huge reflection attributes. They may be used as broadband reflectors in the visible and near-infrared regions of the electromagnetic spectrum. This study of 1D-PC with Tio₂/Te materials may help make broadband reflector devices using thin-film technology. It may give us new knowledge about broadband reflector devices in visible and near-infrared regions.

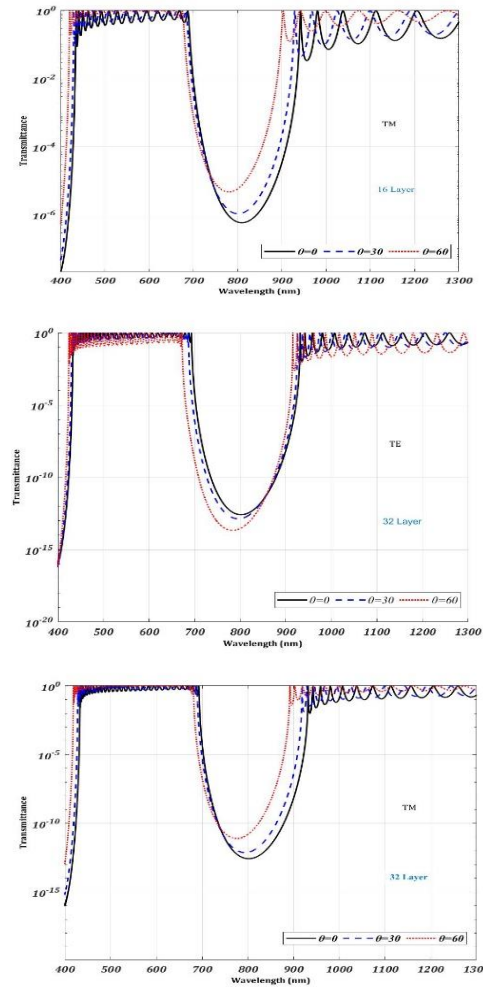
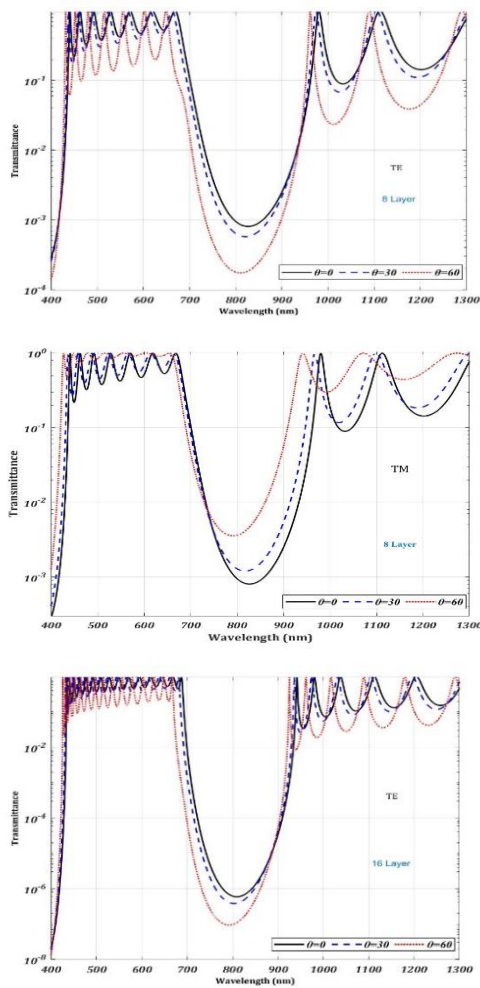


Figure 6 Transmission spectra of S4 S5 S6 Titanium dioxide (TiO₂) and Terllium (Te) periodic structure for TE and TM polarization at a different angle of the incident as 00 (black solid line), 300(blue dashed line), and 600(red dotted line)

CONCLUSION

The transfer matrix approach revealed that the photonic crystal structure consisting of TiO₂ and Te is sensitive to light radiation angle, wavelength, and crystal layer number. By carefully choosing the number of layers and materials, this structure may provide extremely specialized spectrum filtering or reflectance qualities, making it valuable for many applications. Photonic crystals can phase-control light propagation, including spectrum filtering, waveguiding, and sensing, as shown in our work. These structures will be more significant in developing next-generation optoelectronic devices such as high-speed communication systems, sensors, and solar cells. Our discoveries on photonic crystal structure design and optimization should

motivate more studies on this intriguing subject.

REFERENCES

- [1] S. R. Entezar, "Photonic Crystal Wedge As A Tunable Multichannel Filter," *Superlattices Microstruct.*, vol. 82, no. June, pp. 33–39, 2015, doi: 10.1016/j.spmi.2015.01.039.
- [2] C. López, "Materials Aspects of Photonic Crystals," *Adv. Mater.*, vol. 15, no. 20, pp. 1679–1704, 2003, doi: 10.1002/adma.200300386.
- [3] S. John, "Strong Localization of Photons in Certain Disordered Dielectric Superlattices," *Phys. Rev. Lett.*, vol. 58, no. 23, pp. 2486–2489, 1987, doi: 10.1103/PhysRevLett.58.2486.
- [4] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," *Phys. Rev. Lett.*, vol. 58, no. 20, p. 2059.
- [5] X. Lv *et al.*, "Research Progress in Preparation and Application of Photonic Crystals," *Chinese J. Mech. Eng.*, vol. 36, no. 1, pp. 1–17, 2023, doi: 10.1186/s10033-023-00836-2.
- [6] A. Shakoob, K. Nozaki, E. Kuramochi, K. Nishiguchi, A. Shinya, and M. Notomi, "Compact 1D-silicon photonic crystal electro-optic modulator operating with ultra-low switching voltage and energy," *Opt. Express*, vol. 22, no. 23, pp. 28623–28634, 2014, doi: 10.1364/oe.22.028623.
- [7] A. H. Aly, Z. A. Zaky, A. S. Shalaby, A. M. Ahmed, and D. Vigneswaran, "Theoretical study of hybrid multifunctional one-dimensional photonic crystal as a flexible blood sugar sensor," *Phys. Scr.*, vol. 95, no. 3, 2020, doi: 10.1088/1402-4896/ab53f5.
- [8] M. Notomi, "Theory of light propagation in strongly modulated photonic crystals: Refractionlike behavior in the vicinity of the photonic band gap," *Phys. Rev. B - Condens. Matter Mater. Phys.*, vol. 62, no. 16, pp. 10696–10705, 2000, doi: 10.1103/PhysRevB.62.10696.
- [9] A. Madani and S. R. Entezar, "Optical properties of one-dimensional photonic crystals containing graphene sheets," *Phys. B Condens. Matter*, vol. 431, pp. 1–5, 2013, doi: 10.1016/j.physb.2013.08.041.
- [10] Y. Trabelsi and M. Kanzari, "Omnidirectional reflection from deformed quasiperiodic one-dimensional photonic crystals in high frequency," *Phys. Procedia*, vol. 2, no. 3, pp. 947–951, 2009, doi: 10.1016/j.phpro.2009.11.048.
- [11] H. Rahimi, "Analysis of photonic spectra in Thue-Morse, double-period and Rudin-Shapiro quasiregular structures made of high temperature superconductors in visible range," *Opt. Mater. (Amst.)*, vol. 57, pp. 264–271, 2016, doi: 10.1016/j.optmat.2016.04.022.
- [12] R. D. V. Meade, S. G. Johnson, and J. N. Winn, *Photonic Crystals Molding the Flow of Light*. United Kingdom: Princeton University Press, 305AD.
- [13] R. B. Wehrspohn, H. S. Kitzerow, and K. Busch, *Nanophotonic Materials: Photonic Crystals, Plasmonics and Metamaterials*, vol. 204, no. 11. Wiley-VCH, 2008.
- [14] K. Sakoda, *Optical Properties of Photonic Crystals*. New York: Springer Berlin Heidelberg, 2007.
- [15] A. Kumar, K. B. Thapa, and S. P. Ojha, "A Tunable Broadband Filter of Ternary Photonic Crystal Containing Plasma and Superconducting Material," *Indian J. Phys.*, vol. 93, no. 6, pp. 791–798, 2019, doi: 10.1007/s12648-018-1335-9.
- [16] A. Kumar, N. Kumar, and K. B. Thapa, "Tunable Broadband Reflector and Narrowband Filter of a Dielectric and Magnetized Cold Plasma Photonic Crystal," *Eur. Phys. J. Plus*, vol. 133, no. 7, pp. 1-8, 2018, doi: 10.1140/epjp/i2018-12073-3.
- [17] A. Kumar, P. P. Singh, and K. B. Thapa, "A New Idea for Broad Band Reflector and Tunable Multichannel Filter of One Dimensional Symmetric Photonic Crystal with Magnetized Cold Plasma Defects," *AIP Conf. Proc.*, vol. 1953, pp. 1–5, 2018, doi: 10.1063/1.5032774.
- [18] A. Kumar, P. Singh, K. Pal, N. Kumar, and K. B. Thapa, "Broadband reflector of 1D photonic crystal containing TiO₂/SiO₂ material at visible region," *AIP Conf. Proc.*, vol. 2220, no. May, pp. 2–6, 2020, doi: 10.1063/5.0002138.
- [19] K. S. J. Wilson, and V. Revathy,

- "Investigation of Photonic Band Gap in Si-Based One-Dimensional Photonic Crystal," vol. 2013, no. December, pp. 365–368, 2013, doi: 10.4236/opj.2013.38057.
- [20] S. V. Gaponenko, "Introduction to nanophotonics," *Fundam. Appl. Nanophotonics*, pp. 1–11, 2016, doi: 10.1016/B978-1-78242-464-2.00001-4.
- [21] S. Massaoudi, A. De Lustrac, and I. Huynen, "Properties of Metallic Photonic Band Gap Material with Defect at Microwave Frequencies: Calculation and Experimental Verification," *J. Electromagn. Waves Appl.*, vol. 20, no. 14, pp. 1967–1980, 2006, doi: 10.1163/156939306779322710.
- [22] D. N. Chigrin, A. V. Lavrinenko, D. A. Yarotsky, and S. V. Gaponenko, "Observation of Total Omnidirectional Reflection From a One-Dimensional Dielectric Lattice," *Appl. Phys. A Mater. Sci. Process.*, vol. 68, no. 1, pp. 25–28, 1999, doi: 10.1007/s003390050849.
- [23] Y. Fink *et al.*, "A Dielectric Omnidirectional Reflector," *Science (80-.)*, vol. 282, no. 5394, pp. 1679–1682, 1998, doi: 10.1126/science.282.5394.1679.
- [24] C. F. Ramirez-Gutierrez, H. D. Martinez-Hernandez, I. A. Lujan-Cabrera, and M. E. Rodriguez-García, "Design, fabrication, and optical characterization of one-dimensional photonic crystals based on porous silicon assisted by in-situ photoacoustics," *Sci. Rep.*, vol. 9, no. 1, pp. 1–15, 2019, doi: 10.1038/s41598-019-51200-1.
- [25] E. Gondek and P. Karasiński, "One-dimensional photonic crystals as selective back reflectors," *Opt. Laser Technol.*, vol. 48, pp. 438–446, 2013, doi: 10.1016/j.optlastec.2012.11.012.
- [26] F. K. Mbakop, N. Djongyang, and D. Raïdandi, "One-dimensional TiO₂/SiO₂ photonic crystal filter for thermophotovoltaic applications," *J. Eur. Opt. Soc.*, vol. 12, no. 1, 2016, doi: 10.1186/s41476-016-0026-4.
- [27] F. K. Mbakop, N. Djongyang, G. W. Ejuh, D. Raïdandi, and P. Wofo, "Transmission of light through an optical filter of a one-dimensional photonic crystal: application to the solar thermophotovoltaic system," *Phys. B Condens. Matter*, vol. 516, pp. 1–29, 2017, doi: 10.1016/j.physb.2017.04.033.
- [28] S. Jena *et al.*, "Omnidirectional photonic band gap in magnetron sputtered TiO₂/SiO₂ one dimensional photonic crystal," *Thin Solid Films*, vol. 599, pp. 138–144, 2016, doi: 10.1016/j.tsf.2015.12.069.
- [29] P. J. Kim, S. Y. Park, M. D. Huang, Y. H. Lu, Y. P. Lee, and J. Y. Rhee, "Fabrication of oxide materials for one-dimensional photonic crystals," *J. Korean Phys. Soc.*, vol. 49, no. 3, pp. 869–872, 2006.
- [30] Pochi Yeh, *Optical Waves in Layered Media*. Wiley-Interscience Publication, 2005.
- [31] X. H. Deng, J. R. Yuan, W. Q. Hong, and H. Ouyang, "Tunable filters based on Thue-Morse quasicrystals composed of single-negative materials," *Phys. Procedia*, vol. 22, pp. 360–365, 2011, doi: 10.1016/j.phpro.2011.11.056.
- [32] S. Rashidi, A. Rashidi, and S. R. Entezar, "Tunable NIR Absorption in a Ge₂Sb₂Te₅-based 1D Asymmetric Nonlinear Hybrid Nanostructure," *Opt. Laser Technol.*, vol. 157, no. January 2023, p. 108664, 2023, doi: 10.1016/j.optlastec.2022.108664.
- [33] Y. Zhang *et al.*, "A New Method Study of Spectral Measurement and Prediction Based On The Nonlinear Solution Concentration of Alcohol," *Phys. B Condens. Matter*, vol. 516, no. April, pp. 32–35, 2017, doi: 10.1016/j.physb.2017.04.019.
- [34] A. Y. Herrera, *Dual-Periodic Photonic Crystal Structures*. Croatia: Intech.
- [35] F. L. Pedrotti, L. M. Pedrotti, and L. S. Pedrotti, "Introduction to Optics," *Introd. to Opt.*, 2017, doi: 10.1017/9781108552493.
- [36] C. Wang, "Light field distributions in one-dimensional photonic crystal fibers," *JOSA B*, vol. 26, no. 4, pp. 603–609, 2009, doi: 10.1364/JOSAB.26.000603.
- [37] E. Diaz-Escobar, L. Mercade, A. I. Barreda, J. Garcia-Ruperez, and A. Martinez, "Photonic Bandgap Closure and Metamaterial Behavior in 1D Periodic Chains of High-Index

- Nanobricks," *Photonics*, vol. 9, no. 10, pp. 1–7, 2022, doi: 10.3390/photonics9100691.
- [38] S. Matsushita *et al.*, "Calculation and Fabrication of Two-Dimensional Complete Photonic Bandgap Structures Composed of Rutile TiO₂ Single Crystals in Air/Liquid," *J. Mater. Sci.*, vol. 51, no. 2, pp. 1066–1073, 2015, doi: 10.1007/s10853-015-9436-8.
- [39] F. K. Mbakop, A. Tom, A. Dadjé, A. K. C. Vidal, and N. Djongyang, "One-Dimensional Comparison of TiO₂/SiO₂ and Si/SiO₂ Photonic Crystals Filters for Thermophotovoltaic Applications in Visible and Infrared," *Chinese J. Phys.*, vol. 67, pp. 124–134, 2020, doi: 10.1016/j.cjph.2020.06.004.