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Theoretical Study on Polycarbonate-Based One-Dimensional Ternary Photonic Structures from Far-Ultraviolet to Near-Infrared Regions of Electromagnetic Spectrum

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Citation: Matar, Z.S.; Al-Dossari, M.; Awasthi, S.K.; Abd El-Gawaad, N.S.; Hanafy, H.; Amin, R.M.; Fathy, M.I.; Aly, A.H. Theoretical Study on Polycarbonate-Based One-Dimensional Ternary Photonic Structures from Far-Ultraviolet to Near-Infrared Regions of Electromagnetic Spectrum. *Crystals* **2022**, *12*, 642. https://doi.org/10.3390/cryst12050642

Academic Editors: Muhammad Ali Butt, Svetlana Nikolaevna Khonina and Xiaoming Duan

Received: 18 March 2022
Accepted: 25 April 2022
Published: 30 April 2022

Abstract: In the present research work, we have theoretically analyzed the photonic band-gap properties of one-dimensional photonic structures composed of polycarbonate and non-glass materials. These photonic structures, PC_1, PC_2, PC_3 and PC_4, are composed of alternating layers of polycarbonate/Al_2O_3, polycarbonate/MgF_2, polycarbonate/BaF_2 and polycarbonate/TiO_2 materials, respectively. The period of each photonic structure is made up of a thin non-glass material layer sandwiched between two identical polycarbonate layers. The transfer matrix method has been used to investigate the transmission properties of PC_1 to PC_4. The comparison between the transmission spectra of PC_1 to PC_4 shows that the polycarbonate and TiO_2-based photonic structure (PC_4) possess three PBGs of zero transmission located at far-ultraviolet, visible and near-infrared regions of the electromagnetic spectrum at normal and oblique incidence (θ_0 = 55°), both corresponding to TE wave only. The index of refraction of all five materials used in this study was obtained by applying the Sellmeier-type dispersion relationship to ensure accuracy in the results. The purpose of selecting polycarbonate along with Al_2O_3, TiO_2, MgF_2 or BaF_2 as constituent materials of these photonic structures is due to the heat resistance properties of polycarbonate and the unique optical properties of oxide and fluoride materials with wide transparency from the ultraviolet to the near-infrared regions of the electromagnetic spectrum. The proposed work can be used to design some influential wavelength-selective reflectors composed of 1D PCs behind the active region of the solar cells for improving the photovoltaic performance of solar panels. This study can further be utilized for the fabrication of advanced solar cell designs consisting of 1D photonic mirror-based luminescence and reflection concentrators. The low temperature problem which arises in satellites may also be overcome with the help of smart windows based on the proposed multilayer structures.

Keywords: polycarbonate; TMM; photonic crystals; Al_2O_3; MgF_2; BaF_2; TiO_2

1. Introduction

Photonic crystals (PCs) are periodic structures with a tremendous ability to control the propagation of electromagnetic waves. These PCs possess spectral regions which rein the propagation of electromagnetic waves and are commonly known as photonic band gap (PBG) materials due to multiple Bragg scattering [1–5]. Such structures have emerged as a novel optical material due to their potential applications in the field of optical engineering and technology since the initial predications of Yablonovitch and John [6,7]. Nowadays, lots of attention has been given to photonic devices due to their tremendous ability to control and manipulate the light passing through them [8]. The interaction of electromagnetic waves with the various periodic structures consisting of dielectrics, meta-materials, superconductors, plasma, etc., have been investigated by various research groups for the designing of several photonic devices such as sensors, super capacitors, switches, etc. [9–12]. Moreover, PCs have potential applications in the field of optics and optoelectronics due to the development of tunable filters, zero-phase shift filters, omnidirectional filters and tunable resonators based on PCs which could work in the millimeter and sub-millimeter ranges [13–19]. Recently, photonic devices, due to nanotechnology-based easier fabrication techniques, have emerged as a key technology for addressing global energy requirements through the development of solar cells composed of selective back reflectors based on photonic crystals for concentrating solar radiation falling on them to improve their efficiency [20–23]. Moreover, such structures can be used to fabricate photonic crystal mirror-based luminescence and reflection concentrators for improving the efficiency of solar cells. These structures open a new gateway for the development of photonic crystal-based smart windows which could address the decreasing temperature problem of satellites [24]. For example, the experimental work of Gondek et al. showed that the 1D PC-based selective back reflector can be used as a sunlight concentrator to design improved photovoltaic systems [20]. Saravanan et al. showed how the performance of amorphous silicon-based solar cells can be enhanced by using back reflectors composed of 1D PC [21]. Apart from the piece of excellent research work discussed above, the photonic devices which could work in an ultraviolet to visible region are still difficult to realize because of the low impact strength, moderate transparency, poor dimensional stability and high temperature resistance of the constituent materials [25–27].

On the other hand, polycarbonate (PYC), an amorphous thermoplastic polymer material with low moisture absorption and temperature-independent dielectric constant properties, is a very suitable material for fabricating PCs due to additional degrees of freedom to overcome the above-mentioned limitations. The polycarbonate provides the mechanical stability to the constituent material layers during their deposition on the substrate, which is cleanly thermally removed. Although they are made commercially available in a variety of colors, perhaps translucent, perhaps not, the raw material allows for the internal transmission of light nearly in the same capacity as glass. Polycarbonate polymers are used to produce a variety of materials and are particularly useful when impact resistance and/or transparency are a product requirement (e.g., in bulletproof glass). Polycarbonate is commonly used for plastic lenses in eyewear, in medical devices, automotive components, protective gear, greenhouses, digital disks (CDs, DVDs and Blu-ray) and exterior lighting fixtures. Polycarbonate also has very good heat resistance and can be combined with flame retardants without significant material degradation. Polycarbonates are engineered plastics which are typically used due to their heat resistance capabilities and robust nature, in applications such as “glass-like” surfaces [28–30].

Polycarbonate has been considered as a major constituent material of our proposed design due to the above remarkable properties. Apart from polycarbonate, we have also selected some oxide and fluoride materials as other constituent materials because of their unique characteristics and wide transparency from the ultraviolet to near-infrared region of the electromagnetic spectrum [31–34]. Moreover, the optical absorption loss along with the thermal expansion coefficient of these materials is also very low. They have good resistance to temperature, corrosion and radiation as well. In addition, the reason behind the selection of oxide and fluoride materials along with polycarbonate for constructing our structures is to ensure the small refractive index difference between the constituent material layers. The fulfillment of this requirement makes the fabrication process of PC easier by maintaining the high Q factor. The high Q factor is the mandatory requirement in a real time-controlled deposition process which allows a precise deposition rate and the maintenance of uniformity in the thickness of the film to be deposited [35]. There are several deposition techniques for the fabrication of 1D photonic structures with a variety of materials, such as the sol-gel method, electron beam evaporation and glance angle deposition in the ultraviolet to near-infrared region [36]. Motivated by the above-mentioned qualities of polycarbonate, oxide and fluoride materials, we proposed 1D photonic structures composed of these materials to work from the far-ultraviolet to near-infrared region of the electromagnetic spectrum. To the best of our knowledge, such structures have been rarely reported.

The paper is organized as follows: The theoretical formulation of the proposed problem and corresponding analytical formulae such as wavelength-dependent refractive index of constituent materials along with the transmission coefficient are introduced in Section 2. The device fabrication requirements and its spectrum analysis are discussed in Section 3. Numerical results pertaining to the dispersion properties of constituent materials and transmission characteristics of PC_1 to PC_4 are discussed in Section 4. Finally, conclusions are presented in Section 5.

2. Structural Design and Theoretical Formulation

In this section, we introduce the schematic view of a 1D ternary photonic structure (TPC) [air/(PXP)^N/air] as shown in Figure 1. The letters P and X are being used to represent two different layers of materials, polycarbonate and non-glass, respectively. The period of the proposed structure is composed of sandwiching a thin layer of non-glass material of refractive index n_X between two identical polycarbonate layers of refractive index n_P. The period of the structure is given by $d = d_P + d_X + d_P$; here, d_P and d_X are representing the thickness of polycarbonate and non-glass material layers, respectively. The period number of the 1D ternary photonic structure is given by N. Suppose a plane wave is injected into 1D TPC at an incident angle θ_0 with respect to the stratification direction, which is along the positive direction of the z-axis. The layers are situated in an xy plane as shown in Figure 1. In general, electric and magnetic field vectors of incident light at two interfaces of any layer j can be correlated by a transfer matrix method (TMM) [24,37] as:

$$M_j = \begin{pmatrix} \cos\delta_j & -\frac{i}{p_j}\sin\delta_j \\ -ip_j\sin\delta_j & \cos\delta_j \end{pmatrix} \tag{1}$$

where $\delta_j = \frac{2\pi}{\lambda_0} n_j d_j \cos\theta_j$, λ_0 is the wavelength of the incident electromagnetic wave, d_j is the thickness of the jth layer, θ_j is the ray angle inside jth layer of refractive index n_j and $\cos\theta_j = \sqrt{1 - \left(\frac{n_0 \sin\theta_0}{n_j}\right)^2}$. Here, n_0 is the refractive index of the environment wherein the incident wave tends to enter into the structure at an angle θ_0. For the TE and TM waves, $p_j = n_j \cos\theta_j$ and $p_j = \frac{\cos\theta_j}{n_j}$, respectively. For a finite-layer 1D periodic structure as shown in Figure 1, we used TMM, which is one of the most effective techniques to analyze the transmission properties of various 1D photonic structures. The total transfer matrix of the whole structure, as depicted in Figure 1, which connects the electric and magnetic fields of the first and last layers, can be derived as:

$$\begin{pmatrix} E_1 \\ H_1 \end{pmatrix} = (M_P M_X M_P) - - - (M_P M_X M_P) \begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix} = M^N \begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix} \tag{2}$$

Here, M_P and M_X are the transfer matrix of polycarbonate and various non-glass material layers, respectively. Here, M^N is the total transfer matrix connecting electric and magnetic fields at the incident end (E_1, H_1) and exit end (E_{n+1}, H_{n+1}).

The transmission coefficient of the whole structure is given by:

$$t = \frac{2p_0}{(m_{11} + m_{12}p_{n+1})p_0 + (m_{21} + m_{22}p_{n+1})} \tag{3}$$

Here, p_0 and p_{n+1} are representing the first ($z < 0$) and last ($z > L$) media of the structure. The alphabet L is used to represent the total length of the structure. For a TE wave, $p_0 = p_{n+1} = n_0 \cos\theta_0$, whereas for a TM wave, $p_0 = p_{n+1} = \frac{\cos\theta_0}{n_0}$.

In order to study the transmission characteristics of various 1D photonic structures composed of polycarbonate and non-glass materials such as Al_2O_3, MgF_2, BaF_2 and TiO_2, we used the Sellmeier approximation formulae to calculate the wavelength-dependent refractive index of the materials polycarbonate, Al_2O_3, MgF_2 and BaF_2 at room temperature to obtain more realistic results, as in [29–31]:

$$n_X = n'_X - in''_X = \sqrt{A + \frac{B_1\lambda_0^2}{\lambda_0^2 - C1} + \frac{B_2\lambda_0^2}{\lambda_0^2 - C_2} + \frac{B_3\lambda_0^2}{\lambda_0^2 - C_3}} \tag{4}$$

The dispersion properties of the refractive index of the TiO_2 material layer are also taken into account by considering another type of Sellmeier approximation relationship, as in [31]:

$$n_{TiO_2} = n'_{TiO_2} - in''_{TiO_2} = \sqrt{5.913 + \frac{0.2441}{\lambda_0^2 - 0.0803}} \tag{5}$$

In Equations (4) and (5), n'_X and n'_{TiO_2} are used to represent a real part of the complex refractive index of the materials polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2, respectively, whereas the imaginary parts n''_X and n''_{TiO_2} are known as extinction coefficients, which measure the absorption in the medium.

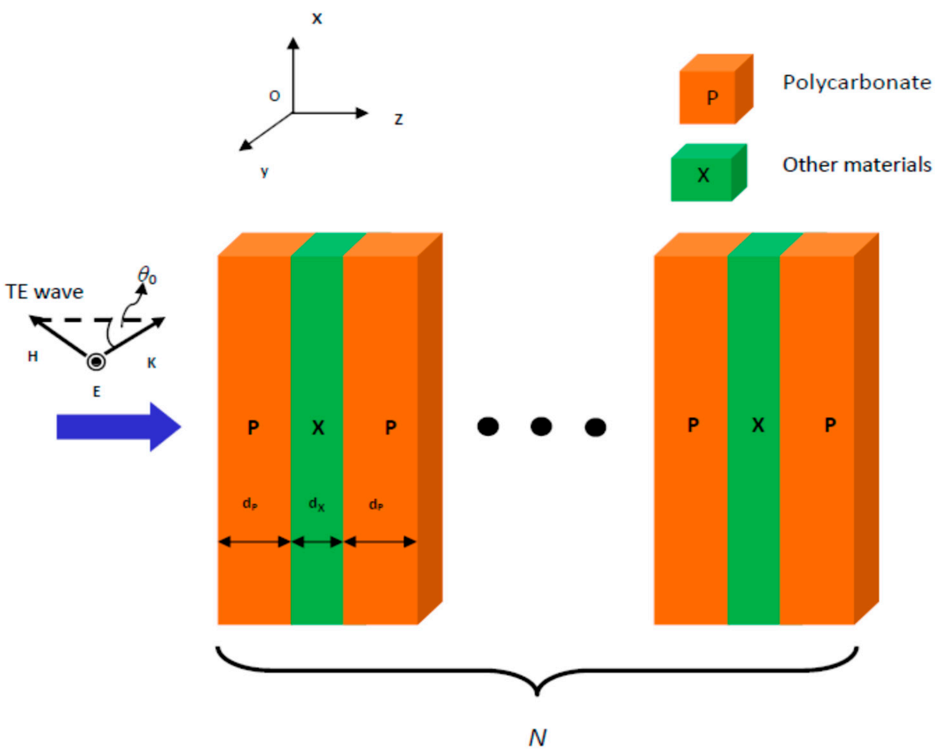

Figure 1. The schematic design of 1D ternary photonic structures considered in this work. Here, the letters P and X are being used to represent polycarbonate and other material layers (Al_2O_3, TiO_2, MgF_2 and BaF_2) of thickness d_p and d_x, respectively.

3. Experimental Section Pertaining to the Device Fabrication and Spectrum Analysis

The proposed structures can be realized by using a spin-coating fabrication technique in addition to a sol-gel method, because the spin-coating process can allow the fabrication of a periodic layered structure composed of many materials, including nano-particles and polymer solutions. To initiate the spin-coating process, a precursor solution is dropped over the flat substrate, then the solvent is evaporated from the substrate with the help of the spin process. Before spinning the next layer, we use an annealing procedure to solidify the earlier deposited layer on the substrate. The aforementioned process is repeated until we obtain a stack of the required number of layers. The thickness of each film of the multilayer periodic stack can be controlled with the variation of either rotational speed or cast solution concentration. Since the sol-gel technique does not require any complex installations associated with technology, this minimizes the fabrication cost of the photonic structure. The experimental setup required to analyze the performance of the coating is shown in Figure 2 below. The broad-band light source is used to launch the light into the proposed photonic structures through an input port with the help of a single-mode fiber (SMF) in addition to existing splicing techniques available for SMFs. The transmission spectra of the proposed photonic structures are coupled into the computer for measurements through an optical spectrum analyzer (OSA) as shown in Figure 2 below.

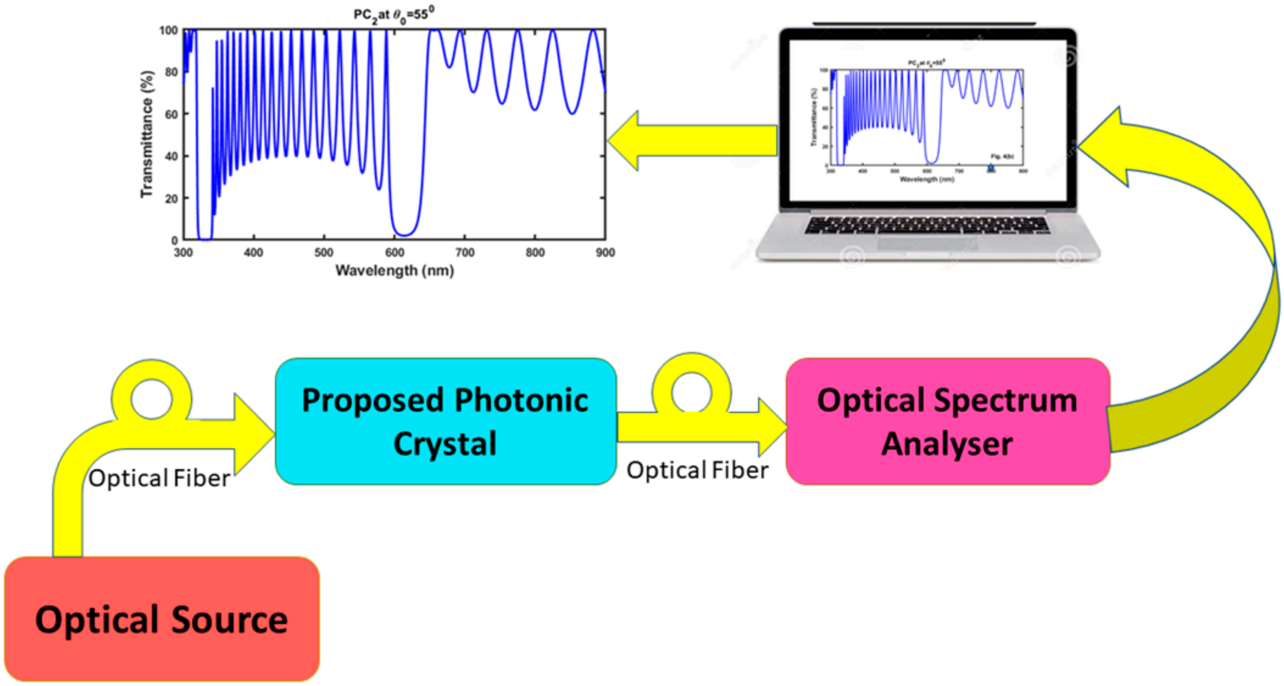

Figure 2. Systematic showing experimental setup for spectrum analysis.

4. Numerical Results and Discussion

In this section, numerical results showing the transmission properties of photonic structures PC_1 to PC_4 at normal and oblique incidence, both in the wavelength range 300–900 nm corresponding to TE wave only, are presented. PC_1, PC_2, PC_3 and PC_4 are composed of polycarbonate and other non-glass materials, Al_2O_3, MgF_2, BaF_2 and TiO_2, respectively. The thickness of polycarbonate and other non-glass material layers are taken as 94.4 nm and 50 nm, respectively. The thicknesses of the material layers are identical for all structures under consideration. The period of the structures PC_1 to PC_4 is fixed to 20. Before we discuss the transmission behavior of PC_1 to PC_4 at incident angles; $\theta_0 = 0^{\circ}$ and $\theta_0 = 55^{\circ}$, it is necessary to examine the wavelength-dependent behavior of polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2 materials. For this purpose, we used the Sellmeier approximation formulae as defined in Equations (4) and (5) to obtain the wavelength-dependent refractive index of polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2 materials at room temperature, respectively. Table 1 summarizes the Sellmeier coefficients associated with polycarbonate, Al_2O_3, MgF_2 and BaF_2 materials as given below.

Table 1. Sellmeier coefficients of polycarbonate, Al_2O_3, MgF_2 and BaF_2 materials used in the proposed 1D ternary photonic designs, PC_1 to PC_3.

Materials	A	B_1 C_1	B_2 C_2	B_3 C_3	References
Polycarbonate	1	1.4182 0.0213	- -	- -	[38]
Al_2O_3	1	1.43135 0.07266	0.65055 0.11932	5.3414 18.0283	[39,40]
MgF_2	1	0.48755 0.04338	0.39875 0.09461	2.31204 23.7936	[32]
BaF_2	1.3397	0.8107 0.10065	0.19652 29.87	4.52469 53.82	[34]

First, we discuss the wavelength-dependent dispersive properties of polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2 materials used in the proposed photonic designs. Figure 3 shows variation in the refractive index and extinction coefficient of polycarbonate, Al2O_3, MgF_2, BaF_2 and TiO_2 materials with respect to wavelength, which varies from the far-ultraviolet to near-infrared region of the electromagnetic spectrum. Figure 3a shows the dependence of the refractive index and extinction coefficient of polycarbonate material on the wavelength of incident light. As evidenced in Figure 3a, the variation in the refractive index of polycarbonate material exhibits asymptotic behavior near the far-ultraviolet (FUV) region and varies from 1.645 to 1.575 in the wavelength range 370–900 nm. The extinction coefficient of polycarbonate in this range is almost zero, i.e., polycarbonate is working as a lossless medium in the region of investigation that varies from 300 nm to 900 nm. This is one reason for selecting polycarbonate as a major contributor to our structures. Almost similar observations have been noticed for Al_2O_3, MgF_2 and BaF_2 materials as evidenced in Figure 3b–d, respectively. In addition, the dependence of the refractive index and extinction coefficient of TiO_2 material on wavelength is also plotted in Figure 3e. It shows that the refractive index of material TiO_2 varies from 2.814 to 2.26 in the wavelength range 300 nm to 900 nm. On the other hand, its extinction coefficient also varies from 0.025 to 0.000 between the wavelengths 300 and 900 nm. The losses in TiO_2 material are relatively prominent between 300 nm and 500 nm. After 500 nm, the TiO_2 serves as a lossless medium [41–44]. The above discussion justifies our choice of selecting polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2 as constituent materials to design PC_1 to PC_4 structures.

Next, we will examine the transmission properties of the proposed ternary photonic structures PC_1, PC_2, PC_3 and PC_4 at $\theta_0 = 0^\circ$. These structures were made by sandwiching the Al_2O_3, MgF_2, BaF_2 and TiO_2 material layers between two identical polycarbonate layers of thickness of 94.4 nm, one by one, to make PC_1, PC_2, PC_3 and PC_4 structures, respectively. The thickness of the sandwiched layer was fixed to 50 nm in all four structures. In order to compare the optical properties of the proposed designs in a true sense, all the structural parameters of PC_1 to PC_4 were made identical, except the index of the refractive layers of materials Al_2O_3, MgF_2, BaF_2 and TiO_2 to be sandwiched between two identical polycarbonate layers to form PC_1 to PC_4, respectively.

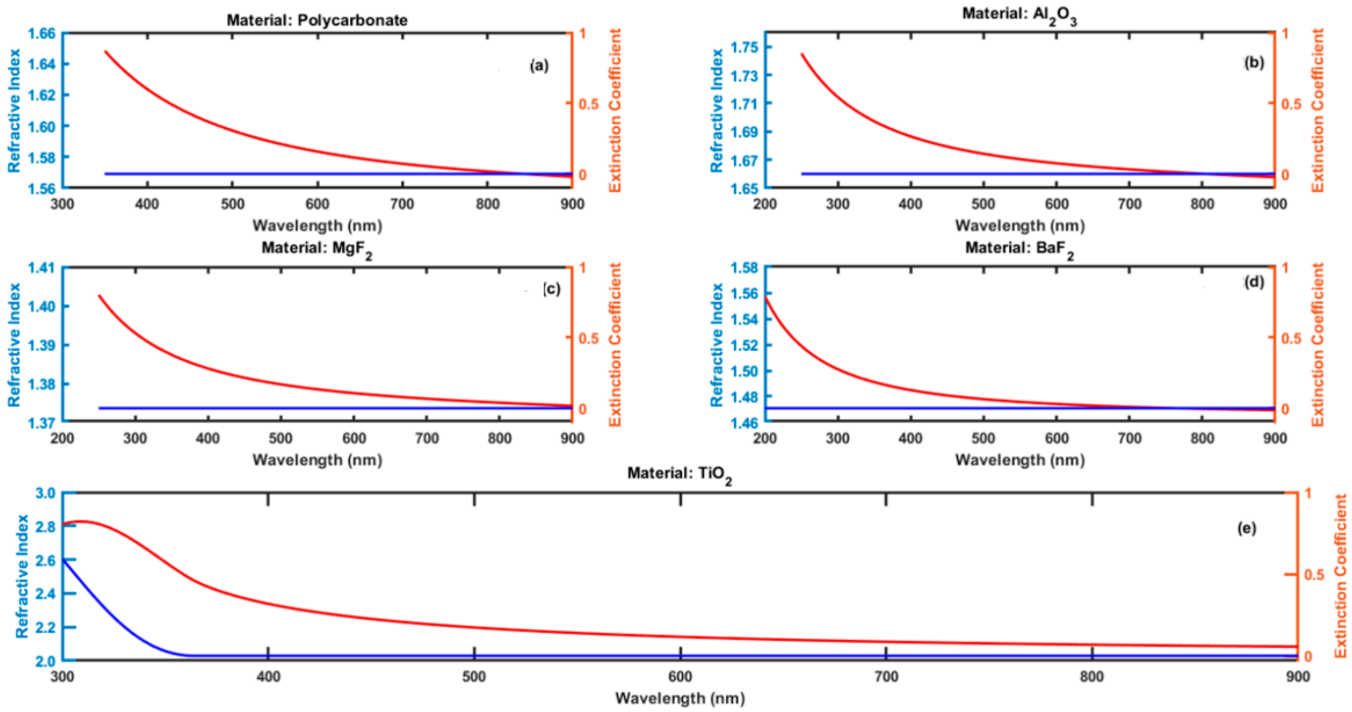

Figure 3. The wavelength-dependent refractive index and extinction coefficient of polycarbonate, Al_2O_3, MgF_2, BaF_2 and TiO_2 materials are in (**a**–**e**), respectively. Here, red and blue solid lines are used to represent the refractive index and extinction coefficient of the respective materials.

The wavelength-dependent transmission properties of PC_1 to PC_4 at normal incidence are presented in Figure 3 with the help of TMM. Figure 4a–d show the transmission properties of PC_1, PC_2, PC_3 and PC_4, respectively. Figure 3 shows the number of PBGs of different widths, depths and central wavelengths depending upon the refractive index contrast between the constituent materials used in the respective photonic designs. It is evident from Figure 4a–c that PC_1, PC_2 and PC_3 each possess two PBGs of different widths and depths. Out of these two PBGs, one exists between 300 nm and 410 nm and the other one exists between 700 nm and 820 nm. The PBGs located at the lower and higher side of the electromagnetic spectrum are narrower and wider, respectively. The comparison in Figure 4a–c also shows that only PC_2 possesses a narrow PBG of negligible transmission located between 300 nm and 410 nm. This is due the higher refractive contrast between the polycarbonate and MgF_2 material layers, as evidenced in Figure 3a,c. Thus, the higher value of the refractive contrast between the constituent material layers of the structure determines the width of PBGs of negligible transmission. On the other hand, the transmission spectra of PC_4 show three PBGs of negligible transmission. The width of these PBGs varies from smaller to larger as we move from lower to higher wavelength sides, respectively, as shown in Figure 4d. The existence of these three PBGs can be explained on the basis of the refractive index variation in TiO_2 from 2.826 to 2.084 between the wavelengths 300 nm and 900 nm, as shown in Figure 3e. The reason behind the existence of these PBGs is the multiple reflections that occur at internal interfaces of the structure. The wavelengths of incident light, which are satisfied by Equation (6), will be reflected back and are not allowed to pass through the structure [45].

$$2(n_1 d_1 \cos\theta_1 + n_2 d_2 \cos\theta_2 + n_3 d_3 \cos\theta_3) = m\lambda_0 \quad (6)$$

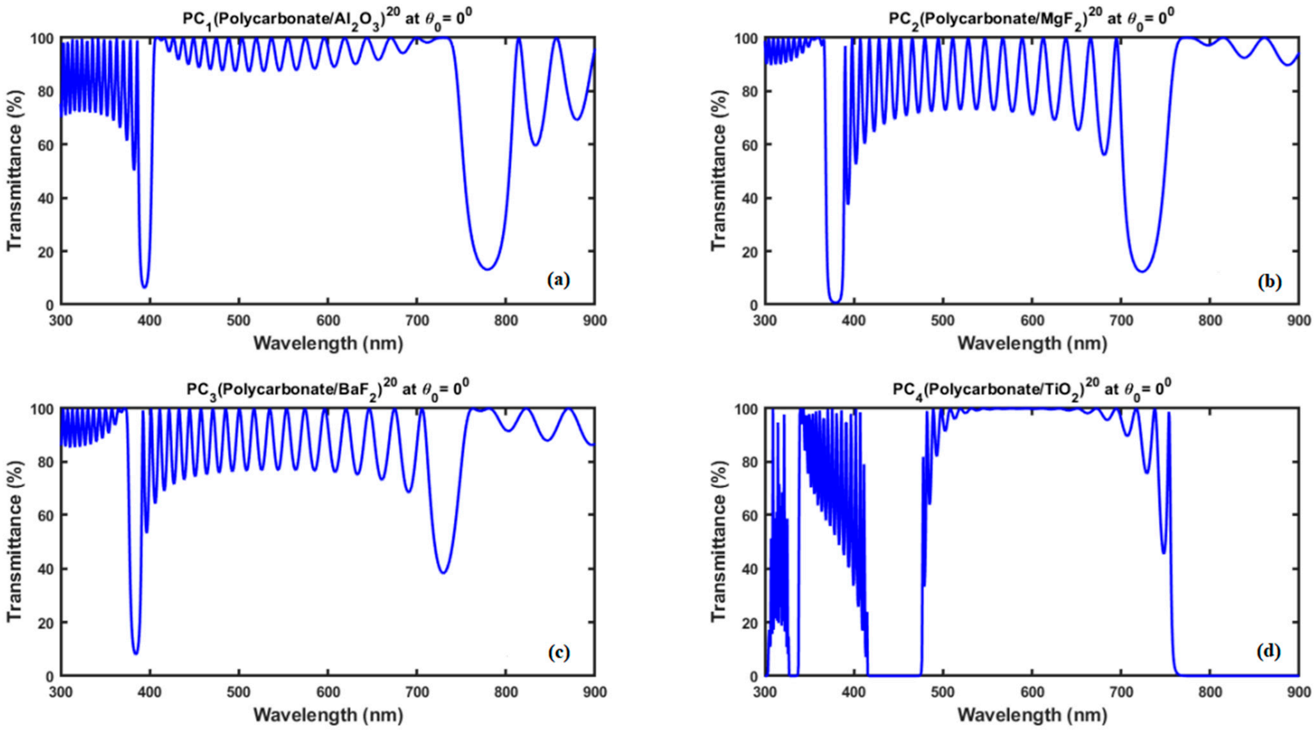

Figure 4. The calculated transmission spectra of 1D polycarbonate-based ternary photonic structures PC_1, PC_2, PC_3 and PC_4 as a function of wavelength at normal incidence are shown: (**a**) polycarbonate/Al_2O_3, (**b**) polycarbonate/MgF_2, (**c**) polycarbonate/BaF_2 and (**d**) polycarbonate/TiO_2.

Here, λ_0 is the free-space wavelength of incident light and m = 1, 2, 3, . . . represents the order of the reflection. This is the well-known Bragg's law and is responsible for the formation of PBG or the Bragg gap. The wavelengths that lie inside the PBGs of these structures can be determined with the help of the structural parameters by using Equation (6). The major parameters that decide the central wavelengths of the Bragg gap are refractive indices (n_j), thickness (d_j) and ray angles (θ_j) inside the jth layer of the period of the structure. In order to find the central wavelength of the Bragg gap we can modify Equation (6) as [45]:

$$\lambda_0^c = \frac{2(n_1 d_1 \cos\theta_1 + n_2 d_2 \cos\theta_2 + n_3 d_3 \cos\theta_3)}{m} \quad (7)$$

Since the period of the proposed photonic structures PC_1 to PC_4 is composed of three layers of two materials, we can write $n_1 d_1 \cos\theta_1 = n_3 d_3 \cos\theta_3$. Thus, the central wavelength of each PBG can be obtained with the help of modified Equation (8) as:

$$\lambda_0^c = \frac{n_2 d_2 \cos\theta_2}{1 + \frac{2d_1}{d_2}} \left(1 + \frac{2n_1 d_1 \cos\theta_1}{n_2 d_2 \cos\theta_2}\right) \frac{1}{m} \quad (8)$$

Next, we examine the behavior of the transmission properties of PC_1 to PC_4 at θ_0 = 55° corresponding to the TE wave only. Figure 5a–d shows the transmittance of PC_1, PC_2, PC_3 and PC_4 at θ_0 = 55° corresponding to the TE wave only. As evidenced in Figure 5, the PBGs of structures PC_1 to PC_4 shifted to the lower wavelength side as the angle of incidence changed from 0° to 55° corresponding to the TE wave. The width and height of their PBGs of finite transmission are also relatively reduced. On the other hand, the transmission properties of PC_4 show that both the edges of all three PBGs shifted to the lower wavelength side. Additionally, their width increases in contrast to the properties, as depicted in Figure 4d. Thus, the variation in the angle of incidence can be used for tuning the PBG position as per our desire.

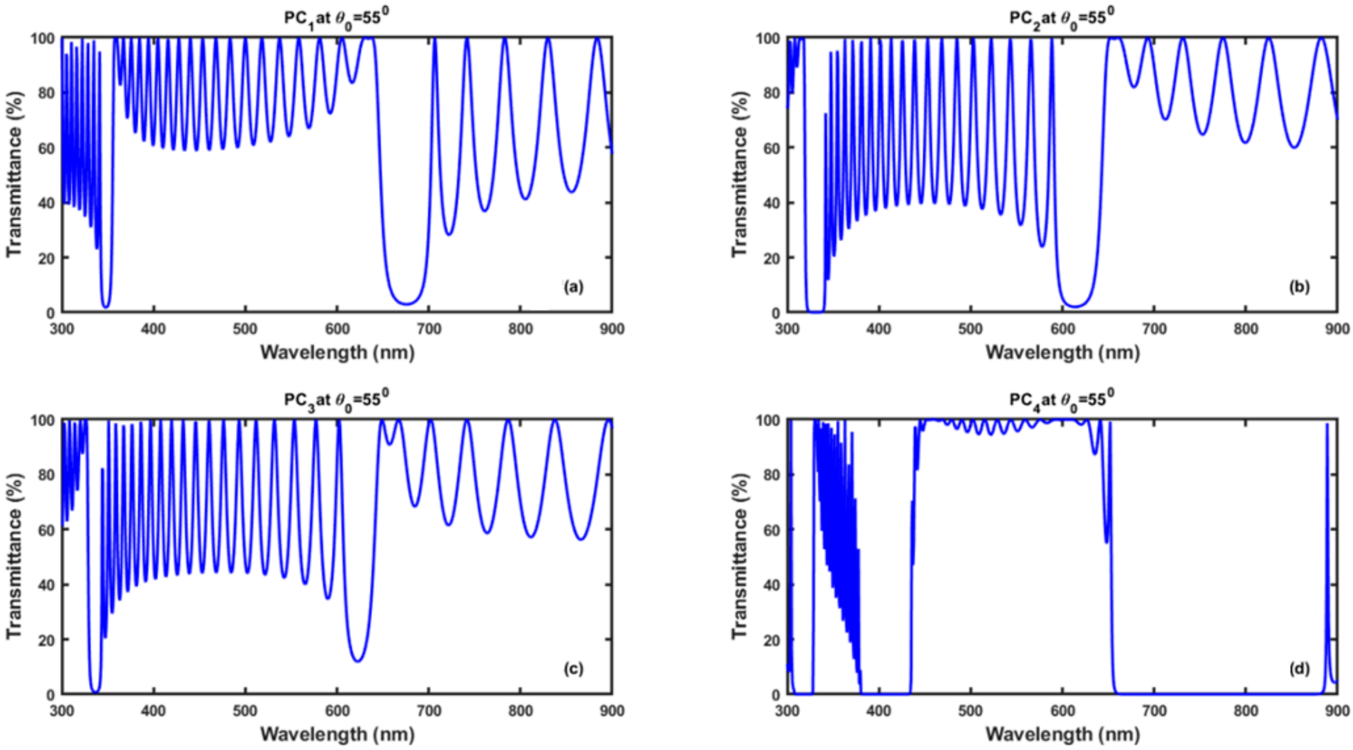

Figure 5. The calculated transmission spectra of 1D polycarbonate-based ternary photonic structures PC_1, PC_2, PC_3 and PC_4 as a function of wavelength at θ_0 = 55° are shown: (**a**) polycarbonate/Al_2O_3, (**b**) polycarbonate/MgF_2, (**c**) polycarbonate/BaF_2 and (**d**) polycarbonate/TiO_2.

As discussed above, we studied the transmission properties of four different kinds of PCs made up of polycarbonate and other oxide and fluoride materials: TiO_2, Al_2O_3, MgF_2 and BaF_2. The above study was carried out to explore the utility of polycarbonate for the designing of photonic structures suitable to work in far-ultraviolet to near-infrared regions of the electromagnetic spectrum. The polycarbonate-based photonic structures can be used for designing selective back reflectors, luminescence, and reflection concentrators to improve the performance of solar cells.

5. Conclusions

In conclusion, we studied the polycarbonate-based one-dimensional ternary photonic structures, which can be used from the far-ultraviolet to near-infrared region of the electromagnetic spectrum. These structures were designed by sandwiching Al_2O_3, MgF_2, BaF_2 and TiO_2 material layers between two identical layers of polycarbonate to form PC_1, PC_2, PC_3 and PC_4 structures, respectively. We studied the transmission properties of PC_1 to PC_4 at normal and oblique incidence, both with the help of a transfer matrix method. These findings may be helpful for designing durable and heat-resistant thin-film coatings with mechanical stability based on such 1D polycarbonate photonic structures with the ability to work in far-ultraviolet to near-infrared regions of the electromagnetic spectrum. For improving the photovoltaic performance of solar cells, we could design some significant selective back mirrors made up of the proposed 1D PC designs. This study may also open new gateways for the designing of luminescence as well as reflection concentrators based on 1D PCs, which can notably improve the efficiency of solar cells. Moreover, the proposed work may also provide some insight for designing 1D PC-based smart windows, which could efficiently handle the low temperature satellite problem, affecting the working efficacy.

Author Contributions: Conceptualization, A.H.A.; Data curation, Z.S.M., M.A.-D., N.S.A.E.-G. and H.H.; Formal analysis, H.H., R.M.A. and M.I.F.; Funding acquisition, Z.S.M., M.A.-D., N.S.A.E.-G. and H.H.; Methodology, Z.S.M. and S.K.A.; Project administration, A.H.A.; Software, R.M.A., M.I.F. and A.H.A.; Supervision, A.H.A.; Validation, S.K.A.; Writing—original draft, S.K.A.; Writing—review and editing, S.K.A. and A.H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research funded by Research Center for Advance Materials (RCAMS) at King Khalid University, Saudi Arabia. This work was supported by the King Khalid University through a grant KKU/RCAMS/22.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the King Khalid University through a grant KKU/RCAMS/22 under the Research Center for Advance Materials (RCAMS) at King Khalid University, Saudi Arabia.

Conflicts of Interest: The authors declare that there are no conflict of interest.

References

1. Joannopoulos, J.; Johnson, S.; Winn, J.; Meade, R. *Photonic Crystals: Molding the Flow of Light*, 2nd ed.; Princeton Univ.: Princeton, NJ, USA, 2008.
2. Knight, J.C.; Broeng, J.; Birks, T.A.; Russell, P.S.J. Photonic band gap guidance in optical fibers. *Science* **1998**, *282*, 1476–1478. [CrossRef] [PubMed]
3. Bowden, C.M. Development and application of materials exhibiting photonic band gaps. *J. Opt. Soc. Am. B* **1993**, *10*, 280–413. [CrossRef]
4. Altug, H.; Englund, D.; Vučković, J. Ultrafast photonic crystal nanocavity laser. *Nat. Phys.* **2006**, *2*, 484–488. [CrossRef]
5. Painter, O.; Lee, R.; Scherer, A.; Yariv, A.; O'brien, J.; Dapkus, P.; Kim, I. Two-dimensional photonic band-gap defect mode laser. *Science* **1999**, *284*, 1819–1821. [CrossRef] [PubMed]
6. Yablonovitch, E. Inhibited spontaneous emission in solid-state physics and electronics. *Phys. Rev. Lett.* **1987**, *58*, 2059. [CrossRef] [PubMed]
7. John, S. Strong localization of photons in certain disordered dielectric superlattices. *Phys. Rev. Lett.* **1987**, *58*, 2486. [CrossRef]
8. Aly, A.H.; Zaky, Z.A.; Shalaby, A.S.; Ahmed, A.M.; Vigneswaran, D. Theoretical study of hybrid multifunctional one-dimensional photonic crystal as a flexible blood sugar sensor. *Phys. Scr.* **2020**, *95*, 035510. [CrossRef]
9. Aly, A.H.; Mohamed, D.; Matar, Z.; Trabelsi, Y.; Vigneswaran, D.; Tayeboun, F.; Mohaseb, M. Tunability and Fano Resonance Properties in Different Types of One-Dimensional Superconductor Photonic Crystals. *Mater. Res.* **2021**, *24*, e20200507. [CrossRef]
10. Aly, A.H.; Mohamed, D. BSCCO/$SrTiO_3$ one dimensional superconducting photonic crystal for many applications. *J. Supercond. Nov. Magn* **2015**, *28*, 1699–1703. [CrossRef]
11. Aly, A.H.; Ghany, S.-S.A.; Kamal, B.; Vigneswaran, D. Theoretical studies of hybrid multifunctional $YaBa_2Cu_3O_7$ photonic crystals within visible and infra-red regions. *Ceram. Int.* **2020**, *46*, 365–369. [CrossRef]
12. Awad, M.; Aly, A.H. Experimental and theoretical studies of hybrid multifunctional TiO_2/TiN/TiO_2. *Ceram. Int.* **2019**, *45*, 19036–19043. [CrossRef]
13. Wang, X.; Fujimaki, M.; Awazu, K. Photonic crystal structures in titanium dioxide (TiO_2) and their optimal design. *Opt. Express* **2005**, *13*, 1486–1497. [CrossRef] [PubMed]
14. Zaky, Z.A.; Sharma, A.; Aly, A.H. Gyroidal Graphene for Exciting Tamm Plasmon Polariton as Refractive Index Sensor: Theoretical Study. *Opt. Mater.* **2021**, *122*, 111684. [CrossRef]
15. Ok, J.G.; Seok Youn, H.; Kyu Kwak, M.; Lee, K.-T.; Jae Shin, Y.; Jay Guo, L.; Greenwald, A.; Liu, Y. Continuous and scalable fabrication of flexible metamaterial films via roll-to-roll nanoimprint process for broadband plasmonic infrared filters. *Appl. Phys. Lett.* **2012**, *101*, 223102. [CrossRef]
16. Zaky, Z.A.; Aly, A.H. Modeling of a biosensor using Tamm resonance excited by graphene. *Appl. Optics* **2021**, *60*, 1411–1419. [CrossRef]
17. Aly, A.H.; Sayed, F.A. THz cutoff frequency and multifunction $Ti_2Ba_2Ca_2Cu_3O_{10}$/GaAs photonic bandgap materials. *Int. J. Mod. Phys. B* **2020**, *34*, 2050091. [CrossRef]
18. Shaban, S.M.; Mehaney, A.; Aly, A.H. Determination of 1-propanol, ethanol, and methanol concentrations in water based on a one-dimensional phoxonic crystal sensor. *Appl. Optics* **2020**, *59*, 3878–3885. [CrossRef]
19. Elsayed, H.A.; Sayed, H.; Taha, T.A.; Alharbi, A.G.; Alenad, A.M.; Alshammari, B.A.; Ahmed, A.M.; Mehaney, A.; Aly, A.H. Simple and efficient design towards a significant improvement of the optical absorption of amorphous silicon solar cell. *J. Quant. Spectrosc. Radiat. Transf.* **2021**, *275*, 107890. [CrossRef]

20. Gondek, E.; Karasiński, P. One-dimensional photonic crystals as selective back reflectors. *Opt. Laser Technol.* **2013**, *48*, 438–446. [CrossRef]
21. Zaky, Z.A.; Aly, A.H. Gyroidal graphene/porous silicon array for exciting optical Tamm state as optical sensor. *Sci. Rep.* **2021**, *11*, 19389. [CrossRef]
22. Rowan, B.C.; Wilson, L.R.; Richards, B.S. Advanced material concepts for luminescent solar concentrators. *IEEE J. Sel. Top. Quantum Electron.* **2008**, *14*, 1312–1322. [CrossRef]
23. Van Sark, W.G.; Barnham, K.W.; Slooff, L.H.; Chatten, A.J.; Büchtemann, A.; Meyer, A.; McCormack, S.J.; Koole, R.; Farrell, D.J.; Bose, R. Luminescent Solar Concentrators-A review of recent results. *Opt. Express* **2008**, *16*, 21773–21792. [CrossRef] [PubMed]
24. Aly, A.H.; Ameen, A.A.; Elsayed, H.A.; Mohamed, S.; Singh, M.R. One-dimensional metallo-superconductor photonic crystals as a smart window. *J. Supercond. Nov. Magn.* **2019**, *32*, 2313–2318. [CrossRef]
25. Awasthi, S.K.; Malaviya, U.; Ojha, S.P. Enhancement of omnidirectional total-reflection wavelength range by using one-dimensional ternary photonic bandgap material. *J. Opt. Soc. Am. B-Opt. Phys.* **2006**, *23*, 2566–2571. [CrossRef]
26. Dadabayev, R.; Malka, D. A visible light RGB wavelength demultiplexer based on polycarbonate multicore polymer optical fiber. *Opt. Laser Technol.* **2019**, *116*, 239–245. [CrossRef]
27. van Eijkelenborg, M.A.; Argyros, A.; Leon-Saval, S.G. Polycarbonate hollow-core microstructured optical fiber. *Opt. Lett.* **2008**, *33*, 2446–2448. [CrossRef]
28. Calvo, M.E.; Colodrero, S.; Hidalgo, N.; Lozano, G.; López-López, C.; Sanchez-Sobrado, O.; Miguez, H. Porous one dimensional photonic crystals: Novel multifunctional materials for environmental and energy applications. *Energy Environ. Sci.* **2011**, *4*, 4800–4812. [CrossRef]
29. Guillaume, S.M. *Handbook of Telechelic Polyesters, Polycarbonates, and Polyethers*; Pan Stanford Publishing Pte. Ltd.: Sligo, Ireland, 2017.
30. Brunelle, D.J.; Korn, M.R. *Advances in Polycarbonates*; American Chemical Society: Washington, DC, USA, 2005.
31. Palik, E.D. *Handbook of Optical Constants of Solids*; Academic Press: Cambridge, MA, USA, 1998; Volume 3.
32. Dodge, M.J. Refractive properties of magnesium fluoride. *Appl. Optics* **1984**, *23*, 1980–1985. [CrossRef]
33. Tatian, B. Fitting refractive-index data with the Sellmeier dispersion formula. *Appl. Optics* **1984**, *23*, 4477–4485. [CrossRef]
34. Malitson, I.H. Refractive properties of barium fluoride. *JOSA* **1964**, *54*, 628–632. [CrossRef]
35. Bellingeri, M.; Chiasera, A.; Kriegel, I.; Scotognella, F. Optical properties of periodic, quasi-periodic, and disordered one-dimensional photonic structures. *Opt. Mater.* **2017**, *72*, 403–421. [CrossRef]
36. Xiao, X.; Wenjun, W.; Shuhong, L.; Wanquan, Z.; Dong, Z.; Qianqian, D.; Xuexi, G.; Bingyuan, Z. Investigation of defect modes with Al2O3 and TiO2 in one-dimensional photonic crystals. *Optik* **2016**, *127*, 135–138. [CrossRef]
37. Born, M.; Wolf, E. Basic Properties of the Electromagnetic Field. In *Principles of Optics*; Cambridge University Press: Cambridge, UK, 1980; Volume 44, pp. 1–70.
38. Sultanova, N.; Kasarova, S.; Nikolov, I. Dispersion proper ties of optical polymers. *Acta Phys. Pol. -Ser. A Gen. Phys.* **2009**, *116*, 585. [CrossRef]
39. Malitson, I.H.; Dodge, M.J. Refractive-index and birefringence of synthetic sapphire. *J. Opt. Soc. Am.* **1972**, *62*, 1405.
40. Dodge, M. Refractive index. In *Handbook of Laser Science and Technology*; CRC Press: Boca Raton, FL, USA, 1986; Volume 2, pp. 21–47.
41. Cardona, M.; Harbeke, G. Optical properties and band structure of wurtzite-type crystals and rutile. *Phys. Rev.* **1965**, *137*, A1467. [CrossRef]
42. Vos, K.; Krusemeyer, H. Reflectance and electroreflectance of TiO2 single crystals. I. Optical spectra. *J. Phys. C Solid State Phys.* **1977**, *10*, 3893. [CrossRef]
43. Daude, N.; Gout, C.; Jouanin, C. Electronic band structure of titanium dioxide. *Phys. Rev. B* **1977**, *15*, 3229. [CrossRef]
44. Yu, P.; Cardona, M. *Fundamentals of Semiconductors: Physics and Materials Properties*; Springer Science and Business Media: New York, NY, USA, 2010.
45. Zhao, J.; Li, X.; Zhong, L.; Chen, G. Calculation of photonic band-gap of one dimensional photonic crystal. *J. Phys. Conf. Ser.* **2009**, *183*, 012018. [CrossRef]