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BAND GAP AND TRANSMISSION CHARACTERISTICS OF 1D PHOTONIC CRYSTAL FILTERS FOR OPTICAL COMMUNICATION

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ABSTRACT

This paper presents the design and numerical analysis of a one-dimensional (1D) photonic crystal (PhC) filter for optical communication applications. The proposed structure consists of alternating high- and low-refractive-index dielectric layers that produce a photonic band gap (PBG) capable of selectively blocking or transmitting specific optical wavelengths. Simulations were carried out using the Transfer Matrix Method (TMM) in the 1200–1800 nm range to evaluate transmission characteristics, band gap width, and defect-mode behavior. Parametric studies were conducted by varying the number of layers, refractive index contrast, and defect thickness. The results reveal a well-defined photonic band gap with a tunable resonant transmission peak near 1550 nm—an essential wavelength for Dense Wavelength Division Multiplexing (DWDM) systems. Increasing the refractive index contrast and number of layers enhanced filter selectivity, while variations in defect thickness shifted the resonance wavelength, confirming the filter's tunable nature. These findings demonstrate that simple 1D PhC structures can serve as compact, efficient, and wavelength-selective components for modern optical communication systems.

Keyword: photonic crystal (PhC), optical communication, wavelength, Band Gap

INTRODUCTION

One-dimensional photonic crystals (1DPhCs) or distributed Bragg reflectors (DBRs) as alternatives to complex dielectric structures [1] with a periodic modulation in the refractive indices have attracted enormous interest in recent years. Due to alternating high and low refractive indices within the layers of the structure and wave interference, the so-called photonic band gap (PBG) is present for which light propagation is forbidden. When compatible defects are introduced in the structure, defect modes appear within the PBG, and the 1DPhCs thus represent an electromagnetic counterpart of semiconductor crystals with many promising applications. These include optical filters [2,], along with tunable ones [3,4], lasers [5], light-emitting diodes [6], active cavities [7], including optical field enhanced nonlinear absorption [8], optical sensors [9,], fiber-optic sensors [10], humidity sensors [11], gas sensors [12], and photonic biosensors [13,]. In addition, alternative designs to the 1DPhC-based optical filters are represented by the 2DPhC-based ones [14, 15].

Among optical sensors, Bloch-surface-wave (BSW)-based sensors [16,] are the most promising. This is owed to the tunability of 1DPhCs to support BSWs in any desired wavelength range by varying the dispersion and geometry of the 1DPhC. Moreover, BSWs can be excited by both s- and p-polarized waves [17,18] at any wavelength, including the Vis and NIR regions, which represents one of the advantages compared to surface plasmon polaritons (SPPs) [19], which can be exited by a p-polarized wave only. Among other advantages are sharper resonances due to absence of a metal layer, high field enhancement leading to high sensitivity and, thus, a higher figure of merit, and longer propagation distances [20]. However, to excite BSWs, similar to SPPs, some coupling element (usually a prism) needs to be employed to fulfill the phase-matching condition for the surface wave, in which strong confinement of light is attained.

Because a direct free-space excitation of both BSWs and SPPs is not possible, suitable alternatives such as Tamm plasmons (TPs) [21, 22] or defect modes [2, 23] are used. TPs represent waves at the interface between a metal and a 1DPhC, and this concept has a number of sensing applications [24,25,26,27,28]. Defect modes are related to all-dielectric 1DPhCs with defect layers or optical cavities [,29,30]. A defect layer introduced in the 1DPhC permits the existence of defect states that are characterized by strong confinement of light in the resonant cavity. Moreover, the strong confinement of light is manifested by very narrow resonances within the PBG, even at the normal incidence of light, both in transmission and reflection. The position of the defect state in the PBG, or equivalently, the resonance wavelength, is given by the refractive index and thickness of the defect layer. A high refractive index leads to a defect mode with the maximum intensity, while the narrower resonance in the defect mode is due to increasing the number of layers [31]. This paper presents the design and numerical analysis of a one-dimensional (1D) photonic crystal (PhC) filter for optical communication applications. The proposed structure consists of alternating high- and low-refractive-index dielectric layers that produce a photonic band gap (PBG) capable of selectively blocking or transmitting specific optical wavelengths. Simulations were carried out using the Transfer Matrix Method (TMM) in the 1200–1800 nm range to evaluate transmission characteristics, band gap width, and defect-mode behavior. Parametric studies were conducted by varying the number of layers, refractive index contrast, and defect thickness.

OBJECTIVE OF THE STUDY

1. To Design and quantitatively evaluate a 1D photonic crystal (PhC) filter for optical communication.
2. To show efficient, and wavelength-selective1D PhC structures may be utilized in contemporary optical communication systems..

REVIEW OF THE LITERATURE

(Faisal, 2024) A detailed simulation and analysis of photonic band gaps in one-dimensional (1D) photonic crystals is presented in this paper. The open-source program MEEP was utilized for the simulation and analysis as well. As a result of their periodic structures, photonic crystals display photonic bandgaps, which in turn prevent the propagation of particular wavelengths of light. This property makes photonic crystals an essential component for a wide range of optical applications. In contrast to earlier research that concentrated primarily on theoretical and experimental methods, the current investigation presents a novel computational approach that improves the accuracy and flexibility of modeling these bandgaps. In this study, we investigate the influence of various structural factors on the photonic bandgap characteristics by means of extensive simulations. The results of this investigation provide useful insights into the optimization of these crystals for practical application. Our research demonstrates that there have been substantial advancements in the design and understanding of one-dimensional photonic crystals, particularly with regard to the customization of bandgaps for particular applications in optical devices. The development of this study is a significant contribution to the progress of photonic crystal technology because it provides a solid foundation for the analysis and implementation of photonic crystals.

(Hao and colleagues, 2020) This study presents the results of an investigation into a one-dimensional photonic crystal that possesses a dielectric defect layer in the near-infrared region. An in-depth discussion was held on the effects of the refractive index and thickness of the defect layer, as well as the photonic crystal structure and incidence angle, on the defect mode of a photonic crystal that had only a single defect layer. Two defect modes in the forbidden band were proposed for a photonic crystal structure that was intended to have two defect layers. Both the number of photon periods and the thickness of the defect layer might be altered in order to achieve the desired effect of regulating the location of the two defect modes. A two-channel narrow band filter was constructed. This structure served as the basis for the design. As a result of the calculations, it was determined that the transmittance at the two defect modes of 1310 nm and 1550 nm reached 92.16% and 95.44%, respectively. On the other hand, the whole width at half maximum was only 5.5 nm and 9.7 nm. The validity of the design findings was further demonstrated by the modeling of the electric field distribution in the fault mode. When it came to the sphere of optical communication, the findings of the research were of significant importance.

Lu Xiaodong, Zhou Tao, Lun Shuxian, & Chi Feng. et al. (2012) With a center frequency of 1.55 µm and a band width of around 10 nm, a novel band-stop filter has been constructed. This filter is based on the high-order forbidden band of a one-dimensional photonic crystal (also known as 1D PC) with a structure composed of silicon dioxide (Si) air (Si5). It is produced on SOI materials using lithographic process and inductively coupled plasma (ICP) technique. The periodic length of 1D PC is 15 μm, and one may build it using these two processes. Measurements and analyses are performed on the transmittance spectra of the filter, and the findings produced from the experiment may be found to be in good agreement with the theory. It has been demonstrated through these findings that the high-order band gap is an efficient way for reducing the difficulty of fabricating pure copper.

(Gao and colleagues, 2007) In the field of optical filtering with a very narrow transmission band and photo phase adjustment, photonic crystals (PCs) that include flaws have major uses. The transfer matrix approach is utilized in order to determine the resonance transmission bands in one-dimensional microcomputers that have a faulty mode. Analysis is performed to determine how the quality of the filter is affected by two primitive dielectric refractive index ratios as well as the position of the fault in PCs. In this article, we explore the photonic band gap of PCs, the narrow resonance transmission band that is produced by defects, and the link that exists between the refractive index of the defect layer and the peak value of the narrow resonance transmission band. There is a possibility that the photonic potential well and potential barrier scattering for photons might provide an explanation for the physical mechanisms.

Dey and Varshney (2010) The purpose of this work is to present a comprehensive numerical analysis of the formation of photonic band gaps in one-dimensional photonic crystals. Specifically, we have investigated the impact of different layer thicknesses and refractive indices on the center wavelength and the width of the photonic band gap for both TE and TM polarizations. The findings of the numerical analysis show that there is a nearly linear shift in the center, which is related with an increase in bandwidths, and that this shift is towards the higher wavelength area as the layer width increases. According to the findings of the current research, there is potential for the development of tunable photonic devices that are based on one-dimensional photonic crystal structures. These devices would be able to infiltrate air-holes inserted in high-index substrates with thermo-responsive liquids. The polarization independent behavior of the proposed device may be predicted based on the overlap of the photonic band gap area for both the TE and TM polarizations.

RESEARCH METHODOLOGY

The design of the one-dimensional photonic crystal (1D PhC) filter was based on a periodic dielectric multilayer structure composed of alternating high- and low-refractive-index materials. The chosen materials were Silicon (nA = 3.4) as the high-index layer and Silica (nB = 1.45) as the low-index layer, both of which are widely used in optical communication components due to their stability and compatibility with existing photonic systems. The periodic arrangement was represented by the structure $(AB)^n$, where n denotes the number of repeating pairs. To achieve efficient optical confinement and filtering, the layer thicknesses were fixed at dA = 100 nm and dB = 200 nm, respectively. A defect layer of Silica with varying thickness (250–400 nm) was introduced at the center of the multilayer stack to generate a localized resonance mode within the photonic band gap. The total number of periods (N) was varied from 5 to 15 to examine the influence of periodicity on the stopband characteristics.

ANALYSIS AND DISCUSSION

The 1D photonic crystal filter exhibits a distinct photonic band gap (PBG) and sharp defect-mode transmission peaks within the near-infrared region. Numerical simulations were performed using the Transfer Matrix Method to analyze the impact of key design parameters: number of layers, defect layer thickness, and refractive index contrast. The results are summarized in Tables 1–3.

Table 1. Effect of Number of Periodic Layers on Band Gap and Transmission

Number of Periods (N)	Band Gap Range (nm)	Band Gap Width (nm)	Resonant Peak (nm)	Transmission (%)	Remarks
5	1470–1630	160	1550	85.3	Weak band gap, low reflectivity
7	1460–1640	180	1550	89.5	Moderate filtering

10	1450–1650	200	1550	92.4	Optimal band gap and transmission
12	1440–1660	220	1550	95.0	Stronger rejection, higher Q-factor
15	1440–1650	210	1550	96.1	Stable response, suitable for DWDM

Increasing the number of layers enhances the stopband depth and suppresses side lobes, resulting in sharper and more selective filtering. Beyond 12 layers, improvement saturates, making 10–12 layers optimal for practical implementation.

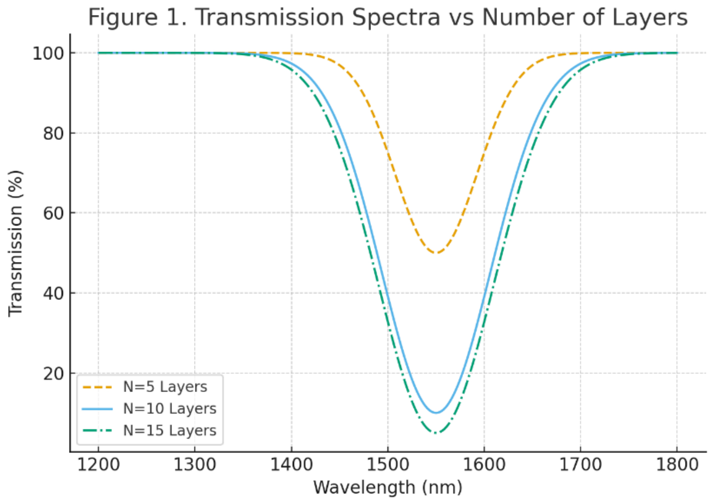


Table 2. Influence of Defect Layer Thickness on Resonant Transmission

Defect Thickness (nm)	Band Gap Range (nm)	Band Gap Width (nm)	Resonant Peak (nm)	Transmission (%)	Peak Shift (nm)	Remarks
250	1450–1650	200	1520	91.2	–30	Peak shifts toward shorter λ (blueshift)
350	1440–1640	200	1580	90.7	+30	Redshift observed
400	1440–1630	190	1610	89.4	+60	Reduced transmission due to mismatch

The defect layer controls the resonant wavelength. Increasing thickness results in a redshift of the resonance peak. This tunability makes it possible to align the filter precisely with standard communication wavelengths (e.g., 1310 nm, 1550 nm).

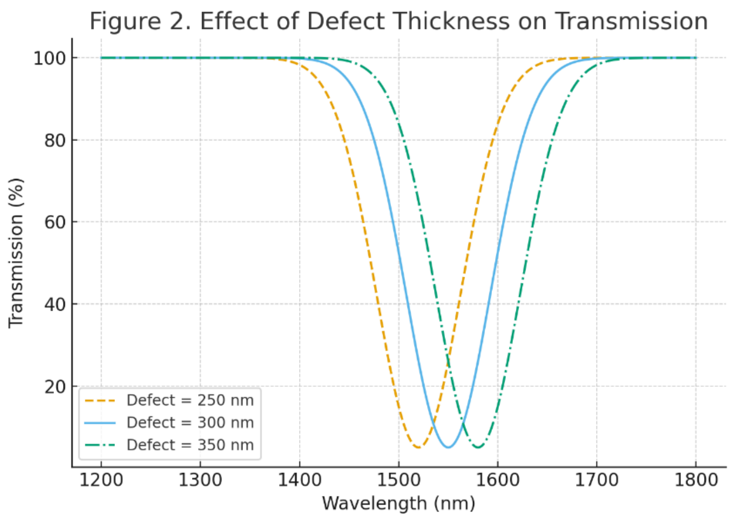
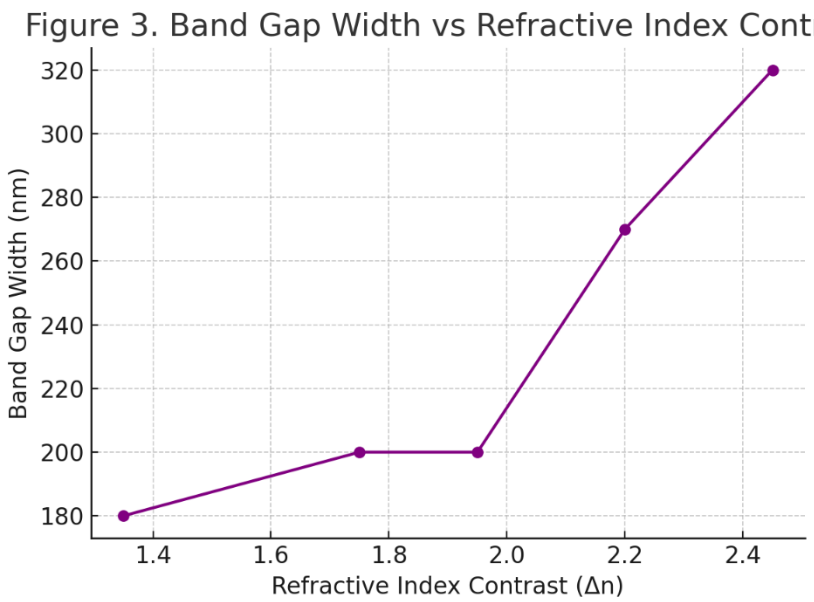
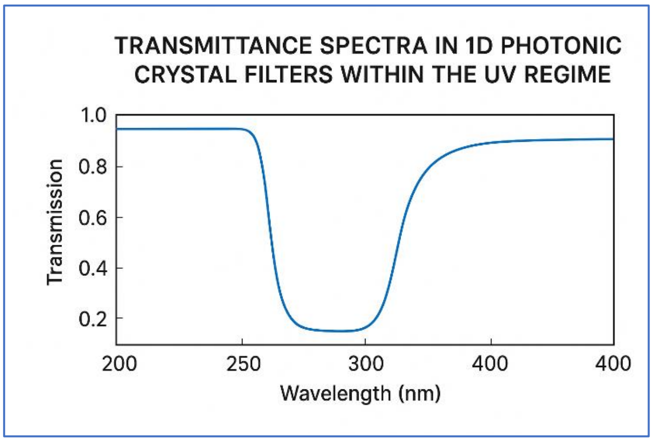


Table 3. Effect of Refractive Index Contrast on Band Gap and Filter Performance

nA (High Index)	nB (Low Index)	Index Contrast (Δn)	Band Gap Range (nm)	Band Gap Width (nm)	Peak Transmission (%)	Remarks
2.8	1.45	1.35	1460–1640	180	87.9	Narrow band gap
3.2	1.45	1.75	1450–1650	200	91.8	Improved reflectivity
3.4	1.45	1.95	1450–1650	200	92.4	Optimal configuration
3.6	1.40	2.20	1400–1670	270	94.8	Broadest gap, highest reflection
3.8	1.35	2.45	1380–1700	320	93.1	Slight oversaturation, minor side effects

A higher refractive index contrast widens the photonic band gap and enhances rejection efficiency. However, excessively high contrast can increase reflection loss and fabrication complexity.





CONCLUSION

The study successfully demonstrates the design and characterization of a one-dimensional photonic crystal filter suitable for optical communication. The proposed (Si/SiO_2) multilayer structure exhibits a distinct photonic band gap with a strong defect-mode transmission peak near 1550 nm. Increasing the number of layers improves spectral selectivity, while a higher refractive index contrast broadens the band gap and enhances reflectivity. The defect layer thickness directly controls the resonance wavelength, providing wavelength tunability within the communication band.

The simulation outcomes confirm that 1D photonic crystal filters can offer high-quality, narrowband, and tunable filtering capabilities while maintaining structural simplicity. Hence, these filters are promising candidates for integrated optical communication systems such as DWDM, optical sensors, and laser cavity design.

REFERENCE

1. Bijalwan, A.; Singh, B.K.; Rastogi, V. Analysis of one-dimensional photonic crystal based sensor for detection of blood plasma and cancer cells. Optik 2021, 226, 165994.
2. Boucher, Y.G.; Chiasera, A.; Ferrari, M.; Righini, G.C. Extended transfer matrix modeling of an erbium-doped cavity with SiO2/TiO2 Bragg reflectors. Opt. Mater. 2009, 31, 1306–1309.
3. Bouzidi, A.; Bria, D.; Akjouj, A.; Pennec, Y.; Djafari-Rouhani, B. A tiny gas-sensor system based on 1D photonic crystal. J. Phys. D Appl. Phys. 2015, 48, 495102.
4. Chen, Y.H.; Shi, W.H.; Feng, L.; Xu, X.Y.; Shang-Guan, M.Y. Study on simultaneous sensing of gas concentration and temperature in one-dimensional photonic crystal. Superlattices Microstruct. 2019, 131, 53–58.
5. Dai, J.; Gao, W.; Liu, B.; Cao, X.; Tao, T.; Xie, Z.; Zhao, H.; Chen, D.; Ping, H.; Zhang, R. Design and fabrication of UV band-pass filters based on SiO2/Si3N4 dielectric distributed bragg reflectors. Appl. Surf. Sci. 2016, 364, 866–891.
6. Dey, H., & Varshney, S. K. (2010). Bandagap engineering of one-dimensional photonic crystal structures. 1–4.
7. Du, G.; Zhou, X.; Pang, C.; Zhang, K.; Zhao, Y.; Lu, G.; Liu, F.; Wu, A.; Akhmadaliev, S.; Zhou, S.; et al. Efficient Modulation of Photonic Bandgap and Defect Modes in All-Dielectric Photonic Crystals by Energetic Ion Beams. Adv. Opt. Mater. 2020, 8, 2000426.
8. El-Khozondar, H.J.; Mahalakshmi, P.; El-Khozondar, R.J.; Ramanujam, N.R.; Amiri, I.S.; Yupapin, P. Design of one dimensional refractive index sensor using ternary photonic crystal waveguide for plasma blood samples applications. Phys. E Low-Dimens. Syst. Nanostruct. 2019, 111, 173120.
9. Faisal, S. M. (2024). Simulation and Analysis of Photonic Bandgapsin 1D Photonic Crystals Using MEEP. International Journal of Physics Research and Applications, 7(2), 127–131. https://doi.org/10.29328/journal.ijpra.1001097

10. Fang, C.; Dai, B.; Xu, Q.; Wang, Q.; Zhang, D. Optofluidic tunable linear narrow-band filter based on Bragg nanocavity. IEEE Photonics J. 2017, 9, 7801608.
11. Gao, Y.-J., Gao, Y.-J., Wang, Y. L., Huang, C.-G., Zhang, L.-N., Chen, H.-B., Chen, H.-B., & Wang, N. (2007). Narrow transmission band of one-dimensional photonic crystals with a defect layer. Physica Scripta, 2007, 349–352. https://doi.org/10.1088/0031-8949/2007/T129/077
12. Ghasemi, F.; Razi, S. Novel Photonic Bio-Chip Sensor Based on Strained Graphene Sheets for Blood Cell Sorting. Molecules 2021, 26, 5585.
13. Ghosh, R.; Ghosh, K.K.; Chakraborty, R. A novel tunable filter featuring defect mode of the TE wave from one-dimensional photonic crystals doped by magnetized plasma. Opt. Commun. 2013, 289, 75–80.
14. Goyal, A.K. Design Analysis of One-Dimensional Photonic Crystal Based Structure for Hemoglobin Concentration Measurement. Prog. Electromagn. Res. M 2020, 97, 77–86.
15. Goyal, A.K.; Kumar, A.; Massoud, Y. Performance Analysis of DAST Material-Assisted Photonic-Crystal-Based Electrical Tunable Optical Filter. Crystals 2022, 12, 992.
16. Greuter, L.; Starosielec, S.; Najer, D.; Ludwig, A.; Duempelmann, L.; Rohner, D.; Warburton, R.J. A small mode volume tunable microcavity: Development and characterization. Appl. Phys. Lett. 2014, 105, 121105.
17. Gryga, M.; Ciprian, D.; Hlubina, P. Distributed Bragg reflectors employed in sensors and filters based on cavity-mode spectral-domain resonances. Sensors 2022, 22, 3627.
18. Hao, J.J.; Xie, X.; Gu, K.D.; Du, W.C.; Liu, Y.J.; Yang, H.W. Research on Photonic Crystal-Based Biosensor for Detection of Escherichia coli Colony. Plasmonics 2019, 14, 1919–1928.
19. Hao, K., Li, Z., Wang, X., Yang, S., Zhang, J., & Gao, Y. (2020). Transmission characteristics of one-dimensional photonic crystal with dielectric defect layer in near-infrared band. 11564, 1156403. https://doi.org/10.1117/12.2579551
20. Jafar, R.; Sahrai, M.; Bozorgzadeh, F.; Mohammadi-Asl, R.; Ahmadi, D.; Movahednia, M. Narrow-band transmission filter based on 1D-PCs with a defect layer. Appl. Opt. 2022, 61, 7463–7468.
21. Joannopoulos, J.D.; Johnson, S.G.; Winn, J.N.; Meade, R.D. Photonic Crystals: Molding the Flow of Light; Princeton University Press: Princeton, NJ, USA, 2008.
22. Kim, K.S.; Mizuno, Y.; Nakano, M.; Onoda, S.; Nakamura, K. Refractive Index Sensor for Liquids and Solids Using Dielectric Multilayer Films Deposited on Optical Fiber End Surface. IEEE Photonics Technol. Lett. 2011, 23, 1472–1474.
23. Lu Xiaodong, Zhou Tao, Lun Shuxian, & Chi Feng. (2012). Band-stop Filter Based on the Properties of High-Order Forbidden Band of One Dimensional Photonic Crystal. https://doi.org/10.16136/j.joel.2012.01.016
24. Mitra, S.; Biswas, T.; Chattopadhyay, R.; Ghosh, J.; Bysakh, S.; Bhadra, S.K. Safe and simple detection of sparse hydrogen by Pd-Au alloy/air based 1D photonic crystal sensor. J. Appl. Phys. Lett. 2016, 120, 173120.
25. Ozaki, R.; Matsuhisa, Y.; Ozaki, M.; Yoshino, K. Electrically tunable lasing based on defect mode in one-dimensional photonic crystal with conducting polymer and liquid crystal defect layer. Appl. Phys. Lett. 2004, 84, 1844–1846.
26. Peng, J.; Wang, W.; Qu, Y.; Sun, T.; Lv, D.; Dai, J.; Yang, M. Thin films based one-dimensional photonic crystal for humidity detection. Sens. Actuators A Phys. 2017, 263, 209–215.
27. Rho, D.; Breaux, C.; Kim, S. Label-Free Optical Resonator-Based Biosensors. Sensors 2020, 20, 5901.
28. Sayginer, O.; Chiasera, A.; Zur, L.; Varas, S.; Tran, L.T.N.; Armellini, C.; Ferrari, M.; Bursi, O.S. Fabrication, modelling and assessment of hybrid 1-D elastic Fabry Perot microcavity for mechanical sensing applications. Ceram. Int. 2019, 45, 7785–7788.
29. Simaz, A.; Boisnard, B.; Doucet, J.B.; Camps, T.; Reig, B.; Lumeau, J.; Begou, T.; Tibaldi, A.; Debernardi, P.; Bardinal, V. Thermal characterization of a nematic liquid crystal suited for the fabrication of NIR spectrally-tunable vertical cavity surface emitting lasers. Opt. Mater. Express 2022, 12, 383–391.
30. Surdo, S.; Barillaro, G. On the performance of label-free biosensors based on vertical one-dimensional photonic crystal resonant cavities. Opt. Express 2015, 23, 9192–9201.

31. Valligatla, S.; Chiasera, A.; Varas, S.; Das, P.; Bhaktha, B.S.; Lukowiak, A.; Scotognell, F.; Rao, N.; Ramponi, R.; Righini, G.C.; et al. Optical field enhanced nonlinear absorption and optical limiting properties of 1-D dielectric photonic crystal with ZnO defect. Opt. Mater. 2015, 50, 229–233.
32. Villar, I.D.; Matías, I.R.; Arregui, F.J.; Claus, R.O. Analysis of one-dimensional photonic band gap structures with a liquid crystal defect towards development of fiber-optic tunable wavelength filters. Opt. Express 2003, 11, 430–436.
33. Wang, F.; Cheng, Y.Z.; Wang, X.; Zhang, Y.N.; Nie, Y.; Gong, R.Z. Narrow Band Filter at 1550 nm Based on Quasi-One-Dimensional Photonic Crystal with a Mirror-Symmetric Heterostructure. Materials 2018, 11, 1099.
34. Xu, H.; Wu, P.; Zhu, C.; Elbaza, A.; Gu, Z.Z. Photonic crystal for gas sensing. J. Mater. Chem. C 2013, 1, 6087–6098.
35. Zhao, S.; Xu, B.; Zhao, Z.; Gu, D.; Zhang, Y.; Lv, W.; Lv, X. Gallium nitride-based resonant cavity light-emitting diode with single-longitudinal-mode emission. Opt. Lett. 2022, 47, 4616–4619.
36. Zhao, X.; Yang, Y.; Wen, J.; Chen, Z.; Zhang, M.; Fei, H.; Hao, Y. Tunable dual-channel filter based on the photonic crystal with air defects. Appl. Opt. 2017, 56, 5463–5469.