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Analysis of 1 Dimensional Photonic Crystal Optical Limiters

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Abstract

Most of the optical limiting mechanisms depend upon substances with nonlinear optical responses that allow light to regulate light and are gaining popularity once again. The realisation of innovative optical limiters functioning for extremely low limiting threshold and high damage threshold throughout a larger domain is advantageously facilitated by one-dimensional photonic crystals (1D PhC). Researchers have extensively studied 1D PhC, a periodic nanostructure having a refractive index distribution along one direction. Unfortunately, there is little evidence in the research community of their usefulness in limiting high-intensity radiation to safeguard expensive optical sensors and systems. Here, a summary of the theoretically suggested, computationally simulated, mathematically modelled, and empirically realised 1D PhC reflecting optical limiters is given. This review focuses on the limited but noteworthy examination of optical systems based on 1D photonic crystals.

Keywords: *Optical limiter, defect layer, photonic crystal, Non-linear.*

Introduction

Recent developments in high-power lasers in many applications such as communications, energy, healthcare, military and defence, and environmental monitoring [1-5] also require optical limiters to protect sensitive optical detectors and the human eye. Optical limiters are the building blocks of a new class of nonlinear optical elements. Until now, there are various passive optical limiters based on nonlinear mechanisms, such as saturable[6] and inverse saturable absorption[7,8], two-photon absorption[9], multi-photon absorption[10,11], etc. to many research groups to develop efficient optical limiters. Conventional homogeneous optical limiters offer a low activation threshold between 0.01 and 0.1 J/cm^2 under ns pulses in the visible and NIR wavelength range [12,13]. Optical limiters are preferably used in addition to data processing to protect optical sensors from excessively damaging laser radiation. Since the 1970s, various approaches have been developed to develop optical limiters [14]. However, there is still a lack of practical OLs to protect optical sensors. The main problem of existing OLs is that their working principle based on nonlinear optical effects requires relatively high intensity radiation. Because of this, in most cases, the optical limiter begins to reduce its transmittance at the level of incoming radiation, which is much higher than the level necessary to protect the optical sensor. Therefore, one of the earliest requirements in the development of optical limiters is to lower the limiting threshold. In addition, existing passive optical limiters

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often cause overheating and irreversible damage when directly exposed to strong radiation. Reflective optical limiters based on 1D photonic crystals can be a solution to the sacrificial problem of these optical limiters. In the last decade, photonic crystals have attracted the attention of researchers due to their ability to block the propagation of light in a special region called the photonic band gap (PBG) [15]. Since the pioneering efforts of Yablonovitch [16] and John [17] in 1987, materials with 1D photonic bandwidth have been used to build various functional and advanced devices due to their physical properties [18,19]. Among the existing 1D, 2D and 3D photonic crystals, 1D photonic crystals are most widely used due to their simplicity [20]. These robust 1D photonic crystal structures lead to various applications such as optical sensors, optical switches, optical limiters, temperature sensors, omnidirectional high reflectors, etc.[12, 21-23] Metallic nanocomposites composed of semiconductors chalcogenides photonic crystals are kept inside mind and is best suited for optical switching and limiting applications[24, 25] .However, photonic crystals consisting of superconductors and dielectric materials [26-30] find wide applications in biosensing[22], temperature measurement [20], bio photonics due to their wider bandwidth, smaller dielectric losses and negligible degradation. and gas sensors and sea water devices that measure desertification and seawater salinity, etc.[22, 23] The performance of photonic crystals changes greatly by changing device parameters such as refractive index. of materials, number of layers, thickness of each layer. [20, 30] Photonic crystals, when used as OLs, are nanoscale periodic optical structures that can guide and manipulate light in the same way as semiconductor electrons. When a defect layer is placed in the centre of the photonic crystal structure, the localized state appears as a defect plane in the PBG, and the incident light can be confined to that defect layer in the PBG. This light localization leads to an increased electric field in the defect layer. When a nonlinear material is used as a defect carrier, an increase in nonlinearity is expected. This increased nonlinearity can reflect high-intensity radiation that shields both the advanced optical devices and the linearity material. Many researchers have done little but significant work in the last decade. Considering the truth that there are several reviews on the development history and current performance of limiting materials, their mechanisms, and devices [14, 44-47]. Here we offer a critical overview of optical limiters based on 1D photonic crystals. In our previous work [24], we presented a brief overview of 1D multilayer reflection-based optical limiters together with other homogeneous limiters. However, to our knowledge, there is no such attempt to study reflective optical limiters in detail.

Basic design and mechanism of 1D photonic crystal reflective optical limiter: The traditional optical limiter based on non-linear material provides good protection against strong radiation. The enthusiasm of the researchers led to the invention of an alternative structure that could protect both the sensitive target and the containment material from irreversible laser damage. Yoo and Alfano presented a multilayer structural scheme to describe optical effects using an approximate and appropriate scheme. Kahn also explained the same idea by presenting a model with alternating linear and non-linear material layers. After explicit research, Makri and colleagues arrived at the basic experimental design of a reflective optical limiter. The components of a practical reflective optical limiter include a planar microcavity and a layer of nonlinear material. Invented by Charles Fabry and Alfred Perot in 1899, a planar microcavity, also called a Fabry-Perot cavity, is formed by placing two identically spaced Bragg reflectors (DBRs) opposite each other. That cavity contains two pairs of partially reflecting mirrors, which can be composed of semiconductors, insulators, optical glass, or any other organic compound. These mirrors are placed opposite each other, their reflecting surfaces against each other. When a light ray from one mirror hits the cavity, it hits the second mirror and some of it is reflected within the medium and travels towards the first mirror. A similar pattern is followed by incoming light bouncing back and forth in the cavity, with small parts missing at various stages. When the phase difference is 2π or an integral multiple of 2π, a standing wave is formed in the cavity, which describes the maximum disturbance that causes the cavity to resonate. The resonant wavelength depends on the geometric space between the two F-P mirrors, the reflectivity of the mirror and the refractive index of the F-P cavity.

Distributed Bragg Reflector (DBR): It is an optical structure that consists of an F-P cavity and is created by layering alternating dielectric films in many layers. As depicted in Figure 1, these films, which have varying refractive indices, are periodically placed on top of one another.

Figure 1 shows a schematic of a microcavity in a 1D photonic crystal with a half-wave defect layer sandwiched between two identical Bragg reflectors, each composed of alternating quarter-wave layers with marginally differing refractive indices.

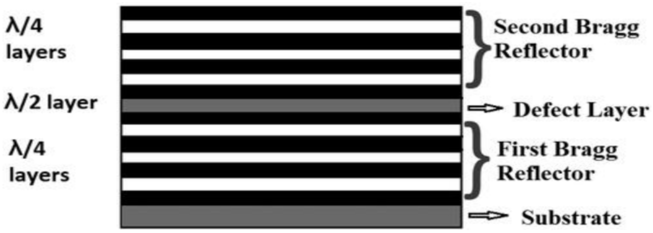

Figure 1

The total internal reflection of a DBR structure is the superposition of all the reflected light. When light is incident on a DBR structure, a portion of it is reflected at each contact between the layers. There would be a constructive reflection with the highest reflection occurring at the centre wavelength if the centre wavelength was four times the thickness of each film.

Fabrication Technique: DBR structures were traditionally constructed using thick metal oxide layers and vacuum-grown semiconductor thin films. Devices used for light management, such as LEDs, optical filters, etc., use this state-of-the-art technology. Other techniques have also been employed to create Fabry-Perot microcavities, which allow for the creation of thin dielectric layers with high Q factors. Sol-gel,electron beam evaporation, ion plating, sputtering, molecular beam epitaxy, and [24] for 1 D PBG manufacturing are some of the approaches presented in the literature.

Sputtering is the most practical and often used method among these for creating reflecting optical limiters and multilayer thin film depositions. Sputtering has the benefit of making it simple to sputter compounds with exceptionally high melting temperatures with thin films whose composition is very similar to the source material. Sputtering is a cost-effective method for creating dielectric microcavities with a large surface area and precise composition. Creating alternating dielectric layers with exact thicknesses and refractive indices is a dynamic process. By adjusting the substrate temperature during the sputtering process, the structural and optical characteristics of the thin films can also be changed. To create uniform and superior photonic crystals, high melting temperature metals, photovoltaic layer architectures, and transparent conducting oxides can be sputtered. Sputtered films' adherence will also be improved.

Mathematically modelled and theoretically studied reflective optical limiters: Yoo and Alfano investigated mathematical modelling of multilayer systems to simulate the non-linear effects. They all shared the same optical limitation for several factors and parameter-dependent threshold intensity in their uniform intensity approximation. Kahn examined numerous multilayer system models using the same modelling technique to assess the utility of various multilayer compositions as optical power limiters. Kahn created models of a few systems with features that were quite similar to the ideal attributes. For instance, the ten-bilayer system, which had transmission plateaus that were almost flawless, had alternate layer permittivity values of 2.25 (linear) and 1.25 (nonlinear) correspondingly. The fluctuation in transmission coefficient with increasing input strength, wavelength incident, and dynamic range was explained by Kerr nonlinearity.

Experimentally realized reflective optical limiters The last two decades have been devoted to experimental work to control and improve emission properties of limiters by modifying the dielectric surrounding of the source. Numerous strategies have been examined for the same purpose, including planar interfaces, solid-state planer microcavities, photonic crystals, spherical micro resonators, and dielectric nanospheres. The most easily exploitable PBG devices for regulating the spontaneous excited atom emission rate in the weak coupling regime among these systems are planar microcavity resonators, such as 1 D photonic crystals. The optical limiting in 1D metal nanocomposites photonic crystals,[25]1D photonic bandgap structures with embedded semiconductor nanocrystals,2D photonic crystal structures in the visible, and IR region as well as 3D polystyrene band-edge photonic crystals has been the subject of extensive research up to this point.

Phase change material [PCM] based reflective optical limiters: By using resonant transmission-based 1 D photonic crystal reflective optical limiters, the primary issues of bulk material-based optical limiters, such as their high limiting threshold, low damage threshold, and overheating, are ultimately eliminated. These advanced new PBG optical limiters do, however, have a constrained transmission width and angular sensitivity. These limitations are tolerable in some communication domains and LADAR applications, but they cannot be ignored in spectroscopic and imaging applications due to the vast spectrum range and incident angle dependence. Li and coworkers [137] put out a fresh approach to address these issues in innovative limiting devices, explaining how topological phase reversal-based transmission works in 1 D PBG structures. The authors merged a 1 D photonic crystal with a non-linear photonic crystal L.

Conclusion and Future Outlook

A reliable optical limiter that is also resistant to damage caused by lasers is the most important criterion among the other requirements for novel optical limiters. In order to protect both themselves and the target sensors, 1 D PhC based reflecting optical limiters have been carefully researched as prospective solutions. In this case, a thorough study has been given to show the beneficial outcomes of using a 1 D photonic resonator for self-protecting optical limiting. Rare earth metals and semiconductor materials have the ability to reflect high-intensity radiation to the environment, protecting complex sensors, when used as defect layers in a 1 D photonic crystal. Phase-changing materials that are inserted as defect layers in PhC optical limiters have been studied.

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Conflict of Interest Declaration: I hereby declare that there is no conflict of interest that can influence the work reported in this paper. The review work reported in this paper has not been published fully or partially elsewhere. The plagiarism check has been done using Turnitin software and it was found to be less than 10%.

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References

1. Shirk, J. S. Protecting the War Fighter's Vision in a Laser-Rich, Battlefield Environment. Optic. Photonic. News. 2000, 11, 19. doi:10.1364/OPN.11.4.000019 [Crossref], [Google Scholar]
2. Monchalin, J.-P. Progress towards the Application of Laser-Ultrasonics in Industry. Rev. Prog. Quant. Nondestruct. Eval 1993, 12, 495–506. [Crossref], [Google Scholar]
3. Vizbaras, A.; Dvinelis, E.; Trinkunas, A.; Šimonyte, I.; Greibus, M.; Kaušylas, M.; Žukauskas, T.; Songaila, R.; Vizbaras, K. High-Performance Mid-Infrared GaSb Laser Diodes for Defence and Sensing Applications. Laser Technol. Def. Secur. X 2014, 9081, 90810P. doi:10.1117/12.2054493 [Crossref], [Google Scholar]
4. Tittel, F. K.; Richter, D.; Fried, A. Mid-Infrared Laser Applications in Spectroscopy. Solid-State Mid-Infrared Laser Sources 2007, 516, 458–529. [Google Scholar]
5. Waynant, R. W.; Ilev, I. K.; Gannot, I.; Meyer, J. R.; Sirtori, C. Mid-Infrared Laser Applications in Medicine and Biology. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 2001, 359, 635–644. doi:10.1098/rsta.2000.0747 [Crossref], [Web of Science ®], [Google Scholar]
6. Meškinis, Š.; Vasiliauskas, A.; Andrulevičius, M.; Jurkevičiūtė, A.; Peckus, D.; Kopustinskas, V.; Viskontas, K.; Tamulevičius, S. Self-Saturable Absorption and Reverse-Saturable Absorption Effects in Diamond-like Carbon Films with Embedded Copper Nanoparticles. Coatings. 2019, 9, 100–114. doi:10.3390/coatings9020100 [Crossref], [Web of Science ®], [Google Scholar]
7. Mishra, S. R.; Rawat, H. S.; Mehendale, S. C. Reverse Saturable Absorption and Optical Limiting in C60 Solution in the near-Infrared. Appl. Phys. Lett. 1997, 71, 46–48. doi:10.1063/1.119464 [Crossref], [Web of Science ®], [Google Scholar]
8. Harris, J.; Gai, L.; Kubheka, G.; Mack, J.; Nyokong, T.; Shen, Z. Optical Limiting Properties of 3,5-Dithienylenevinylene BODIPY Dyes at 532 nm. Chemistry. 2017, 23, 14507–14514. doi:10.1002/chem.201702503 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
9. Sanchez, F.; Boudebs, G.; Cherukulappurath, S.; Leblond, H.; Troles, J.; Smektala, F. Two- and Three-Photon Nonlinear Absorption in As2Se3 Chalcogenide Glass: Theory and Experiment. J. Nonlinear Optic. Phys. Mat. 2004, 13, 7–16. doi:10.1142/S0218863504001724 [Crossref], [Web of Science ®], [Google Scholar]
10. Bindra, K. S.; Bookey, H. T.; Kar, A. K.; Wherrett, B. S.; Liu, X.; Jha, A. Nonlinear Optical Properties of Chalcogenide Glasses: Observation of Multiphoton Absorption. Appl. Phys. Lett. 2001, 79, 1939–1941.

doi:10.1063/1.1402158 [Crossref], [Web of Science ®], [Google Scholar]

11. Hurlbut, W. C.; Vodopyanov, K. L.; Kuo, P. S.; Fejer, M. M.; Lee, Y. S. Multiphoton Absorption and Nonlinear Refraction of GaAs in the Mid-Infrared. Opt. Lett. 2007, 32, 668–670. doi:10.1364/ol.32.000668 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
12. Sun, Y. P.; Riggs, J. E.; Liu, B. Optical Limiting Properties of [60] Fullerene Derivatives. Chem. Mater. 1997, 9, 1268–1272. doi:10.1021/cm960650v [Crossref], [Web of Science ®], [Google Scholar]
13. Brunel, M.; Chaput, F.; Vinogradov, S. A.; Campagne, B.; Canva, M.; Boilot, J. P.; Brun, A. Reverse Saturable Absorption in Palladium and Zinc Tetraphenyltetrabenzoporphyrin Doped Xerogels. Chem. Phys 1997, 218, 301–307. doi:10.1016/S0301-0104(97)00084-0 [Crossref], [Web of Science ®], [Google Scholar]
14. Hollins, R. C. Materials for Optical Limiters. Curr. Opin. Solid State Mater. Sci. 1999, 4, 189–196. doi:10.1016/S1359-0286(99)00009-1 [Crossref], [Web of Science ®], [Google Scholar]
15. Haus, J. W.; Soon, B. Y.; Scalora, M.; Sibilia, C.; Mel'nikov, I. V. Coupled-Mode Equations for Kerr Media with Periodically Modulated Linear and Nonlinear Coefficients. J. Opt. Soc. Am. B. 2002, 19, 2282–2291. doi:10.1364/JOSAB.19.002282 [Crossref], [Web of Science ®], [Google Scholar]
16. Yablonovitch, E. Inhibited Spontaneous Emission in Solid-State Physics and Electronics. Phys. Rev. Lett. 1987, 58, 2059–2062. doi:10.1103/PhysRevLett.58.2059 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
17. John, S. Strong Localization of Photons in Certain Disordered Dielectric Superlattices. Phys. Rev. Lett. 1987, 58, 2486–2489. doi:10.1103/PhysRevLett.58.2486 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
18. Ohtera, Y.; Yamada, H. Photonic Crystals for the Application to Spectrometers and Wavelength Filters. IEICE Electron. Express 2013, 10, 20132001–20132013. doi:10.1587/elex.10.20132001 [Crossref], [Web of Science ®], [Google Scholar]
19. Tekeste, M. Y.; Yarrison-Rice, J. M. High Efficiency Photonic Crystal Based Wavelength Demultiplexer. Opt. Express. 2006, 14, 7931–7942. doi:10.1364/oe.14.007931 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
20. Awad, M. A.; Aly, A. H. Experimental and Theoretical Studies of Hybrid Multifunctional TiO2/TiN/TiO2. Ceram. Int 2019, 45, 19036–19043. doi:10.1016/j.ceramint.2019.06.145 [Crossref], [Web of Science ®], [Google Scholar]
21. Tran, P. Optical Switching with a Nonlinear Photonic Crystal: a Numerical Study. Opt. Lett. 1996, 21, 1138–1140. doi:10.1364/ol.21.001138 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
22. Amiri, I. S.; Paul, B. K.; Ahmed, K.; Aly, A. H.; Zakaria, R.; Yupapin, P.; Vigneswaran, D. Tri-Core Photonic Crystal Fiber Based Refractive Index Dual Sensor for Salinity and Temperature Detection. Microw. Opt. Technol. Lett. 2019, 61, 847–852. doi:10.1002/mop.31612 [Crossref], [Web of Science ®], [Google Scholar]
23. Ben Ali, N.; Alsaif, H.; Trabelsi, Y.; Chughtai, M. T.; Dhasarathan, V.; Kanzari, M. High Sensitivity to Salinity-Temperature Using One-Dimensional Deformed Photonic Crystal. Coatings 2021, 11, 713. doi:10.3390/coatings11060713 [Crossref], [Web of Science ®], [Google Scholar]
24. Ryzhov, A. A. Optical Limiting Performance of a GaAs/AlAs Heterostructure Microcavity in the near-Infrared. Appl. Opt. 2017, 56, 5811–5816. doi:10.1364/AO.56.005811 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]
25. Husaini, S.; Teng, H.; Menon, V. M. Enhanced Nonlinear Optical Response of Metal Nanocomposite Based Photonic Crystals. Appl. Phys. Lett. 2012, 101, 111103. doi:10.1063/1.4751840 [Crossref], [Web of Science ®], [Google Scholar]
26. Sabra, W.; Aly, A. H. A Comparative Study of the Effective Surface Impedance of an HTc Superconducting Thin Film from Visible to mid-IR Region. Opt. Quantum Electron 2021, 53, 1–11. [Crossref], [Web of Science ®], [Google Scholar]
27. Aly, A. H. Metallic and Superconducting Photonic Crystal. J. Supercond. Nov. Magn. 2008, 21, 421–425. doi:10.1007/s10948-008-0352-x [Crossref], [Web of Science ®], [Google Scholar]
28. Aly, A. H.; Ghany, S. E. S. A.; Kamal, B. M.; Vigneswaran, D. Theoretical Studies of

Hybrid Multifunctional YaBa2Cu3O7 Photonic Crystals within Visible and Infra-Red Regions. Ceram. Int 2020, 46, 365–369. doi:10.1016/j.ceramint.2019.08.270 [Crossref], [Web of Science ®], [Google Scholar]

29. Aly, A. H.; Sayed, F. A. THz Cutoff Frequency and Multifunction Ti2 Ba2 Ca2 Cu3O10/GaAs Photonic Bandgap Materials. Int. J. Mod. Phys. B. 2020, 34, 2050091–2050013. doi:10.1142/S0217979220500915 [Crossref], [Web of Science ®], [Google Scholar]

30. Aly, A. H.; Mohamed, D. The Optical Properties of Metamaterial-Superconductor Photonic Band Gap with/without Defect Layer. J. Supercond. Nov. Magn. 2019, 32, 1897–1902. doi:10.1007/s10948-018-4922-2 [Crossref], [Web of Science ®], [Google Scholar]

31. Zaky, A. Z.; Aly, A. H. Modeling of a Biosensor Using Tamm Resonance Excited by Graphene. Appl. Opt. 2021, 60, 1411–1419. doi:10.1364/AO.412896 [Crossref], [PubMed], [Web of Science ®], [Google Scholar]

32. Aly, A. H.; Zaky, A. Z.; 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. doi:10.1088/1402-4896/ab53f5 [Crossref], [Web of Science ®], [Google Scholar]

33. Natesan, A.; Kuppusamy, P. G.; Gopal, T. R.; Dhasarathan, V.; Aly, A. H. Tricore Photonic Crystal Fibre Based Refractive Index Sensor for Glucose Detection. IET Optoelectron. 2019, 13, 118–123. doi:10.1049/iet-opt.2018.5079 [Crossref], [Web of Science ®], [Google Scholar]

34. Aly, A. H.; Mohamed, D.; Mohaseb, M. A.; El-Gawaad, N. S. A.; Trabelsi, Y. Biophotonic Sensor for the Detection of Creatinine Concentration in Blood Serum Based on 1D Photonic Crystal. RSC Adv. 2020, 10, 31765–31772. doi:10.1039/D0RA05448H [Crossref], [PubMed], [Web of Science ®], [Google Scholar]

35. Zaky, Z. A.; Ahmed, A. M.; Shalaby, A. S.; Aly, A. H. Refractive Index Gas Sensor Based on the Tamm State in a One-Dimensional Photonic Crystal: Theoretical Optimisation. *Sci. Rep.* 2020, ***10***, [Crossref], [PubMed], [Web of Science ®], [Google Scholar].