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1. Design and Analysis of All-Optical Logic Gates Based on a Germanium Dielectric Material Micro Ring Resonator Using Photonics Crystal Technology

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ABSTRACT

In this paper, plan and examination of optical NOT and OR logic gates based on 2-Dimensional (2D) Photonic Crystals (PhC) design is proposed. The proposed structure is shaped with the combination of line abandons and rectangular ring resonator structure. The execution of the structure is analyzed utilizing 2D Finite Difference Time Domain (FDTD) strategy. The band gap examination is gotten utilizing Plane Wave Expansion (PWE) strategy. The structure has the lattice constant and refractive index as 580 nm and 4.0, respectively. The response time is about 0.306 ps and the dimension of the proposed structure is about 10.6 × 11.6μm2 which is highly compact and integrable. The wide band range is achieved between 1272.0 nm and 1987.4 nm with center wavelength at 1550 nm. All-optical logic gates satisfy their truth tables with reasonable power contrast ratio between logic '1' and logic '0'.

KEYWORDS:

Photonic Crystals, Band Gap Structures; Optical Logic Gates; FDTD Method, PWE Method; Optical Ring Resonator.

1. Introduction:

The optical signal processing techniques overcomes the speed limitation and high-power consumption; however, use of logic gates for the signal processing is complicated and need cumbersome electro-optic conversion technique [1]. All-optical logical gates designed so far are implemented using various technologies like Semiconductor laser amplifier loop mirror [2] Semiconductor Optical Amplifier (SOA) with optical filter [3], Four Wave Mixing (FWM) in SOAs [4], a SOA based ultrafast nonlinear interferometer (UNI)[5] and SOA based Mach-Zehnder Interferometer (SOA- MZI) [6] Quantum dot semiconductor amplifier [7-10] and TOAD D-flip flops [11]. Everyday increasing demand of the higher bandwidth services need high speed signal processing systems. Hence, the development of all optical logic gates has gained much attraction in current research. As the conventional electronics signal processing systems are limited in speed and consume huge power, whereas optical signal processing has been researched for the past two decades. However, these schemes of implementation have several drawbacks such as latency, speed, size, power consumption and signal-to-noise ratio. Hence, all-optical gates are implemented by Photonic Crystals to overcome the aforementioned issues. Depending on their periodicity, PhCs are classified as 1D PhCs, 2D PhCs and 3D PhCs. The PhCs are made up of metallo-dielectric nanostructures or periodic dielectric materials. PhCs are periodic nanostructures that will guide the motion of photons. The propagation of light through the crystals is determined by the Photonic Band Gap (PBG).

A new configuration of AND gate is investigated by applying the probe input [18]. However, the creation of self-collimated light in all cases is tedious process. The Mach-Zehnder interferometer-based logic gate is reported which is limited by complex integration and sensitivity to random phase change [19].

The 2D PhCs are used in various applications such as Ring Resonator [12, 13] Channel Drop Filter [14] and Add-Drop Filter [15] and Band Pass Filter [16] and etc. The AND and XOR logic gates were proposed [28] based on nonlinear PhCs. Because of their unique property, they find novel application in Microwave technologies, Optics, Optoelectronics, Quantum Engineering, Acoustics, Bio-Photonics and so on. Logic gates have been implemented from the several phenomena's such as self-collimation effect [21] Resonance [22, 23] Interference [24] and etc. All-optical OR and XOR logic gates were proposed [26] in which logical function is implemented using self-collimation and beam splitting. An AND gate was proposed based on the concept of nonlinear Kerr effect [27]. The XOR gate is designed by using the photonic crystal ring resonator in order to improve the efficiency of transmission spectrum [20]. The PBG is defined as the region where the propagation of light is totally zero for particular frequency ranges. To avoid this limitation, the SOA based switches are replaced by Optical logic gates [17].

Many technologies reported to realize optical Logic gate functions using Semiconductor Optical Amplifier (SOA), which is limited by spontaneous noise and low speed of operation. The design of all-optical logic gates such as AND, NOT and NOR based on photonic crystal structure was proposed [25] where the logical function is accomplished by resonance frequency shift of the micro cavity by Kerr nonlinearity. The remaining portion of this paper is given as takes after; plan strategy in conjunction with band gap calculations of the proposed structure are displayed in Section II.

The working standards and the truth tables of NOT, AND, and OR gates with proposed plan and simulations is talked about in Area III. The recreation comes about and conclusion is portrayed in point IV and V, individually.

2. Photonic Band Gap Analysis:

We have proposed a plan that's based on 2D square lattice PhC structures of germanium (Ge) rods, with a relative permittivity of 16, with rods in air structure. The differentiate proportion between the dielectrics constants of Ge and discuss is high, which permits wide ranges of working wavelengths of PhC gates. Ge is additionally consistent with the ordinary CMOS manufacture technology [22].

We have utilized the plane wave extension strategy to choose the cross section consistent (lattice constant) (a) with optimization methods and the rod radius (r) [23, 24]. We utilize the Plane Wave Expansion (PWE) strategy [25–29] to calculate the band structure and the gap maps. The light signal is accepted to be of a Transverse Electric (TE) mode. The TE mode is when the light proliferates within the 2D surface whereas the electric field vector wavers parallel to the poles. The working wavelength is chosen to be λ = 1550nm, which is the foremost common wavelength in broadcast communications at the third optical telecommunication window [30].

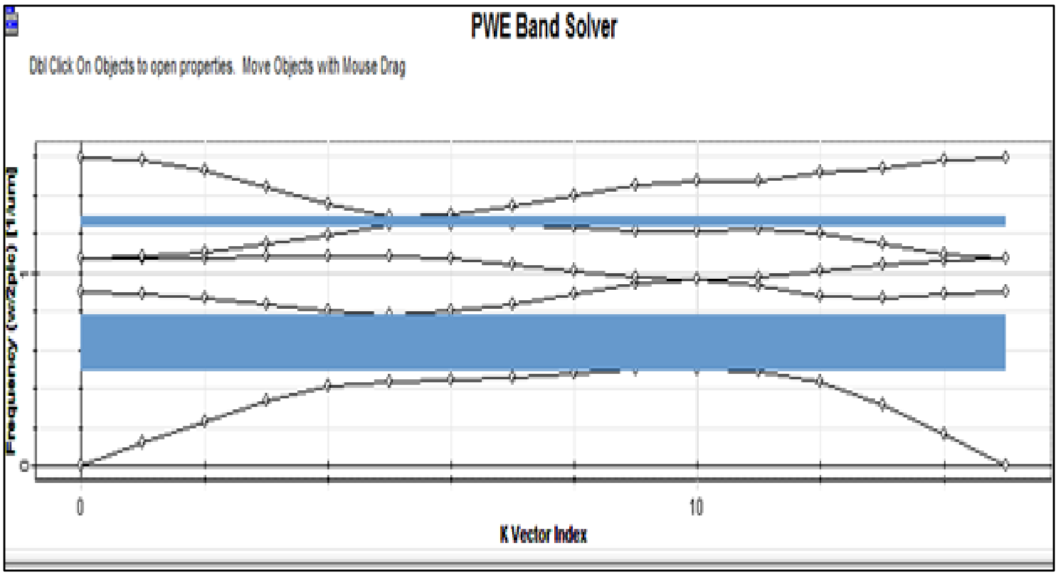


Figure 1: The band structure of the proposed 2D square lattice PhC logic gate of Ge rods in air background for TE mode at r/a = 0.15 and refractive index as 4.

The photonic band gap in Fig. 1 is plotted against the normalized recurrence, ω, on the y-axis. Here, ω is the working recurrence $\omega/2\pi$ isolated by the proportion c/a, where c is the speed of light in space. Subsequently, to attain the center working wavelength of λ = 1550 nm, the cross section consistent a is outlined to be 0.58μm. The corresponding band structure with chosen parameters is shown in Fig. 1. It is evident from Fig. 1 that there are two photonic band gaps.

The most extreme hole is realized at *r/a*=0.15, as band crevice = 0.282952 with band crevice run from 0.503169 1/λ to 0.786121 1/λ and band hole 1 = 0.035103 with band crevice 1 extend from 1.25143 1/λ to 1.28653 1/λ. Agreeing to the chosen parameters, the comparing range of wavelengths of the band gap is found to be from 1272.0 nm to 1987.4 nm and 0.777 nm to 0.799 nm.

Design Methodology

The PBGs characterize the ranges of frequencies that are forbidden to engender through the PhC structure. Presenting line abandons within the PhC structure act as waveguides for signals of the forbidden frequencies. Hence, we are able to design optical logic gates by fitting the appropriate waveguides for each input to realize the gates capacities. Our proposed PhC logic gates are based on the impedances impact. In common, logic '1' and logic '0' values are gotten at the yield port by introducing constructive and destructive interference, separately. In the event that the input signal interferes beside a phase contrast of $2n\pi$, where n is an integer, this leads to constructive interference. By differentiate, in the event that the stage contrast of the input signals is $(2n + 1)\ \pi$ where they meet, at that point a destructive interference happens. The stage contrasts in our proposed gates are gotten by making path differences between the signals.

To ponder the logic gates behavior, we mimic them utilizing the free Finite-Difference Time-Domain simulation computer program OptiFDTD of Optiwave Systems Inc. [30]. The boundaries of each gate structure are set to Perfectly Matched Layers (PMLs). The gates execution is examined by calculating the Contrast Ratio (CR), which is the proportion between the yield powers of logic '1' and logic '0' as take after [10].

$$CR = 10log\,(P1/P0) \qquad (1)$$

Where $P1$ and $P0$ are the power values at the yield port for logic '1' and logic '0', separately. In all of our reenactments, we utilized a light source of control Po to be propelled to the input ports of the gates. The identified control at the yield port is considered logic '0' in case the control is less than or rise to to $0.27P0$, and is considered logic '1' in case the control is more prominent than or rise to to $0.42Po$, as appeared in Fig. 2.

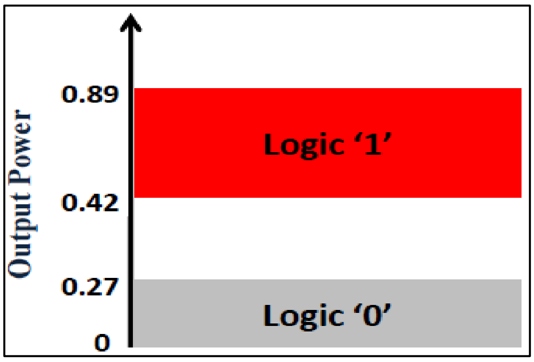
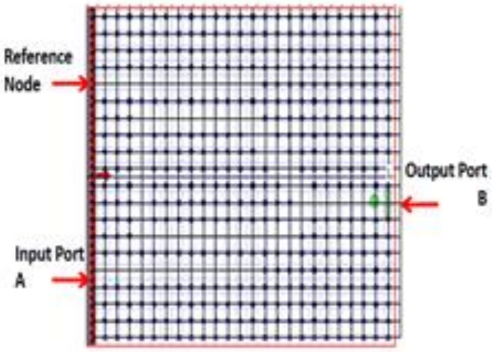


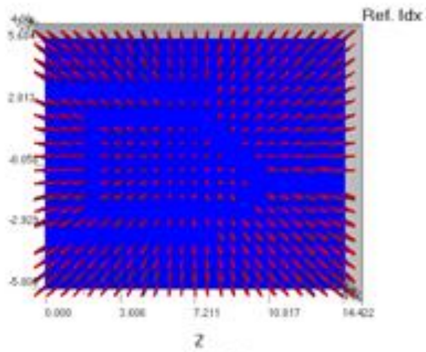
Figure 2: The range of output power values at the output port with the corresponding logic.

2.2 Design of NOT Logic Gate:

For planning the NOT logic gate, the input is propelled from port A, and the yield is collected from yield observation point B. There's a reference node (probe) to actuate the specified functionality. In case there's no probe signal, the light will essentially pass from port A to yield port B. But if the test is active, the yield signal will be turned around, which implies the rationale state of the yield signal is consistent “0/1” when the inputs are at “HIGH/LOW” level. Agreeing to the yield transmission in Fig. 2, the edge boundary between “LOW” and “HIGH” level is considered as 0.15. The enormous interim between coherent “0” and “1” can make negligible mistake in detecting “0” and “1” in yield, which is an advantage of this structure. Proposed design of optical NOT gate is appeared in figure 3 (a) and its refractive index profile see is appeared in figure 3(b) where Ge rods are vertically set on the glass wafer with refractive index of 1.45 in air periodicity with refractive index 1. The truth table of NOT logic gate is appeared in figure 3(c). A yield transmission of 0.81 is accomplished which can be respected as logic “1”, this transmission esteem is higher than 0.42 obtained in Fig. 3(d), which is due to the reference node, where no input light from port A. Portion of the light will couple from reference node port to ring resonator, that, the light will totally couple into the yield C. When from both the input ports A and B light couple into the ring resonator, an asymmetrical resonant form creates and the particular incident lights will destructively interfere with each other, consequently leads to a very insignificant value at the yield port, which can be respected as logical “0”, as appeared in Fig. 3(e).



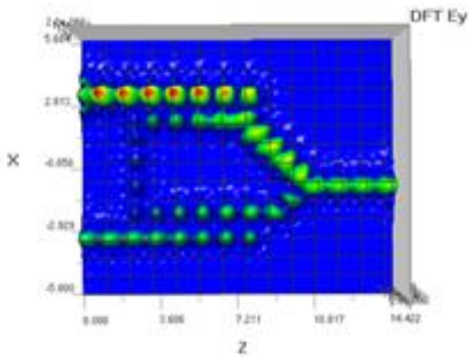
(a)



(b)

Probe A	Input B	Output C	Output Transmiss
0	1	1	0.78
1	0	1	0.81
1	1	0	0.00009

(c)



(d)

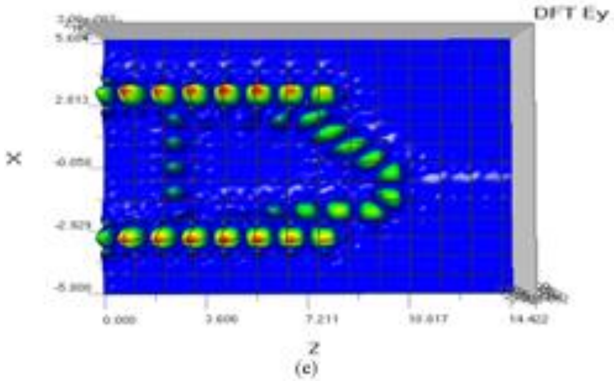
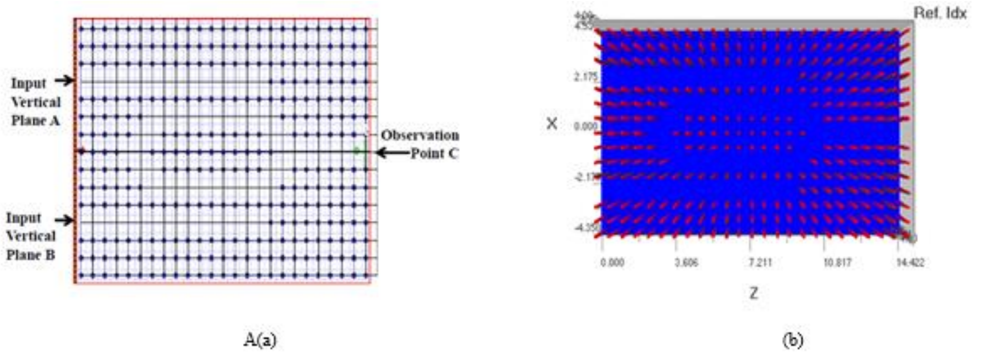


Fig: 3. NOT logic gate design and operation. (a) Proposed design of NOT logic gate where A & B are the input ports and C is the output port (b) Refractive index profile view of proposed NOT logic gate (c) NOT logic gate truth table with input and outputs (d) The electric field distribution when the input is at logical "LOW" level and output is logical "HIGH" (e) The electric field distribution when the input is at logical "HIGH" level output is logical "LOW".

2.3 Design of OR Logic Gate:

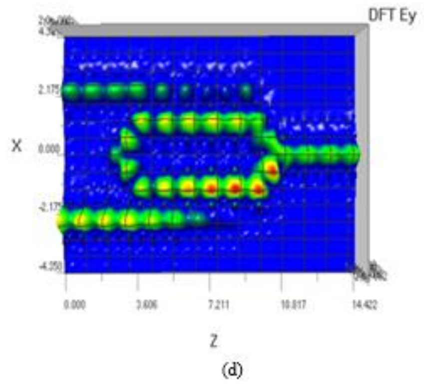
The proposed OR gate is appeared in Fig. 4, where it comprises of a resonator with two waveguides are made by expelling dielectric poles from the PhC structure to create a deformity. In this way, when an optical signal with particular operating wavelength is propelled into the structure, this wave can be confined and guided. The two waveguides are the waveguides of the input signals, which are coupled to the resonator by means of a line of rods. The signal is at last guided through a line defect to the yield port and its refractive index profile see is appeared in figure 4(b) where Ge rods are vertically set on the glass wafer with air periodicity. The proposed OR gate has an approximate measure of14 × 9.44 μm^2.

On the other hand, if two signals are launched at ports A and B simultaneously, due to the path length from port A to the output port C is exactly the same as the path length from port B to the output port C, the two signals meet at the output port with the same phase, which leads to a strong constructive interference at the output port resulting in the logic value '1' at the output as shown in figure 4(f). When an input signal only at input A is launched, the wave will be guided in the upper waveguide till it couples with the resonator. When the coupling occurs, a part of the signal propagates inside the resonator in the Clockwise (CW) direction while the other part propagates in the Counter Clockwise (CCW) direction, where these two parts eventually meet at the entrance of the output waveguide. 4, and the truth table together with the output power are shown in Table 4(c). Due to the small phase difference between the CW and the CCW signals, a partial constructive interference occurs and the signal remains strong and propagates to the output port giving output logic '1' as shown in figure 4(d). Similarly, if a signal is launched only at port B, the logic value '1' is obtained at the output as shown in figure 4(e). Different operations of the OR gate are shown in Fig. Finally, if no signals at all are launched at any input port, hence, no signal is detected at the output port.signal is detected at the output port.



Input A	Input B	Output C	Output Transmission
0	0	0	0
0	1	1	0.79
1	0	1	0.79
1	1	1	0.85

((c)



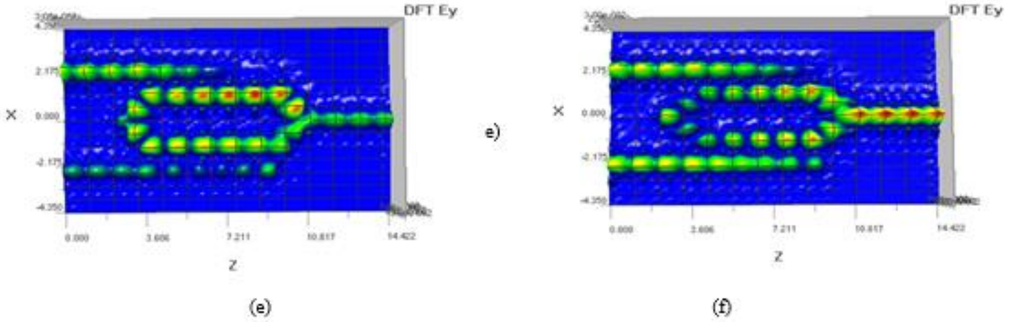


Figure 4. OR logic gate design and operation. (a) Proposed design of OR gate where A & B are the input ports and C is the output port (b) Refractive index profile view of proposed OR gate (c) OR gate table with inputs and outputs (d) The electric field distribution when the input is at logical "LOW/HIGH" level and output is logical "HIGH" (e) The electric field distribution when the input is at logical "HIGH/LOW" level and output is logical "HIGH" (f) The electric field distribution when the input is at logical "HIGH/HIGH" level and output is logical "HIGH"

The comparative analysis has been carried out and based on available designing techniques, along with the shape of the structure. Three important parameters which have been theoretically investigated in this paper are compared with other researchers around the world as Contrast Ratio (CT), Response Time (RT), and Dimensions (Size) of the proposed structure.

Table 1. Comparison analysis of the designed logic gates with previous designs.

Paper Details	Technique	Photonic crystal Structure Shape	Response time (ps)	Contrast ratio (dB)	Dimensions of thestructure (µm2)
Fu et al. (2013) [30]	Light beam interference effect	Hexagonal	-	20	588
Ghadrdan and Mansouri-Birjandi (2013) [31]	Photonic crystal ring resonator	Square	0.84	10.79	144
Jianga et al. (2014) [32]	Light beam interference effect	Hexagonal	-	9.33	729
Singh and Rawal (2015) [33]	PBG and resulting guided modes	Hexagonal	-	5	122
Dsouza and Mathew (2016) [34]	Interference effect and phase difference	Square	-	19.02	465
Shaik and Rangaswamy (2016) [35]	Interference based defects	Square	0.35	8.59	25
Preeti Rani et al. (2017) [36]	Optical interference effect	Square	2.168	3.74	-
Mahmood Seifouri et al. (2018) [37]	Interference effect	Square	0.317	43.40	85
Hussein et al. (2018) [38]	Interference effect	Square	-	12.15	155
Mohebzadeh-Bahabady and Olyaee (2019) [39]	Interference effect	Hexagonal	0.466	20.75	282
In our proposed designed work	Interference effect	Square	0.306	49.54	122

By analyzing the comparative analysis with Table 1, the proposed structure has higher contrast ratio and less response time than already examined structures. The proposed logic gate includes a small measurement which makes it conceivable to be utilized in PICs. From the over designs and results, it can be taken note that we must maintain the input signals in phase to get the proper logic functions of each gate. Moreover, for all gates, the yield power levels are different than the initial values at the input. Subsequently, for gates able to reestablish the proper control values of logic ‘0’ and logic ‘1’ by utilizing both a threshold limiter that stifles logic ‘0’ to zero control, and an optical amplifier that recovers logic ‘1’ to the proper power level.

3. Conclusion:

We show modern designs of all-optical logic gates to be specific; NOT, and OR, utilizing 2D square lattice photonic crystals, and the designs are based on the optical interference phenomenon. The 2D PhC structure comprises of dielectric material rods of Germanium with air in periodicity. The proposed logic gates display wide extend of working wavelengths between 1272.0 nm and 1987.4 nm with center resonating wavelength1550 nm to fulfill different necessities of diverse applications. The wave behavior and the field distribution of the signals inside the PhC structures of the logic gates were examined utilizing the FDTD strategy. Each gate shows a sensible contrast ratio between logic '1' and logic '0' at the yield of the gate. The response time is around 0.306ps, contrast ratio around 49.54dB and the measurement of the proposed structure is almost 122μm^2.

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References:

1. Ishizaka, Y. Kawaguchi, Y. Saitoh, K. Koshiba, M.: Design of ultra-compact all-optical XOR and AND logic gates with low power consumption. Optics Communication, 284, 3528–3533 (2011)
2. Stubkjaer, K. E.: Semiconductor Optical Amplifier-Based All-Optical Gates for High-Speed Optical Processing. IEEE Journal on selected topics in quantum electronics, 6, 1428-1435(2000)
3. Li, Z. Liu, Y. Zhang, S. Ju, H. de Waardt, H. Khoe, G. D. Lenstra, D.: All-optical logic gates based on an SOA and an optical filter. 31st European conference on Optical Communication, 2, 229-230(2005)
4. Li, L.P. Xiu, H. D. Liang, Z. X.: Ultrahigh-Speed Multifunctional All-Optical Logic Gates Based on FWM in SOAs with PolSK Modulated Signals. Optical Fiber Communication /National Fiber Optic Engineers Conference, 1, 1-3, (2008)
5. Zoiros, K.E, Das, M.K, Gayen, D.K, Maity, H.K, Chattopadhyay, T, Roy, J.N.: Alloptical pseudorandom binary sequence generator with TOAD-based D flip-flops. Optics Communications, 284, 4297-4306, (2011)
6. Singh, S. Lovkesh.: Ultrahigh Speed Optical Signal Processing Logic Based on an SOA-MZI. IEEE Journal of Selected Topics in Quantum Electronics.18, 970 – 977(2011)
7. Dimitriadou, E and Zoiros K.E.: On the design of reconfigurable ultrafast all-optical NOR and NAND gates using a single quantum-dot semiconductor optical amplifier-based Mach-Zehnder interferometer. Journal of Optics, 14, 105401 (2012)
8. Dimitriadou, E and Zoiros K.E.: Proposal for ultrafast all-optical XNOR gate using single quantum-dot semiconductor optical amplifier-based Mach-Zehnder interferometer. Optics and Laser Technology, 45, 79-88 (2013)
9. Kotb, A and Zoiros K.E.: Simulation of all-optical logic XNOR gate based on Quantum-dot semiconductor optical amplifiers with amplified spontaneous emission. Optical and Quantum Electronics, 45, 1213-1221 (2013)
10. Kotb, A and Zoiros K.E.: 1 Tb/s high quality factor NAND gate using quantum-dot semiconductor optical amplifiers in Mach–Zehnder interferometer. Journal of Computational Electronics, 13, 555-561 (2014)
11. Younis, R. M. Areed, N. F. F. Obayya, S. S. A.: Fully Integrated AND and OR optical logic gates. IEEE Photonics Technology Letters, 26, 1900-1903 (2014)

12. Robinson, S. Nakeeran, R.: Photonic Crystal Ring Resonator Based Optical Filters from Advances in photonic Crystals: Passaro, V.M.N (ed.), pp. 1-22, InTech, (2013)
13. Ghorbanpour, H. Makouei, S.: 2-channel all optical demultiplexer based on photonic crystal ring resonator. Frontiers of Optoelectronics, 6, 224-227 (2013)
14. Djavid, M. Abrishamian, M. S.: Multi-channel drop filters using photonic crystal ring resonators. International Journal for Light and Electron optics, 123, 167-170 (2012).
15. Mahmoud, Y. M. Bassou, G. Taalbi, A.: A new optical add-drop filter based on two-dimensional photonic crystal ring resonator. International Journal for Light and Electron Optics, 124, 2864-2867 (2012)
16. Badaoui, H. Feham, M. Abri, M.: Photonic Crystal Band pass Resonant Filters Design Using the Two Dimensional FDTD Method. International Journal of Computer Sciences Issues, 8, 127-132 (2011)
17. Kim, J. Y. Kang, J.M. Kim, T.Y and Han S.K.: 10Gbit/s all optical logic gates with XOR, NOR, OR and NAND functions using SOA-MZI structures, Electronics Letters, 42, 303-304 (2006)
18. Enaulhaq, S. and Nakkeeran, R.: Design of Photonic Crystal based all-optical AND gate using T-shaped Waveguide, Journal of Modern Optics, 63, 941-949 (2015)
19. Ajay kumar, Santosh Kumar, SK Raghuwansi.: Implementation of XOR/XNOR and AND logic gates by using Mach-Zehnder interferometers, Optik-International Journal for Light and Electron Optics, 125, 5764-5767 (2014).
20. RiadhBchir, AfrahBardaoui.: Design of silicon-based two-Dimensional photonic integrated circuits: XOR gate, IET Optoelectronics, 7, 25-29 (2013)
21. Susan Christina, X. Kalibilan, A.P.: Design of optical logic gates using self-collimated beams in photonic crystals, Photonic sensor, 2, 173-179 (2012)
22. Wen-PiaLin, Yu-FanHsu, and Han-LaungKuo.: Design of Optical NOR Logic gates using Two Dimensional Photonic Crystals, Journal of Modern Physics, 2, 144-147 (2014)
23. Seraj Mohammadi, H. Absalan.: All optical NAND gate based on nonlinear photonic crystal ring resonator, Information processing in Agriculture, 3, 119-123(2016)
24. Preetha Rani, and Yogita,: Design of all optical logic gates in photonic crystal waveguide, Optik-International Journal for Electron Optics, 126, 950-955 (2015)
25. Noshad, M. Abbasi, A. Ranjbar, R. Kheradmand, R.: Novel all-optical logic gates based on Photonic Crystal structure. International Symposium on Optics and its Applications, 350, 1-6 (2012)
26. Kabilan, A. P. Christina, S. X. Caroline, E. P.: Photonic Crystal based all optical OR and XOR logic gates, Second International Conference on Computing, Communication and Networking Technologies, 1, 1-4, (2010)
27. Danaie, M. Kaatizian, H.: Design and simulation of all-optical photonic crystal AND gate using nonlinear Kerr effect. Optical and Quantum Electronics, 44, 27-34(2012)
28. Ghadran, M. Birjandi, M. A. M.: Concurrent implementation of all-optical half adder and AND& XOR logic gates based on nonlinear photonic crystal. Optical and Quantum Electronics, 45, 1027-1036(2013)
29. Maurya A.K., Maurya V.N. and Singh R.K., Computational approach for performance analysis of photonic band gap structure on defected ground surface with microwave and band stop filter, American Journal of Engineering Technology, Academic & Scientific Publishing, New York, USA, Vol.1(7),10-18 (2013)
30. Fu, Y., Hu, X., Gong, Q.: silicon photonic crystal all-optical logic gates. Phys. Lett. A 377, 329–333 (2013)

31. Ghadrdan, M., Mansouri-Birjandi, A.: All-optical NOT logic gate based on photonic crystals. Int. J. Electr. Comput. Eng. 3, 478–482 (2013)
32. Jianga, Y.C., Liua, S.B., Zhanga, H.F., Konga, X.K.: Reconfigurable design of logic gates based on a two-dimensional photonic crystals waveguide structure. Opt. Commun. 332, 359–3653 (2014)
33. Singh, B.R., Rawal, S.: Photonic crystal based all-optical NOT logic gate. J. Opt. Soc. Am. A 32(12), 2260–2263 (2015)
34. Dsouza, N.M., Mathew, V.: Interference based square lattice photonic crystal logic gates working with different wavelengths. Opt. Laser Technol. 80, 214–219 (2016)
35. Shaik, E.H., Rangaswamy, N.: Design of photonic crystal-based all-optical and gate using t-shaped waveguide. J. Mod. Opt. 63(10), 941–949 (2016)
36. Preeti Rani, Shiba Fatima, Yogita Kalra, R.K. Sinha.: Realization of all optical logic gates using universal NAND gates on photonic crystal platform, Superlattices and Microstructures, Volume 109, p. 619-625 (2017)
37. Olyaee S., Seifouri, M., Mohebzadeh-Bahabady, A., Sardari, M.: Realization of all-optical NOT and XOR logic gates based on interference effect with high contrast ratio and ultra-compacted size, Optical and Quantum Electronics, 50: 11, 385 (2018)
38. Hussein, M., Tamer, A., Rafat, N.: New designs of a complete set of photonic crystals logic gates. Opt. Commun. 411, 175–181 (2018)
39. Mohebzadeh-Bahabady, A. & Olyaee, S.: Designing low power and high contrast ratio all-optical NOT logic gate for using in optical integrated circuits, Opt Quant Electron, 51: 3, (2019)

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