Design and Simulation of Linear All-Optical Comparator Based on Square-Lattice Photonic Crystals

Fariborz Parandin (fparandin@yahoo.com)
Razi University, Kermanshah, Iran  https://orcid.org/0000-0001-9044-3048

Reza Kamarian
Islamic Azad University Branch of Kermanshah

Mohamadreza Jomour
Islamic Azad University Branch of Kermanshah

Research Article

Keywords: Optical comparator, Photonic crystals, Defect, PBG.

DOI: https://doi.org/10.21203/rs.3.rs-343170/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

An optical comparator is an important logic circuit used in digital designs. Photonic crystals are among the platforms for implementing different kinds of gates and logic circuits. Photonic crystals are structures with alternating refractive indices. In digital optics, logical values “0” and “1” are defined based on the level of optical power. In this paper, an optical comparator based on square-lattice photonic crystals is designed and simulated. In the design of this comparator, a small-sized structure is used. The simulation results show that in the proposed comparator, there is a long distance between logical values “0” and “1”. Due to the small size of this comparator and the adequate distance between logical values “0” and “1”, this structure suits photonic integrated circuits with high accuracy.

1. Introduction

Electrons are considered the charge carriers in electronic circuits. In these circuits, a transistor serves as the base part. In other words, all circuits are designed using transistors. Since the movement of electrons in transistors is determined by the size of this part, the speed of the transistor circuits is limited by the size of the transistors. If electronic parts are replaced with optical parts, the photons will be the charge carriers. Given the high speed of photons, if optical parts are used, their speed will increase drastically. Therefore, it is better to use optical circuits in the design of high-speed integrated circuits (John 1987; Fan et al. 2006; Miri et al. 2010; Ahmadlou et al. 2006; Miri et al. 2013; Khavasi et al. 2010).

Photonic crystals are among the platforms that suit the design of optical circuits. One of the reasons for paying more attention to this structure is that it is possible to design different types of circuits using photonic crystals. In the digital field, many logic gates have been designed with photonic crystals (Olyaee et al. 2018a; Parandin and Karkhanehchi 2017; Gupta and Medhekar 2016; Parandin et al. 2017; Rezaei et al. 2020; Parandin et al. 2018; Serajmohammadi et al. 2015; Abdollahi and Parandin 2019; Farmani et al. 2019; Pirzadi et al. 2016; Ghadrdan and Mansouri-Birjandi 2013; Mohebzadeh-Bahabady and Olyaee 2018; Olyaee et al. 2018b; Naghizade et al. 2021; Gilarlue et al. 2019; Gilarlue and Badri 2019). Moreover, many logic circuits such as adders, subtractors, decoders, encoders, and de-multiplexers have been designed (Parandin 2019; Neisy et al. 2018; Parandin et al. 2018; Saghaei et al. 2018; Moniem 2015; Karkhanehchi et al. 2017; Naghizade and Saghaei 2020; Sani et al. 2020; Naghizade and Saghaei 2021; Parandin and Moayed 2020; Parandin et al. 2021; Vahdati and Parandin 2019). The two-bit comparator is among the logic circuits. This circuit compares two bits. Very few studies have been conducted so far on the design of optical comparators with photonic crystals (Rathi et al. 2017; Fakouri-Farid and Andalib 2018; Serajmohammadi et al. 2019; Surendar et al. 2019; Jalali et al. 2019; Seraj et al. 2020).

Recently, several papers have been penned on the design of comparators. In 2017, Rathi et al. designed a small-sized structure for an optical comparator based on square-lattice photonic crystals. In this paper, it is shown that using optical power distribution the structure can act as a comparator and the output values are not determined quantitatively (Rathi et al. 2017). In 2018, Fakouri-Farid et al. used a square-lattice photonic crystal structure to design a comparator. The distance between the high and low logical
values was acceptable in this comparator, but the size of the structure was extremely large. Moreover, due
do the use of a ring resonator in the structure, the delay time of the circuit is increased (Fakouri-Farid and Andalib 2018).

Another comparator was designed by Serajmohammadi et al. in 2019. In this paper, the distance between
the high and low logical values was satisfactory but the circuit size was large and a ring resonator is
used (Serajmohammadi et al. 2019). In 2019, Surendar et al. used photonic crystals to design a comparator. In this comparator, an X-shaped resonator is used. In this structure, the distance between “0” and “1” values is sufficient but the use of a resonator and the large size of this structure are among the pitfalls (Surendar et al. 2019).

A comparator was also designed in 2019 by Jalali et al. This structure also consists of four ring
resonators, which increase the circuit size and the circuit delay time (Jalali et al. 2019). In 2020, Seraj et
al. designed a comparator based on photonic crystals. Despite the small size of this structure, the
distance between the high and low logical values is not long (Seraj et al. 2020).

In this paper, a photonic crystal structure with a square lattice is used to design an optical comparator. In
the design of this structure, it is tried to select the small comparator size. Moreover, in this structure, the
distance between the logical values “0” and “1” is also taken into account. Furthermore, it is tried to avoid
the use of ring resonators to create a high-speed structure. Therefore, the circuit delay time is reduced and
its speed is increased.

2. Design Of Optical Comparator

A basic photonic crystal structure consisting of silicon rods with a circular cross-section in the air context
is used to design the comparator. There are 24×19 rods that form a two-dimensional square lattice. The
refractive index of the rods is 3.46, which is designed for the approximately 1.55µm wavelength. The
lattice constant, which is the distance between the centers of the rods, is set to a=0.6µm for this structure.
The radius of the silicon rods is also r=0.2a.

This alternating structure leads to the creation of an attribute called the photonic band gap (PBG). Based
on this attribute, propagation of a range of wavelengths in the structure is not allowed. The band
structure calculations are also used to calculate this wavelength range. The plane wave expansion (PWE)
method is used to calculate the band structure. Figure 1 depicts the results of the band structure
calculations.

As seen in Figure 1, no wavelength can enter the structure in the 0.28 to 0.42 normalized range. Since the
normalized values are defined as , the equivalent wavelength for this range is . Hence, this wavelength
has to fall within the PGB range to select a suitable wavelength that can be controlled and directed in the
structure. The 1.55µm is selected as the operating wavelength, which is within the aforementioned range.
A combination of linear and point defects is used to obtain the optical comparator. The A and B inputs are placed on the top and bottom of the structure and a constantly activated input called Ref is also placed on the left side of the structure. When both inputs are off, the output for their equality has to be activated. The Ref input serves this purpose. Moreover, to improve the structure performance, Ref source has a phase shift in relation to the two input references. Three outputs are also selected for three possible states, which include A<B, A=B, and A>B. The outputs of these three states also include F_1(A<B), F_2(A=B), and F_3(A>B). Figure 2 depicts the arrangement of the inputs and outputs and the link between their paths.

As seen in Figure 2, linear defects are used to obtain the comparator and create the input and output paths. These defects are created by omitting all the rods. Point defects are also used at the intersection of the waveguide paths. The radius of the rods is changed for the point defects. Figure 2 shows the size of the radius of these rods. Some of the rods are also displaced as follows to improve comparator efficiency.

1. Rods with R1 and R2 radii: 0.2a rightward and 0.3a upward
2. Rods with R3 radii: 0.3a rightward and 0.2a upward
3. Rods with R4 radii: 0.3a rightward and 0.6a upward
4. Rods with R5 radii: 0.2a upward
5. Rods with R6 radii: 0.2a downward
6. Rods with R7 radii: 0.3a rightward and 0.6a downward
7. Rods with R8 radii: 0.3a rightward and 0.2a downward
8. Rods with R9 and R10 radii: 0.2a rightward and 0.3a downward
9. Rod a: 0.6a rightward and 0.1a upward
10. Rod b: 0.5a rightward
11. Rod c: 0.6a rightward and 0.1a downward

The comparator is simulated in four input states and the optical power distribution in the structure is obtained in these states. Figure 3 also shows the simulation results. In Figure 3(a) shows power distribution for A=B=0. As seen in this figure, the F_2 output has considerable optical power and it could be considered the equivalent to logical value “1”. The optical power in the output is supplied by Ref input.

In this state, the decrease in power in the outputs is caused by the interference of the waves emitted from the input source and Ref input at the intersection while optimal power is only distributed along path F_2 after colliding with the rods and the power level is very low in the other outputs. Figure 3 (b) depicts the optical power distribution in this state.

Figure 3 (c) shows the results when the inputs are A=0, B=1. Since in this state A<B, the F_1 output is expected to be in the “1” state and the other outputs are expected to be zero. As seen in this figure, the
power distribution in the $F_1$ output is significant and is equal to the logical value “1”.

If the inputs are $A = 1$, $B = 0$, i.e. $A > B$, the $F_3$ output has to have high optical power and other outputs have to have very low power due to the symmetry of the circuit. Figure 3 (d) confirms this state. In other words, $F_3$ equals logical value “1” and the other outputs are in the “0” state.

Figure 4 presents the time curve of the variations of the optical power range in the comparator outputs. As seen in this figure, when $A=B=0$, the normalized power in the $F_2$ output equals 0.67, and power in the other two outputs equals 0.01. In other words, the $F_2$ output equals logical value “1”. In addition, when $A=B=1$, the power in the $F_2$ output equals 0.70 while in other outputs it is equal to 0.17. In other words, in this state, $F_2$ equals logical value “1” (see figures 4 (a) and 4 (b)).

Figure 4 (c) shows the normalized power diagram in the outputs of the comparator circuit for $A=0$, $B=1$. In this state, the optical power in the $F_1$ output is 0.66, which equals logical value “1”. In the other two outputs, power equals 0.20, which equals logical value “0”. The normalized power diagram for $A=1$, $B=0$ is also shown in Figure 4 (d). As seen in this figure, power in the $F_3$ output, which has to be in the logical state “1”, equals 0.66, while in the other outputs the optical power is low and equals 0.20.

Several new articles are reviewed and their results are compared to compare the proposed structure with the previous studies. Table 1 shows the results of this comparison. It is worth noting that very few studies have been conducted on photonic crystal comparators. In Table 1, the size of this structure is compared to other papers. In addition, the worst value of each output in the “0” and “1” logical value states, i.e. the maximum power for “0” and the lowest power for “1”, are shown in this table and are compared to other structures.
As seen in Table 2, in references (Fakouri-Farid et al. 2018) and (Serajmohammadi et al. 2019), the circuit size is large and does not suit the photonic integrated circuits despite the highly satisfactory “0” value. In reference (Surendar et al. 2019), the values of “0” are not reported and the values of “1” are good logical values but the circuit size is large. In reference (Jalali et al. 2019), the logical value “0” is high and the structure is also large. Finally, in reference (Seraj et al. 2020), the structure is small, but two outputs are used simultaneously to compare the inputs. The value “1” in this circuit is also weak. In these circuits, the logical values “0” and “1” and the size of the structure are not optimized but in the proposed comparator the circuit size is small while the long distance between the two logical values is also taken into account.

### 3. Conclusion

In this study, a one-bit comparator is designed and simulated. This circuit can compare two input bits and put one of the three outputs in the logical state “1”. One of the characteristics of the designed structure is its small size, which makes the comparator suitable for photonic integrated circuits. Moreover, the distance between two logical values is taken into account in designing the comparator to ensure the distance is relatively good. Another characteristic of this circuit is its simple design, which involves simple linear and point defects and does not include resonators that increase the circuit delay time.
References

1. John, S.: Strong localization of photons in certain disordered dielectric superlattices. Phys. Rev. Lett. 58, 2486–2489 (1987)

2. Fan, S., Yanik, M.F., Wang, Z., Sandhu, S., Povinelli, M.L.: Advances in Theory of Photonic Crystals. JOURNAL OF LIGHTWAVE TECHNOLOGY, 24(12) (2006)

3. Miri, M., Khavasi, A., Mehrany, K. Rashidian, B.: Transmission-line model to design matching stage for light coupling into two-dimensional photonic crystals. Optics letters, 35(2), 115-117 (2010)

4. Ahmadlou, M., Kamarei, M. Sheikh, M.H.: Negative refraction and focusing analysis in a left-handed material slab and realization with a 3D photonic crystal structure. Journal of Optics A: Pure and Applied Optics, 8(2), 199-204 (2006)

5. Miri, M., Sodagar, M., Mehrany, K., Eftekhar, A.A., Adibi, A., Rashidian, B.: Design and fabrication of photonic crystal nano-beam resonator: Transmission line model. Journal of lightwave technology, 32(1), 91-98 (2013)

6. Khavasi, A., Mehrany, K., Miri, M., Jahromi, A.K. and Khorasani, S.: Study of beam propagation in finite photonic crystals. Physics and Simulation of Optoelectronic Devices XVIII, 7597, 759728 (2010)

7. Olyaee, S., Seifouri, M., Mohebzadeh-Bahabady, A., et al.: Realization of all-optical NOT and XOR logic gates based on interference effect with high contrast ratio and ultra-compacted size. Opt. Quant. Electron 50(11), 385 (2018)

8. Parandin, F., Karkhanehchi, M.M.: Terahertz all-optical NOR and AND logic gates based on 2D photonic crystals. Superlattices Microstruct. 101, 253–260 (2017)

9. Gupta, M.M., Medhekar, S.: All-optical NOT and AND gates using counter propagating beams in nonlinear Mach–Zehnder interferometer made of photonic crystal waveguides. Optik, 127, 1221–1228 (2016)

10. Parandin, F., Malmir, M.R., Naseri, M.: All-optical half-subtractor with low-time delay based on two dimensional photonic crystals. Superlattices Microstruct. 109, 437–441 (2017)

11. Rezaei, M.H., Boroumandi, R., Zarifkar, A., Farmani, A.: Nano-scale multifunctional logic gate based on graphene/hexagonal boron nitride plasmonic waveguides. IET Optoelectronics, 14(1), 37-43 (2020)

12. Parandin, F., Malmir, M.R., Naseri, M., Zahedi, A.: Reconfigurable all-optical NOT, XOR, and NOR logic gates based on two dimensional photonic crystals. Superlattices Microstruct. 113, 737–744 (2018)

13. Serajmohammadi, S., Alipour-Banaei, H., Mehdizadeh, F.: All optical decoder switch based on photonic crystal ring resonators. Opt Quant Electron, 47, 1109-1115 (2015)

14. Abdollahi, M., Parandin, F.: A novel structure for realization of an all-optical, one-bit half-adder based on 2D photonic crystals. J. Comput. Electron. 18, 1416–1422 (2019)

15. Farmani, A., Mir, A., Irandejar, M.: 2D-FDTD simulation of ultra-compact multifunctional logic gates with nonlinear photonic crystal. Journal of the Optical Society of America B, 36(4), 811-818 (2019)
16. Pirzadi, M., Mir, A., Bodaghi, D.: Realization of Ultra-Accurate and Compact All-Optical Photonic Crystal OR Logic Gate. IEEE PHOTONICS TECHNOLOGY LETTERS, 28(21), 2387-2390 (2016)
17. Ghadrdan, M., Mansouri-Birjandi, M.A.: Concurrent implementation of all-optical half-adder and AND & XOR logic gates based on nonlinear photonic crystal. Opt Quant Electron, 45, 1027–1036 (2013)
18. Mohebzadeh-Bahabady, A., Olyaee, S.: All-optical NOT and XOR logic gates using photonic crystal nano-resonator and based on an interference effect. IET Optoelectron. 12(4), 191–195 (2018)
19. 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. Opt Quant Electron, 50, 385 (2018)
20. Naghizade, S., Mohammadi, S., Khoshshima, H.: Design and simulation of an all optical 8 to 3 binary encoder based on optimized photonic crystal OR gates. Journal of Optical Communications. 42(1), 31-41 (2021)
21. Gilarlue, M.M., Nourinia, J., G Hobadi, Ch., Badri, S.H, Rasooli-Saghai, H.: Multilayered Maxwell’s fisheye lens as waveguide crossing. Optics Communications, 435, 385-393 (2019)
22. Gilarlue, M.M., Badri, S.H.: Photonic crystal waveguide crossing based on transformation optics, Optics Communications. 450, 308-315 (2019)
23. Parandin, F.: High contrast ratio all-optical 4 × 2 encoder based on two-dimensional photonic crystals. Optics & Laser Technology, 113, 447-452, 2019
24. Neisy, M., Soroosh, M., Ansari-Asl, K.: All optical half adder based on photonic crystal resonant cavities. Photon Netw. Commun. 35, 245–250 (2018)
25. Parandin, F., Karkhanehchi, M.M., Naseri, M., Zahedi, A.: Design of a high bitrate optical decoder based on photonic crystals. J. Comput. Electron. 17, 830–836 (2018)
26. Saghaei, H., Zahedi, A., Karimzadeh, R., Parandin, F.: Line defects on photonic crystals for the design of all-optical power splitters and digital logic gates. Superlattices Microstruct. 110, 133–138 (2017)
27. Moniem, T.A.: All-optical digital 4×2 encoder based on 2D photonic crystal ring resonators, Journal of Modern Optics, 63(8), 735-741 (2015)
28. Karkhanehchi, M.M., Parandin, F., Zahedi, A.: Design of an all optical half-adder based on 2D photonic crystals. Photon Netw. Commun. 33, 159–165 (2017)
29. Naghizade, S., Saghaei, H.: A novel design of all-optical 4 to 2 encoder with multiple defects in silica-based photonic crystal fiber. Optik, 222, 165419 (2020)
30. Sani, M.H., Tabrizi, A.A., Saghaei, H., et al.: An ultrafast all-optical half adder using nonlinear ring resonators in photonic crystal microstructure. Opt Quant Electron 52, 107 (2020)
31. Naghizade, S., Saghaei, H.: A novel design of all-optical half adder using a linear defect in a square lattice rod-based photonic crystal microstructure. J. Appl. Res. Electr. Eng., 1(1), 1010 (2021)
32. Parandin, F., Moayed, M.: Designing and simulation of 3-input majority gate based on two-dimensional photonic crystals. Optik Int. J. Light Electron Opt. 216, 164930 (2020)
33. Parandin, F., Kamarian, R., Jomour, M.: A novel design of all optical half-subtractor using a square lattice photonic crystals. Opt Quant Electron 53, 114 (2021)

34. Vahdati, A., Parandin, F.: Antenna Patch Design Using a Photonic Crystal Substrate at a Frequency of 1.6 THz. Wireless Personal Communications, 109, 2213-2219 (2019)

35. Rathi, S., Swarnakar, S., Kumar, S.: Design of one-bit magnitude comparator using photonic crystals. J. Opt. Commun. 40(4), 363–367 (2017)

36. Fakouri-Farid, V., Andalib, A.: Design and simulation of an all optical photonic crystal-based comparator. Optik, 172, 241-248 (2018)

37. Serajmohammadi, S., Alipour-Banaei, H., Mehdizadeh, F.: A novel proposal for all optical 1-bit comparator using nonlinear PhCRRs. Photonics and Nanostructures - Fundamentals and Applications, 34, 19-23 (2019)

38. Surendar, A., Asghari, M., Mehdizadeh, F.: A novel proposal for all-optical 1-bit comparator using nonlinear PhCRRs. Photon Netw Commun 38, 244–249 (2019)

39. Jalali, S.M., Soroosh, M., Akbarizadeh, G.: Ultra-fast 1-bit comparator using nonlinear photonic crystal based ring resonators. Journal of Optoelectronical Nanostructures 4(3), 59-72 (2019)

40. Seraj, Z., Soroosh, M., Alaei-Sheini, N.: Ultra-compact ultra-fast 1-bit comparator based on a two-dimensional nonlinear photonic crystal structure. Applied Optics, 59(3) (2020)

**Figures**
Figure 1

PBG range for the basic structure
Figure 2

The proposed optical comparator structure
Figure 3

The optical power distribution of the comparator in different input states
Figure 4

The normalized power diagram in the comparator outputs for different input states