A Low Crosstalk Photonic Crystal-Based Optical Binary Divider with Ring Resonator Structure for DWDM Communication Systems

Mahmoud Baghbanzadeh[1], Hassan Rasooli Saghai[2], Hamed Alipour-Banaei[3], Shahram Mojtahedzadeh[1], Mohammad Ali Tavakkoli[1]

[1]Department of Electrical Engineering, Aza.C., Islamic Azad University, Azarshahr, Iran

[2]Department of Electrical Engineering, Ta.C., Islamic Azad University, Tabriz, Iran

[3]Department of Electronics, Ta.C., Islamic Azad University, Tabriz, Iran

*Corresponding Author Email: ha.alipour@iau.ac.ir

Receive Date: 16Aug 2025 Revise Date: --- Accept Date: 05Sep 2025

Abstract

In this paper, we utilize a photonic crystal ring resonator structure to design a 2-channel optical wavelength binary divider. By the artificial intelligence method, the amounts of physical parameters of the photonic crystal structure are selected, such as refractive indices, radii, and so on. It has been demonstrated that wavelength separation is possible using photonic crystal ring resonators. To choose two channels with different central wavelengths, we employed two resonant rings with different structural parameters. The platform used for designing the proposed binary divider is a square lattice of dielectric rods immersed in air. The proposed binary divider has two channels with central wavelengths equal to λ_1 *= 1573.7 nm and* λ_2 *= 1575.5 nm. The transmission efficiency of this binary decoder structure exceeds 98%. The quality factors for the first and second channels are 3934 and 5251, respectively. The total footprint of the structure is 263.5* μm^2*; therefore, the proposed structure has good potential for use in all-optical integrated circuits and wavelength multiplexing applications. Also, the crosstalk phenomenon between the channels is low.*

Keywords: photonic crystal, photonic band gap, binary divider, crosstalk, defect, ring resonator, DWDM

1. Introduction

Designing ultra-compact devices is an interesting and crucial goal for electronic and photonic designers. Especially in the field of optical devices, due to poor confinement of light waves inside small spaces, reducing the footprint of devices and designing optical devices suitable for all optical integrated circuits was a great challenge until the proposal of photonic crystals (PhCs) in 1987 [1]. PhCs are regular arrays of dielectric materials in which the distribution of refractive index is periodic [2]. This periodicity results in a special region in their band structure in which no optical waves are allowed to propagate inside the PhC. This special region is called the photonic band gap (PBG) [3]. PBG is an excellent property that enables PhC to confine light waves inside compact spaces. PBG depends on the refractive indices of dielectric materials and the structural parameters of PhCs [4]. Photonic crystals can be used for designing optical reflectors [5], optical filters [6-9], optical binary devices [10-13], optical switches [14-15], etc.

In optical communication networks, optical waves are used to transfer data and information inside optical fibers. By employing wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) technologies, we can optimize the use of a single optical fiber's capacity by launching multiple optical channels with different wavelengths through a single optical fiber. However, at the user end, we need a device to separate these channels from each other according to their central wavelengths. This device is an optical binary divider.

Due to the crucial importance of PhC-based binary devices in future optical communication networks, many researchers have devoted their work to designing and proposing novel optical binary devices. Recently, different mechanisms have been proposed for performing wavelength multiplexing based on PhC structures, such as: Coupling and cascading PhC-based waveguides [16], multimode interference [17], Y-shaped waveguides with different radius of rods [18], Supper prisms [19-20], and resonant cavities [21-22].PhC ring resonators [23] are another structure used for designing all-optical devices such as optical filters [24], optical switches [25], optical logic gates [26], and optical binary devices [27]. Improving the transmission efficiency, crosstalk values, quality factor, and reducing channel spacing are the most important goals in designing all-optical binary devices.

In this paper, we propose optical binary devices based on PhC ring resonators with two different configurations. The transmission efficiency of our structure exceeds 98%, and the channel spacing is less than 2 nm. The total footprint of the structure is 263.5 μm^2. High transmission efficiency, high quality factor values make our proposed structure a potential candidate to be used in WDM applications.

The rest of the paper is organized as follows: in Section 2, we describe the theoretical methods and design procedure of the structure. By the artificial intelligence method, the amounts of physical parameters of the photonic crystal structure are selected, such as refractive indices, radii, and so on. In Section 3, we discuss the simulation process and the results obtained from our simulations, and finally, in Section 4, we conclude from our work.

2. Theoretical methods and design

For designing the proposed binary divider, we employed a 30*30 square lattice of dielectric rods immersed in air. The effective refractive index of the dielectric rods is 3.46, and their radius is $r=0.17*a$, where a is the lattice constant of the PhC. First of all, we should calculate the band structure of the fundamental structure and extract its PBG region. For this purpose, we used the plane wave expansion (PWE) method. PWE is a numerical method in the frequency domain by which we can calculate the eigenmodes and eigenfrequencies of periodic structures by iteratively solving Maxwell's equations in the frequency domain [28]. Due to accuracy and time considerations in our work, we used the Band solve simulation tool of Rsoft Photonic CAD software for extracting the band structure diagrams and

PBG region of our structure, which performs the calculations based on the PWE method. The band structure diagram of our structure with the aforementioned values for refractive index, radius of rods, and lattice constant is shown in Fig.1. Fig.1 shows that there are 3 PBGs, two PBGs in transverse magnetic (TM) mode and one in transverse electric (TE) mode. The first PBG in TM mode is wide enough for our applications. The normalized frequency range of this PBG is 0.31<*a/λ*< 0.45, considering *a=606* nm, the wavelength range of this PBG will be 1346 nm <λ< 1954 nm. Therefore, all the simulations will be done in TM mode

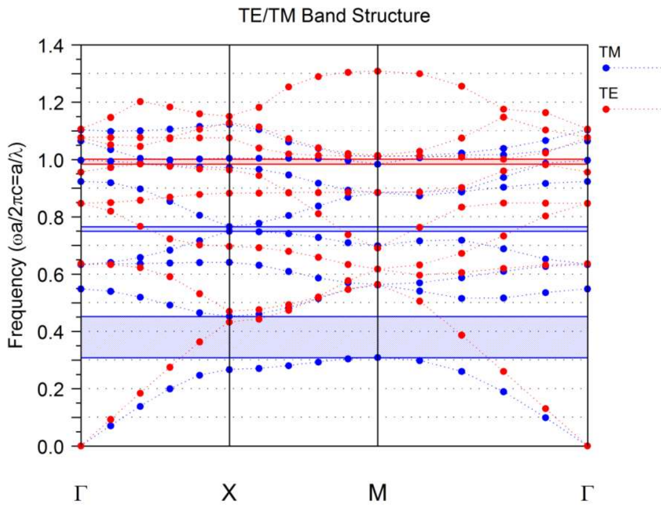


Fig. 1. The band structure of the proposed structure with *r=0.17*a* nm and n=3.46

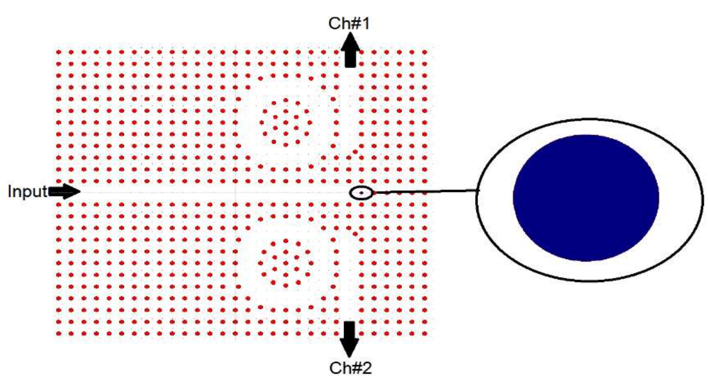
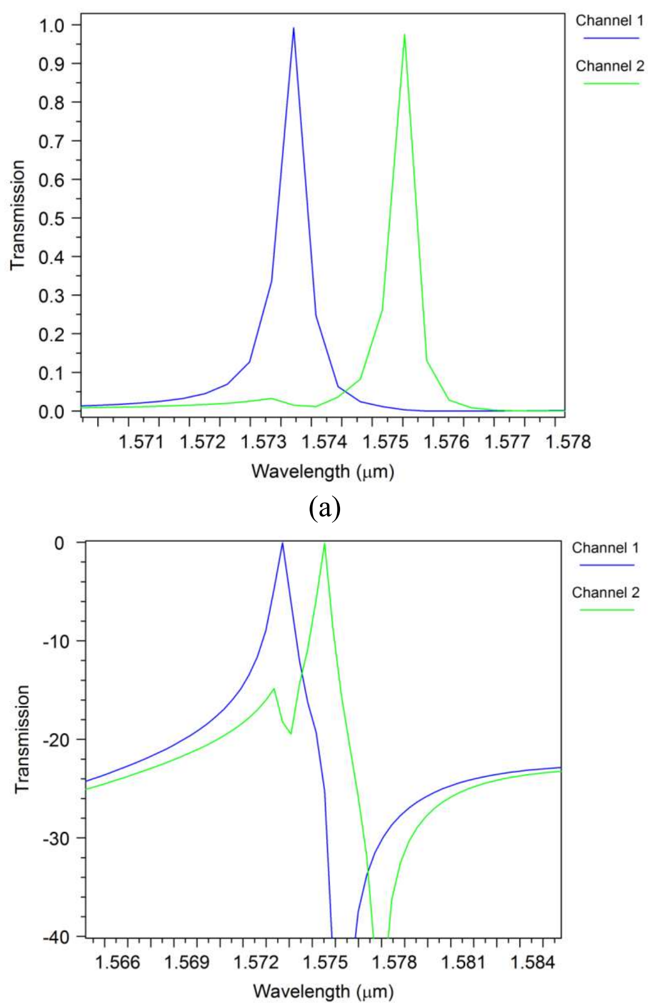


Fig. 2. The final sketch of the proposed binary divider

The second step in designing our proposed structure is to create the binary divider structure within the fundamental 2D photonic crystal (PhC) structure. As we mentioned, our proposed binary divider is based on a PhC ring resonator, so the wavelength selection is done via resonant rings. The input waveguide has been created by removing 24 rods from the central row of the PhC structure in Γ-X direction, and then we created the two output waveguides at the proper positions inside the crystal in X-M direction, and finally put a resonant ring between the input waveguide and each output waveguide. It has been shown that the resonant wavelength of ring resonators depends on the refractive index and structural parameters of the ring [29], so to select two different wavelengths at the output ports, the resonant rings of our structure should be different from each other.

R_1 and $a_1$are the radius and lattice constant of the first ring –the ring adjacent to output channel#1-respectively. R_2 and $a_2$are the radius and lattice constant of the second ring –the ring adjacent to output channel#2, respectively. The final sketch of our proposed binary divider is shown in Fig.2. The values of these parameters are: R_1= 98 nm, a_1= 576 nm, R_2= 103 nm, and a_2= 606 nm. There is a point defect at the end of the input whose radius is 40 nm; this point defect controls the transmission efficiency of the output channels and is shown in dark blue in Fig.2.The total footprint of the proposed structure is 263.5 μm^2

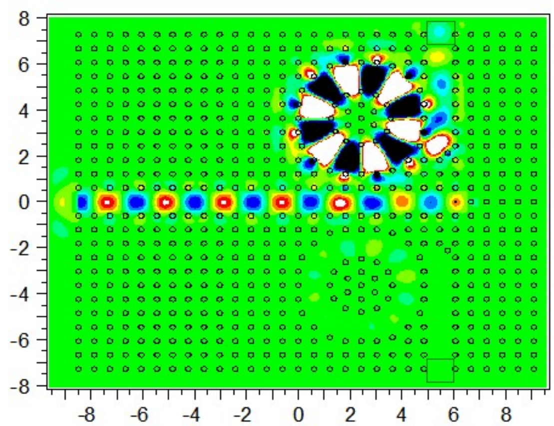


(b)

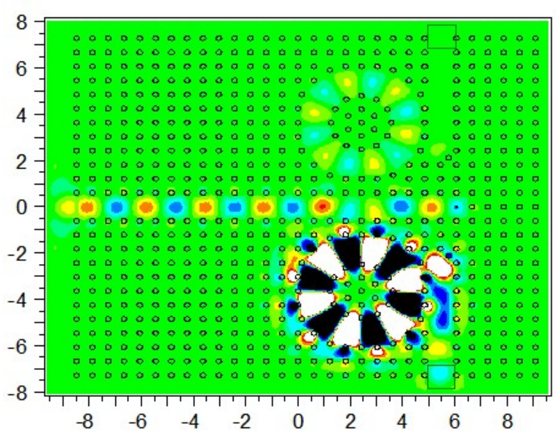
Fig. 3. output spectrum of the binary devisor (a) linear and (b) dB scale

3. Simulation and results

The final step in designing our proposed binary divider is simulating and obtaining the optical characteristics of the binary divider. For this purpose, we used the Full wave simulation tool of Rsoft Photonic CAD software for testing our proposed binary divider. Full wave studies the propagation of light inside PhC-based devices based on the finite difference time domain (FDTD) method [30]. We used the Perfectly Matched Layer (PML) boundary condition for simulating our proposed binary dividers [31]. We choose the PML width surrounding our structures to be 500 nm. For accurate modeling of the binary divider, we need a 3D simulation, but it requires a great amount of run time and a very powerful computer. So, we used the effective index approximation method of PhCs for satisfying this requirement, and with this approximation, we reduce the 3D simulations to 2D simulations [32]. Grid sizes (Δx andΔy) in FDTD parameters are chosen to be a/16, which equals 39 nm. Due to stability considerations of the simulation, the time step Δt should satisfy thecondition $\Delta t \le \frac{1}{c\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}}}$, where C is the velocity of light in free space [30].



(a)



(b)

Fig. 4. Distribution of optical power at (a) λ=1573.7 nm and (b) λ=1575.5 nm

Table 1. Simulation results of the binary divider

channel	λ_0 (nm)	$\Delta\lambda$ (nm)	Q	Transmission
1	1573.7	0.4	3934	99%
2	1575.5	0.3	5251	98%

Table 2. Crosstalk values of Binary divider (dB)

X_{ij}	1	2
1	-	-17
2	-22	-

Following the above-mentioned rule for time step, $\Delta t = 0.026\, nm$ was chosen. The simulation is done during 20000-time steps, which requires 130 min run time and 20 MB memory size for our proposed binary divider. The output spectrum of the binary divider has been obtained and shown in Fig.3. This binary divider has 2 channels with central wavelengths equal to $\lambda_1 = 1573.7\, nm$ and $\lambda_2 = 1575.5\, nm$. The channel spacing for this binary divider is 1.8 nm, and the transmission efficiency is more than 98%. The bandwidth for the first and second channels is 0.4 and 0.3 nm, respectively, so the quality factors will be 3934 and 5251. Complete specifications of the binary divider are listed in Table 1. Also, the crosstalk values are listed in Table 2, in which crosstalk values are named as X_{ij}, (i,j varies from 1to2), which shows the effect of j-th channel in i-th channel at the central wavelength of i-th channel. In Table 2, i and j indices are column and row.

The distribution of the optical wave inside the structure for two different wavelengths is shown in fig.4. at λ=1573.7 nm the optical waves due to dropping function of the first resonant ring will drop to the first out waveguide and travel toward first output channel (fig.4(a)) and at λ=1575.5 nm the optical waves due to dropping function of the second resonant ring will drop to the second out waveguide and travel toward first output channel (fig.4(b)).

4. Conclusion

In this paper, we propose a 2-channel all-optical wavelength binary divider. Wavelength selection task in our proposed structure is done via low-loss and high-quality factor micro ring resonators. By the artificial intelligence method, the amounts of physical parameters of the photonic crystal structure are selected, such as refractive indices, radii, and so on. In order to select different wavelengths, we choose different values for the structural parameters of the ring. The proposed structure can separate 2 channels with central wavelengths at 1573.7 nm and 1575.5 nm. Minimum transmission efficiency of the channels is 98%. The quality factor and crosstalk values are better than 3934 and -17dB. Considering the overall performance of the structure, it is suitable for WDM applications.

References

[1] S. John," Strong localization of photons in certain disordered dielectric superlattices" Physical Review Letters 58(23), 2486-2489 (1987).

[2] K. Sakoda, "Optical Properties of Photonic Crystals" Springer-Verlag, Berlin, (2001).

[3] J.D. Joannopoulos, R.D. Mead, J.N. Winn, Photonic Crystals: Molding the Flow of Light, Princeton University Press, Princeton, NJ, USA, 1995.

[4] F. Mehdizadeh, H. Alipour-Banaei, "Band gap management in two-dimensional photonic crystal thue-morse structures", Journal of Optical Communications 34 (2013) 61-65.

[5] F. Mehdizadeh, H. Alipour-Banaei, and Z. Daie-Kuzekanani, "All optical multi reflection structure based on one dimensional ohotonic crystals for WDM communication systems", Optoelectronics and Advanced Materials-Rapid Communications 6 (2012) 527-531.

[6] H. Alipour-Banaei, and F. Mehdizadeh "A PROPOSAL FOR ANTI-UVB FILTER BASED ON ONE-DIMENSIONAL PHOTONIC CRYSTAL STRUCTURE" Digest Journal of Nanomaterials and Biostructures.7 (2012) 361-367.

[7] H. Alipour-Banaei, F. Mehdizadeh, " Significant role of photonic crystal resonant cavities in WDM and DWDM communication tunable filters", Optik (2012) http://dx.doi.org/10.1016/j.ijleo.2012.07.029.

[8] H. Alipour-Banaei,M. Hassangholizadeh-Kashtiban, F. Mehdizadeh, " WDM and DWDM optical filter based on 2D photonic crystal Thue-Morse structure", Optik (2013) http://dx.doi.org/10.1016/j.ijleo.2013.03.027.

[9] H. Alipour-Banaei, F. Mehdizadeh, M. Hassangholizadeh-Kashtiban "Important Effect of Defect Parameters on the Characteristics of Thue-Morse Photonic Crystal Filters" Advances in OptoElectronics (2013) 2013, 856148.

[10] A.Khorshidahmad, and A. G. Kirk, "Composite superprism photonic crystal binary divider: analysis and design" Opt. Express 48 26518–26528 (2010).

[11] H. P. Bazargani "Proposal for a 4-channel all optical binary divider using 12-fold photonic crystal quasicrystal" Optics Communication 685 1848-1850 (2012).

[12] G. Manzacca, D. Paciotti, A. Marchese, M. S. Moreolo, and G. Cincotti, "2D photonic cavity based WDM multiplexer" Photonic and Nanostructures – Fundamentals and Applications 5 164-176 (2007).

[13] Zhang X, Liao Q, Yu T, Liu N and Huang Y "novel ultra-compact wavelength division binary divider based on photonic band gap" 2012Optics Communication.285 274-276.

[14] Edilson A. Camargo, Harold M.H. Chong, Richard M. De La Rue, 2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure, Opt. Express. 12 (4) (2004) 588–592.

[15] AlainHach e, Martin Bourgeois, Ultra fastall-opticals witching in a silicon- based photonic crystal, Appl.Phys.Lett.77(25)(2000)4089–4091.

[16] F. S. Chien, S. C. Cheng, Y. J. Hsu, and W. F. Hsieh, "Dual band multiplexer/binary divider with photonic crystal waveguide couplers for bidirectional communications" Optics Communication266 592-597 (2006).

[17] Chung L W and Lee S L 2006, "Multimode interference based broad band binary dividers with internal photonic crystals" Opt. Express 42 4020-4027.

[18] Zhang X, Liao Q, Yu T, Liu N and Huang Y "novel ultra-compact wavelength division binary divider based on photonic band gap" 2012Optics Communication.285 274-276.

[19] B. Momeni, J. Huan, M. Soltani, M. Askari, S. Mohammadi, M. Rakhshandehroo, and A. Adibi, "Compact wavelength demultiplexing using focusing negative index photonic crystal super prisms," Opt. Express 42 2410–2422 (2006).

[20] D. Bernier,X. Le Roux, A. Lupu, D. Marris-Morini, L. Vivien, and E. Cassan, "Compact low crosstalk CWDM binary divider using photonic crystal superprism", Opt. Express 42 17260–17214 (2008).

[21] A. Rostami, F. Nazari, H. Alipour Banaei, and A. Bahrami, "A nove proposal for DWDM binary divider design using modified T P\photonic crystal structure" Photonic and Nanostructures – Fundamentals and Applications 8 14-22 (2010).

[22] A. Rostami, H. Alipour Banei, F. Nazari, and A. Bahrami, "An ultra-compact photonic crystal wavelength division binary divider using

resonance cavities in a modified Y-branch structure" Optik 466 1481-1485 (2011).

[23] M. Djavid, M. S. Abrishamian, "Multi-channel drop filters using photonic crystal ring resonators", Optik, 123 (2011) 167-170.

[24] A. Taalbi, G. Bassou, M. Y. Mahmoud," New design of channel drop filters based on photonic crystal ring resonators" Optik (2012),doi: 10.1016/j.ijleo.2012.01.045.

[25] T. Ahmadi-Tame, B. M. Isfahani, N. Granpayeh, A. M. Javan, "Improving the performance of all optical switching based on nonlinear photonic crystal micro ring resonator", Int. J. Electron. Commun (AEU) 65 (2011) 281-287.

[26] P. Andalib, N. Granpayeh, "All optical ultracompact photonic crystal AND gate based on nonlinear ring resonators" J. Opt. Soc. Am. B 26 (2009) 10-16.

[27] M. R. Rakhshani, M. A. M. Birjandi, "Design and simulation of wavelength binary divider based on heterostructure photonic crystals ring resonators" Physica E, 50 (2013) 97-101.

[28] S.G. Johnson, J.D. Joannopoulos, Block-iterative frequency-domain methods for Maxwell's equations in a plane wave basis, Opt. Express 8 (2001) 173–190.

[29] F. Mehdizadeh, H. Alipour-Banaei, S. Seraj Mohammadi, "Channel-Drop filter based on a photonic crystal ring resonator", J. Opt. 15 (2013) 075401 (7pp).

[30] Gedney S D 2010 Introduction to Finite-Difference Time-Domain (FDTD) Method for Electromagnetics (Lexington KY: Morgan Claypool).

[31] Taflove A and Hegnese S C 1998Computational Electrodynamics: The Finite-Difference Time-Domain Method(Boston, MA:Artech House).

[32] Min Qiu, Effective index method for heterostructure-slab-wave-guide-based two-dimensional photonic crystals, Appl. Phys.Lett. 81 (2002) 1163–1165.