Improvement in the Transmission Coefficient of Photonic Crystal Power Splitter using Selective Optofluidic Infiltration

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ABSTRACT:
In this paper, a 1*2 all-optical power splitter has been presented which is suitable for the third window of optical communications based on photonic crystal structures. This structure can provide a 50% transmission coefficient at a wavelength of 1550 nm in each splitter output branch. The device has been designed based on an input waveguide, two output waveguides, and an L4 resonant cavity in which the transmission coefficient of the structure is improved by infiltrating an optical fluid in some holes without any changes in the place and size of the radius of holes.

KEYWORDS: Photonic Crystal, Optofluidic, Bandgap, Splitter.

1. INTRODUCTION

Nowadays, Photonic Crystal (PhC) structures are applied as one of the best technologies for the miniaturization of all-optical devices as they can guide and control the light in micro-scale waveguides. These crystals are generally considered by different structures of dielectric materials in several 1D, 2D, or 3D structures with periodic changes of refractive indexes. Since the 2D PhCs, made by creating air holes on the dielectric substrate or dielectric rods in the background air, have easier fabrication and integrability with other optical components, they have received a great deal of researchers` attention. Hence, 2D PhCs are expected to play an important role in the future of all-optical circuits [1], [2]. In PhCs, alternating refraction indexes of the dielectrics prevents the propagation of the electromagnetic waves through the crystal at certain wavelengths, which is called the photonic bandgap [3], [4]. It acts as a light reflector for a specific wavelength of electromagnetic waves, when there is no defect in these structures. Hence, for the electromagnetic wave propagation in this region, the defect in the periodic structure has to be created. This property is employed in the design of many optical devices such as optical filters [5], demultiplexers [6], optical gates [7], and power splitters as one of the most important features [8]. Power splitters can separate optical power into polarized light beams, which are designed usually in three shapes; the Y-junction, T-junction, and based on the directional coupling. This study aimed to achieve a power splitter based on the PhC to divide the power along the arms with high efficiency without any changes in the size of the radius of holes. In this regard, the Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) techniques were applied to examine the behaviour of the structure [9], [10]. In the following, the way of designing a 1*2 Y-junction power splitter is discussed in section 2, then the analysis of the results is described in section 3, and the conclusions are expressed in section 4.

2. DESIGN PROCEDURE

In this study, a Y-shaped junction was utilized in a hexagonal PhC slab. The current study`s design consists of air-holes with the triangular lattice structure. The air-holes were inserted in the slab with the effective refractive index [11] of n=3.44. The radius of the holes and the lattice constant are equal to r=120 nm and a=400 nm, respectively. The contour map of the index profile of the structure has been shown in Fig. 1(a). According to Fig. 1(b), there are two bandgaps for the electric field parallel to air-holes along with the normalized frequency range of $0.208 \leq \frac{a}{\lambda} \leq 0.276$ and $0.59 \leq \frac{a}{\lambda} \leq 0.62$ where λ represents the free space optical wavelength. Considering the amount of lattice constant, the range of the first bandgap's wavelengths was $1449nm \leq \lambda \leq 1923nm$.

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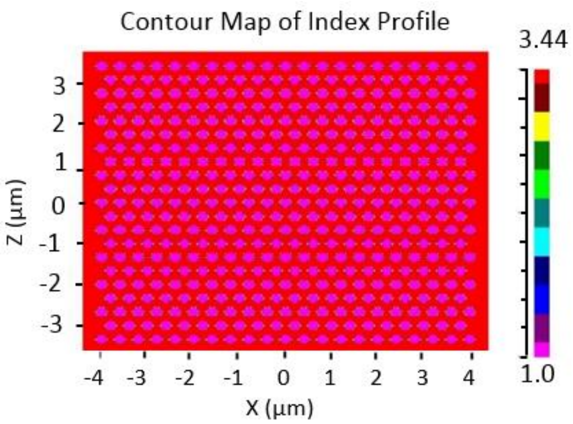

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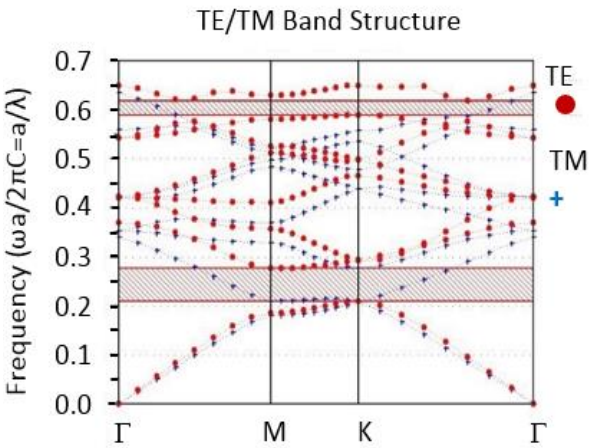

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Fig. 1. (a). The contour map of the index profile of structure. (b). the band structure.

The Y-junction was made by connecting three waveguides, the input waveguide with two output branches at 120°.Then the two output branches were bent at 60°. An L4 resonant cavity was designed between the two output ports (the L4 cavity is obtained by removing 4 holes) (Fig. 2).

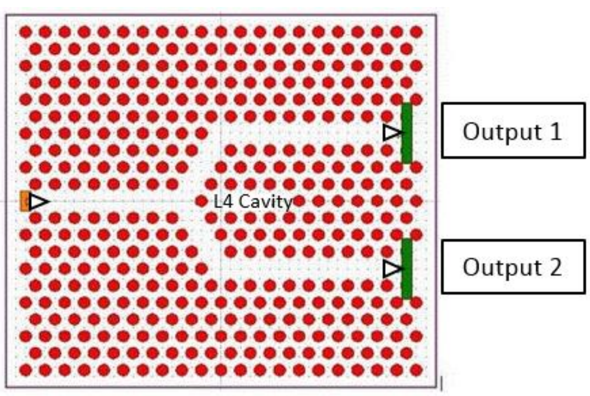
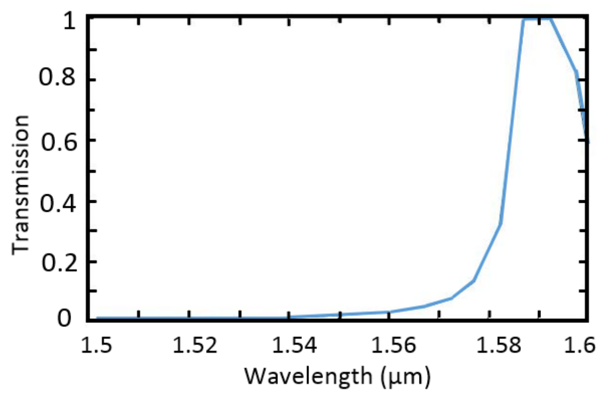


Fig. 2. The splitter structure.

In this study, a Gaussian source was used in the input waveguide. As long as the structure has no defects, it acts as an optical reflector due to the bandgap. By creating a line defect as a waveguide, the wave is confined within the waveguide to pass through. To increase the transmission efficiency at the output ports, the wavelength trapping mechanism was used by the L4 resonant cavity. According to Table 1 and Fig. 3, the resonance range of the L4 cavity was in the desired wavelength range (1550 nm).



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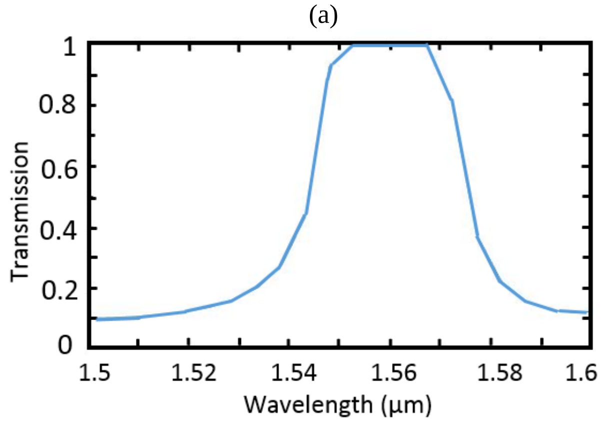

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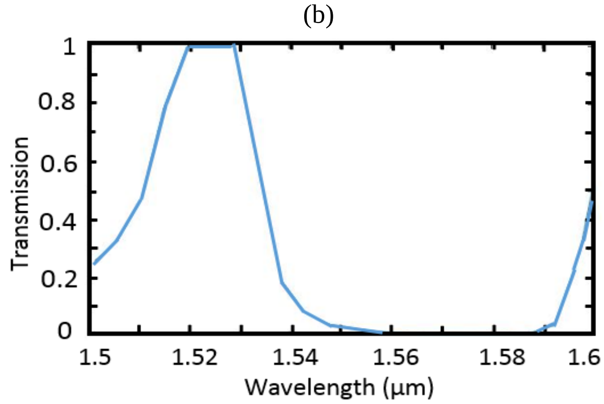

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Fig. 3. (a). The range of resonance wavelengths of (a) L3 cavity, (b) L4 cavity, (c) L5 cavity.

Table 1. The range of resonance wavelength of

cavities.

Lx cavity	Range of resonance wavelength between 1500 nm to 1600 nm
L3 cavity	1584nm to 1597 nm
L4 cavity	1545 nm to 1575 nm
L5 cavity	1515 nm to 1530 nm

Accordingly, the trapped electromagnetic field was coupled with the two output waveguides, which increased the transmission coefficient at the output ports; this could be shown in Fig. 4. As can be seen from this figure, the transfer efficiency in the case of the structure with the L4 cavity was increased by 10% compared to the case of without the cavity.

According to Fig. 4, in both output ports, the efficient transmission of 48% can be seen in 1550 nm wavelength (with L4 cavity); therefore, the total transmission for the two ports was 96%. Hence, from both output ports, the same transmission efficiency was observed with a little loss.

When the input wave reaches to Y-shape junction, due to the widening property of the junction, the new modes may be created and some of input power could be returned to the input as a reflected power. Then the output power will be reduced. Therefore, to create a suitable structure, the unwanted reflections should be minimized with proper changes in the joints. For example, according to the results of previous works, by placing the holes close to the bend or changing their diameters, or adding a hole at the center of the junction, the mode expansion at the junction could be suppressed and the reflection of them reduced [12]-[19].

Since most of the previous cases are sensitive to fabrication toleraces, this study aimed to present an easy method for optimizing the structure, without any changes in the diameter or place of air holes, and only by infiltrating the fluid into some of the holes.

In this regard, the use of optofluidic could make it possible to control and adjust the refractive index of certain regions of the photonic crystal slab; as a result, the specifications and properties of the device could be easily controlled. By infiltrating fluid into the holes of the edge of the output waveguides in the 120 ° bend (as shown in Fig. 5), the refractive index of these holes can be increased compared to other holes in the structure. Therefore, this mechanism would prevent the modes produced in the junction locations from returning to the input waveguide.

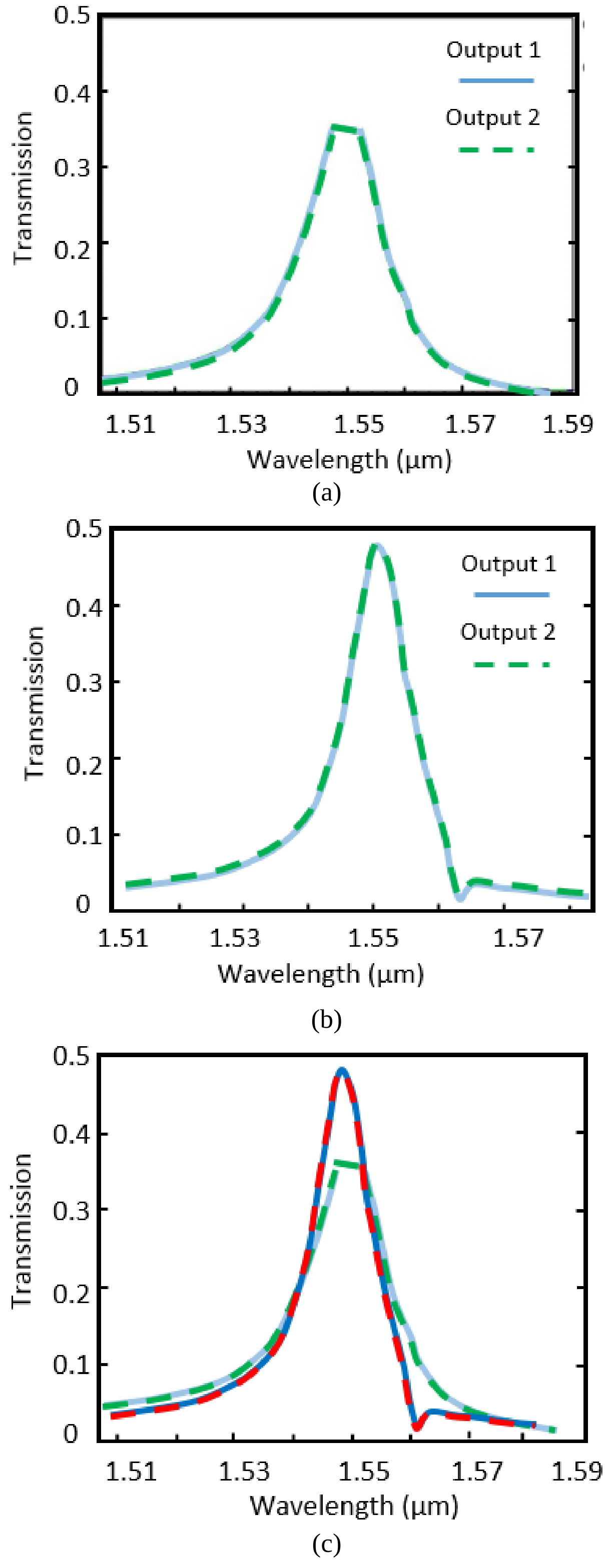
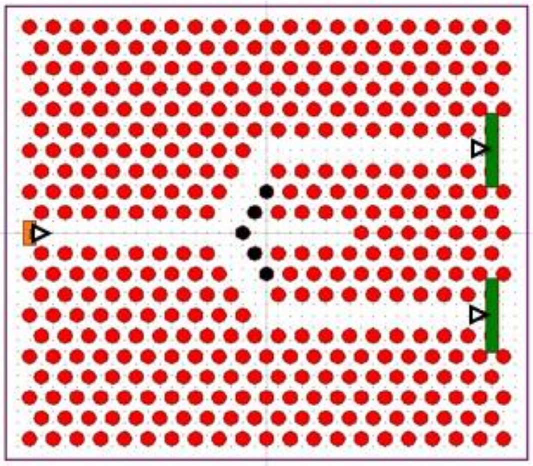


Fig. 4. (a) Output power of structure without L4 cavity, (b) output power of structure with L4 cavity, (c) comparison of (a) and (b).



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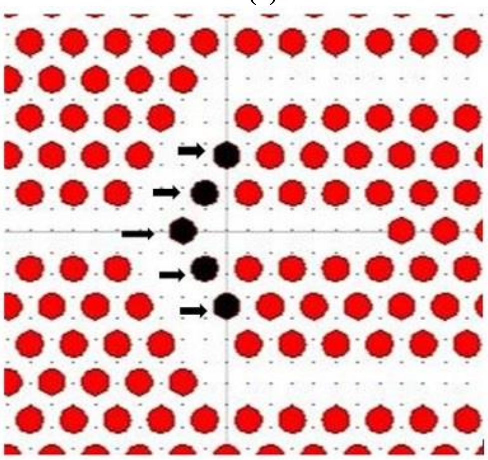

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Fig. 5. (a) The splitter structure with marked holes for water infiltration, (b) more detail of marked holes.

3. SIMULATION AND RESULTS

The current power splitter mechanism was based on creating defects as waveguides and resonant cavity. The input field entered the structure through the input waveguide and was distributed in the middle of the structure in the two output waveguides. Wavelengths of the cavity resonance were trapped by the cavity and then coupled to the output waveguides, leading to an increase in the efficiency of the splitter. Besides, to improve the transmission coefficient and prevent the return of the produced modes to the input waveguide, the fluid infiltrating mechanism was utilized to change the refractive index of the holes, shown in Fig. 5 (These holes were selected after testing a large number of holes). We changed the refractive index values of the marked holes many times and reviewed their simulation results. We concluded that by changing the refractive index of these holes to 1.316, the best result is obtained. Reference [20] states that water has a refractive index of 1.316 at a wavelength of 1.55 µm. Also, the refractive index of other materials mentioned in this article is given in reference [20] at a wavelength of 1.55 µm. That's why we chose these fluids. Water infiltration is a common microfluidic process for PhC structures [21], [22]. In this study, a 2D modelling of the PhC slab was taken into account due to the less required time in comparison with the 3D modelling and being more suitable for optimization. Moreover, considering the computational limitations, in practice, 2D simulation is more preferable to 3D. Here, an effective refractive index was used to simulate the PhC waveguide to bring a 2D simulation closer to the real model in three dimensions. In simulation of PhC devices, perfectly matched layer (PML) must be considered as boundary conditions to prevent the reflection of all possible waves that strike the virtual boundaries. In the presented structure for having the high performance, the PML with the 500 nm width is considered. The space steps of Δx and Δz in FDTD mesh (grid sizes) were equal to 25 nm as chosen by $\Delta x = \Delta z = a/16$, in which "a" refers to the lattice constant. For 2D structures, after determining the space steps, the time step was obtained from equation 1.

$$\Delta t \leq \left(1 \Big/ C\sqrt{1/\Delta x^2 + 1/\Delta z^2} \right) \quad (1)$$

Where *C* is the velocity of light in free space.

Fig. 6 demonstrates the transfer efficiency diagram of both output ports after water infiltration into the marked holes. It can be seen that the total input power had been divided into two equal parts and could be received from two output ports without any losses. According to this figure, in both output ports, the efficient transmission of 50% can be seen in 1.5506 µm central wavelength, therefore, the total transmission for the two ports would be 100%.

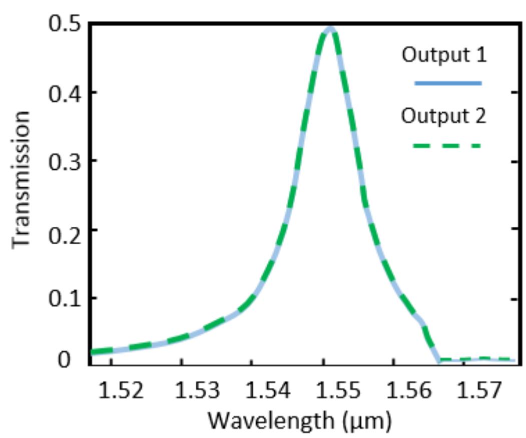


Fig. 6. The transfer efficiency diagram of output ports after water infiltration in to the marked holes.

Furthermore, using the fluid infiltration method into the holes, the output power of the ports could be adjusted to be different. Infiltrating of water, 2-butanol, chloroform, and benzene into some specified holes, are shown in Fig. 7, output power of the ports would be different, as shown in Fig. 8 and Table 2.

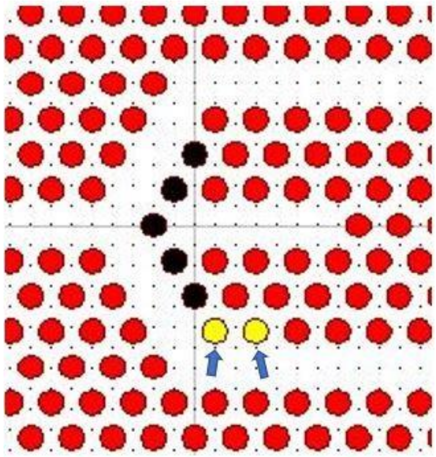
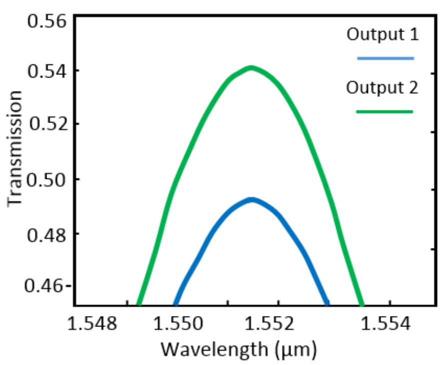


Fig. 7. The two marked holes for fluid infiltration to have different output powers.

Table 2. The results of non-symmetric infiltration of water, 2-butanol, chloroform, and benzene into the marked holes shown in Fig. 7.

Fluid/ refractive index	Central wavelength (µm)	Power transmission (%) output 1	Power transmission (%) output 2	Output power difference (%)
Water/ 1.316	1.5515	49.2	54	4.8
2-Butanol / 1.386	1.5517	48.7	54.8	6.1
Chloroform/ 1.432	1.5518	48.4	55.3	6.9
Benzene/ 1.478	1.552	48	55.7	7.7



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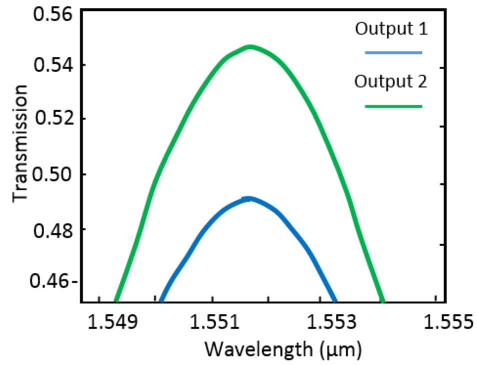

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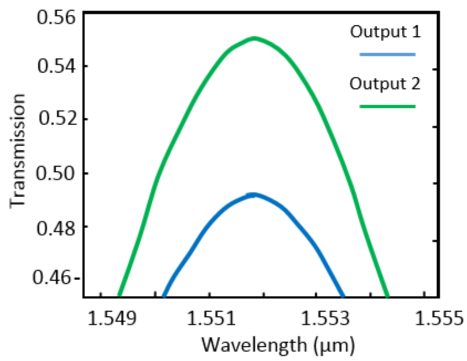

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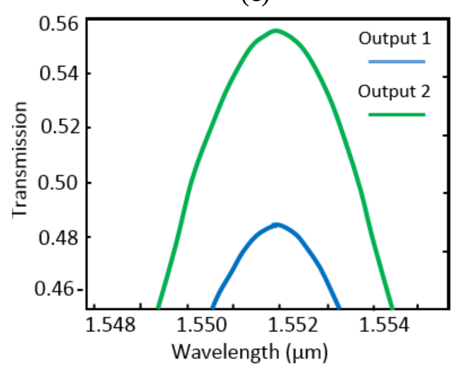

(d)

Fig. 8. The output power of the two ports after water infiltration into the marked holes in Fig. 5 and also infiltration of (a) water, (b) 2-butanol, (c) chloroform, and (d) benzene into the marked holes in Fig. 7.

Finally, comparison of the previous works with the proposed structure was listed in Table 3. In all of the previous studies, resizing the radius and movement of the rods or holes have been used to achieve the appropriate output power, but in the present study, the optimal output power was performed without any changes in size or place of the holes.

Table 3. Comparison of the proposed structure with the previous structures.

Ref.	Transmission (%)
[14]	95
[15]	86
[16]	98
[17]	90
This work	100

4. CONCLUSION

In previous works, optimization of the transmission efficiency in the designed PhC splitters was dependant on resizing the radius of rods or holes at nano-scale as well as changing in bending length and angle, most of which, seems in most of the cases, the fabrication is impossible. In this study, the mechanism of infiltrating fluids into some holes has been employed to improve the transmission efficiency of outputs without any changes in position and size of the holes. Through the use of this method, the need for high-precision fabrication was reduced. As a result, the current structure has easier fabrication.

REFERENCES

[1] G.H. Delphi, S. Olyaee, M. Seifouri, A. Mohebzadeh-Bahabady, "**Design of low crosstalk and high-quality factor 2-channel and 4-channel optical demultiplexers based on photonic crystal nano ring resonator**", *Photonic Netw Commun,* Vol. 38, pp. 250-257, 2019.

[2] K. Venkatachalam, D.S. Kumar, S. Robinson., "**Innestigation on 2D photonic crystal based eight-channel wavelength-division demultiplexer**", *Photonic Netw Commun*, Vol. 34, pp. 100–110, 2016.

[3] Tavousi, M.A. Mansouri-birjandi., "**study on the similarity of photonic crystal ring resonator cavity modes and whispering gallery-like modes in order of designing more efficient optical power dividers**", *Photonic Netw Commun*., Vol.32, pp. 160–170, 2016.

[4] F. Mehdizadeh, M. Soroosh, "**A new proposal for eight-channel optical demultiplexer based on photonic crystal resonant cavities**", *Photonic Netw Commun*., vol. 31, pp. 65–70, 2015.

[5] S. Naghizade, S.M. Sattari-esfahlan, "**Excellent quality factor ultra-compact optical communication filter on ring-shaped cavity**", *J. Opt. Commun*, Vol.40, pp. 1–5, 2017.

[6] S. Naghizade, S.M. Sattariesfahlan, "**An optical five channel Demultiplexer-Based Simple Photonic Crystal Ring Resonator for WDM Applications**", J. Opt. Commun, Vol. 41, pp. 1–7, 2018.

[7] A. Mohebzadeh bahabady, S. Olyaee, "**All optical NOT and XOR logic gates using a photonic crystal nano-resonator and based on interference effect**", *IET Optoelectronics*, Vol. 12, pp. 191–195, 2018.

[8] Ghaffari, A., Monifi, F., Djavid, M., et al. "**Analysis of photonic crystal power splitters with different configurations**", *Res. J. Appl. Sci*., Vol. 8, pp. 1416–1425, 2008.

[9] S.G. Johnson, JD. Joannopoulos,"**Block iteractive frequency domain methods for Maxwell's equations in a plane wave basis**", *Opt. Express*, Vol. 8, pp. 173–190, 2001.

[10] A. Taflove, S.C. Hegness, **Computational Electrodynamics: The Finite Difference Time Domain Method**, London, England, Artech House, 2005.

[11] M. Qiu, "**Effective index method for heterostructure-slab-waveguide-based two-dimensional photonic crystals**," *App. Phys. Lett*., Vol. 81, pp. 1163-1165, 2002.

[12] W. Yang, X. Chen, X. Shi, W. Lu, "**Design of a high transmission Y-junction in photonic crystal waveguides**" *physica B*., Vol. 405, pp. 1832-1835, 2020.

[13] H. Badaoui1, M. Feham1, and M. Abri, "**Double bends and Y-shaped splitter design for integrated optics**" *Prog Electromagn Res*., Vol. 28, pp. 129-138, 2012.

[14] T. Chantakit, K. Srinuanjan, Preecha P. Yupapin, "**Two-dimension photonic crystal Y-branch beam splitter with variation of splitting ratio based on hybrid defect controlled**", *Appl. Phys. A*. Vol. 117, pp. 547-552, 2014.

[15] M.K.Moghaddam, M.M. Mirsalehi, A.R. Attari, "**Slow light transmission in a photonic crystal power splitter with parallel output**" *Photon. Nanostructures: Fundam. Appl*., Vol. 12, pp. 75-82, 2014.

[16] H.A. Badaoui, M. Abri, "**Optimized 1*8 compact splitter based on photonic crystal using the two-dimensional finite-difference time-domain technique**", *Opt. Eng*., vol. 54, pp. 067104, 2015.

[17] M. Danaie, R. Nasiri, A. Dideban, "**Design of a High-Bandwidth Y-Shaped Photonic Crystal Power Splitter for TE Modes**", *IJOP*., Vol. 12, pp. 33-42, 2016.

[18] H. Razmi, M. Soroosh, Y. S. Kavian, "**A new proposal for ultra-compact polarization independent power splitter based on photonic crystal**" *J. Opt. Commun*., Vol. 39, pp. 1-5, 2017.

[19] P. Jindal, H. J. Kaur, "**Analysis of the photonic crystal power splitter based on the junction defect radius for optimum resonance**" *Optoelectronics, Instrumentation and Data Processing.*, Vol. 54, pp. 576-581, 2018.

[20] E. John, S. Aunders, C. Sanders, H. P. Loock, "**Refractive indices of common solvents and solutions at 1550nm**", *applied optics.*, Vol. 55, pp. 947–953, 2016.

[21] P. S. Nunes, N. A. Mortensen, J. P. Kutter, and K. B. Mogensen, "**Photonic crystal resonator integrated in a microfluidic system**", *Optics Letters*., Vol. 33, pp.1623-1625, 2008.

[22] Monat, P. Domachuk, and B. J. Eggleton, "**Integrated optofl uidics: A new river of light**", *Nature Photonics*., Vol. 1, pp.106-114, 2007.