Journal of Nano- and Electronic Physics
Vol. **15** No 5, 05006(5pp) (2023)

Журнал нано- та електронної фізики
Том **15** № 5, 05006(5cc) (2023)

Effect of PMMA Temperature on Optical Performances of 1 × 2 Hybrid Photonic Crystals Waveguide Beam Splitters

M.El. Hathat[1,2*], M. Boulesbaa[1,2†], S. Gamouh[1,3,‡]

[1] *Electronic and Telecommunications Department, University Kasdi Merbah of Ouargla 30000 Ouargla, Algeria*
[2] *L.R.P.P.S. Laboratory, University Kasdi Merbah of Ouargla, 30000 Ouargla, Algeria*
[3] *Laboratory of Hyper Frequency and Semiconductors (L.H.S.), Constantine, Algeria*

(Received 20 August 2023; revised manuscript received 14 October 2023; published online 30 October 2023)

In this study, a new design of 1 × 2 photonic crystal beam splitters is proposed to achieve symmetrically higher power splitting. Two different splitters based on hybrid couplers made from silicon (Si) and poly(methyl methacrylate) (PMMA) materials were studied. One splitter had two outputs, and the other had four outputs. The PMMA temperature was varied from 0 °C to 130 °C to enhance the optical performance of the proposed splitters. The power intensity and photonic band gap (PBG) values were numerically investigated using the finite-difference time-domain (FDTD) and plane wave expansion (PWE) methods. The effect of temperature on these values was also studied to obtain the optimal conditions for high efficiency. The efficiency values were satisfactory. They could reach 49.9 % from the two output ports at a temperature of 80 °C.

Keywords: Beam splitter, PMMA, Photonic band gap, Coupling, Transmission.

DOI: 10.21272/jnep.15(5).05006 PACS numbers: 41.85.Qg, 42.25.Bs, 42.82.Et

1. INTRODUCTION

Photonic crystals are among the materials that have been developed using the nanotechnology. They have a special property that can limit the light flow through them within a certain frequency band. This phenomenon is known as photonic bandgap (PBG) [1]. Therefore, researchers have shown considerable interest in photonic crystal (PhC) technology. This feature has enabled scientists to control the spread of electromagnetic waves in photonic crystals. This causes defects in their basic design, and many optical devices have been designed based on this basis. An additional benefit of the PhC is its reduced size compared to its conventional counterparts. This property improves the efficiency of integration density in optoelectronic circuits.

Several studies have been conducted to develop many of these devices [2-3], including demultiplexers [4], sensors [5], logic gates [6], and beam splitters [7] for photonic integrated circuits (PIC) and telecommunication applications. Most of these devices are designed using 2D-PhC as a slab, enabling the integration of silicon-on-insulator (SOI) technology. Moreover, this technology is less complicated to manufacture [8].

As mentioned above, power splitters are essential in the development of various devices. They can be described as photonic crystal waveguides (PhCWs), either linked or coupled to each other in a certain way [9] the number of PhCWs considered as inputs are less than those considered as outputs, for an equal or different distribution of power at the outputs.

We aim to achieve the highest power division without reflecting the input field power.

In recent years, numerous researchers have investigated optimal power division by proposing different designs. Most of these studies aimed to create photonic crystal waveguide beam splitters PhCWBSs based on three different models. The first model depends on creating a group of PhCWs that are linked together in a specific area [1, 10, 11], into which the light is divided. However, when designing PhCWBSs with more than two outputs, these designs undergo a large size problem. The second model of PhCWBSs is based on photonic crysta (PhCRR), in which light is divided at the resonance frequency of the PhCRR. However, this model still faces challenges at the fabrication level [12]. The third model of the PhCWBSs is based on photonic crystal waveguide directional coupler (PhCWDC) [1], which provided a balance in terms of splitting efficiency and fabrication simplicity. Nevertheless, this model is still unable to achieve ideal splitting efficiency. This deficit is due to the optical properties of PhCWs in the coupling region, especially when using materials with a high refractive index, such as silicon (Si) and indium phosphide (InP).

Therefore, in this study, we propose a new type of PhCWBS based on directional couplers (DC), a hybrid-PhCWBS (H-PhCWBS), which consists of a group of hybrid directional couplers formed from Si and poly (methyl methacrylate) (PMMA) materials. The PMMA has a low refractive index, approximately $n = 1.49$, at a temperature of 0 °C.

The main idea is to embed the PMMA material into the coupling region of the splitter to generate a PhCW from PMMA rather than a PhCW from Si. In proposed structures, the Si and PMMA are the guest material and air is the host. This combination of Si and PMMA provides high power-splitting efficiency. This is because the PhCWBS based on Si has a large PBG, which guarantees more confinement of light. In contrast, the PhCW

---

[*] hathat.med_fateh@univ-ouargla.dz

[†] boulesbaa.mohammed@univ-ouargla.dz

[‡] samia.gamouh@univ-ouargla.dz

formed from the PMMA in-coupling region decreases the mismatching mode between the other PhCWs. However, it is well known that PMMA is highly sensitive to temperature changes [13]. The temperature variation affects both the physical and optical properties of PMMA. Thus, these changes were reflected in the splitting efficiency of H-PhCWBS. our study purposefully tackles the effect of temperature variation on the splitting efficiency of H-PhCWBS with two outputs, the finite-difference time-domain (FDTD) method was used to achieve a high-power splitting intensity of 49.95 % at $\lambda = 1550$ with a bandwidth of 40 nm.

2. DESIGN AND PRINCIPALS

The proposed device is fundamentally based on a two-dimensional PhC system, which is a hexagonal lattice from of silicon rods with a refractive index $n_{si} = 3.4$. In addition, the refractive index of the background n_{air} equal to 1. The cross-section of these rods forms circles with a radius $r = 0.3006a$, where a is the lattice constant.

Three PBGs for TE polarisation were determined using the plane wave expansion (PWE) method, as shown in Fig. 1. We chose the second PBG in this band diagram, where the frequency range (a/λ) extended from 0.4189 to 0.5376, with λ being the free-space wavelength.

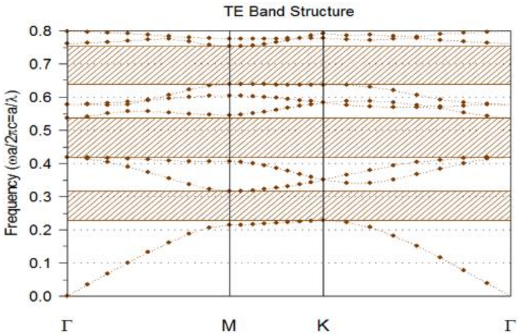


Fig. 1 – The photonic band gaps of the basic model

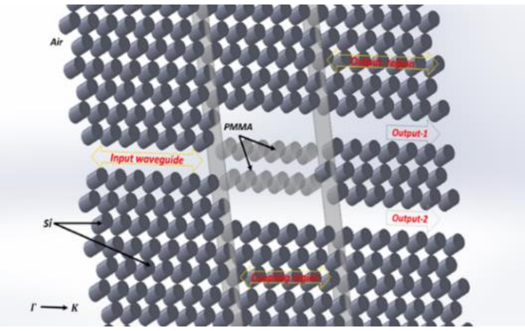


Fig. 2 – The design of the proposed structure of the H-PhCWBS

The defects in three successive rows of the lattice in the ΓK direction were used to create three PhCWs.

As shown in Fig. 2, the H-PhCWBS can be divided into three regions. The first region, which contains one PhCW, is called the input region. The second region contains three PhCWs. Each of the two PhCWs is separated by a single row extending over a certain length, called the coupling length (L_c), where we add the PMMA material instead of Si. The third region, which contains two separate PhCWs, is called the output region.

The input field propagates through the first PhWC in the input region and is coupled with other PhWCs in the coupling region. L_c is the main parameter of this process, Considering the coupling region as a multimode region and according to self-imagine phenomena [14], we can determine the L_c as [15]:

$$L_c = \frac{\pi}{\beta_0 - \beta_1}\ , \tag{1}$$

here the β_0 and β_1 are the propagation constants at a specific a/λ.

In this H-PhCWBS, as mentioned previously, the rods separating the PhWCs in the coupling region are the poly (methyl methacrylate) (PMMA) source. It is a common polymer used in waveguides [16].

Similar to most solid materials, when PMMA is exposed to a change in temperature, it expands or contracts with a value of ΔL, which can be expressed as [13]:

$$\Delta L = \Delta T . L_0 . \propto_L , \tag{2}$$

with

$$\Delta T = T_i - T_0 , \tag{3}$$

where Ti and T_0 are the changing and initial temperatures, respectively. L_0 is the initial length and $\propto_L$ is the leaner coefficient of thermal expansion (CTE).

In addition, the physical influence and the effect of the temperature variation extend to the optical properties of PMMA, where the refractive index varies as a function of temperature. We have used a model that expresses this variation as [16]:

$$n(T) = n_0 + aT + bT^2 , \tag{4}$$

where

$$n_0 = 1.49538, \qquad a = -0.000115, \;\; b = -5.17358 \times 10^{-7}$$

These thermal (optical/physical) effects directly influence the power obtained at the outputs of the PhCWBS. To obtain higher power-splitting efficiency, we heated the PMMA rods in the coupling region using microlasers [17] placed above the component, as described in Fig. 3. The copling length $L_c = 5.82a \approx 6a$ for $a/\lambda = 0.4935$.

Fig. 4 displays the variation in r_2/a_2 according to the change in temperature. We noticed that r_2/a_2 is linear and it extends from $r_2/a_2 = 0.30846$ for $T_i = 0°C$ to $r_2/a_2 = 0.31107$ for $T_i = 120°$. In contrast, r_1/a_1 is constant. In Table 1, all structural constants and variables of the proposed structures are presented.

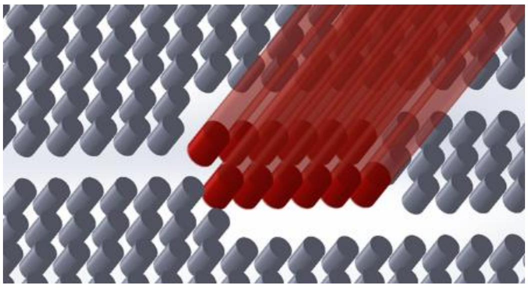


Fig. 3 – Visualisation of the process of heating the PMMA within the coupling region of the proposed 1 × 2 splitter

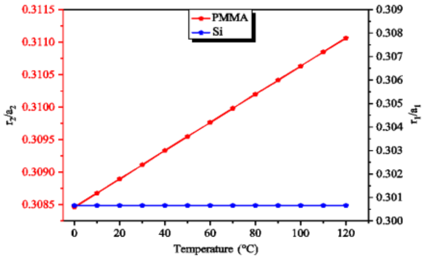


Fig. 4 – The remarkable change in the optical properties of PMMA under the influence of the temperature change applied to it

Table 1 – The design parameters of the suggested 1 × 2 H-PhCWBS splitter structures

Parameter	Symbol	Value
Configuration	rods with hexagonal lattice	-
Fill factor 1	R_1/a_1	0.3006
Fill factor 2	r_2/a_2	0.30846 at 0 °C
Coupling length	L_c	6a
Si rods refractive index	n_{Si}	3.40
PMMA rods refractive index	n_{PMMA}	1.49538 at 0 °C
Air background refractive index	n_{air}	1.00

The 2-Dimension Finite Difference Time Domain (2D–FDTD) method was used to calculate the power in the two outputs. It is well known that the time-sensibility condition must be respected [18]:

$$\Delta t \leq \frac{1}{c\sqrt{\Delta x^{-2}+\Delta z^{-2}}} \tag{5}$$

The domain is surrounded by perfectly matched layers to absorb outgoing waves with minimal reflections. At the input entrance, we launched a Gaussian wave with a normalised frequency of 0.4935, and every lattice constant contained 32 FDTD grid cells

3. RESULTS AND DISCUSSION

3.1 Propagation of the TM into the 1 × 2 H-PhCWBS

Fig. 5 shows the spread of the electric field across H–PhCWBS along the ΓK direction. We can clearly observe that a Gaussian wave with normalised frequency $a/\lambda = 0.4935$ propagates through the single-mode waveguide in the input region to the multi-mode region because it is included in the PBG range. According to $L_c = 6a$ corresponding to the normalised frequency $a/\lambda = 0.4935$ and the power-splitting mechanism for the directional coupler, the input field is split into two folded images. Thus, the two modes propagate through two completely separated waveguides in the output region.

Fig. 5b shows the electric field propagation in the H–PhCWBS, where the PMMA rods are under the influence of a temperature of 80 °C. The refractive indices of the PMMA rods will be $n_{PMMA} = 0.48286$ and the $r_2/a_2 = 0.3101$ at 80 °C. It is clearly seen that the splitting efficiency is better than it was at a PMMA temperature of 20 °C, as shown in Fig. 5a.

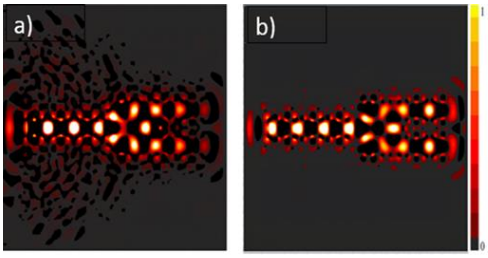


Fig. 5 – Electric field propagation in the proposed 1 × 2 H–PhCWBS based on Si/PMMA hybrid for PMMA rods under a temperature (a) of 20 °C and (b) for 80 °C

3.2 Effect of the Temperature Change in Coupling PMMA Rods

Fig. 6 shows the evolution of the power intensity as a function of the PMMA rod temperature for each of the two outputs of the proposed 1 × 2 beam splitter. The results were obtained using the 2D-FDTD method. This figure shows that the power intensity splitting value increased from 46.82 % to 49.92 % at each of the two outputs of the proposed 1 × 2 beam splitter as the temperature of the PMMA rods increased from 10 °C to 80 °C. On the contrary, we observed that an increase in the temperature of the PMMA rods from 80 °C to 120 °C led to a slight reduction in the power split value from 49.92 % to 49.21 %.

Therefore, the PMMA material with a temperature of 80 °C provides the best opto-geometrical properties and, consequently, a good coupling feature for obtaining the highest power splitting efficiency of the proposed 1 × 2 beam splitter.

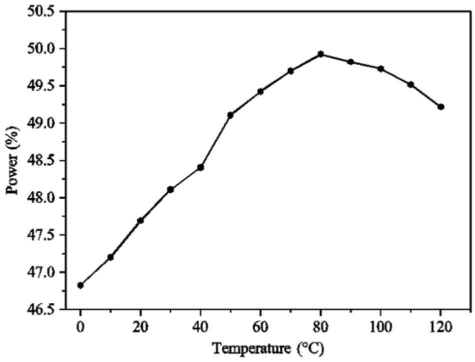


Fig. 6 – The change of the power splitting value of the proposed 1 × 2 beam splitter compared to the change in the PMMA rods temperature at a wavelength of λ = 1550 nm

The splitting operation by DC allows an equal energy distribution over a wide range of wavelengths at each of the H-PhCWBS outputs. However, the presence of back reflection always prevents achieving an ideal separation process of 100 %. This is due to the mismatch between the input waveguide and coupling region caused by the difference in optical properties between Si and PMMA. Similarly, changing the temperature of the PMMA rods affects their optical and radius properties. This change in the PMMA rod temperature led to an increase in the fill factor (r_2/a_2) of the PMMA rods from 0.3087 to 0.3102, as shown in Fig. 4.

Fig. 7a shows the change in the normalised power splitting in terms of (r_2/a_2) for the 1 × 2 proposed splitter.

A linear correlation between the normalised powers (p) and fill factors (r_2/a_2) from 0.3085 to 0.3102 for the suggested 1 × 2 splitter is presented in Fig. 8. The linear curve can be expressed as follows:

$$p = 1869.72\left(\frac{r_2}{a_2}\right) - 529.87, \tag{6}$$

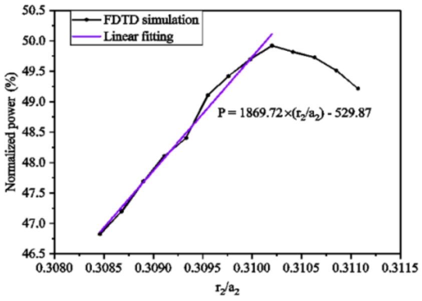
with a correlation coefficient $r = 0.994$.

In addition, the refractive index of all PMMA rods embedded in the coupling region of the 1 × 2 beam splitter was slightly reduced from 1.4942 to 1.4829.

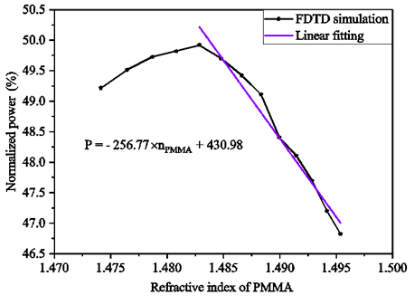
Fig. 7b illustrates the variation in the power splitting value versus the n_{PMMA}, whose change approximates a linear function for the PMMA temperature varying from 10 °C to 80 °C as follows:

$$p = 430.98 - 256.77 \times n_{PMMA}, \tag{7}$$

with a correlation constant $r = -0.987$.



(a)



(b)

Fig. 7 – Variation in the normalised power at each output of the proposed 1 × 2 beam splitter power versus (a) r_2/a_2 and (b) n_{PMMA}

Under these conditions, the corresponding refractive index and radius of the PMMA rods promote efficient coupling owing to a decrease in the mismatch mode. Therefore 80 °C is an appropriate temperature that can be provided to reduce the percentage of mismatching between the Si and PMMA materials.

Fig. 8 shows the transmission spectra of the power splitting efficiency of the proposed 1 × 2 beam splitter based on a hybrid directional coupler from the Si/PMMA at various PMMA temperatures varying from 0 °C to 120 °C. This figure indicates that the total normalised power average of over 99 % of the two outputs is obtained from a spectral range up to 40 nm, in addition to high efficiency at a wavelength of 1550 nm, reaching 49.9 % at a temperature of 80 °.

We conducted a comparative study with some published papers found in the literature that treat various structures of the 1 × 2 beam splitter to discuss the performances of the proposed structure. The obtained data were collected at a wavelength around $\lambda = 1.55\ \mu m$. The different performances of the proposed 1 × 2 beam-splitter structure are listed in Table 2. This Table shows that the proposed 1 × 2 splitter structure provides a maximum transmission efficiency of approximately 49.90 % at each output port (O_1 and O_2). In addition, an equal power distribution was achieved for both the output ports of the proposed structure.

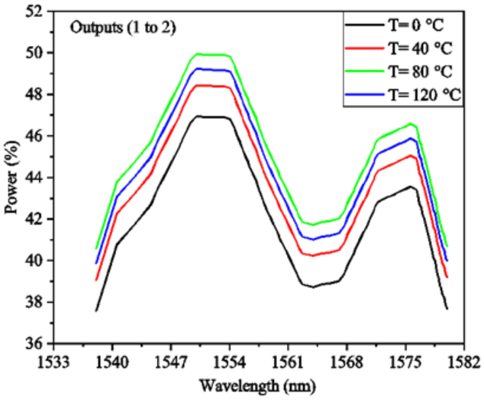


Fig. 8 – The distribution of power intensity along the spectrum of the proposed 1 × 2 H–PhCWBS based on Si/PMMA hybrid for the PMMA rods under various temperatures ranging from 0 °C to 120 °C

Table 2 – The optimal performances of the proposed 1 × 2 splitter structure at a PMMA temperature of 80 °C. versus those of models in some published works

Ref.	Type structure	Materials rods	Computing wavelength λ (μm)	Transmission efficiency (%)		Total (%)
				Output 1	Output 2	
[19]	1 × 2 Y splitter	Si	1.55	49 %	49 %	98 %
[20]	1 × 2 splitter	elliptical Si rods	1.972	48.15 %	48.15 %	96.30 %
Our work	1 × 2 splitter	Si/PMMA	1.55	49.90 %	49.90 %	99.80 %

4. CONCLUSION

This study focuses on creating a new type of photonic crystal beam splitter based on a directional coupler. It consisted of silicon and PMMA rods anchored in the air to create a hybrid coupler splitter. Two joints were created in this regard; the first with two outputs and the second with four outputs. We can conclude that in both structures, the PMMA rods were heated in the coupling region using microlasers, where PMMA was combined in the coupling region. The beam splitter properties were numerically investigated using the plane wave expansion (PWE) and finite-difference time-domain (FDTD) methods. The splitting efficiency for both splitters with and without using the FDTD and PWE methods was extracted by utilizing the latter's distinct properties and repeatedly applying a different temperature to the proposed splitters. In short, the results showed very high splitting values, especially at the temperature of 80 °C, where power intensity values can reach 49.9 % at $\lambda = 1550$ nm for 1 × 2-output H–PhCWBS.

AKNOWLEDGEMENTS

The LRPPS laboratory, university of Ouargla, Algeria is acknowledged for supporting this work.

REFERENCES

1. P-G. Luan, K-D. Chang, *Opt. Express.* **15**, 4536 (2007).
2. J. Shi, M.E. Pollard, C.A. Angeles, R. Chen, J.C. Gates, M.D.B. Charlton, *Sci. Rep.* **7**, 4765 (2017).
3. K. Chen, X. Zhou, X. Cheng, R. Qiao, Y. Cheng, C. Liu, Y. Xie, W. Yu, F. Yao, Z. Sun, F. Wang, K. Liu, Z. Liu, *Nat. Photon.* **13**, 754 (2019).
4. L. Qing-Hua, F. Hong-Ming, C. Shu-Wen, W. Tong-Biao, Y. Tian-Bao, H. Yong-Zhen, *Opt. Commun.* **331**, 160 (2014).
5. J-J. Wu, X. Shen, X. Luo, X-W. Hu, J-G.Peng, L-Y. Yang, J-Y. Li, N-L. Dai, *Opt. Commun.* **401**, 80 (2017).
6. C. Tang, X. Dou, Y. Lin, H. Yin, B. Wu, Q. Zhao, *Opt. Commun.* **316**, 49 (2014).
7. M. Boulesbaa, M.E. Hathat, A. Bounegab, O.O. Haddar, *AIP Conf. Proc.* **2440**, 020001 (2022).
8. F. Monifi, M. Djavid, A. Ghaffari, M.S. Abrishamian, *J. Opt. Soc. Am. B.* **25**, 1805 (2008).
9. M.E.F. Hathat, M. Boulesbaa, S. Gamouh, *1st Int. Conf. Commun. Control Syst. Signal Process.* 552 (2020).
10. T. Liu, A.R. Zakharian, M. Fallahi, J.V. Moloney, M. Mansuripur, *IEEE Photon. Technol. Lett.* **17**, 1435 (2005).
11. L.J. Kauppinen, T.J. Pinkert, H.J.W.M. Hoekstra, R.M. De Ridder, *IEEE Photon. Technol. Lett.* **22**, 966 (2010).
12. H. Saghaei, A. Zahedi, R. Karimzadeh, F. Parandin, *Superlattice. Microst.* **110**, 133 (2017).
13. González-Benito, E. Castillo, J.F. Cruz-Caldito, *Chem. Phys.* **17**, 1849 (2015).
14. R.W. Chuang, M.T. Hsu, Y.C. Chang, Y.J. Lee, S.H. Chou, *IET Optoelectron.* **6**, 147 (2012).
15. I. Park, H-S. Lee, H-J. Kim, K-M. Moon, S-G. Lee, B-H. O, S-G. Park, E-H. Lee, *Opt. Express* **12**, 3599 (2004).
16. M. Kovačević, A. Djordjevich, *Acta Phys. Pol. A* **116**, 649 (2009).
17. T. Chantakit, K. Srinuanjan, P.P. Yupapin, *Appl. Phys. A Mater. Sci. Process.* **117**, 547 (2014).
18. K. Yee, *IEEE Trans. Anten. Propag.* **14**, 302 (1966).
19. M. Danaie, R. Nasiri Far, A. Dideban, *Int. J. Opt. Photon.* **12** No 1, 33 (2018).
20. Y-F. Gao, J-P, Sun, N. Xu, Z. Jiang, Q-C. Hou, H. Song, M-C. Jin, C. Zhang, *Opt. Commun.* **483**, 126646 (2021).

Вплив температури PMMA на оптичні характеристики 1 × 2 гібридних фотонних кристалів хвилеводних розщеплювачів променя

M.El. Hathat[1,2], M. Boulesbaa[1,2], S. Gamouh[1,3]

[1] *Electronic and Telecommunications Department, University Kasdi Merbah of Ouargla 30000 Ouargla, Algeria*
[2] *L.R.P.P.S. Laboratory, University Kasdi Merbah of Ouargla, 30000 Ouargla, Algeria*
[3] *Laboratory of Hyper Frequency and Semiconductors (L.H.S.), Constantine, Algeria*

У дослідженні запропоновано нову конструкцію 1 × 2 фотонно-кристалічних дільників пучка для досягнення симетрично вищого розподілу потужності. Було досліджено два різних розгалужувачі на основі гібридних сполучників, виготовлених із матеріалів кремнію (Si) і полі(метилметакрилату) (PMMA). Один розгалужувач мав два виходи, а інший – чотири виходи. Температуру ПММА змінювали від 0 до 130 °C для покращення оптичних характеристик запропонованих розгалужувачів. Інтенсивність потужності та значення забороненої зони фотонної зони (PBG) були чисельно досліджені з використанням кінцево-різницевих методів у часовій області (FDTD) і методів розширення плоскої хвилі (PWE). Також було вивчено вплив температури на ці значення, щоб отримати оптимальні умови для високої ефективності. Показники ефективності були задовільними. Вони могли досягати 49,9% з двох вихідних портів за температури 80 °C.

Ключові слова: Світлорозділювач, PMMA, Фотонна заборонена зона, Зв’язок, Передача.