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Different Configurations of Photonic Crystal Power Splitters for PIC's - A Review

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Abstract

Power splitter is one of the vital constituents in optical integrated circuits. Paper presents the previous research as well as the current scenario in the domain of photonic crystal based power splitters. From the literature survey it is clear that it is possible to design ultra- compact and highly efficient power splitters due to fascinating characteristics of photonic crystal materials. At the same time the paper also briefed the different designs of power splitters and the various methods to realize a power splitter with high output efficiency in the literature are also presented.

Keywords: Photonic Crystal, Photonic bandgap, Photonic integrated circuits (PIC's), Photonic crystal waveguide (PCW)

INTRODUCTION

Photonic crystals (PCs) are the materials that have the potential to deliver ultra-compact photonic devices that would revolutionize the integrated optics by miniaturization of optical circuits. PCs have been the areas of research because of their remarkable applications in optoelectronic circuits. PCs are periodic arrangement of dielectric materials which consist of alternating deposits of high and low refractive index materials. The refractive index repeats after certain time period in accordance with the wavelength of light [1]. The PC structure can be classified as 1 D, 2D and 3D PC's based on the periodicity of dielectric material as shown in the following figure.

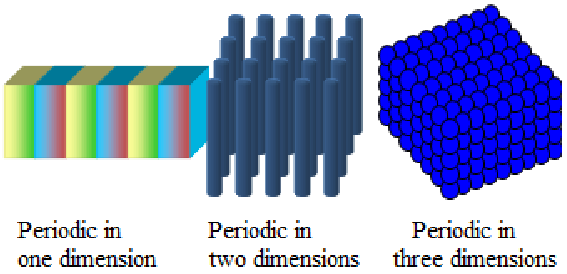

Figure 1. Schematic of different types of Photonic Crystal [2]

There is only one type of lattice structure for 1D photonic crystal and five different types for 2D photonic crystals like square, rectangular, triangular or hexagonal, centered rectangular and oblique and fourteen lattice structures for 3D photonic crystals. When the incident light travels through this periodic structure, it experiences reflection at each boundary of two alternate refractive indices. In reference to dense optical integration power splitters are the main building blocks in linking the different sections on the photonic integrated chips. Power splitter is a device which splits the incoming power into output branches without significant losses. Photonic crystal based power splitters have a photonic band gap (PBG) in which no propagating modes exist in any direction. By introducing the defects in the crystal structure the propagation of light inside the crystal can be molded and a range of compact (micrometer scale) optical devices can be designed [3]. The other photonic crystal based optical devices which show remarkable characteristics are filters[4], multiplexers[5], demultiplexers[6], switches[7], sensors[8], directional couplers [9] and are believed as good contenders of future optical integrated circuits.

ELECTROMAGNETIC WAVES PROPAGATION IN PERIODIC MEDIA

The knowledge of Maxwell's equations is required to understand the light propagation in periodic dielectric materials (PC's). The basic form of macroscopic Maxwell's equations in Gaussian units is given by the equation 1a-1d.

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t} \qquad (1a)$$

$$\nabla \times H = \frac{1}{c}\frac{\partial D}{\partial T} + \frac{4\pi}{c}J \qquad (1b)$$

$$\nabla . D = 4\pi\rho \qquad (1c)$$

$$\nabla . B = 0 \qquad (1d)$$

Where field vectors E and H are termed as the macroscopic electric and magnetic fields, B and D are the macroscopic magnetic and displacement fields, ρ and J are the free charges and current and c is the velocity of light in free space.

Plane wave expansion (PWE) and finite difference time domain (FDTD) methods are used for analyzing the dispersion characteristics and transmission spectra of PCs. PWE technique is helpful in investigating the PC structures which can be represented as superposition of an arrangement of plane waves.

Wave Equations

Following Maxwell's equation is solved for calculating the electric field in the band diagram.

$$\nabla\times\frac{1}{\varepsilon(r)}\nabla\times E(r)=\frac{\omega^2}{c^2}E(r) \qquad (2)$$

Where c is the velocity of light, ω is the angular frequency, ε(r) is the dielectric constant and E(r) is the electric field of the periodic function. The Equation 2 describes the flow of light in photonic crystals and is based on Bloch theorem.

Equation 3 is the initial point to solve the macroscopic Maxwell's equation for alternate dielectric medium.

$$\frac{\partial E_x}{\partial z}=\frac{\partial}{\partial x}\left[-\frac{1}{ik_o\varepsilon(r)}\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right)\right]+ik_oH_y \qquad (3a)$$

$$\frac{\partial E_y}{\partial z}=\frac{\partial}{\partial y}\left[-\frac{1}{ik_o\varepsilon(r)}\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right)\right]+ik_oH_x \qquad (3b)$$

$$\frac{\partial H_x}{\partial z}=\frac{\partial}{\partial x}\left[\frac{1}{ik_o}\left(\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right)\right]-ik_o\varepsilon(r)E_Y \qquad (3c)$$

$$\frac{\partial H_y}{\partial z}=\frac{\partial}{\partial y}\left[\frac{1}{ik_o}\left(\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right)\right]+ik_o\varepsilon(r)E_x \qquad (3d)$$

Where $k_o=\omega/c=2\pi f/c$. These equations give the propagation of light in periodic medium and are obtained as the result of Bloch theorem which states that that EM waves can propagate without scattering in periodic medium [10].

Fundamentals of Photonic Crystals

Direct Lattice

For 2D PC the dielectric constant $\varepsilon(r)$ is written as-

$$\varepsilon(r)=\varepsilon(r+R) \qquad (4)$$

where R represents the 2D lattice vector in space and is defined as

$$R=m_1a_1+m_2a_2$$

where m_1 and m_2 are numerals and a_1,a_2 are the vectors.

Reciprocal Lattice

The reciprocal lattice G is written as-

$G=n_1b_1+n_2b_2$

where n_1 and n_2 are numerals and b_1 and b_2 are the reciprocal lattice constant. M is the center of an edge, T is the center of Brillouin zone and X is the center of a face.

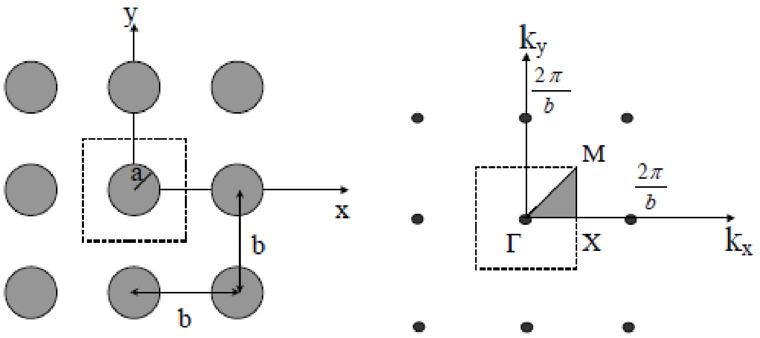

Figure 2. Direct Square lattice with the equivalent reciprocal lattice with highlighted portion as Brillouin zone[11]

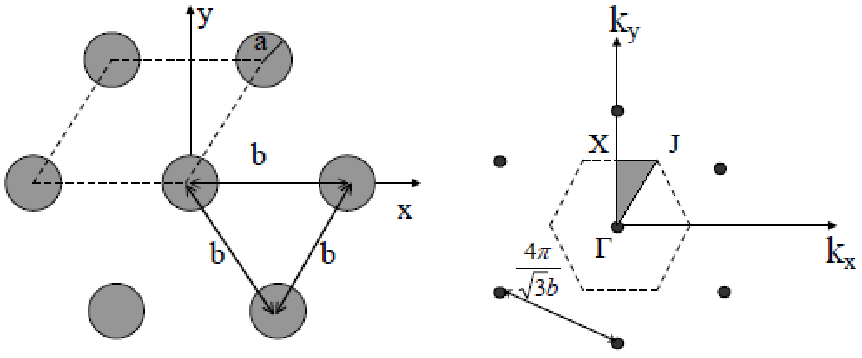

Figure3. Direct triangular lattice with the equivalent reciprocal lattice with highlighted portion as Brillouin zone [11]

For square and triangular lattices the vectors a and b can be defined as shown in the following table.

Table 1. Definition of vectors a and b for square and triangular lattice [11]

Square lattice	$a_1 = ax$ $a_2 = ay$	$b_1 = 2\pi/ax$ $b_2 = 2\pi/ay$
Triangular lattice	$a_1 = ax$ $a_2 = (x + \sqrt{3}y)$	$b_1 = 2\pi/a(x - \sqrt{3}\backslash 3y)$ $b_2 = 2\pi/a2\sqrt{3\backslash 3y)}$

Photonic bandgap

Photonic bandgap (PBG) which is an important property of photonic crystal is that range of frequencies which forbids the light propagation through the crystal structure. PBG is similar to forbidden energy gap in case of semiconductors. In a photonic crystal light cannot enter the crystal because of the presence of band gap which acts like an insulator of light and would change the velocity of light to zero. Thus location of light and spontaneous emission of light can be controlled inside the crystal by adding certain amount of impurities like defects in the crystal structure [12]. For example the band structure of square lattice with dielectric rods is illustrated in figure 4. The left portion presents the brillouin zone and the blue color portion shows the irreducible brillouin zone and the cross sectional view of the structure is shown in the right inset.

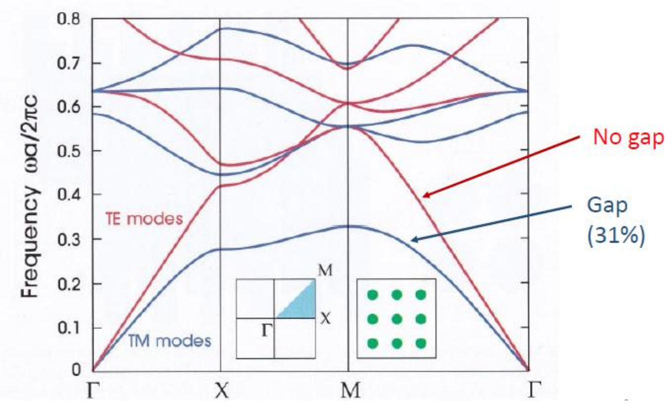

Figure 4. Band diagram and photonic band gap for TM and TE waves [13]

Different Configurations of Photonic Crystal based Power Splitters

Interactions of light through patterned nanostructures whose period is considered according to the wavelength of the interacting light have wonderful new applications in optics and optoelectronics. In the future, to handle and process the data in modern computer and communication networks, miniaturized photonic chips for optical integrated circuits will be needed. Due to the presence of photonic band gap (PBG) effect, PC can be used to design several optical applications which are not possible in conventional waveguides [13].

There are different optoelectronic directions where PC structures can be used. The most significant are the optical insulators, optical switches, waveguides, power splitters, combiners etc. In photonic integrated circuits (PIC's), PC beam splitters can be used to guide and route the EM waves between different sections. Waveguide having splitting efficiency (e.g. power splitter) is required where power distribution to multiple outputs is needed. They are assumed to become the important constituents for compact PIC's utilized in fiber optic networks [14].

Numerous configurations of the power splitter had been proposed in the literature. Power dividers denote a class of optical devices that can divide an optical power in certain amount into polarized light rays. The PC based power splitter can be shown as some waveguides connected together at one point. In such a waveguide the incoming light beam is divided at the junction point as shown in the following diagram [15].

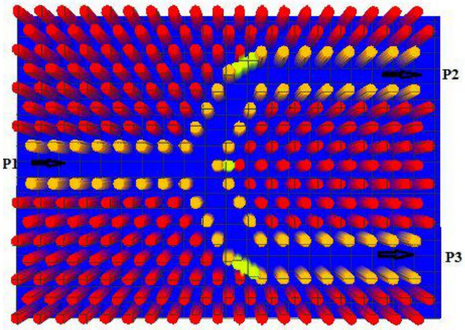

Figure 5. 1x2 Power Splitter[16]

Until now single mode PC waveguide has been focused but now the interest has arisen for multimode interference (MMI) regions in PC waveguide as it provides extraordinary characteristics. MMI components are vital for photonic integrated circuits because of their basic construction, small polarization variance, little loss and huge data transfer capacity in optics. These devices offer power splitters/combiners and have created lot of scope as 3dB couplers.

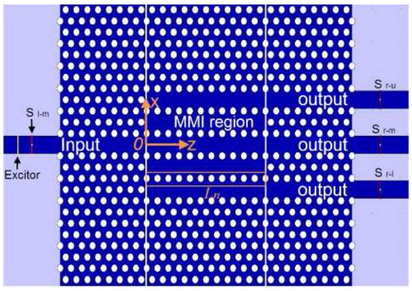

Figure 6. Schematic layout of a 1x3 splitter with input, MMI and output PC waveguides [17]

Another kind of beam splitter is created based on the coupling between parallel waveguide branches with minimum distance among them. By varying the parameters of the waveguide, the amount of power to be transmitted to the output port can be easily adjusted.

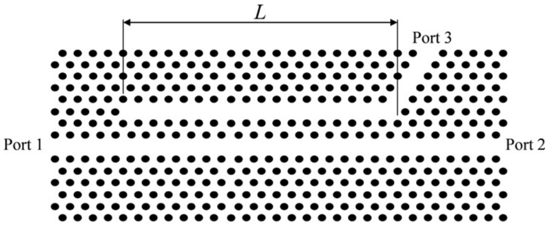

Figure 7. A coupler of length L in the interaction section [18]

Another type of power splitter was proposed by deploying directional couplers and ring resonators. Ring resonators provide bends with low losses for designing highly efficient splitters. The EM waves coupled from one waveguide to another will be confined in the L shaped bend of ring resonator.

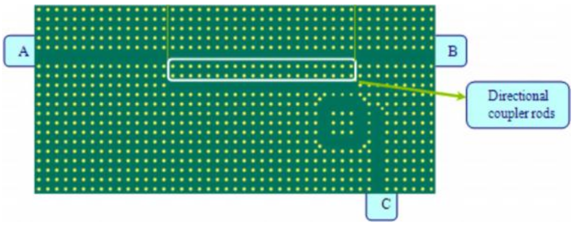

Figure. 8. Ring resonator coupled between two waveguides [19]

By adjusting the coupling length different power levels at output can be attained. The ring resonator shown in the following figure is created by removing a column in the ring shape from a rectangular lattice. Silicon rods having a refractive index n = 3.46 and radius of rods, r = 0.185a where a is the lattice constant are used. This ring resonator will couple the electromagnetic energy at resonant frequency to the waveguide [19].

In another attempt 1x3 power splitter is designed by cascading two 1x2 power splitters and equal distribution of power is achieved in all the output arms of the splitter by placing flexible structural defects in the splitting area as shown in the following figure. The splitter is designed using PC slab of triangular lattice with air holes. It consists of three waveguides connected together at an angle of 120 º .The green color in the back ground indicates silicon with n= 3.4 and the white region represents air.

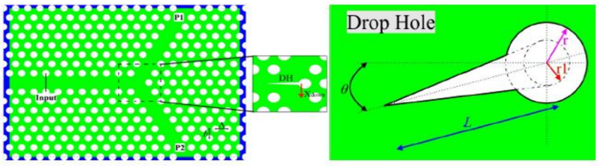

Figure: 9. Flexible defect in power splitter with defect parameters r, θ and L[20]

The power splitter using single drop hole (DH) is shown in the above figure is the defect which is inserted into the splitting area. The PC slab has a lattice constant of a = 440nm, radius r of air hole = 135nm and the slab thickness = 230nm. Plane wave expansion method is used which shows that this structure displays huge transverse electric (TE) band gap. The 1x3 power splitter operates at a wavelength of 1561 nm with power distribution as 29.8%, 28.9% and 30.1% [20].

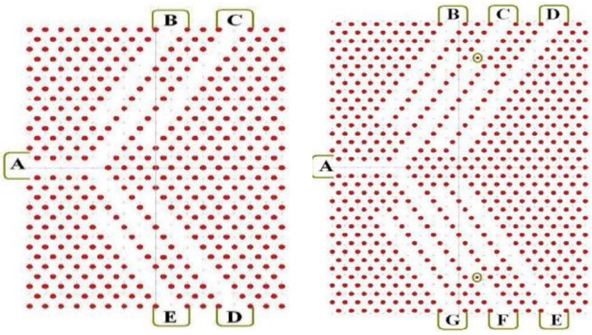

Figure 10. Schematic diagram of 1x4 splitter and 1x6 splitter with two additional rods marked by circles [21]

[21] investigated splitters based on directional couplers for 2D photonic crystal and achieved high efficiency over a wide bandwidth. The work shows that by placing extra rods and by varying the radius of the rods uniform distribution of power can be achieved. Also the size of the 1x4 splitter is 1.054µm x 17.98µm and 13.02µm x 21.7µm for 1x6 splitter.

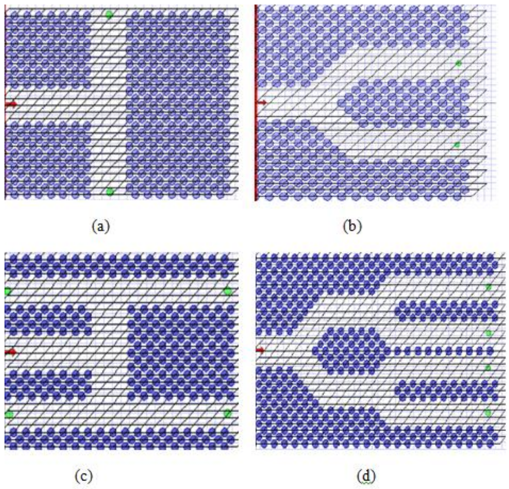

Figure 11. (a) layout design of 1x2 splitter with T junction (b) 1x2 splitter with Y junction (c) 1x4 splitter with T junction (d) 1x4 splitter with Y junction[22]

[22] designed optimized and compared the performance of Y junction and T junction splitter for different lattice structures like rectangular, hexagonal for 2D photonic crystal. The paper presents the design of very compact (80µm - 100 µm) power splitters having 2 output (1 x 2), four (1 x 4), six (1 x6) output branches. By the variation in the parameters like radius of holes = 0.128 µm, λ (wavelength) = 1.55 µm, n_1 (refractive index) = 1.52 and n_2=3.45 of a rectangular lattice structure, the performance of all splitters are compared with each other for maximum transfer of power.

Advantages of Photonic Crystal based Power Splitters

The advantage of using PC based power splitters is that very sharp bends can be realized inside waveguides which is not possible with conventional optical waveguide with low losses. For conventional waveguides the angle of bend has to be very large otherwise during transmission much of the light would be lost because total internal reflection cannot be satisfied. This limitation of conventional optical waveguides restricts the volume integration of optical integrated circuits. Moreover with PC light can be spatially controlled of the order of wavelength of light and PC based power splitters can be realized in micron size thus makes them suitable for constructing optical integrated circuits.

LITERATURE REVIEW

The features of various types of PC based power splitters worked on by various researchers have been summarized in the table 2.

Table 1. Analysis based on survey

Ref. No.(s)	Journal/Workshop/ Conference Name	Methodology	Efficiency
23	Optical Letters, Optical Society of America	• Silicon on insulator material • Y junction and 60^0 low loss bend • Range 1560-1585nm • 15µm x20 µm in size	
24	Journal of Physics D, Applied Physics	• Polarization beam splitters • 2D PC • Dielectric cylinders in air arranged in an square array • Length of 62a in Y direction and 32a in X direction.	42.5%
25	Optical and Quantum Electronics, Springer	• Super modes • Variations in the air hole radius • Minimized backward reflections	45%
16	Journal of Optics A: Pure and Applied Optics	• Three parallel single mode waveguides • GaAs rods on a triangular lattice • 9.92µm in length	30%
26	Journal of Optical Society of America A, Optics & Image Science & Vision	• PC $90\ ^0$ bend based power splitter • Super defect between two orthogonal waveguides	42.5%
18	Journal of Optics Communication, Elsevier	• Right angled low loss bends T junction • PC ring resonator (PCRR) • Variations in ring size	47%
27	Journal of Optical Society of America B, Optical Physics	• Power splitters in a 2D PC structure • rods of dielectric material in air • lattice - square • Bandgap for TM mode	24.35%
28	Optics Letters, Optical Society of America	• Flexible optical waveguides • Arbitrary angles	47.5%
29	Journal of Optics Express, Optical Society of America	• 60^0 low loss bend • polarization beam splitter • air hole structure	45%

30	Journal of Optical Physics, Optical Society of America B	• Omnidirectional reflection of 2D PC • Optical waveguiding structure • 90^0 waveguide bend	49%
31	Applied Optics, Optical Society of America	• Minimized polarizing beam splitter • PC ring resonator (PCRR). • Orthogonal polarized states • length of polarizing separation is 3.1µm	47.5%
32	Optical Engineering	• air holes in triangular lattice • Bandwidth of 70nm • A solo defect hole introduced in the photonic crystal waveguide	49.5%
33	Journal of light Wave Technology	• 1x3 power splitter • silicon slab PC • Triangular lattice and air holes • Y branch at an angle of 120 • Two drop holes placed at the junction • Minimized reflection loss	33%
34	Journal of Optics and Photonics	• A very small (80-100 µm^2) integrated power splitter • Two, four and six output ports • T junction and Y junction Multiple line defect PC waveguide (MLDPCW) • Rectangular PC structure slab of InAs	23.2% for 1x4 splitter and 13.5% for 1x6 splitter
35	Journal of Applied Physics A, Springer	• A 2D PC • Y-branch hybrid • InP rods • Hexagonal array	33%
36	Modern Physics Letters B	• 1x4 optical power splitter • PC waveguide with two branches • Triangular lattice of air holes • Bandwidth 80nm • 12x12µm^2 in size	24.85%
37	Journal of Optical Communication	• Optical power divider in a 2D PC • Triangular lattice • One input and four output ports • Three parallel single mode PC waveguides	22%
38	Optik	• Integrated multi arm power splitter • Line defects introduced into a 1x5 power splitter	5.2%, 16.9%, 14.6%, 12.1%, and 3.4% in each arm respectively.

In this table the different structural designs of the photonic crystal power splitter are presented. Various researchers have worked on the different lattice structures like square, triangular or hexagonal with the periodic variation in the refractive index created by using different types of materials. The output efficiency of each splitter is also given based on the effect of variation in various parameters of the splitters like rod radius, the dielectric material's refractive index. Some splitters with very compact size like 9.92µm in length, 80-100 µm^2, 12x12µm^2 [13, 24, 27] have also been listed in the table.

Comparison of Different Power Splitters

Table 3. Comparison of different types of power splitters based on configuration, efficiency, size and spectrum

Parameters	1x4 Splitter	1x3 Splitter	Splitter based on Ring Resonator	Splitter with parallel output ports
Configuration	Square lattice with silicon rods	Triangular lattice with air holes	Rectangular lattice with dielectric rods	Square lattice with dielectric rods in air
Maximum Power Transmission at Each Port (%)	50%	33%	49%	48.7%
Device Size	225µm^2	21 µm x14 µm	6 to 30 rods	201x25 lattice constant
Spectrum	1430nm	1.519-1.569 µm	1588 and 1594nm	0.343(2πc/a)-0.420(2πc/a)

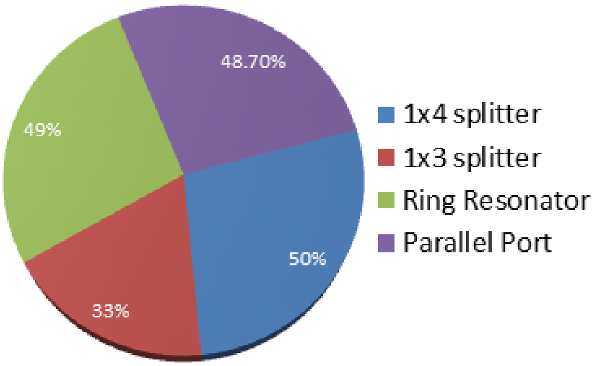

Figure 12. Comparison of transmission efficiency of different type of power splitters

CONCLUSION

The power splitter is a promising field of research in photonics. The paper briefed the different designs of power splitters and the various methods to realize a power splitter in the literature are also presented. Y splitter in different lattice configurations (square, rectangular, hexagonal) are investigated. Then in some papers the idea of optimized bends and additional rods was also discussed to reduce the backward reflections. Power splitters are very significant devices for designing of PIC's. The main aim of this paper was to examine the different configurations of power splitters based on photonic crystals. Then a comparison of different types of power splitter structures on the basis of configuration, size, per arm transmission efficiency and the wavelength is also presented.

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