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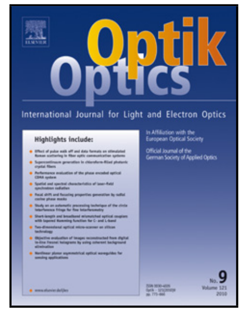

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An Ultra-Compact 1×5 and 1×10 Beam-Splitters In Photonic Crystal Slab

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Abstract— In this paper, an ultra-compact 1×5 and 1×10 beam splitters operating in optical C-band signals were numerically investigated and optimized in triangular lattice PhC slab employing the FDTD simulations. The high performances of both beam-splitters were reached by altering the junction area of the beam-splitter structure using topology optimization. The results show thatthe beam is distributed almost equally with extremely efficient total transmissions of about 99.23% and 94.39% and low insertion losses of about 0.03 and 0.25 dB for the 1×5 and 1×10 beam-splitters successively around the optical operating wavelength 1550 nm.

Index Terms— PhC slab; 1×5 beam-splitter; 1×10 beam-splitter; reflecting mirror (RM).

I. Introduction

There are several methods for the light emission in optical devices, but choosing a suitable environment with minimum power dissipation remains a major goal in these devices. Photonic crystals PhCs are the optical components that have been investigated by researchers in the last decades [1]. These materials with exotic properties have proven very important device for integrated optics. Among the PhCs devices, the power splitter [2] witch is a passive key component that is used in many systems. Ideally, they ensure sending light around sharp bends or compactly separate an incident light beam into two or more beams with orthogonal linear polarizations that travel in different directions [3], but without significant reflection or radiation losses and should be compact in size. Now power splitters have been extensively studied for their potential applications in various optical communication areas [4].

There are some possible ways how to split optical power from one input channel to two or more output channels such as multimode interference (MMI) splitter [5] or through directional coupling between two or more photonic crystal waveguides. It is possible to divide the input light into two or more identically powered output channels [6]. To our knowledge the most straight forward optical power splitter is the Y-junction structure [7]-[8] where their design consists of three single defect waveguides joined together at 120° which leads to strong reflections and narrow bandwidth operation [9]. To analyze the photonic crystal devices, a diversity of computational techniques have been exploited [10]-[16]. The FDTD method is one of the major computational electromagnetic techniques extensively employed and suitable for iterative optimizations or conceptual studies offering precise results.

In this paper, we propose a schematic structure of PhC slab Y-junction based 1×5 and 1×10 power splitters exhibiting an equal amount of power distribution where the optical modeling of the proposed structure was investigated by the FDTD simulation.

This paper is organized as follows: the 1×5 beam-splitter is presented in section II with the description of the design and used parameters, and then its simulation with optimization is interpreted. In section III, a 1×10 beam-splitter is proposed, and its performance is analyzed and optimized using the same previous technique.

II. Basic 1×5 beam-splitter configuration

Figure 1 shows the schematic representation of the proposed beam-splitter implemented on a PhC structure where air rods are placed in a triangular representation with the following geometrical and physical characteristics: n_{eff}= 3.24 provides high transmittance and a PBG at near-infrared band, r =0.36a and air filling factor equal to 47%. The proposed 1×5 beam-splitter was designed by a unique input PhC channel waveguide and five exits. The suggested slab is formed by cascading the 1×3 beam-splitter with the 1×2 beam-splitters S_1 and S_2 on each exit channel of the extremity of the 1×3 beam-splitter symmetrically, which is realized by creating two mono rows; consequently, five exit channels are attained.

Toward to reach a similar beam-splitting ratio at 1550 nm for optical C-band wavelength and decrease the reflection losses inspired from [17]-[18], topology optimization scheme is adopted to adapt the topology at the division region, where we employ two methods to change the origin shape, firstly we get the external junction curve lobes to the interior of the bend, using reflecting mirror at the junction bend. Secondly, we eliminate rods radius in opposite of the RM region; some additional rods are placed at the center of the beam-splitter, and containing three rods in shape of triangles as displayed in Figure 1.

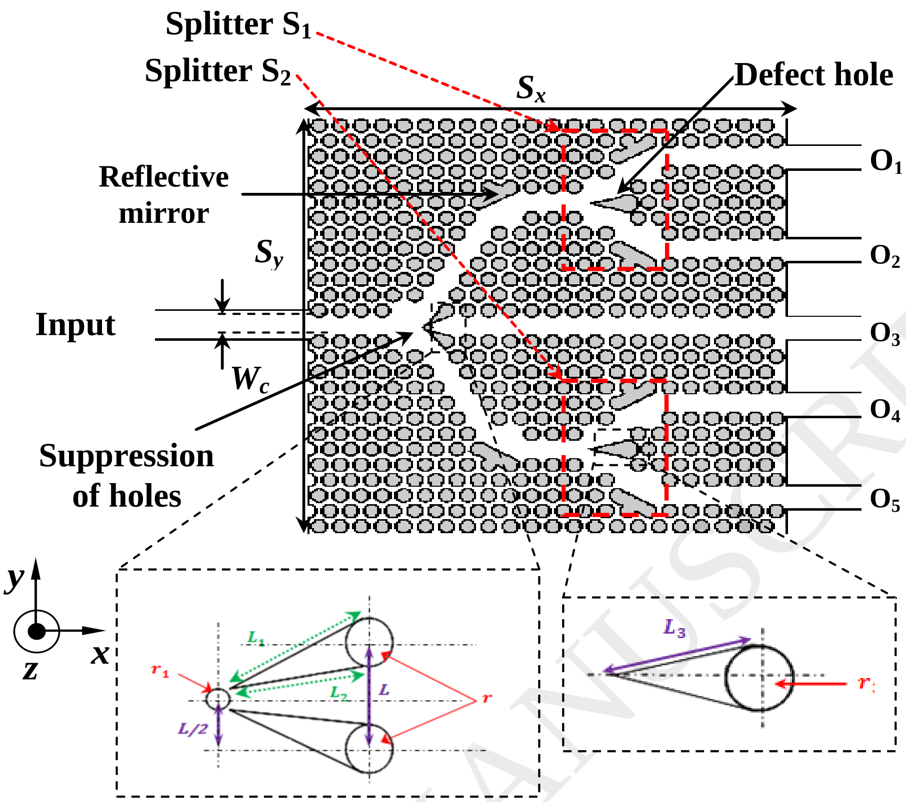

Figure 1. Schematic view of the optimized PhC slab 1×5 beam-splitter, with parameters: Sx = 27 µm, S_y = 24 µm, Δx =0.05 µm, Δy =0.05 µm,r_1 = 0.167a, r_1 is the radius of the air rod at the center of the Y-junction, L = 3.46µm, L_1 = 1.48 µm, L_2 = 0.98 µm, r_3 = 0.5a and L_3 = 1.85 µm.

The spectrum of the normalized transmission T graphs computed at exits in the region band of wavelengths [1.53- 1.57 µm] have been plotted in Figure 2.

The graph shows that, the proposed device will split the input optical beam to the five output channels almost evenly with a transmittance more than 19.78% per each channel output the working wavelength 1.55 µm, which presents the ideal spot where the maximum transmission can reach 99.23%. In the other hand, the weak back reflection is realized over the entire designed wavelength range, this is mainly the cause of the confinement of light in splitting and bending regions resulting in losses.

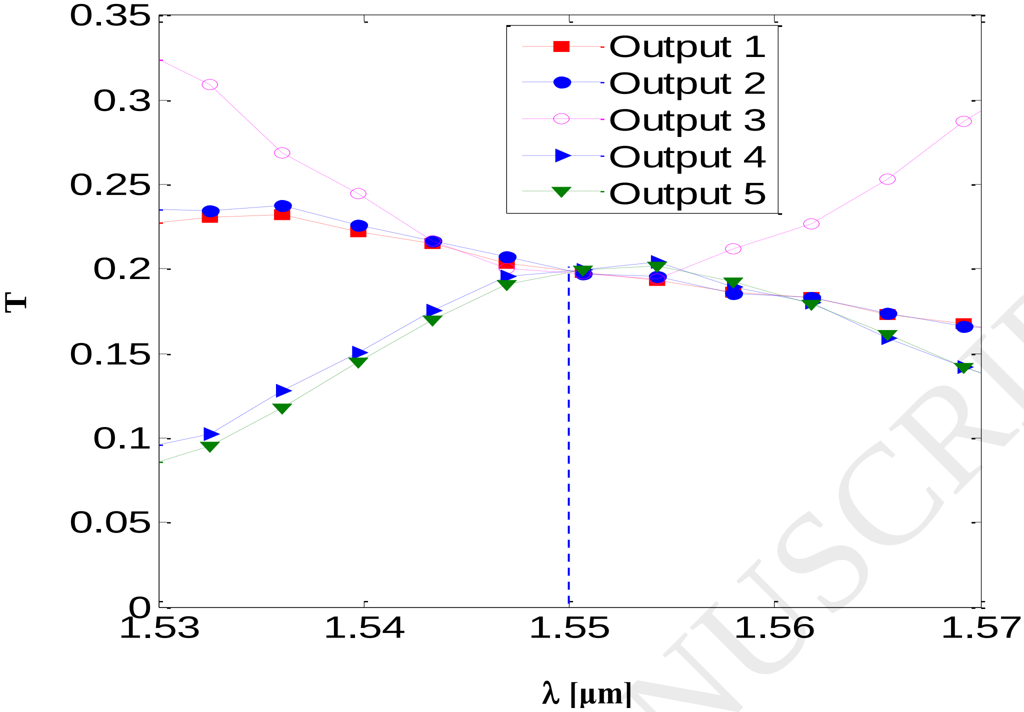

Figure 2. 1×5 beam divider transmission graphs which is composed on the optimized Y-junction splitting geometry.

To discuss our proposed structure, a comparative study has been done with all the papers found from literatures that treat 1×5 beam-splitter. The obtained statistics are completed at the wavelength 1.55 µm. The 1×2 and 1×5 beam-splitters performances are summarized in table I and II.

TABLE I. 1×2 DIVIDEROPTIMAL RESULTS

	Computing wavelength [µm]	Transmission %		Total %
		P_{01}	P_{02}	
1×2 splitter S_1	at : 1.55	45.41	45.41	90.82
1×2 splitter S_2	at : 1.55	45.41	45.34	90.75

TABLE II. 1×5 DIVIDER OPTIMAL RESULTS VERSUS SOME PUBLISHED PAPERS

	Computing Wavelength [µm]	Transmission %					Total %
		O_1	O_2	O_3	O_4	O_5	
Ref. [18]	2.35	18	18	18	18	18	90
Ref. [19]	1.61	17.7	17.7	17.7	17.7	17.7	88.50
Our Work	1.55	19.87	19.87	19.78	19.84	19.87	99.23

It is easy to observe, according to Table I, that maximum transmissions which exceed 19.50% for the optimized structures are attained, which shows a noticeable improvement over the references [18] and [19]. Besides, the division is perfectly equitable.

The magnetic field Hz distribution of the beam-splitter 1×5 excited in TE mode for 4000 time step is show in Figure 3. The source is a pulse with a Gaussian time envelope.

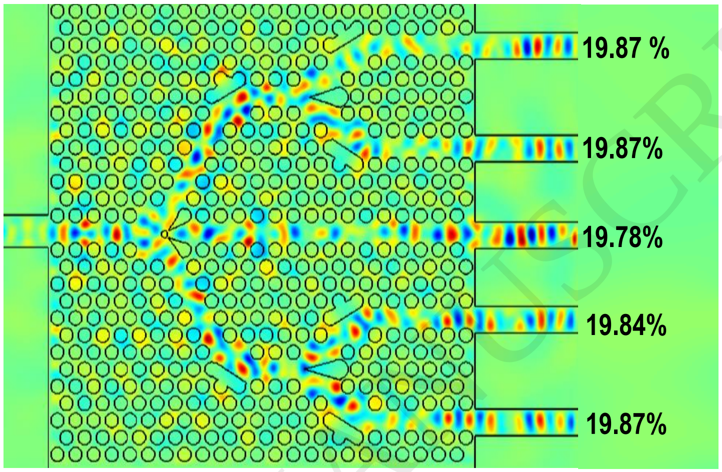

Figure 3. Field H_z distribution of the beam-splitter 1×5 excited in TE mode for 4000 time step.

Obviously, a guiding of the fundamental mode along the guide is observed in the different branches of the 1 × 5 divider. Besides, the optimized topology allows flexible routing of the wave and the exits channels have almost equal output power.

III. Basic 1×10 beam-splitter configuration

In this section, we pay particular attention to the improvement of the 1×10 beam-splitter design, here the identical physical and geometrical properties of the 1×5 device investigated before are kept, then each output is divided in two channels as inspired from [17]-[18] by employing two way splitters S_3, S_4, S_5, S_6 and S_7. Consequently, ten exit channels for the 1×10 beam-splitter are generated. For the optimization procedure of the 1×10 beam junction topology, the similar methods described before are adopted for the optimization of transmission of the proposed 1×5 junction to reach an even splitting. The optimized 1×10 beam-splitter drawing topology is displayed in Figure 4.

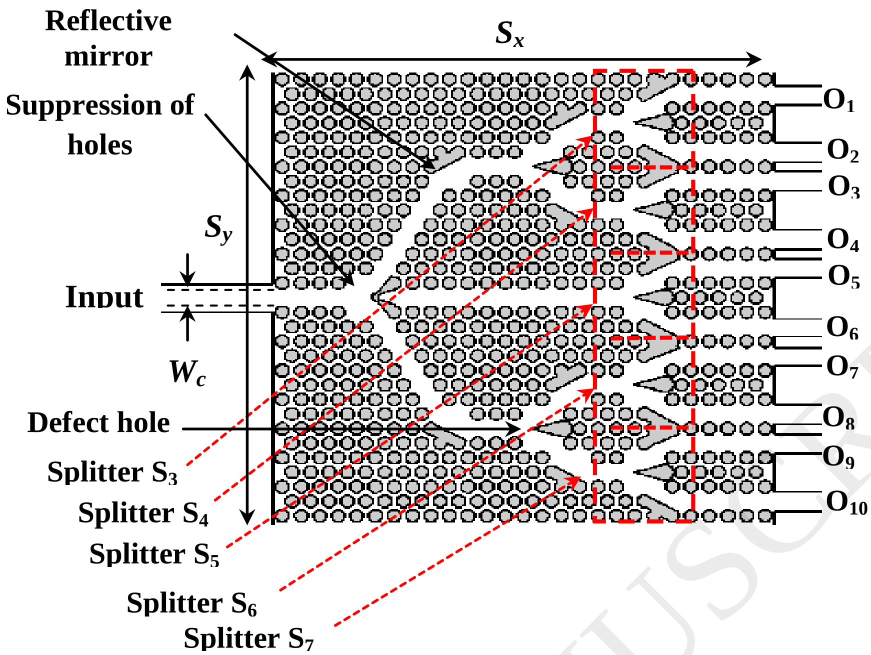

Figure 4. The 1×10 beam splitter optimal design exited in transvers electric mode with parallel output waveguides based on the integration of the Y-junction. The parameters are set such as:r = 0.36a, n_{eff} = 3.24, S_x= 27 µm, S_y = 27.5 µm, Δx =Δy =0.05μm and the areas of the 1×2 splitters.

Figure 5 displays the 1×10 beam-splitternormalized computed transmission spectrum at exits in the region band of wavelengths [1.53- 1.57 µm].

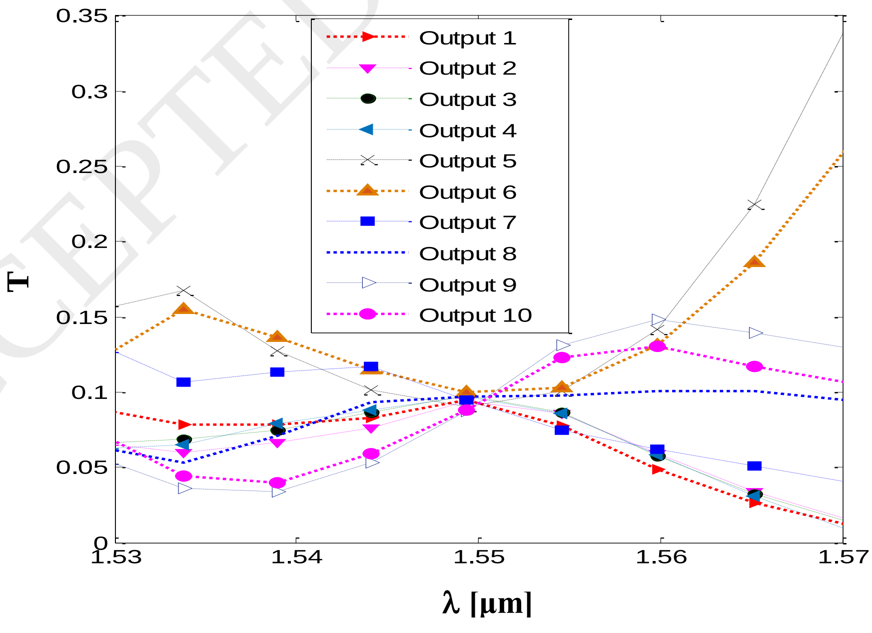

Figure 5. Computed transmission spectra for the structure illustrated in Figure 3. Beam is divided almost equally between the ten outputs.

Depending on the achieved FDTD method computation results, we notice an intersection at the wavelength 1550 nm of all graphs with transmission levels very close. The computed levels at 1550 nm are:~ 9.28%, 9.33%, 9.72%, 9.17%, 10.02%, 9.16%, 9.54%, 9.64%, 9.31% and 9.22% for output 1, output 2, output 3, output 4, output 5, output 6, output 7, output 8, output 9, and output 10, for a total of 94.39%, consequently, an effective beam splitting is reached.

We also calculated the reflection power coefficient parameter, which gave us information on what fraction of the input power was reflected backward from the crystal. The back reflection was less than 5.7%. It is confirmed that the optimal design exhibits interesting results where slight reflection losses are recorded. The optimal transmissions of 1×2 and 1×10 splitters designs are reported in table III and IV.

TABLE III. 1×2 DIVIDER OPTIMAL RESULTS

	Computing wavelength [*nm*]	Transmission %					Total %
		O_1	O_2	O_3	O_4	O_5	
Our Work	at : 1550	9.28	9.33	9.72	9.17	10.02	94.39
		O_6	O_7	O_8	O_9	O_{10}	
		9.16	9.54	9.64	9.31	9.22	

TABLE IV. 1×2 DIVIDERS OPTIMAL RESULTS OF THE 1×10 SPLITTER

	Operating wavelength [nm]	Transmission % O_{01}	Transmission % O_{02}	Total %
1×2 splitter S_3	at : 1550	46.12	46.37	92.49
1×2 splitter S_4	at : 1550	50.15	47.31	97.46
1×2 splitter S_5	at : 1550	49.80	45.52	95.32
1×2 splitter S_6	at : 1550	48.90	49.41	98.31
1×2 splitter S_7	at : 1550	49.00	48.53	97.53

The insertion loss can be defined as the ratio of output power and input power based on the following relationship: $\mathrm{IL} = 10\log_{10}\left({}^{\mathrm{P_{out}}}/_{\mathrm{P_{in}}}\right)$. The table V reports the insertion losses ILsresults for two optimal designs, 1×5 and 1×10 beam-splitters. The associated ILs of the beam-splitter 1×5 are, successively, 7.01, 7.04, 7.03, 7.02, and 7.01 for the five exits from 1 to 5.

Whereas the associated ILs of the 1×10 beam-splitter are, successively, 10.32, 10.30, 10.01, 10.37, 9.99, 10.38, 10.20, 10.15, 10.31, and 10.35 for the ten exits from 1 to 10. Obviously, according to Table I, small achieved ILs are attained.

TABLE V. 1×5 AND 1×10 BEAM-SPLITTER COMPUTED ILS RESULTS

	Full ILs in | dB|	Computed ILsat different channels exit (dB)				
1×5 splitter	0.03	O_1 7.01	O_2 7.04	O_3 7.03	O_4 7.02	O_5 7.01
1×10 splitter	0.25	O_1 10.32	O_2 10.30	O_3 10.01	O_4 10.37	O_5 9.99
		O_6 10.38	O_7 10.20	O_8 10.15	O_9 10.31	O_{10} 10.35

Let us present in Figure 6 the magnetic field Hz distribution of the beam-splitter 1×10 excited in TE mode for 4000 time step.

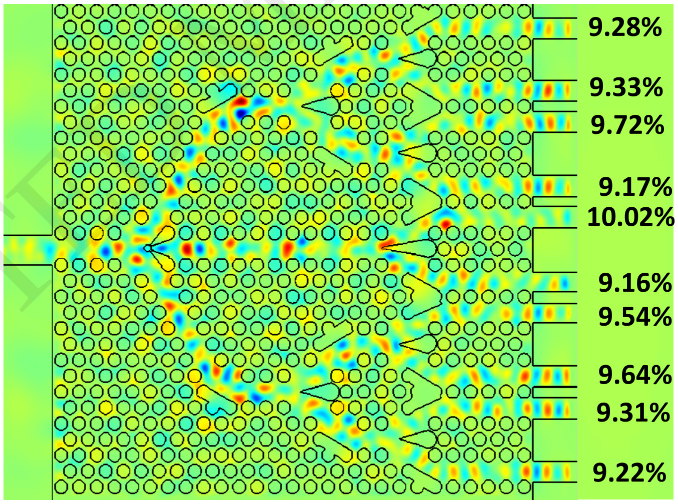

Figure 6. Field Hz distribution the beam-splitter 1×10 excited in TE mode for 4000 time step.

The magnetic field strength Hz distribution of the excited in TE mode for 4000 number of time step as show in Figure 6 revealsnoticeably the guided wave through the beam-splitter 1×5.

IV. Conclusion

In conclusion, we have proposed in this study the design of two ultra-compact beam-splitters. The characteristics of the first 1×5 beam-splitter are calculated by FDTD and it is demonstrated that the parameters of this device are significantly improved compared with the literature, whereas the 1×10 beam-splitter conception that never existed in literature, is capable of dividing the electromagnetic wave power desirably, i.e., transfersa normalized power with a level that exceeds 9.16% at each output channel at the operating frequency. From the simulation results, our design demonstrates anextremelyhigh transmitted normalized power of about 99.23% and 94.39% and low insertion losses of about 0.03 and 0.25 dB for the 1×5 and 1×10 beam-splitters. Thus, these proposed devices could be applied into DWDM systems.

References

[1] Liu, T., Zakharian, A. R. &Fallahi, M. (2004). 'Multimode Interference Based Photonic Crystal Waveguide Power Splitter', Journal of Light-wave technology, Vol. 22, No. 12, pp. 2842-2846, 2004.

[2] Tian Bao Yu, Qi Jie Wang, Jun Zhang, Jian Yi Yang, and Siu Fung Yu, 'Ultra compact 2x2 Photonic Crystal Waveguide Power Splitter Based on Self-Imaging Effect Realized by Asymmetric Interference ', IEEE Photonics Technology Letters, Vol. 23, No. 16, pp. 1151-1153, August 15, 2011.

[3] Shi, Y., 'A compact polarization beam splitter based on a multimode photonic crystal waveguide with an internal photonic crystal section', Progress In Electromagnetics Research, Vol. 103, pp. 393-401, 2010.

[4] Ghaffari, A., Djavid, M., Monifi, F. and Abrishamian, M. S., 'Photonic crystal power splitter and wavelength multi/demultiplexer based on directional coupling', J. Opt. A: Pure Appl.Opt.10 (7), 1-7, 2008.

[5] Kuzma A., Chovan J., Uherek F., Seyringer D, ' Design and Simulation of Planar Passive Optical MMI Splitters', 23rd Conference and Exhibition on Optical Communications 2011, pp. 18-21, 2011.

[6] C. Y. Liu, 'Fabrication and optical characteristics of silicon-based two dimensional wavelength division multiplexing splitter with photonic crystal directional waveguide couplers', Phys. Lett. A, vol. 375, pp. 2754–2758, 2011.

[7] H. Badaoui, M. Feham, and M. Abri, ' Double Bends and Y-Shaped Splitter Design For Integrated Optics', Progress In Electromagnetics Research Letters, Vol. 28, pp. 129-138, 2012.

[8] Hadjira Abri Badaoui, and MehadjiAbri, 'Optimized 1 × 8 compact splitter based on photonic crystal using the two-dimensional finite-difference time domain technique', Optical Engineering 54(6), 067104, June 2015.

[9] Rajat Dey and Jayshri Sabarinathan, '1×3 Power splitter based on 2-D slab photonic crystal multiple line defect waveguides', Proc. of SPIE, Vol. 8007, pp. 1-8, 2011.

[10] Kuzmiak, V. A. A. Maradudin, and F. Pincemin, ‘ Photonic band structures of two-dimensional systems containing metallic components’, Phys. Rev. B, Vol. 50, pp. 16835-16844, Dec. 1994.

[11] Smirnova, E. I., C. Chen, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, ‘Simulation of photonic band gaps in metal rod lattices for microwave applications’, J. Appl. Phys., Vol. 91, No. 3, pp. 960-968, Feb. 2002.

[12] Moreno, E., D. Erni, and C. Hafner, ‘Band structure computations of metallic photonic crystals with the multiple multipole method’, Phys. Rev. B, Vol. 59, No. 3, pp. 1874-1877, Jan. 1999.

[13] Hiett, B. P., J. M. Generowicz, S. J. Cox, M. Molinari, D. H. Beckett, and K. S. Thomas, ‘Application of finite element methods to photonic crystal modeling’, IEE Proceedings Science, Measurement & Technology, Vol. 149, No. 5, pp. 293-296, Sep. 2005.

[14] Qiu, M. and S. He, ‘A nonorthogonal finite-difference time domain method for computing the band structure of a two-dimensional photonic crystal with dielectric and metallic inclusion’, J. Appl. Phys., Vol. 87, No. 12, pp. 8268-8275, Jun. 2000.

[15] Kuang, W., W. J. Kim, and J. D. O'Brien, ‘Finite-difference time domain method for no orthogonal unit-cell two-dimensional photonic crystals ‘, Journal of Light wave Technology, Vol. 25, No. 9, pp. 2612-2617, Sep. 2007.

[16] FedaoucheAmal, Abri Badaoui Hadjira, and AbriMehadji,’ Ultra-Highly Efficient 1×3 and 1×6 Splitters for Terahertz Communication Applications’, IEEE Photonics Technology Letters, Vol. 28, No. 13, pp. 1434-1437, July 1, 2016.

[17] D. C. Tee, N. Tamchek, Y. G. Shee, and F. R. Mahamd Adikan, « Numerical investigation on cascaded 1 × 3 photonic crystal power splitter based on asymmetric and symmetric 1 × 2 photonic crystal splitters designed with flexible structural defects », Optical Society of America (OSA), Vol. 22, No. 20, 6 October 2014.

[18] Jian-Hua Chen, Yang-Tung Huang, Yu-Lin Yang, and Ming-Feng Lu, ‘Design, Fabrication, and Characterization of Si-Based ARROW-B Photonic Crystal Sharp-Bend Waveguides and Power Splitters’, Journal of Light wave Technology, Vol. 30, No. 14, July 2012.

[19] Yuzhou Zahao, Yao Zhang, Baojun Li, Bharat Chaudhari, Soo Jin Chua, ‘ Ultra compact and large-scale power splitters on silicon-based two-dimensional photonic crystals at near-infrared wavelengths’, Optical Engineering 45(2), 024601(1-5), Feb. 2006.

[20] Baojun Li, Yuzhou Zhao, Yao Zhang, Zhiwen Chen, Zhangjian Li, ‘Theoretical demonstration of optical power splitter and spot-size converter in silicon photonic crystal waveguides’, Proc. of SPIE Vol. 5956, 595613(1-9), 2005.