Optica Applicata, Vol. XLVI, No. 4, 2016
DOI: 10.5277/oa160404

Improved low channel spacing high quality factor four-channel demultiplexer based on photonic crystal ring resonators

REZA TALEBZADEH*, MOHAMMAD SOROOSH, FARHAD MEHDIZADEH

Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran

*Corresponding author: r-talebi@phdstu.scu.ac.ir

In this paper, we propose a compact structure to realize the demultiplexing operation for dense wavelength division multiplexing communication systems using improved shell-type ring resonators in a photonic crystal structure. The cross-section of the structure is 790 μm^2 and is desirable for integration based on popular planar technology. To improve power transmission coupling efficiency, we introduce the phase matching condition between ring resonators and waveguides; the results exhibit near 100% transmission efficiency. To obtain a high quality factor, we use interior lower refractive indices spheres inside the ring resonators as the mirrors; a quality factor as high as 15497 is achieved. The average pass bands of channels are near 0.1 nm, and the channel spacing is approximately 0.6 nm. The wavelengths of the demultiplexer are 1549, 1549.7, 1550.3 and 1550.9 nm. The crosstalk is between –14 and –29 dB, and the mean value of the crosstalk is –18.39 dB.

Keywords: photonic crystal, photonic band gap, shell-type ring resonator, quality factor, crosstalk.

1. Introduction

Over the last several years, due to the increasing demand for bandwidth requirements, there has been no choice but to improve the capability and efficiency of communication systems. In 2010, the IEEE 802.3 (Ethernet) standard defined two data rate values: 40 and 100 Gb/s [1]. For 100 Gb/s applications, based on the use of a duplex single -mode fibre, four channels, each running at 25.78125 Gb/s, were wavelength division multiplexed and connected to the single-mode fibre through some interfaces [2]. Then, the first generation of 100 Gb/s transceivers became commercially available [3–6]. As the bandwidth demand quickly increased, the next addition to the IEEE 802.3 standard just three years later resulted in the formation of the 400 Gigabit Ethernet Study Group (400 Gb ESG); this increasing of data rate demands was unavoidable in the following years. To form 400 Gb/s, several solutions have been proposed, all of which pertain to using the parallel optical (wavelength) channel approach over conventional single -mode fibres. 16×25, 8×50 and 4×100 Gb/s architectures were the best candidates for obtaining 400 Gb Ethernet (400 GbE) [7, 8]. Channel spacing values of 200, 400 and

800 GHz were chosen by following the development path of the current 100 GbE standard. For the 200 GHz channel spacing, the space between channels is approximately 1 nm [9]. The main goal in the dense wavelength division multiplexing (DWDM) systems was to achieve the maximum number of channel transmissions in a single-mode fibre in the third communication window. Because in the third communication window (wavelengths between 1500 and 1600 nm) the available bandwidth is constant, to have more channels, the channel spacing must be as low as possible. However, when the channel spacing becomes very low, the crosstalk between channels becomes very important. To have very low crosstalk, the passband of channels must be very low and the channels must be as sharp as possible. In other words, the quality factor of demultiplexed channels must be very high. Because of all the features mentioned, in the very near future, the channel spacing will be much less than 1 nm.

Recently, there has been much interest in the study of the propagation of electromagnetic waves in photonic crystals (PhCs) [10]. PhCs are periodic structures that exhibit forbidden frequency regions, in which electromagnetic waves cannot propagate in any polarization and in any direction. By creating defects in the periodic structure of PhCs, local defect modes can exist. Based on these local defect modes, many applications, such as splitters [11], add–drop filters [12–16], optical switches [17], optical data storages [18], demultiplexers [19–32], *etc*., can be achieved.

Optical demultiplexers based on PhCs are among the best candidates for achieving below 1 nm channel spacing. In addition to the below 1 nm channel spacing, there are many other important challenges that must be taken into account when designing a demultiplexer. These include the crosstalk between adjacent channels, the quality factor of each channel, power transmission efficiency, *etc*.

ROSTAMI and MANSOURI-BIRJANDI proposed a demultiplexer that had a channel spacing of approximately 3.5 nm and power transmission efficiency of more than 80%. However, the passband of the channels and, as a result, the quality factor of their structure was not fine [21]. To obtain better channel spacing, they proposed a so-called improved T-type PhC demultiplexer, in which the channel spacing and passband were 1 and 0.45 nm, respectively. The penalty of improving channel spacing was that the power transmission efficiency of their new scheme was, in some channels, even below 50% [22]. RAKHSHANI *et al.* proposed a heterostructure demultiplexer by using a photonic crystal ring resonator (PhCRR), in which every ring had an individual dielectric constant. Their proposed structure was fine with respect to transmission efficiency but suffered from some aspects, especially the channel spacing between channels, which was 6.1 nm [23]. ALIPOUR-BANAEI *et al.* proposed a demultiplexer with X-shaped resonators, which showed fine characteristics. A space between the channels and the quality factor of 3 nm and more than 1700, respectively, were reported. The main problem of their structure was the very low power transmission efficiency [24]. Another interesting work was published by BOUAMAMI and NAOUM. The power transmission efficiency of their proposed structure was very fine but channel spacing was approximately 40 nm which was too high [25]. A plasmonic waveguide, which consisted of a metal–insulator–metal waveguide coupled with a stab resonator and a baffle, which might be applicable to wavelength demultiplexing, was proposed [26]. By using silicon on an insulator substrate in a Y-type PhC structure, a demultiplexer for two optical communication windows for λ_1 = 1310 nm and λ_2 = 1550 nm was proposed by RAWAL and SINHA power transmission efficiencies of 89% and 69% for the mentioned wavelengths were reported, respectively [27]. Implementing four different refractive indices for rings by using a heterostructure demultiplexer caused four different wavelengths to be demultiplexed within the third communication window. Normalized power transmission efficiency over 85% was reported, but the channel spacing was more than 30 nm, which is too high [28]. Applying two different types of lattices in a modified Y-waveguide air hole in a GaAs slab caused separation of λ_1 = 1310 nm and λ_2 = 1490 nm in the output. It was claimed that their proposed structure also has the ability to separate wavelengths for λ_1 = 1310 nm and λ_2 = 1550 nm by changing lattice parameters. Although a fine power transmission efficiency of above 97% was reported, the channel spacing was not acceptable [29]. Based on the directional coupling of one-dimensional PhC waveguides, a dual channel DWDM was proposed by BING CHEN *et al*. In this structure, a power transmission efficiency of above 95% was reported, but because the demultiplexed wavelengths were λ_1 = 1490 nm, λ_2 = 1630 nm, λ_3 = 1670 nm and λ_4 = 1760 nm, the channel separation between channels was not suitable [30]. LIAO QING-HUA *et al*. proposed a T-shape demultiplexer, which could separate two wavelengths, with a separation channelling of 8 nm. The transmission they reported was below 60% [31].

In our last work, we proposed a demultiplexer using ring resonators in a two-dimensional PhC, which although showed a high quality factor, average quality factor equals 4860, and fine coupling efficiency, possessed a channel spacing that was not fine enough to utilize the maximum efficiency of a fibre [32].

All of the works performed in this area clearly reveal one point: a demultiplexer that can separate channels from input light and is compatible with the high demand for bandwidth increasing is essential. Near 100% power transmission efficiency, below 1 nm channel spacing, a high quality factor of channels and low crosstalk are the key parameters in designing this demultiplexer, which have not been achieved simultaneously so far to our knowledge.

In this paper, we propose an improved four-channel demultiplexer that uses ring resonators in PhCs, yielding a very high quality factor, low crosstalk, near 100% power transmission efficiency and channel spacing below 0.6 nm. The rest of the paper is organized as follows: in Section 2, the photonic band gap will be calculated and then the demultiplexer structure will be introduced. In Section 3, the results will be investigated and compared with those of previous literatures; finally, the conclusion of this work and the simulation results will be presented in Section 4.

2. Proposed demultiplexer

The first step of design is to investigate the photonic band gap (PBG) of the structure. The calculation of the PBG for a demultiplexer is performed using the plane wave expansion (PWE) method [33]. We employed the BandSOLVE simulation tool to perform PWE calculations. The structure we used for design was a 67×26 cubic lattice of dielectric rods immersed in air. For accurate modelling of the proposed device, we need a 3D simulation, which requires a great amount of run time and very powerful computer. Thus, we used the effective index approximation method of PhCs to satisfy this requirement; with this approximation, we reduced the 3D simulations to 2D simulations [34]. The effective refractive index of fundamental dielectric rods was $n = 3.58$, the radius of rods was 175 nm and the lattice constant was $a = 730$ nm. The band structure diagram of the demultiplexer is shown in Fig. 1.

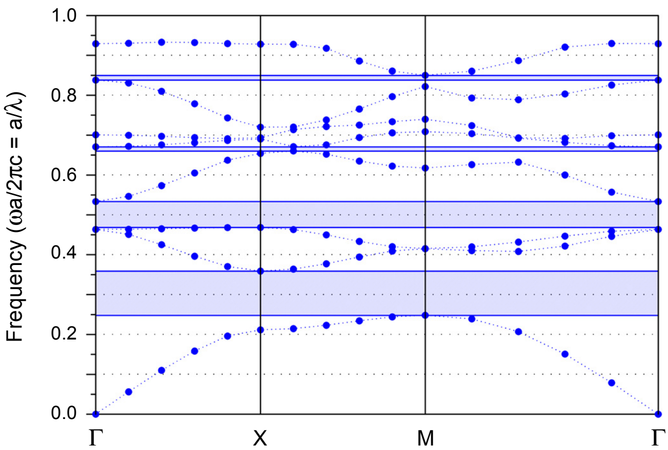

Fig. 1. The band structure diagram of the proposed PhC.

Figure 1 shows that there are four PBG regions in the structure. We designed the device to work in the second PBG region, which has $0.46512 < a/\lambda < 0.5290$ and is equal to $1380\ \text{nm} < \lambda < 1570\ \text{nm}$. The results show that the proposed demultiplexer can work in the third communication window and is suitable for all optical communications.

The structure we designed is shown in Fig. 2**a** and consists of an input waveguide, which was created by removing complete rods of a row and four output waveguides, depicted as ports A, B, C and D. In addition to these waveguides, four ring resonators act as the couplers of the light. The macroscopic view of the first ring is shown in Fig. 2**b**. We used shell-type resonators in the proposed demultiplexer, in which the interior spheres had refractive indices lower than the refractive index of the rings ($n_1 = 1.6$).

The rods of each ring and the coupling rods, *i.e.*, the rods in the waveguides in which coupling occurs between the waveguides and the ring resonator, have exactly the same refractive index and radius. The rods of all four rings, which are shown using dark green, yellow, dark blue and light green for the output ports of A, B, C and D, respectively, have effective refractive indices exactly equal to the refractive index of the basis lattice rods ($n = 3.58$) but different radii. By changing these radii, which are shown in

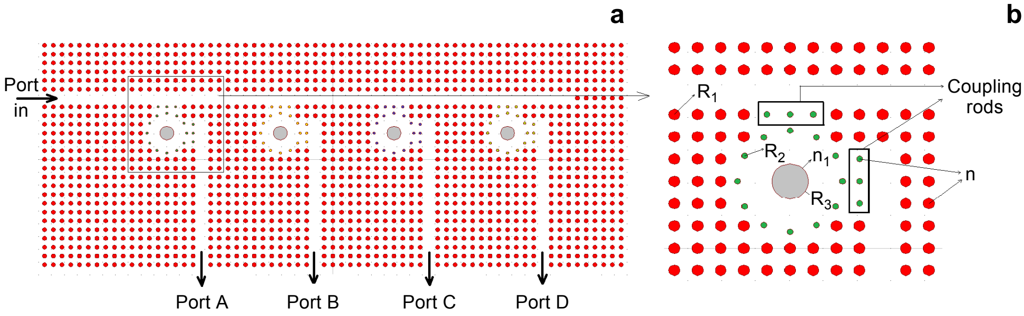

Fig. 2. The schematic diagram of the proposed demultiplexer (**a**); a macroscopic view of the first resonant ring (**b**).

Fig. 2**b** for the first ring by R_{21}, we could change the resonant frequency of the rings and achieve the demultiplexing of channels. The radii of the first, second, third and fourth ring are denoted as R_{21}, R_{22}, R_{23} and R_{24}, respectively, and are $R_{21} = 95$ nm, $R_{22} = 100$ nm, $R_{23} = 105$ nm and $R_{24} = 110$ nm.

To design the proposed demultiplexer, we emphasize three concepts. First, where the coupling occurs, *i.e.*, the coupling between the waveguides and the ring resonator, the rods of the rings and waveguides are chosen to be exactly equal to obtain efficient coupling. The results of the power transmission coupling efficiency verify the validity of this assumption. Second, the refractive indices of the interior spheres (n_1 in Fig. 2**b**) are chosen to be lower than the effective refractive indices of the rings so that they will not let the light go into the centre of the rings. Based on the classic whispering gallery mode (WGM) theory and our last work [35, 36], it is known that if the light propagates more near to the surface of a resonator, a higher quality factor can be achieved. By taking this into account, we could achieve a quality factor of as high as $Q = 15497$ in the structure, which again verifies the accuracy of this assumption. Third, the interior spheres inside the rings are employed instead of the rings. In all the reports in the literature, multilayer ring resonators have been proposed. Because the goal of the interior layers in multilayer ring resonators is to avoid light propagating inside a ring, we employed spheres in the cores of the rings; the simulation results show that the quality factor has improved significantly. From another point of view, because the interior microsphere inside the main ring resonator in the proposed structure has a very large radius value, the fabrication of the proposed demultiplexer can be much easier compared to demultiplexers that consist of a main ring resonator and two ring resonators inside them, with much smaller radii.

3. Simulation results

This paper focuses on the design of a low channel spacing demultiplexer that has a very high quality factor, complete coupling and very fine crosstalk. As shown in Fig. 3, the structure can separate four channels, with central wavelengths equal to $\lambda_1 = 1549$ nm,

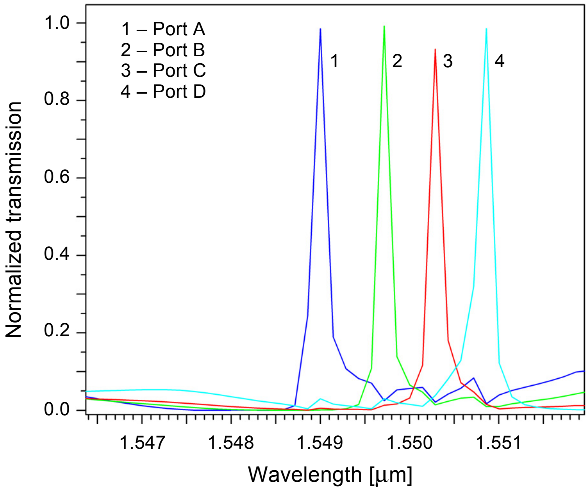

Fig. 3. Output spectrums in ports A, B, C and D.

λ_2 = 1549.7 nm, λ_3 = 1550.3 nm and λ_4 = 1550.9 nm. Figure 3 shows that all ports show near-complete transmission efficiency. One of the most important results that can be noticed is that complete power transmission coupling efficiency is achieved in a situation where the quality factor is high too. As mentioned earlier, in the attempts to increase the transmission efficiency, the quality factor was lost. However, using this demultiplexer, both a complete coupling and high quality factor are obtained. The complete details of the channels are given in Table 1. The quality factor ($Q = \lambda/\Delta\lambda$) varies from 11930 to 15497. The space between output channel ports is 0.7 nm for port A and port B and 0.6 nm for others. This very low channel spacing makes the proposed demultiplexer suitable for DWDM systems. Furthermore, the very high quality factor of the channels (very low passband of every channel) allows more channels to be placed near each other without considerable crosstalking.

The distribution of optical waves inside the demultiplexer for four wavelengths, *i.e.*, λ_1 = 1549 nm, λ_2 = 1549.7 nm, λ_3 = 1550.3 nm and λ_4 = 1550.9 nm, are shown in Fig. 4. Because all the wavelengths are located in the PBG region, they cannot scatter in the structure and propagate in the waveguides. Figure 4**a** demonstrates that the first

T a b l e 1. The output characteristics of the demultiplexer.

Channel	Central wavelength [nm]	Quality factor	Passband [nm]	Transmission efficiency [%]
Port A	1549	12908	0.12	98
Port B	1549.7	15497	0.1	99
Port C	1550.3	14093	0.11	96
Port D	1550.9	11930	0.13	98

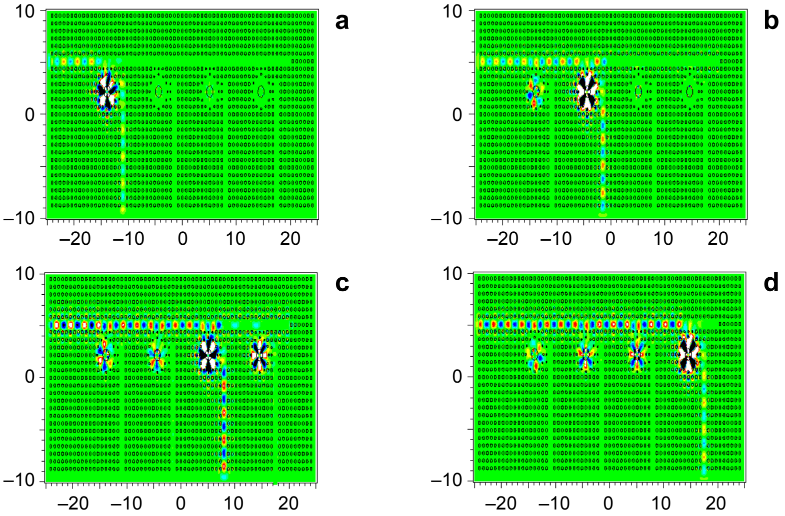

Fig. 4. The calculated field distribution inside the structure at four wavelengths: 1549 (**a**), 1549.7 (**b**), 1550.3 (**c**) and 1550.9 nm (**d**).

ring resonator can drop the incoming light, at a wavelength λ_1 = 1549 nm, to port A, while others cannot couple this wavelength. A similar result can be observed in Figs. 4**b**–4**d**, in which the rings can only couple their resonant wavelengths.

To show the low crosstalking of adjacent channels and compare the crosstalk values of the proposed demultiplexer with other previous works, the output of the proposed device in decibel scale is shown in Fig. 5.

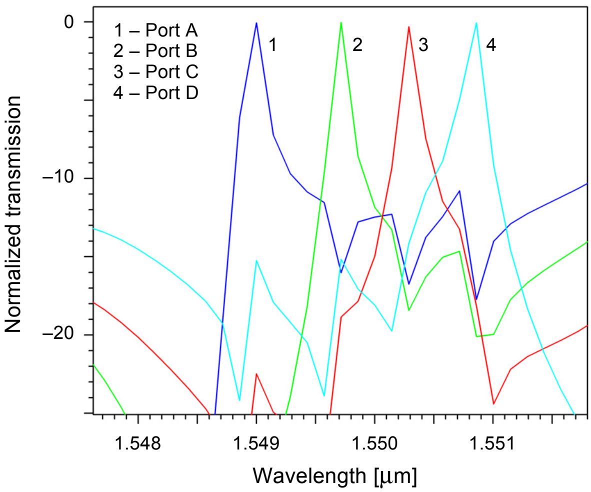

Fig. 5. Output spectrums in ports A, B, C and D in decibel scale.

Table 2. The crosstalk values between the channels.

	Channel 1, λ_1 = 1549 nm	Channel 2, λ_2 = 1549.7 nm	Channel 3, λ_3 = 1550.3 nm	Channel 4, λ_4 = 1550.9 nm
Channel 1, λ_1 = 1549 nm	—	–29	–22.3	–15.3
Channel 2, λ_2 = 1549.7 nm	–15.8	—	–18.7	–15.1
Channel 3, λ_3 = 1550.3 nm	–16.7	–18	—	–14
Channel 4, λ_4 = 1550.9 nm	–17.6	–20.1	–17.6	—

The crosstalk values between the channels are shown in more detail in Table 2. Table 2 shows that the minimum and maximum crosstalks are –14 and –29 dB, respectively, which are low. The mean value of crosstalks is –18.39 dB.

Although when the channel spacing becomes very low, the crosstalks of adjacent channels become challenging, all the values of crosstalks reveal that the proposed structure is suitable even for very low channel spacing. A comparison between the minimum value, maximum value and mean value of crosstalks is given in Table 3.

Table 3. Comparison between the minimum, maximum and mean value of crosstalks of other works with those of the proposed demultiplexer.

Reference	Minimum of crosstalk [dB]	Maximum of crosstalk [dB]	Mean value of crosstalk [dB]
[22]	–14.2	–28.86	–21.1
[24]	–7.5	–23.7	–15.42
[25]	–10.49	–33.18	–22.45
[32]	–20.5	–42	–28.66
This work	–14	–29	–18.39

Average channel separation, average quality factor, average passband and power transmission efficiency of other works and of the proposed demultiplexer are shown in Table 4.

As discussed in Table 4, the proposed demultiplexer has much better performance compared with those of recently proposed works [22–25, 32]. As known, channel spacing, quality factor and transmission efficiency are very vital parameters in demultiplexer performance. To realize all optical communication networks based on DWDM standards, we need a channel spacing of as low as 0.8 nm [37]. Reducing channel spacing requires very narrow band channels. To avoid high crosstalk, in this paper, we succeeded in realizing optical channels with very narrow bands and a quality factor of as high as 13000. As a result, we obtained a channel spacing of approximately 0.6 nm

T a b l e 4. Comparison of obtained results with those of other works.

Reference	Channel separation [nm]	Average quality factor	Average passband [nm]	Average transmission efficiency
[24]	3	1234	1.7	50
[22]	1	3488	0.45	55
[23]	6.1	842	2.75	95
[32]	2	3600	0.3975	99.25
This work	0.6	13607	0.115	98

with acceptable levels of crosstalk. Specially, when the channel spacing is very low, the crosstalk between channels will be a vital parameter. For interference filter-based demultiplexers, their high crosstalk has restricted their application [38, 39].

For the demultiplexers that have been studied based on ring resonators, shell type (multilayer ring resonators) was utilized. Based on conventional WGMs theory, when much light is confined near the surface of a ring, the quality factor of a structure will be improved, and when light penetrates into the centre of a ring resonator, the quality factor will drop significantly [35, 36]. To prohibit light from entering the centre of ring resonators, we used a core with a very large radius. The result of this novelty was an improvement of the quality factor of the device to as high as 13000. Because we only used one large rod (instead of the 12 rods that form the interior ring resonator), fabrication of the proposed structure is much easier compared to previous works. Another parameter that we emphasized was where the coupling occurs between resonators and waveguides. By using the same rods for each ring, we could couple light to a ring and from a ring to the output waveguides more efficiently. The result of this concept was near-complete transmission efficiency of each channel. As the quality factor of channels became more than 13000, the sharpness of channels was improved and also the space between output channels became as low as 0.6 nm. However, by improving the channel spacing and quality factor of the device, the crosstalk of the demultiplexer was acceptable compared with other works [22–24, 32].

4. Conclusions

In this work, a very low channel spacing and high quality factor 4-channel wavelength division demultiplexer based on the PhC was proposed. In the proposed structure, four shell-type resonators with different exterior radii were suggested, in which all the rings had an interior sphere with a lower refractive index compared to the refractive indices of the main resonators and the lattice, thus, being able to act as a reflector; as a result, the demultiplexer could separate the wavelengths. The proposed structure showed very attractive properties, which are excellent bases for demultiplexers. An output power efficiency very near to 100% was obtained using the proposed demultiplexer. Low crosstalk, high quality factor, low bandwidth and very low channel spacing are the significant properties that were achieved. Four channels with a channel spacing of approximately 0.6 nm, average bandwidth of 0.11 nm and mean crosstalk value of –18.39 dB were obtained. The quality factor in port D of the demultiplexer could reach 15497, and the overall size of the demultiplexer was approximately 790 μm^2.

References

[1] IEEE 802.3ba, IEEE Standard, 2010; http://standards.ieee.org/about/get/802/802.3.html

[2] Kanazawa S., Fujisawa T., Nunoya N., Ohki A., Takahata K., Sanjoh H., Iga R., Ishii H., *Ultra -compact 100 GbE transmitter optical sub-assembly for 40-km SMFtransmission*, Journal of Lightwave Technology **31**(4), 2013, pp. 602–608.

[3] Fujitsu, 100GE CFP Transceiver, Part No. FIM37201, 2013; http://jp.fujitsu.com/group/foc/en/services/optical-modules/100gcfp/

[4] Fujisawa T., Kanazawa S., Ishii H., Nunoya N., Kawaguchi Y., Ohki A., Fujiwara N., Takahata K., Iga R., Kano F., Oohashi H., *1.3-μm 4×25-Gb/s monolithically integrated light source for metro area 100-Gb/s Ethernet*, IEEE Photonics Technology Letters **23**(6), 2011, pp. 356–358.

[5] Aruga H., Mochizuki K., Itamoto H., Takemura R., Yamagishi K., Sugitatsu A., *Integrated receiver for 100 GbE*, [In] *16th Opto-Electronics and Communications Conference, OECC 2011*, Kaohsiung, Taiwan, 2011, pp. 460–461.

[6] Yoshimatsu T., Nada M., Oguma M., Yokoyama H., Ohno T., Doi Y., Ogawa I., Takahashi H., Yoshida E., *Compact and high-sensitivity 100-Gb/s (4×25 Gb/s) APD-ROSA with a LAN-WDM PLC demultiplexer*, Optics Express **20**(26), 2012, pp. B393–B398.

[7] Song X., Stassar P., Zeng L., Zhai S., Wang X., Chen W., Zhou W., *Considerations on options for 400 GE optical interfaces*, Presented at IEEE 400 GbESG Interim, Victoria, Canada, 2013; http://www.ieee802.org/3/400GSG/public/13_05/ song_400_01_0513.pdf

[8] Turkiewicz J.P., De Waardt H., *Low complexity up to 400-Gb/s transmission in the 1310-nm wavelength domain*, IEEE Photonics Technology Letters **24**(11), 2012, pp. 942–944.

[9] Torres-Ferrera, P., Gutiérrez-Castrejón R., *Impact of channel-spacing on next 400 Gb/s Ethernet 40-km PMD based on 16×25 Gb/s WDM architecture*, Optical Fiber Technology **20**(3), 2014, pp. 177–183.

[10] Yablonovitch E., *Inhibited spontaneous emission in solid-state physics and electronics*, Physical Review Letters **58**(20), 1987, p. 2059.

[11] Shanhui Fan, Johnson S.G., Joannopoulos J.D., Manolatou C., Haus H.A., *Waveguide branches in photonic crystals*, Journal of the Optical Society of America B **18**(2), 2001, pp. 162–165.

[12] Sharkawy A., Shouyuan Shi, Prather D.W., *Multichannel wavelength division multiplexing with photonic crystals*, Applied Optics **40**(14), 2001, pp. 2247–2252.

[13] Koshiba M., *Wavelength division multiplexing and demultiplexing with photonic crystal waveguide couplers*, Journal of Lightwave Technology **19**(12), 2001, pp. 1970–1975.

[14] Chun-Chih Wang, Lien-Wen Chen, *Channel drop filters with folded directional couplers in two-dimensional photonic crystals*, Physica B: Condensed Matter **405**(4), 2010, pp. 1210–1215.

[15] Robinson S., Nakkeeran R., *PCRR based add drop filter for ITU-T G.694.2 CWDM systems*, Optik – International Journal for Light and Electron Optics **124**(5), 2013, pp. 393–398.

[16] Niemi T., Frandsen L.H., Hede K.K., Harpoth A., Borel P.I., Kristensen M., *Wavelength-division demultiplexing using photonic crystal waveguides*, IEEE Photonics Technology Letters **18**(1), 2006, pp. 226–228.

[17] Cuesta-Soto F., Martinez A., Garcia-Banos B., Marti J., *Numerical analysis of all-optical switching based on a 2-D nonlinear photonic crystal directional coupler*, IEEE Journal of Selected Topics in Quantum Electronics **10**(5), 2004, pp. 1101–1106.

[18] TAO LIU, ZAKHARIAN A., RATHNAKUMAR R., FALLAHI M., MOLONEY J.V., MANSURIPUR M., *Applications of photonic crystals in optical data storage*, Proceedings of SPIE **5380**, 2004, pp. 430–438.

[19] BENISTY H., CAMBOURNAC C., VAN LAERE F., VAN THOURHOUT D., *Photonic-crystal demultiplexer with improved crosstalk by second-order cavity filtering*, Journal of Lightwave Technology **28**(8), 2010, pp. 1201–1208.

[20] LENGLÉ K., GAY M., BRAMERIE L., SIMON J.C., COMBRIÉ S., LEHOUCQ G., DE ROSSI A., MALAGUTI S., BELLANCA G., TRILLO S., *Wavelength division demultiplexing and crosstalk assessment of a photonic crystal filter*, IEEE Photonics Technology Letters **24**(23), 2012, pp. 2109–2111.

[21] ROSTAMI A., ALIPOUR BANAEI H., NAZARI F., BAHRAMI A., *An ultra compact photonic crystal wavelength division demultiplexer using resonance cavities in a modified Y-branch structure*, Optik – International Journal for Light and Electron Optics **122**(16), 2011, pp. 1481–1485.

[22] ROSTAMI A., NAZARI F., ALIPOUR BANAEI H., BAHRAMI A., *A novel proposal for DWDM demultiplexer design using modified-T photonic crystal structure*, Photonics and Nanostructures – Fundamentals and Applications **8**(1), 2010, pp. 14–22.

[23] RAKHSHANI M.R., MANSOURI-BIRJANDI M.A., *Design and simulation of wavelength demultiplexer based on heterostructure photonic crystals ring resonators*, Physica E: Low-dimensional Systems and Nanostructures **50**, 2013, pp. 97–101.

[24] ALIPOUR-BANAEI H., MEHDIZADEH F., SERAJMOHAMMADI S., *A novel 4-channel demultiplexer based on photonic crystal ring resonators*, Optik – International Journal for Light and Electron Optics **124**(23), 2013, pp. 5964–5967.

[25] BOUMAMI S., NAOUM R., *New version of seven wavelengths demultiplexer based on the microcavities in a two-dimensional photonic crystal*, Optik – International Journal for Light and Electron Optics **125**(23), 2014, p. 7072–7074.

[26] ZHAO CHEN, RU HU, LUNA CUI, LI YU, LULU WANG, JINGHUA XIAO, *Plasmonic wavelength demultiplexers based on tunable Fano resonance in coupled-resonator systems*, Optics Communications **320**, 2014, pp. 6–11.

[27] RAWAL S., SINHA R.K., *Design, analysis and optimization of silicon-on-insulator photonic crystal dual band wavelength demultiplexer*, Optics Communications **282**(19), 2009, pp. 3889–3894.

[28] DJAVID M., MONIFI F., GHAFFARI A., ABRISHAMIAN M.S., *Heterostructure wavelength division demultiplexers using photonic crystal ring resonators*, Optics Communications **281**(15–16), 2008, pp. 4028–4032.

[29] XUAN ZHANG, QINGHUA LIAO, TIANBAO YU, NIANHUA LIU, YONGZHEN HUANG, *Novel ultracompact wavelength division demultiplexer based on photonic band gap*, Optics Communications **285**(3), 2012, pp. 274–276.

[30] BING CHEN, CHUNLIANG LIU, GUIZHONG LIU, *A compact wavelength division de-multiplexer based on directional coupling of one-dimensional photonic crystal waveguides*, Optics Communications **285**(24), 2012, pp. 5100–5106.

[31] LIAO QING-HUA, FAN HONG-MING, CHEN SHU-WEN, WANG TONG-BIAO, YU TIAN-BAO, HUANG YONG-ZHEN, *The design of large separating angle ultracompact wavelength division demultiplexer based on photonic crystal ring resonators*, Optics Communications **331**, 2014, pp. 160–164.

[32] TALEBZADEH R., SOROOSH M., *A high quality complete coupling 4-channel demultiplexer based on photonic crystal ring resonators*, Optoelectronics and Advanced Materials – Rapid Communications **9**(1–2), 2015, pp. 5–9.

[33] JOHNSON S.G., JOANNOPOULOS J.D., *Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis*, Optics Express **8**(3), 2001, pp. 173–190.

[34] MIN QIU, *Effective index method for heterostructure-slab-wave-guide-based two-dimensional photonic crystals*, Applied Physics Letters **81**(7), 2002, pp. 1163–1165.

[35] STRUTT J.W. (LORD RAYLEIGH), *Teoriya zvuka*, Vol. 2, Gostekhizdat, Moscow, 1955.

[36] TALEBI R., ABBASIAN K., ROSTAMI A., *Analytical modeling of quality factor for shell type microsphere resonators*, Progress in Electromagnetics Research B **30**, 2011, pp. 293–311.

[37] CHENG-CHUNG LEE [Ed.], *The Current Trends of Optics and Photonics*, Topics in Applied Physics, Vol. 129, Springer Netherlands, 2015.
[38] YUEYU XIAO, SAILING HE, *An MMI-based demultiplexer with reduced cross-talk*, Optics Communications **247**(4–6), 2005, pp. 335–339.
[39] MARTELUCCI S, CHESTER A.N. [Eds.], *Integrated Optics: Physics and Applications*, Series B: Physics, Vol. 91, Plenum Press, New York, 1983.

Received February 5, 2016
in revised form May 12, 2016