Ultracompact 1310/1550 nm wavelength demultiplexer based on subwavelength grating-assisted multimode interference coupler

Fuling Wang, Xiao Xu,* Chonglei Sun, and Jia Zhao
Shandong University, School of Information Science and Engineering, Qingdao, China

Abstract. An ultra-compact 1310/1550 nm wavelength demultiplexer based on multimode interference (MMI) coupler assisted by subwavelength gratings (SWGs) is proposed. Two parallel SWG-based slots are inserted into the MMI section symmetrically. Equivalent refractive index and width of the SWG are designed properly to reduce the device length while keeping a low insertion loss (IL) and high extinction ratio (ER). In this way, the device length shrinks to 34.48 μm. The performance when the device working as a multiplexer and as a demultiplexer are both investigated. From the transmission spectrum, ILs of <0.24 dB, ERs of larger than 15.2 dB and broad 1-dB bandwidths of larger than 90 nm are obtained for the two wavelengths. [DOI: 10.1117/1.OE.60.8.087104]

Keywords: wavelength demultiplexer; subwavelength grating; multimode interference coupler.

Paper 20210527 received May 18, 2021; accepted for publication Jul. 27, 2021; published online Aug. 11, 2021.

1 Introduction

With continuously increasing demand for broadband services, such as big data, cloud computing, and large-capacity communications, wavelength division multiplexing (WDM) technology has been widely used thanks to its ability to increase the number of channels and the transmission bandwidth.[1] Significant attention is paid to wavelength demultiplexers with features of compact size, low insertion loss (IL), high extinction ratio (ER) and broad bandwidth.[2] What's more, silicon on-insulator (SOI) is an attractive platform for wavelength multiplexers due to its high integration density and fabrication compatibility with the complementary metal-oxide-semiconductor technology.

Several solutions to demultiplex two wavelengths in O-band and C-band have been demonstrated such as diffraction grating couplers,[3,4] micro-ring resonators,[5] directional couplers,[6–9] and multimode interference (MMI) couplers.[2,10–12] Diffraction grating couplers can demultiplex multiple wavelengths by diffracting them into different spatial directions, which is not suitable for on-chip interconnects. Wavelength demultiplexers using cascaded silicon micro-ring resonators are compact and scalable, but they are limited by the small bandwidth and the high temperature sensitivity. Directional couplers also suffer from the limited bandwidth and fabrication tolerance due to their precise phase matching condition. MMI-based demultiplexers that provide a relatively broad optical bandwidth, relax fabrication tolerance, and low IL have drawn much attention as the most potential candidates. However, the length of the MMI section must be odd times or even times of the beat lengths for both wavelengths, which leads to a long device length of larger than 100 μm. To reduce the device length, slotted MMI devices have been proposed. It has been verified that introducing N slots reduces the self-imaging length by a factor of $N + 1$.[13] However, effective indices of slots need to be carefully adjusted by varying etching depths, which makes the fabrication process complicated.

On the other hand, subwavelength grating (SWG) has been widely investigated for designing new photonic components because the SWG provides a new degree of freedom to manipulate the refractive index by regulating structural parameters.[14–16] It is worth noting that the SWG's period is

---

*Address all correspondence to Xiao Xu, xuxiao@sdu.edu.cn smaller than its operating wavelength, consequently, the reflection and diffraction effects of the grating are suppressed.[17,18] As a result, the SWG behaves as a homogeneous medium with an equivalent refractive index (n_e), and n_e can be adjusted by changing the period and the duty circle. SWG exhibits the capability of reducing the device length or broadening the bandwidth. The SWG has been inserted into the middle of the MMI section to reduce the beat length for 3-dB coupler[19] and wavelength demultiplexer,[20] and the devices' lengths are reduced. Also, the broadband wavelength demultiplexer assisted by SWG-based directional coupler is proposed and simulated.[21]

In this paper, we propose an ultra-compact 1310/1550 nm wavelength demultiplexer based on MMI coupler with two parallel SWG-based slots. Instead of varying the slot index using a shallow etch depth, two longitudinal SWG structures with the same etch depth are inserted into the MMI section, and equivalent refractive indices of slots are judiciously engineered to shrink the device length. The designed device is only 34.48-μm-length long. The IL, 1-dB bandwidth, ER, and fabrication tolerances of the proposed wavelength demultiplexer are evaluated subsequently. In addition, the performance for the wavelength multiplexer is also demonstrated.

2 Design and Analysis

Schematics of the proposed MMI wavelength demultiplexer are shown in Fig. 1. This device is designed based on the SOI wafer with top Si thickness of 220 nm and the SiO_2 is employed as the upper cladding material. The wavelength demultiplexer is composed by two S-bent input channels, the MMI section, and two S-bent output channels. To reduce the IL and the number of stimulated high-order modes, linear tapered waveguides are used to connect the input and output waveguides with the multimode waveguide. Two parallel SWG-based slots are located symmetrically in the MMI section with lateral offsets of approximately $\pm w_{\mathrm{MMI}}/6$. The period is denoted as Λ and segment length of the high-index medium (Si) along the propagation direction is denoted as a, namely, the segment length of low-index medium (SiO_2) is $\Lambda - a$. According to the effective medium theory,[22] the SWG-based slot can be considered as homogenous medium with an equivalent refractive index of n_e, which is shown in Fig. 1(c).

To keep the SWG operating at the subwavelength region, the grating period must be smaller than the Bragg period (Λ_{Bragg}). For the wavelength with $\lambda_{\min}$ of 1200 nm, the equation of $\Lambda < \Lambda_{\mathrm{Bragg}} = \lambda/(2n_{\mathrm{eff}}) \approx 220$ nm must be fulfilled. In addition, taking the practical fabrication ability into account, we choose the period Λ of 180 nm, and the dimension of Si or SiO_2 segment should be within a range of 40 to 140 nm.

Other parameters used for designing the device are as follows: widths of the input and output channels are 0.45 μm to keep a single-mode operation. Bends with the radius of 15 μm are used to decouple the input and output waveguides. For adiabatic conditions, the taper width w_{taper} and length L_{taper} are set to 0.9 and 5 μm, respectively. The MMI width w_{MMI} is set to 2 μm, which is a tradeoff between a shorter beat length and an easier beam splitting.

The fundamental principle of MMI demultiplexer is the self-imaging effect.[23] Single image or multiple images of the input field can be periodically reproduced after propagating in the multimode waveguide region. When the input field is launched off-center into the MMI device, a direct image (bar state) will be formed at the length of $L = p(3L_\pi)$ with p of an even integer

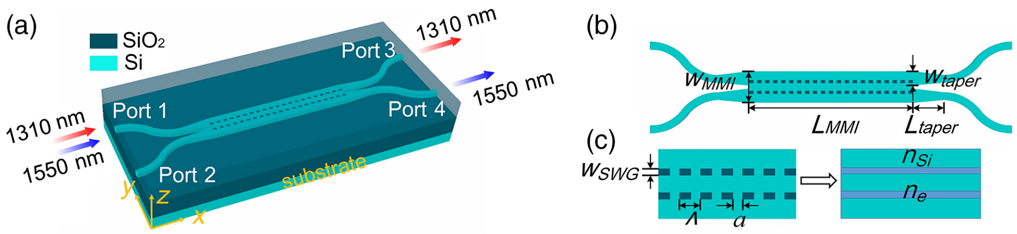

Fig. 1 Schematics of the SWG-based MMI wavelength demultiplexer. (a) Three-dimensional view, (b) top view and (c) the SWG-based slot can be represented as homogeneous medium with an equivalent refractive index n_e.

and a mirrored image (cross state) will be formed with p of an odd integer. Here, L_π is the beat length of the two lowest-order modes. The expected beat length of a standard off-center-stimulated MMI device is given roughly as

$$L_\pi = \frac{\lambda}{2(n_{\mathrm{eff},0}(\lambda) - n_{\mathrm{eff},1}(\lambda))} \approx \frac{4nw_{\mathrm{eff}}^2}{3\lambda}, \tag{1}$$

where $n_{\mathrm{eff},0}(\lambda)$ and $n_{\mathrm{eff},1}(\lambda)$ are effective indices of the two lowest-order modes at wavelength λ, n and w_{eff} are the effective index and effective width of the standard MMI region respectively.

In order to demultiplex the two wavelengths of 1310 and 1550 nm, the length L_{MMI} should satisfy the following equation,

$$L_{\mathrm{MMI}} = p(3L_\pi(1310)) = (p+1)(3L_\pi(1550)), \tag{2}$$

where p is a positive integer. It follows that a direct image is formed for one wavelength as the bar state, and a mirrored image is formed for the other wavelength as the cross state.

With the purpose of shrinking the MMI length, we need to decrease self-imaging length on the one hand and make p smaller on the other hand. Introducing two parallel SWG-based slots to the MMI region can dramatically alter the self-imaging properties.[13] As a result, by properly designing the SWG-slots' parameters, the self-imaging length is reduced by a factor of 3. Therefore, Eq. (2) can be written as

$$L_{\mathrm{MMI}} = pL_\pi(1310) = (p+1)L_\pi(1550). \tag{3}$$

The SWG is considered as homogenous medium, and the equivalent index n_e and the SWG width w_{SWG} play a key role in manipulating the beat length as well as the value of p. 2D mode analysis is used to calculate the effective index of the two lowest modes and beat lengths at 1310 and 1550 nm are obtained based on Eq. (1), respectively. The ratio between L_π (1310) and L_π (1550) as functions of w_{SWG} and n_e is shown in Fig. 2(a). We can see that limited by the practical fabrication ability, the ideal condition with ratio of 2, namely, p value of 1, can hardly be achieved. But the ratio of 1.5, can be obtained by judiciously designing w_{SWG} and n_e of the two SWG-based slots. In a word, the ratio of 1.5 that resulting in $p = 2$ in Eq. (3) are selected and the contour line is highlighted. Dependence of L_π (1310) and $L_\pi(1550)$ on w_{SWG} and n_e are shown in Fig. 2(b) and 2(c), respectively. Considering that a narrower slot has a larger absolute tolerance for n_e,[13] w_{SWG} is chosen to be 60 nm, therefore, n_e is set to 2.44, which is illustrated as a star marker in Fig. 2(a). In that case, L_π (1310) is 17.82 μm and $L_\pi(1550)$ is 11.89 μm. The total MMI length that satisfies the following equation is achieved: $L_{\mathrm{MMI}} = 2L_\pi(1310) = 3L_\pi(1550) \approx 35.65$ μm.

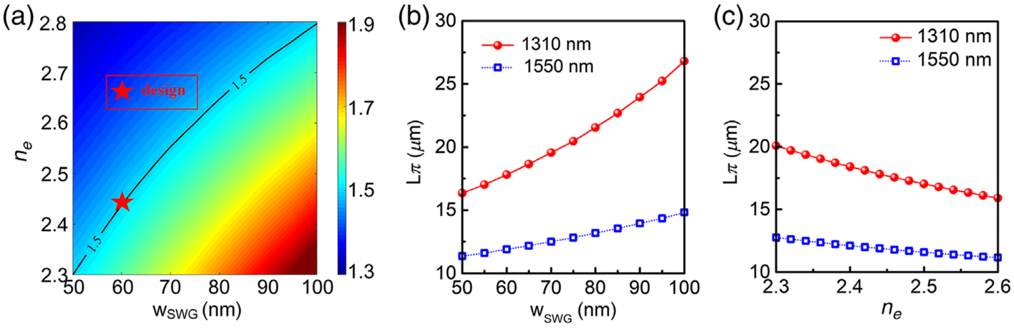

Fig. 2 (a) The ratio between $L_\pi(1310)$ and $L_\pi(1550)$ as functions of SWG width w_{SWG} and equivalent index n_e. Dependence of $L_\pi(1310)$ and $L_\pi(1550)$ on (b) SWG width w_{SWG} and (c) equivalent index n_e.

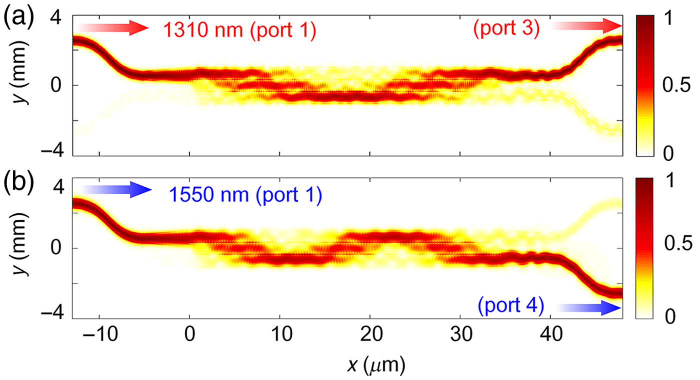

Fig. 3 Field distribution of the SWG-based MMI wavelength demultiplexer at the wavelength of (a) 1310 nm and (b) 1550 nm.

3 Results and Discussion

The relationship between the equivalent refractive index n_e and the grating parameters can be estimated by Rytov's formulas roughly.[14] However, it is not accurate enough especially when the SWG do not operate at the deep subwavelength region. To improve the performance of the wavelength demultiplexer, the actual length and duty circle (or the Si segment length a) need to be optimized by the 3D finite-difference time-domain (FDTD) method.

Taking the wavelength demultiplexer for instance, the 3D FDTD simulation is applied. The optimal silicon segment length a is 80 nm, namely, the duty circle is about 0.44. Field distribution of the optimized demultiplexer at 1310 and 1550 nm are shown in Figs. 3(a) and 3(b), respectively. It shows that light of 1310 nm transmits from Port 1 to Port 3 (bar-state) and that of 1550 nm transmits from Port 1 to Port 4 (cross-state), which is consistent with the aforementioned theoretical analysis. In that case, the actual MMI length L_{MMI} is only 34.48 μm.

Then the transmission spectrum from 1200 to 1650 nm is obtained and shown in Fig. 4, and the IL, ER, and 1-dB bandwidth can be read from the spectrum. IL is 0.12 dB at 1310 nm and 0.24 dB at 1550 nm. ERs of 15.2 and 16.8 dB are achieved at these two wavelengths, respectively. The SWG-based slots introduce disturbance to the original waveguide modes, which leads to a relatively low ER. That's why we bring two slots into the MMI section rather than three or more, regardless of the shorter beat length. As the blue stripes in Fig. 4 indicate, the designed demultiplexer shows a broad 1-dB bandwidth of larger than 90 nm at both wavelengths.

Figure 5 shows the numerical results of fabrication tolerances at 1310 and 1550 nm. IL and ER dependence on the variation of the Si segment length (Δa), SWG-based slot width (Δw_{SWG}),

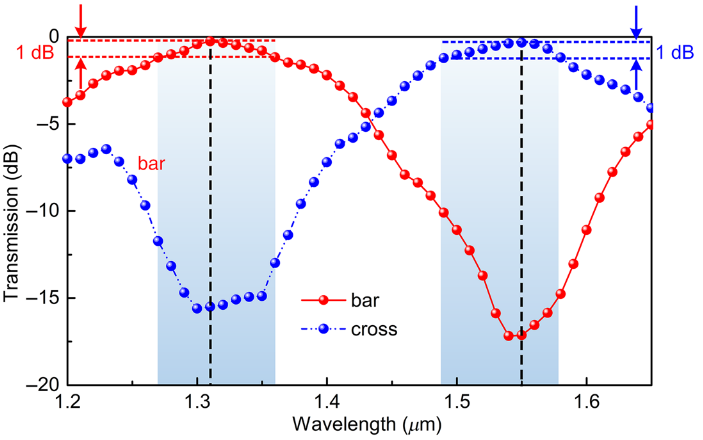

Fig. 4 Transmission spectrum of the wavelength demultiplexer.

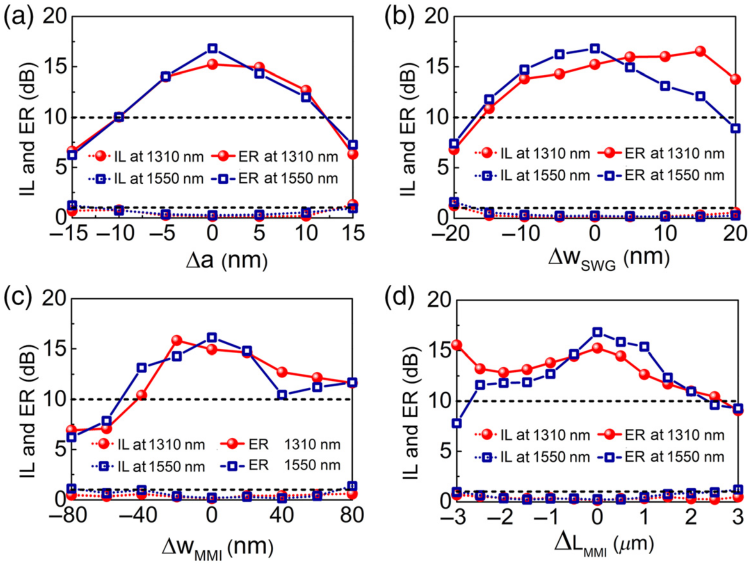

Fig. 5 Fabrication tolerances on the variation of (a) Si segment length Δa, (b) SWG-based slot width Δw_{SWG}, (c) MMI width Δw_{MMI}, and (d) MMI length ΔL_{MMI}.

MMI width (Δw_{MMI}) and MMI length (ΔL_{MMI}) are demonstrated in Figs. 5(a)–5(d), respectively. Here, the tolerances are characterized by the IL of lower than 1 dB and the ER of higher than 10 dB. Under these conditions, the tolerances on Δa and Δw_{SWG} are ± 10 nm and ± 15 nm, respectively. Furthermore, Δw_{MMI} can varies from -40 to 70 nm and the tolerance on ΔL_{MMI} is much larger with the range from -2.5 to 2 μm. Compared with the MMI parameters, the fabrication process is more sensitive to the variation on SWG parameters, and this happens because a and w_{SWG} manipulate the equivalent index greatly.

Besides, performance of the device when working as a wavelength multiplexer is numerically analyzed using the 3D-FDTD method. Figures 6(a) and 6(b) illustrate the field distributions at the two wavelengths. We can see that light of 1310-nm transmits from Port 1 to Port 3 and that of 1550-nm transmits from Port 2 to Port 3. As a result, wavelength multiplexing function is implemented. Also, the ILs are <0.24 dB and the ERs are higher than 15.2 dB for both wavelengths.

Table 1 summarizes the comparison for the representative MMI-based wavelength demultiplexer reported. It can be seen that the designed device is one of the best wavelength demultiplexers regarding the most compact footprint (~34.48 μm) and low IL (<0.3 dB).

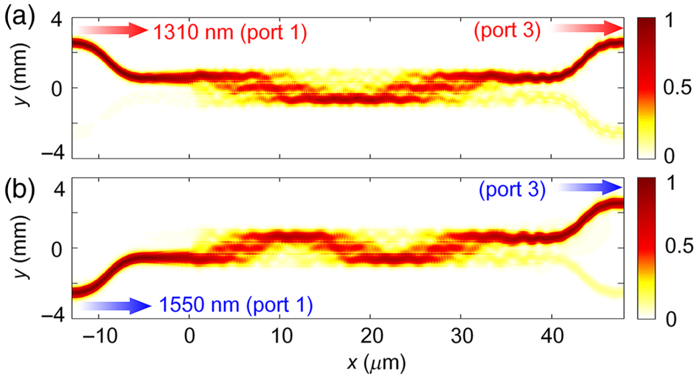

Fig. 6 Field distribution of the SWG-based MMI wavelength multiplexer at the wavelength of (a) 1310 nm and (b) 1550 nm.

Table 1 Comparison of the wavelength demultiplexer reported.

	Length (μm)	1-dB bandwidth (nm)	ER (dB)	IL (dB)
Ref. 2	119.8	NA	> 26 dB	< 0.2 dB
Ref. 24	108.5	74	> 20 dB	< 4 dB
Ref. 25	360	40	> 20 dB	< 0.3 dB
Ref. 20	43.4	120	> 20 dB	< 0.1 dB
This work	**34.48**	**90**	> **15 dB**	< **0.3 dB**

4 Conclusion

We demonstrated the design and performance evaluation of the 1310/1550 nm wavelength demultiplexer based on MMI coupler with two SWG slots. The most compact MMI wavelength demultiplexer with length of 34.48 μm is obtained. Compared with the shallow etched slots, the using of the SWG simplifies the fabrication process by only one-step lithography. Beat lengths for 1310 and 1550 nm and their ratio are effectively adjusted by engineering SWG structures including the period, duty circle and slot width. Finally, the ratio of 1.5 is selected, that is, the p value is 2. According to the results, ILs are <0.24 dB while ERs are higher than 15.2 dB for both wavelengths. 1-dB bandwidths of 90 nm have been obtained, which are broad enough to cover the entire O-band and C-band. From the fabrication tolerance analysis, the device performance is more sensitive to SWG parameters than MMI parameters, which is caused by the significant impact of the SWG structure on the equivalent refractive index. The proposed method of manipulating the beat length using two SWG-based slots offers excellent perspectives for the practical realization of MMI couplers with substantially reduced footprint. Once the fabrication accuracy is improved, p value of 1 can be selected and the device footprint will be shrunk further.

References

1. A. Liu et al., "Wavelength division multiplexing based photonic integrated circuits on silicon-on-insulator platform," *IEEE J. Sel. Top. Quantum Electron.* **16**(1), 23–32 (2009).
2. J. Xiao et al., "Design of an ultracompact MMI wavelength demultiplexer in slot waveguide structures," *Opt. Express* **15**(13), 8300 (2007).
3. G. Roelkens et al., "Silicon-on-insulator ultra-compact duplexer based on a diffractive grating structure," *Opt. Express* **15**(16), 10091 (2007).
4. C. R. Doerr et al., "Diplexer with integrated filters and photodetector in Ge-Si using G-X and G-M directions in a grating coupler," *IEEE Photonics Technol. Lett.* **21**(22), 1698–1700 (2009).
5. L. Xu et al., "Colorless optical network unit based on silicon photonic components for WDM PON," *IEEE Photonics Technol. Lett.* **24**(16), 1372–1374 (2012).
6. Y. Shi et al., "Design of a polarization insensitive triplexer using directional couplers based on submicron silicon rib waveguides," *J. Lightwave Technol.* **27**(11), 1443–1447 (2009).
7. H. Xu and Y. Shi, "On-chip silicon triplexer based on asymmetrical directional couplers," *IEEE Photonics Technol. Lett.* **29**(15), 1265–1268 (2017).
8. J. Chen and Y. Shi, "An ultracompact silicon triplexer based on cascaded bent directional couplers," *J. Lightwave Technol.* **35**(23), 5260–5264 (2017).
9. J. Chen et al., "A polarization-insensitive dual-wavelength multiplexer based on bent directional couplers," *IEEE Photonics Technol. Lett.* **29**(22), 1975–1978 (2017).
10. K. C. Lin and W. Y. Lee, "Guided-wave 1.30/1.55 μm wavelength division multiplexer based on multimode interference," *Electron. Lett.* **32**(14), 1259–1261 (1996).
11. M. H. Ibrahim et al., "Multimode interference wavelength multi/demultiplexer for 1310 and 1550 nm operation based on BCB 4024-40 photodefinable polymer," *Opt. Commun.* **273**(2), 383–388 (2007).

12. S.L. Tsao et al., “A novel 1×2 single-mode 1300/1550 nm wavelength division multiplexer with output facet-tilted MMI waveguide,” *Opt. Commun.* **232**(1-6), 371–379 (2004).
13. D. M. Mackie and A. W. Lee, “Slotted multimode-interference devices,” *Appl. Opt.* **43**(36), 6609–6619 (2004).
14. P. Cheben et al., “Subwavelength integrated photonics,” *Nature* **560**(7720), 565–572 (2018).
15. R. Halir et al., “Subwavelength-grating metamaterial structures for silicon photonic devices,” *Proc. IEEE* **106**(12), 2144–2157 (2018).
16. L. Sun et al., “Subwavelength structured silicon waveguides and photonic devices,” *Nanophotonics* **9**(6), 1321–1340 (2020).
17. S. M. Rytov, “Electromagnetic properties of a finely stratified medium,” *Sov. Phys. J. Exp. Theor. Phys.* **2**, 466–475 (1956).
18. M. W. Farn, “Binary gratings with increased efficiency,” *Appl. Opt.* **31**(22), 4453–4458 (1992).
19. A. Ortega-Moñux et al., “An ultra-compact multimode interference coupler with a subwavelength grating slot,” *Laser Photonics Rev.* **7**(2), 12–15 (2013).
20. L. Liu et al., “An ultra-compact wavelength diplexer engineered by subwavelength grating,” *IEEE Photonics Technol. Lett.* **29**(22), 1927–1930 (2017).
21. J. Chen, “A broadband wavelength demultiplexer assisted by SWG-based directional couplers,” *Optik* **202**, 163602 (2020).
22. P. Lalanne and D. Lemercier-Lalanne, “On the effective medium theory of subwavelength periodic structures,” *J. Mod. Opt.* **43**(10), 2063–2085 (1996).
23. L. B. Soldano and E. C. Pennings, “Optical multi-mode interference devices based on self-imaging: principles and applications,” *J. Lightwave Technol.* **13**(4), 615–627 (1995).
24. L. Xu et al., “Broadband 1310/1550 nm wavelength demultiplexer based on a multimode interference coupler with tapered internal photonic crystal for the silicon-on-insulator platform,” *Opt. Lett.* **44**(7), 1770 (2019).
25. Y. Shi et al., “A polarization-insensitive 1310/1550-nm demultiplexer based on sandwiched multimode interference waveguides,” *IEEE Photonics Technol. Lett.* **19**(22), 1789–1791 (2007).

Fuling Wang received her BE degree in physics from Shandong Normal University in 2017. She is currently a second-year PhD student in the School of Information Science and Engineering, Shandong University, Qingdao, China. Her research interests focus on photonic devices and nanophotonics.

Xiao Xu received her PhD in electric science and technology from Shanghai Jiao Tong University, Shanghai, China, in 2019. She is working as associate research fellow in the School of Information Science and Engineering, Shandong University. Her main research interests are silicon and polymer photonic devices and short-reach optical interconnects.

Chonglei Sun received his PhD from Shandong University, Qingdao, Shandong, China, in 2019, in Electronic science and technology with a major in photonics. He is currently working as a post-doctor in the School of Information Science and Engineering, Shandong University. His research interests include nanophotonics, photonic devices, and integrated circuits, especially computer-aided design technologies for photonic devices and ICs.

Jia Zhao received his BS and PhD degrees from Shandong University, Jinan, Shandong, China, in 2006 and 2011, respectively. He is currently working as a professor in the School of Information Science and Engineering, Shandong University. His research interests include nanophotonics and chip-scale optical interconnection.