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Special Focus on Photonic Devices and Integration

Silicon-based on-chip diplexing/triplexing technologies and devices

Yaocheng SHI*, Jingye CHEN & Hongnan XU

Centre for Optical and Electromagnetic Research, State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310058, China

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Abstract Wavelength-division-multiplexing (WDM) transceiver filters are one of the most essential components for realizing the fiber-to-the-home (FTTH) networks. In recent years, silicon photonics have provided a very attractive platform to build ultra-compact photonic integrated devices with CMOS-compatible processes. In this review, we focus on the recent progresses on diplexers/triplexers based on multimode interference couplers (MMI), and directional couplers (DC). The polarization-insensitive devices are also discussed.

Keywords wavelength division multiplexer, multimode interference coupler, directional coupler, fiber-to-the-home, silicon waveguide

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1 Introduction

With the urgent demand of the big data and optical communication, the fiber to the home (FTTH), emerged with its unique technical advantages, is one of the typical solutions for broadband services. An optical transceiver is a key component of the optical network unit (ONU) or optical network terminal (ONT) in the triple-play service-based FTTH networks. The optical transceiver in the ONU/ONT is working to transmit/receive optical signals at the same time. The dual/triple wavelength (de)multiplexer is the core device in the transceiver since it is the most critical part in reducing the cost. How to simplify such wavelength (de)multiplexers for the transceiver modules is of great interest.

The film filters are commonly used as the wavelength-division (de)multiplexers in the optical communication systems [1–4], but such type of devices suffers from the difficulties in package and volume production, which make them expensive. Integrated waveguide based optical structures offer the possibility to miniaturize bulk optical functions and provide the possibility for future integration of the triplexer with optical sources and receivers. The silicon photonic has been regarded as an attractive platform to build integrated photonic devices over the recent years, due to the great compatibility with mature complementary metal-oxide-semiconductor (CMOS) technology with low cost and high volume processing [5–11]. Moreover, the silicon nanowire waveguide could provide the ultra-high refractive index contrast between the Si (∼3.46) and SiO_2 (∼1.45), which could lead to the sub-micro cross section as well as the sharp waveguide bends. Furthermore, due to the potential to achieve monolithic optoelectronic integrated circuits, the silicon-based diplexer/triplexer could be integrated with laser diode and

* Corresponding author (email: yaocheng@zju.edu.cn)

photodetectors to realize the integrated optical transceiver module [12–14]. Thus, on-chip silicon-based diplexing/triplexing technologies and devices have attracted much attention and achieved great progress in recent years.

The typical multi-beam interferometers include arrayed-waveguide gratings (AWGs) [15–21] and echelle diffraction gratings (EDG) [22–25], which can (de)multiplex tens of WDM channels simultaneously and have been used in practical dense wavelength-division-multiplexings (DWDM) worldwide. However, AWG/EDG would not be good choices for a PON triplexer due to large flat passbands requirement [19–21]. Although DWDM channels are narrow and closely packed, the PON's three channels are necessarily quite broad and widely spaced. Neither AWGs nor EDGs can readily handle the bandwidths required in a PON.

Many other structures, such as Mach-Zehnder interferometers (MZI), multimode interference (MMI) couplers, and directional couplers (DC) have been proposed and demonstrated on the silicon platform. The 3 dB couplers and path length differences of the cascaded MZIs are optimized to separate different wavelength bands [26–28]. Multiplexers utilizing MMI are generally based on the self-imaging phenomenon [29]. Other principles, such as pseudo self-imaging phenomenon [30–35] and dispersive self-imaging mechanism [36–42] are also proposed to realize wavelength multiplexers. Reflectors such as reflective Bragg gratings are further utilized to decrease the footprint of MMI [43–45]. The directional coupler (DC) can be utilized to multiplex different wavelengths since coupling lengths are different for different wavelengths due to chromatic dispersion [46–48]. The DCs constructed by photonic crystal (PhC) waveguides can also be used to separate different wavelengths [49–51]. In this paper, diplexers/triplexers based on cascaded MMIs, tilted MMIs, asymmetrical DCs and cascaded DCs are reviewed in Section 2. Due to the large effective index difference of two perpendicular polarizations (birefringence) in silicon waveguide, the polarization dependent loss (PDL) is very large. Polarization-insensitive devices are usually required [52–59]. In Section 3, some approaches utilized to minimize the polarization-sensitivity of silicon nanowire waveguide based diplexers/triplexers are reviewed [60–65].

2 Silicon-based on-chip diplexer/triplexer

Figure 1 shows the schematic diagram of the diplexers and triplexers in the optical networks. In an ONU, a triplexer is used to separate two downstream signals transmitted in a fiber at two different wavelengths and direct them to a digital signal receiver and an analog signal receiver, while the triplexer couples an upstream optical signal emitted by a digital transmitter to the same fiber. For passive FTTH networks, ITU-T G.983 recommends three wavelengths bands, commonly 1310, 1490 and 1550 nm, which are utilized for upstream data, downstream data and dedicated wavelength for RF digital/analog video, respectively. And the bandwidths of these three wavelength bands should be larger than 100, 20 and 20 nm. In multiplexing systems, diplexers only utilize 1550 nm channel or 1490 nm channel as the signal transmitter and 1310 nm channel as the signal receiver.

2.1 Triplexers based on multimode interference (MMI) couplers

2.1.1 *Triplexer based on cascaded MMI couplers*

The silicon triplexer, based on traditional 2×2 general interference MMI coupler with butterfly geometry structure [29], is proposed to (de)multiplex 1310, 1490, and 1550 nm wavelength bands. The lengths of the MMI sections are chosen to be common multiples of the beat lengths for three wavelengths. The other method is employing pseudo self-imaging phenomenon [30–32], which is utilized to design a relatively simple structure with more compact device. Since the output intensity of the 1310 nm wavelength has a large tolerance, the 1490 and 1550 nm wavelengths are only considered for defining the optimum length of one MMI. Furthermore, cascaded step-size MMI, based on pseudo self-imaging phenomenon, is proposed to separate three wavelengths [33–35]. A cascaded multimode waveguide is utilized to receive pseudo self-image of one wavelength and then outputs a self-image in this MMI.

In recent years, a kind of tilted MMI couplers utilizing dispersive self-imaging mechanism has been proposed [36] and utilized to realize various wavelength-multiplexing devices [37–41]. A compact triplexer

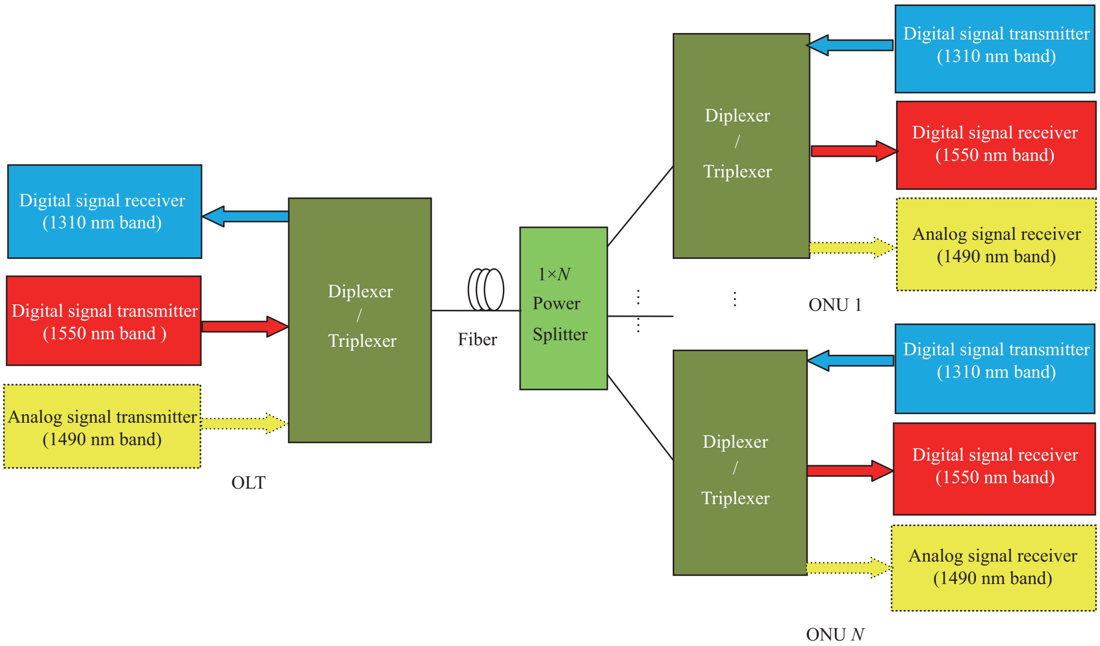

Figure 1 (Color online) Schematic diagram of the wavelength (de)multiplexers (diplexer/triplexer) in optical networks.

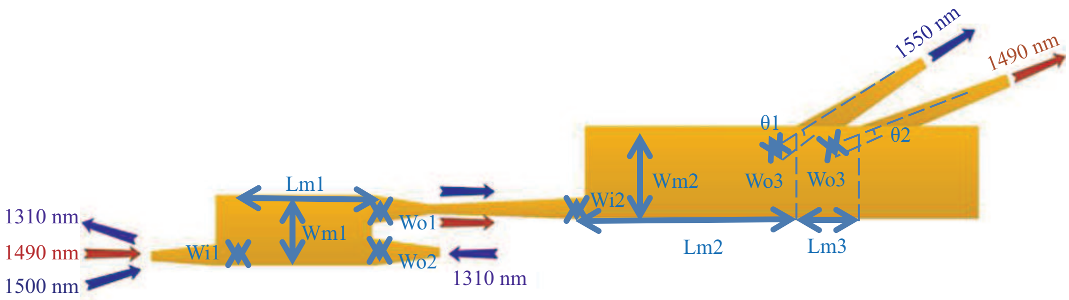

Figure 2 (Color online) Schematic diagram of the triplexer based on cascaded titled multimode interference couplers [42] @Copyright 2018 Elsevier.

has been designed and experimentally demonstrated with cascaded tilted MMI couplers [42] based on dispersive self-imaging mechanism. Figure 2 shows that schematic diagram of the triplexer based on cascaded titled multimode interference couplers. The proposed triplexer consists of two MMI couplers sections. The first one is a common 1 × 2 MMI coupler based on general interference, and the second is the tilted MMI coupler. With the first MMI coupler, the 1310 nm wavelength band is (de-)multiplexed to one port and the other two wavelengths bands (1490 nm/1550 nm) to the other port by using the pseudo self-imaging principle. Then, the two wavelength bands (1490 nm and 1550 nm) are separated by a MMI coupler with tilted output ports. Different wavelength bands can be well separated without satisfying the common multiple of the beat length and the device size can be dramatically reduced by using such type of tilted MMIs. Thus, the size of the present triplexer, which has been designed to reduce the device length compared to the common ones, is dramatically reduced to ∼450 μm. Figure 3(a) shows the optical microscope image and scanning electron micrograph (SEM) images of the fabricated device. Figure 3(b) and (c) show the measured transmission spectra from the three output ports. The device is characterized with ∼1 dB insertion loss (IL) and < -15 dB low crosstalk (CT). The 3 dB bandwidths are around 100, 28, and 32 nm for 1310, 1490, and 1550 nm bands, respectively.

2.1.2 *Triplexer based on Bragg grating assisted MMI couplers*

The device footprints are still relatively large due to the utilization of cascaded MMI to (de)multiplex

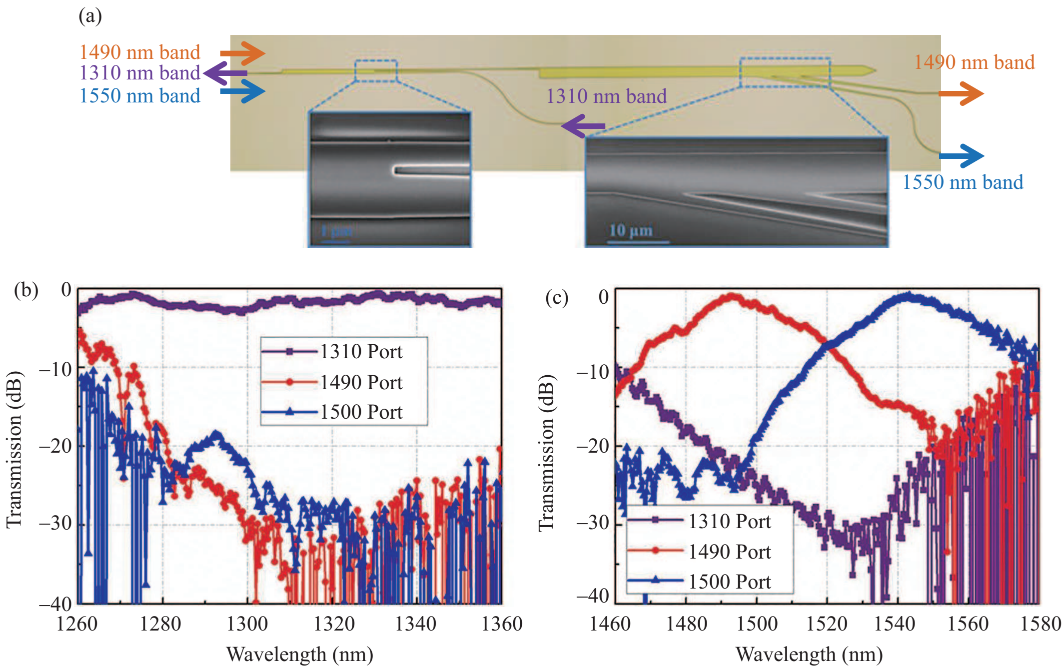

Figure 3 (Color online) (a) Optical microscope image and the SEM images of the specific part of the fabricated device. The normalized transmission spectra of the fabricated device from different output ports: (b) 1310 nm band and (c) 1490 nm/1550 nm band [42] @Copyright 2018 Elsevier.

two wavelengths bands. The device can be more compact with a mirror inserted in the MMI section to reflect one wavelength band first. Then the other two wavelengths can be separated by the MMI with self-imaging principle. The triplexer consists of a 2 × 2 MMI coupler with a shallow-etched Bragg grating adopted as a reflector in the multimode waveguide section [43,44]. The MMI coupler functions as a coarse WDM to separate two of the wavelength bands with generalized multimode interference principle and the other one wavelength is reflected to the third output port. Three wavelengths can be separated with only one MMI section and the device is more compact than the cascaded one.

A silicon triplexer based on Bragg grating-assisted multimode interference couplers has been designed and experimentally demonstrated [45]. Figure 4(a) shows schematic diagram of the triplexer based on silicon Bragg grating-assisted MMI couplers. A broadband Bragg grating is adopted as a reflector in the MMI section to extract the 1310 nm band signal. To reduce the size of the device, the other two wavelengths (1490 nm/1550 nm) bands are separated by the pseudo self-imaging MMIs instead of utilizing generalized multimode interference principle, which has to satisfy the common multiple of the beat length of different wavelengths. Figure 4(b) and (c) shows the simulated optical field distribution at 1490, 1550, and 1310 nm wavelength, respectively. All the three wavelengths are well separated by the Bragg-grating-assisted MMI structure. Compared with the conventional MMI-based triplexers, the device length is not required to be the common multiple of beat length of different wavelengths. The fabricated total device size is only 5.4 μm × 453 μm (with adiabatic tapers) as shown in Figure 5(a)–(d). From the measured transmission spectra shown in Figure 5(e)–(f), one can find that extinction ratios are higher than 15 dB and insertion losses are around 1 dB in all output ports.

2.2 Triplexers based on directional couplers (DCs)

The DC can be utilized to multiplex different wavelengths since the coupling lengths are different for different wavelengths due to chromatic dispersion. However, for the symmetrical DC-based structures [46], the device lengths have to be quite long to separate the three channels since the length must be the common multiple of the coupling lengths for the three wavelengths. Asymmetrical directional couplers (ADC) and bent directional couplers (bent DC) are proposed to decrease the device size.

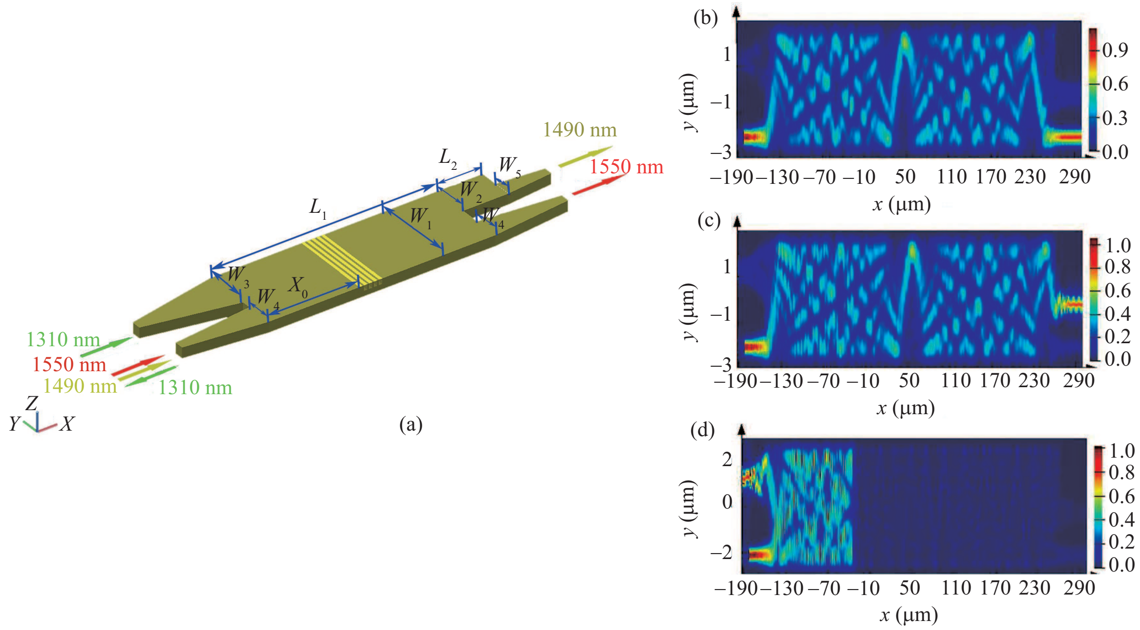

Figure 4 (Color online) (a) The schematic diagram of the triplexer based on silicon Bragg grating-assisted MMI couplers. Simulated optical filed distribution at the wavelength of (b) 1550 nm, (c) 1490 nm, and (d) 1310 nm, respectively [45] @Copyright 2017 IEEE.

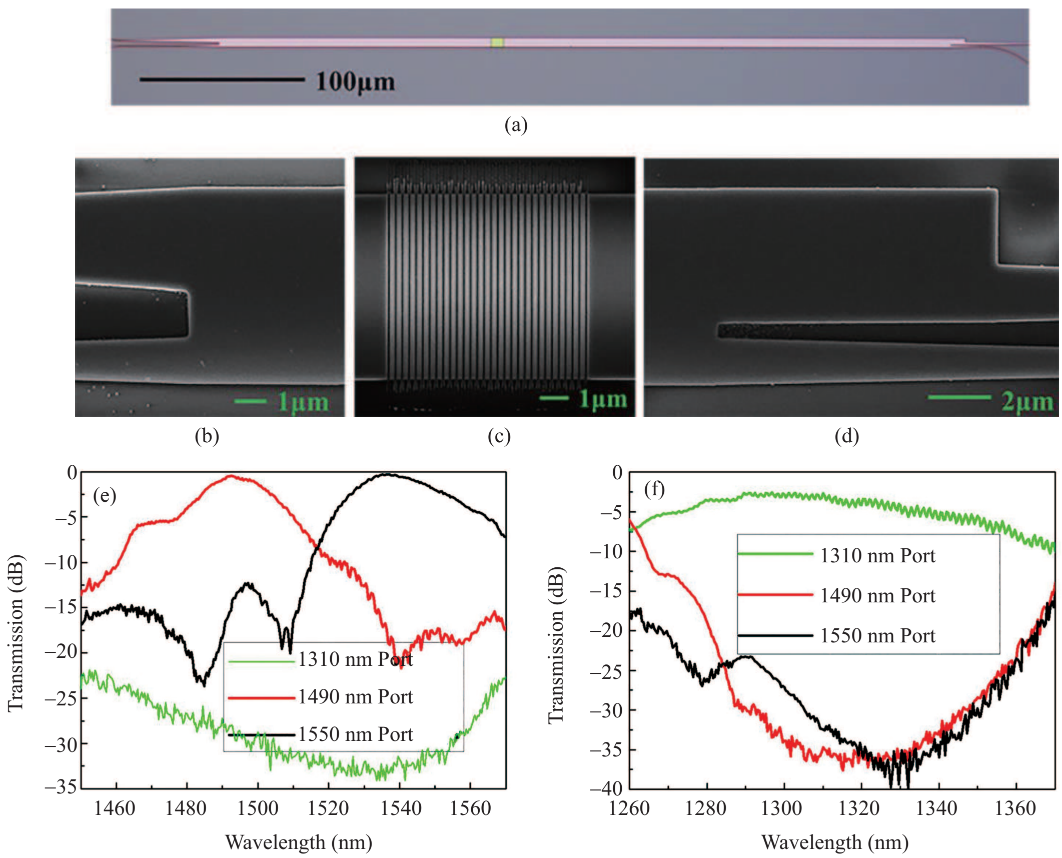

Figure 5 (Color online) (a) The optical microscope image. Enlarged SEM images: (b) the input port and 1310 nm output port, (c) the Bragg grating part and (d) the output ports for 1550 nm and 1490 nm. Measured transmission spectra for the fabricated device at (e) 1490 nm/ 1550 nm and (f) 1310 nm bands [45] @Copyright 2017 IEEE.

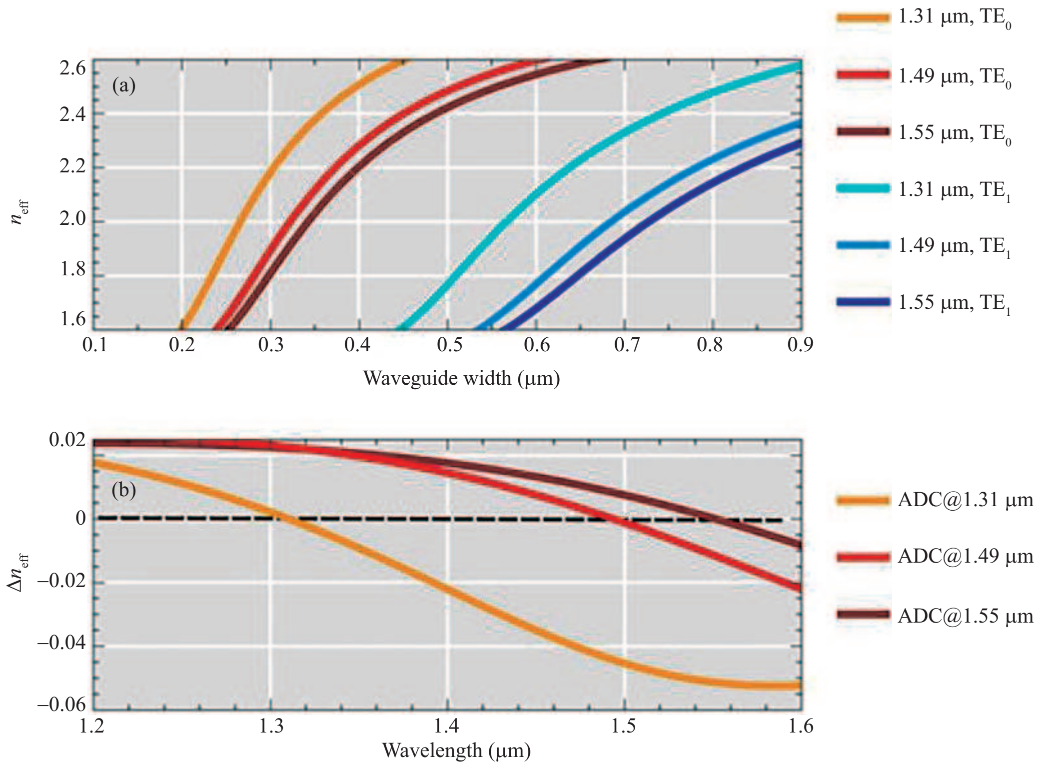

Figure 6 (Color online) (a) The dispersion curves for TE0 and TE1 modes at three wavelength bands. (b) The phase mismatch curves with varied wavelength [47] @Copyright 2017 IEEE.

2.2.1 *Triplexers based on asymmetrical DCs*

Asymmetrical directional couplers (ADCs), which consist of two parallel waveguides with different widths, have been widely used in the PLCs. In [47], the ADCs are utilized to realize the triplexer with low crosstalk and ultra-compact device size. The dispersion curves and the phase mismatch curves for three wavelengths are shown in Figure 6. By carefully designing the phase mismatch and coupling strength for each ADC, the large bandwidth and low crosstalk can be obtained and the coupling length can be efficiently reduced, since the effective index mismatch between the single-mode and multi-mode waveguide is small enough only within a certain wavelength range. Due to the phase mismatching condition, the length of the device should not be the common multiple of the coupling lengths for the three wavelengths. Thus the total length can be reduced with this principle. The designed device is fabricated as shown in Figure 7. O1, O2, and O3 are the output ports of 1490, 1550, and 1310 nm, respectively. The measured excess losses are as small as < 1 dB for all three channels. The measured crosstalks of the device based on ADCs are -27.1, -23, and -25.8 dB at the central wavelengths of 1310, 1490, and 1550 nm, respectively. The 3 dB bandwidths of 70, 30, and 20 nm can be realized for the three output ports (1310, 1490, and 1550 nm). The total length of the ADC-based triplexer is as small as $\sim$150 μm.

2.2.2 *Triplexers based on bent DCs*

Recently, bent DCs have been used widely for light coupling due to high performance and easy fabrication. A novel on-chip triplexer based on bent DCs has been demonstrated to separate three wavelength bands [48]. Compared to the parallel symmetric DCs, bent DCs have more degrees of freedom for optimization. Figure 8 shows the schematic diagram and the SEM image of the triplexer based on bent DCs. By carefully choosing the radii and widths of the parallel bent waveguides, the phase matching or mismatching condition can be satisfied for different wavelengths multiplexing. The first bent DC is utilized to separate the broad 1310 nm wavelength band and 1490 nm/1550 nm wavelength band with phase-mismatching principle. The cascaded DC is used to separate the adjacent 1490 nm and 1550 nm wavelength bands with

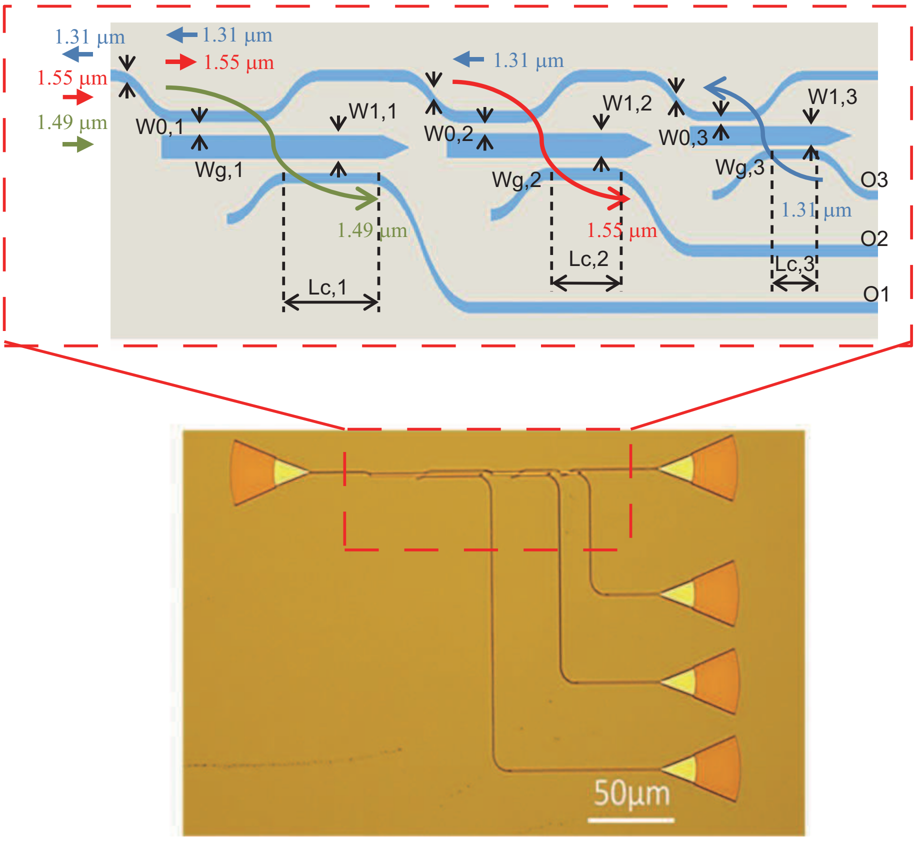

Figure 7 (Color online) The schematic diagram for the triplexers based on asymmetrical DCs and the microscope image for the fabricated device [47] @Copyright 2017 IEEE.

phase-matching condition. The length of the bent DCs for wavelength multiplexing is also not limited to the common multiple of the beat lengths for different wavelengths with phase-mismatched condition. The gap between two bent waveguides can be relatively large for ease of fabrication but with short coupling length and high performance. The footprint of the present triplexer is dramatically reduced to 19 μm × 31 μm. As shown in Figure 9, the fabricated triplexer is characterized with low crosstalks (~ -15 dB) and low insertion losses (< 1 dB). The measured bandwidths for the crosstalk < -15 dB are 70, 15, and 15 nm for 1310, 1490, and 1550 nm channel, respectively.

2.2.3 *Triplexers based on photonic crystal (PhC) DCs*

Photonic crystal (PhC) waveguides, composed of periodic dielectric materials, are popularly studied due to their unique ability in controlling the propagation of lightwave. A design of the dual wavelength demultiplexer (1300 nm/1550 nm wavelengths) based on the unique properties of coupled PhCs is proposed with a hexagonal-loop waveguide [49], which is utilized to decrease the insertion losses and crosstalks of two output ports.

Figure 10(a) shows the schematic diagram for a triplexer based on cascaded PhC-based DCs [50]. The PhC-based DCs are designed to be decoupled at the wavelength of 1310 nm. For the first DC, the length of the coupling region is optimally chosen so that the other two wavelengths (i.e., 1490 and 1550 nm) are separated and the wavelengths of 1310 and 1490 nm are output from the same port to be separated later by the second DC. It is difficult to achieve low crosstalks with conventional PhC DC, since the coupling length of the two parallel PhC waveguides is always an integer of the dielectric rods period. This problem is solved by introducing a tapered coupling region, of which the radii of rods decrease linearly to the center and increase back in the first DC section. The simulated field distributions at different wavelengths are shown in Figure 10(b)–(d). All the wavelengths are well separated. The

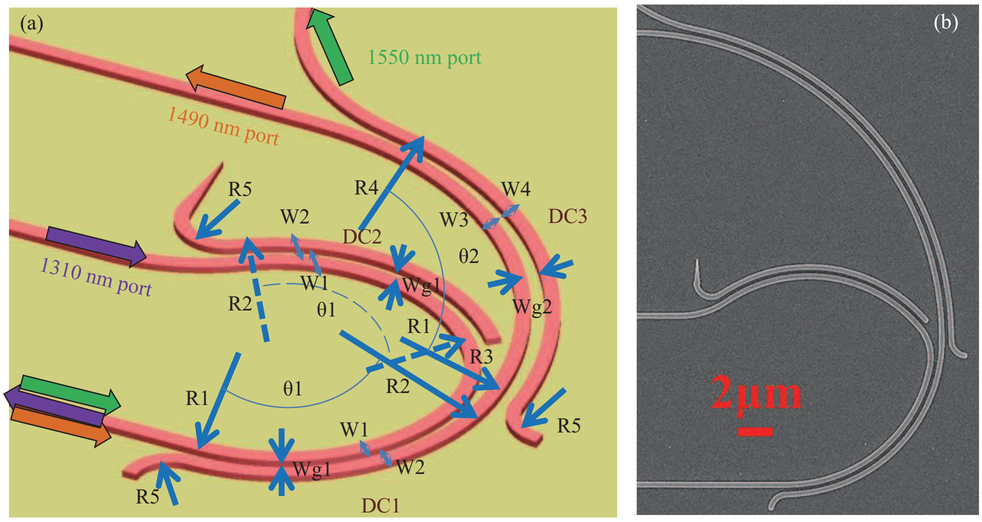

Figure 8 (Color online) (a) Schematic diagram of the silicon triplexer based on cascaded bent DCs; (b) the SEM image of the fabricated device [48] @Copyright 2017 IEEE.

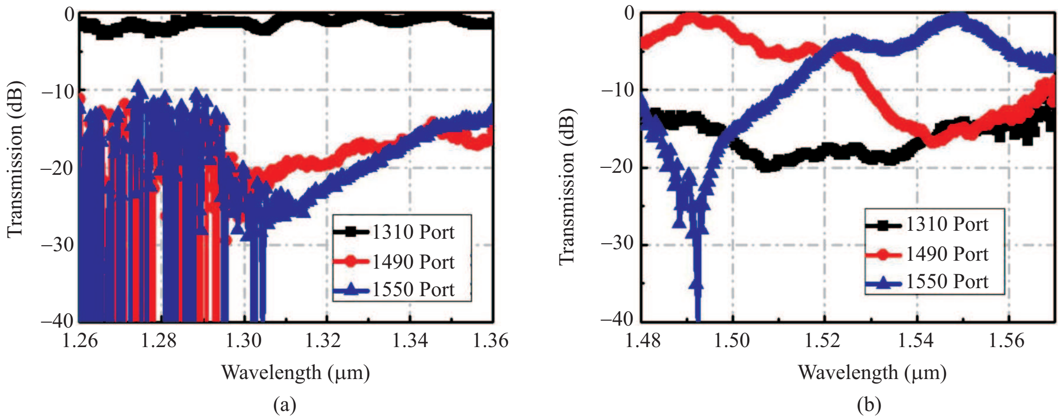

Figure 9 (Color online) The normalized transmission spectra of the fabricated device from different output ports [48] @Copyright 2017 IEEE. (a) 1310 nm band and (b) 1490 nm/1550 nm band.

footprint of the device is ∼50 μm × 20 μm. The calculated insertion losses are ∼ 0.1 dB and crosstalks are ∼ −15 to −20 dB. Another triplexer based on this principle is designed with all the coupling sections tapered to decrease the crosstalk [51]. Though the insertion loss and crosstalk of triplexers based on PhC waveguides are ultra-low, bandwidths of the multiplexers are relatively narrow.

Here, a comparison is given in Table 1 for the silicon-based duplexers/triplexers based on different structures presented previously. The listed performances of the devices are for 1310, 1490, and 1550 nm, respectively.

3 Polarization insensitive diplexers/triplexers

Due to the large birefringence in silicon waveguide, it is necessary to eliminate the polarization dependence in silicon on-chip devices for some applications [52–59]. The polarization-insensitive diplexers/triplexers based on various structures are discussed. Triplexers based on Fourier-transform-based Mach-Zehnder interferometers (MZIs) are proposed with rib waveguide in SOI platform [60, 61]. The wavelength (de)multiplexers are realized by careful design of the couplers (DC or MMI) and the path length difference of the MZI. To reduce the PDL, two layers of thin films on top of the device are utilized to self-compensate the coupling length difference through film stress.

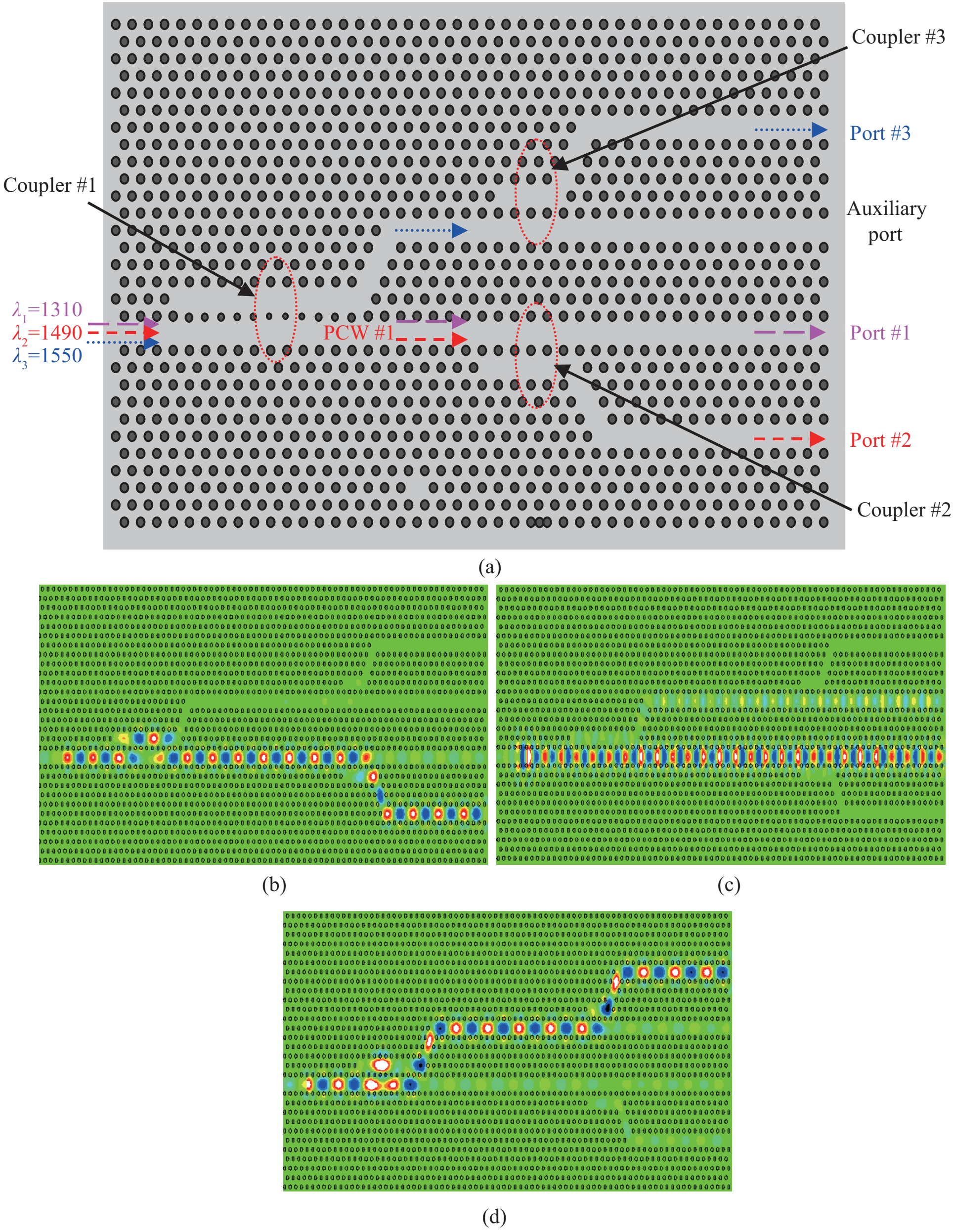

Figure 10 (Color online) (a) Schematic configuration for the present triplexer with tapering in the first directional coupler. Field distributions simulated with an FDTD method for the present triplexer at (b) λ= 1310 nm; (c) λ= 1490 nm; (d) λ= 1550 nm [50] @Copyright 2006 IEEE.

3.1 MMI based polarization insensitive diplexer

MMI couplers could be utilized to decrease the footprints of multiplexers. A polarization-insensitive diplexer based on rib MMI waveguides is designed [62]. It consists of SiON core layer, of which the stress-induced birefringence can be ignored. The beat length difference of two polarizations (TE and TM) varies with the MMI waveguide widths. An appropriate waveguide width can be found to minimize the polarization sensitivity. Figure 11 shows the schematic diagram for another polarization-insensitive diplexer based on sandwiched MMI waveguides, which consist of silicon (Si) upper/down cladding layer and silicon nitride (SiN) core layer [63]. By carefully choosing the refractive index of SiNx and the width for the MMI section, the beat length difference of the two polarizations can be minimized for both wavelengths bands. To realize (de)multiplexing function, the beat length ratio at these two wavelengths is carefully chosen. Thus, the two wavelengths at both polarizations are separated by generalized interfer-

Table 1 Comparison of silicon-based duplexer/triplexer based on different structures

Structures	Insertion losses (dB)	Crosstalks (dB)	3 dB bandwidths (nm)	Length (μm)
Butterfly MMI [29] (simulated)	< 2	< −12	24, 40, 34	900
Tilted MMI [42]	1.23, 1.51, 1.77	−18.9, −15.9, −22.9	100, 28, 32	∼ 450
Bi-directional MMI [44] (simulated)	0.51, 0.65, 0.81	−20.7, −26.3, −20.2	100, 22, 15	851.5
Bragg-grating assisted MMI [45]	2.6, 0.39, 0.56	−27, −15.9, −17.9	85, 23, 31	453
PhC [50] (simulated)	0.03, 0.16, 0.13	−17.2, −23.22, −28.7	48, 20, 15	50
ADC [47]	0.98, 0.69, 0.76	−27.1, −23, −25.8	70, 30, 20	∼ 150
Bent DC [48]	0.54, 0.9, 0.84	−14.4, −15, −22.6	100, 24, 20	31

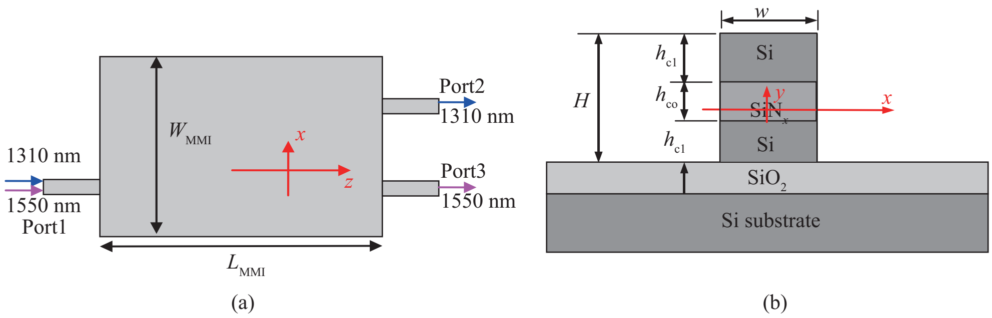

Figure 11 (Color online) Schematic configuration of the demultiplexer structure [63] @Copyright 2007 IEEE. (a) Top view; (b) cross section of the sandwiched waveguide.

ence of MMI as shown in Figure 12. The calculated PDL of this designed device is round 0.3 dB and the broad 3 dB bandwidths are around 50 nm.

3.2 DC based polarization insensitive diplexer

DC could be utilized to further decrease the size of silicon integrated devices. It will be challenging to realize de-multiplexing function for two polarizations simultaneously by utilizing conventional directional couplers since it is difficult to find the common multiples for the coupling lengths. An on-chip polarization-insensitive two wavelength (de-)multiplexer based on cascaded bent DCs is proposed and demonstrated [64]. Figure 13 shows the schematic diagram of the proposed polarization-insensitive diplexer. The first DC is designed to be phase-mismatched for the 1310 nm wavelength band at TE polarization. Due to the weak-confined optical field of TM polarization, the light of TM polarization still have relatively strong coupling even with small phase mismatch. Thus, the remaining signals (1310 nm band upstream at TM polarization and 1490 nm band downstream at TE/TM polarizations) can be separated by carefully choosing the coupling length with coupler radii and widths. By using the bent coupler, the light can be prohibited to be transferred from one waveguide to the other if it is deviated from phase-match condition too much. Figure 14(a) shows the optical microscope image and enlarged SEM images of the fabricated device. The total device size is about 40 μm × 25 μm. From the measured transmission spectrum shown in Figure 14(b), one can find that a low PDL (< 1 dB) and crosstalks < −15 dB have been realized for the fabricated device shows.

3.3 DC based polarization insensitive triplexer

An ultra-compact polarization-insensitive triplexer is designed by utilizing DCs based on submicron silicon rib waveguides [65]. The proposed triplexer includes two stages of DCs as shown in Figure 15. By carefully choosing the cross-sectional geometry of the rib waveguides, the DCs are designed to be polarization insensitive. Then, the coupling region lengths are optimally chosen to separate the three

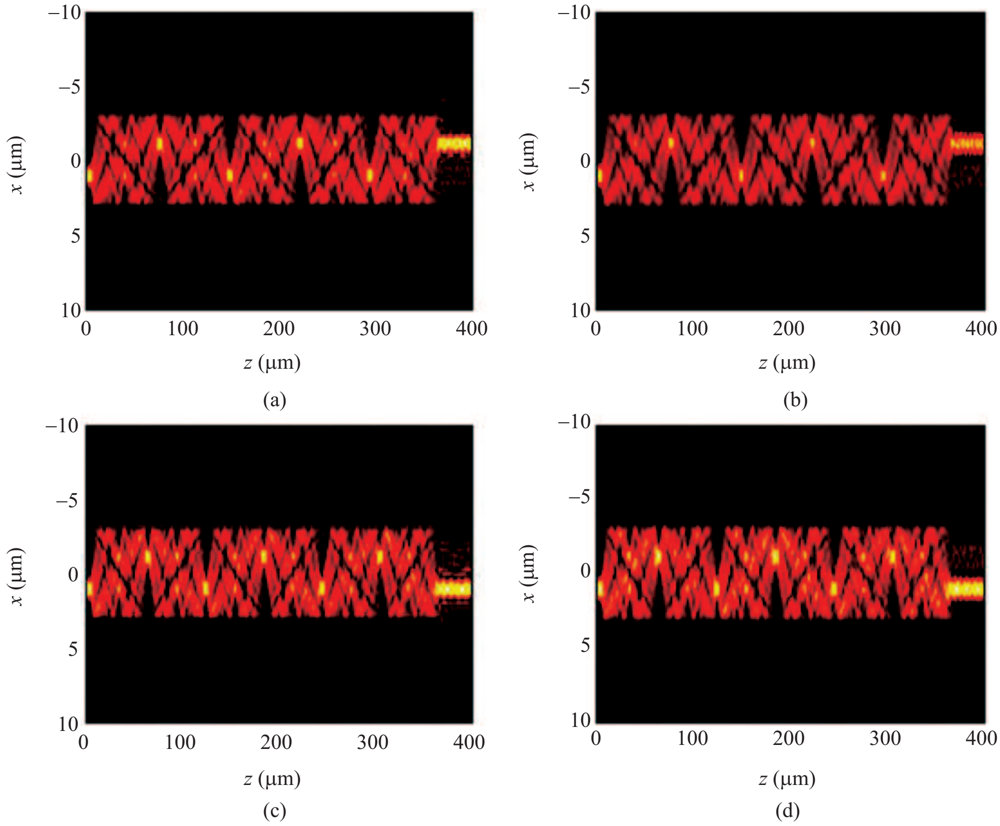

Figure 12 (Color online) 3-D BPM simulations of the field distribution at the middle of the SiN region of the demultiplexer [63] @Copyright 2007 IEEE. (a) Quasi-TE mode, at 1310 nm; (b) quasi-TM mode, at 1310 nm; (c) quasi-TE mode, at 1550 nm; (d) quasi-TM mode, at 1550 nm.

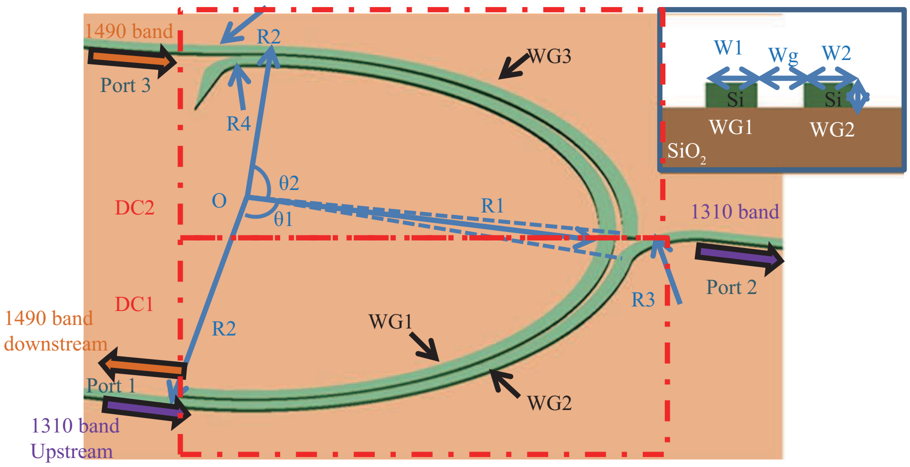

Figure 13 (Color online) Schematic diagram of the polarization-insensitive wavelength (de-)multiplexer based on cascaded bent DCs [64] @Copyright 2017 IEEE.

wavelengths. For the first DC, the length of the coupling region is optimally chosen to separate the three wavelengths into two parallel output waveguides (1490 nm in one waveguide; 1310 and 1550 nm in another). The cascaded DC is designed to separate 1310 and 1550 nm wavelengths from the same port of the first directional coupler. Due to the nearby wavelengths crosstalk, another DC is cascaded to the ouput port of 1490 nm. The total device length is about 400 μm. Three-dimensional BPM simulation has shown that the triplexer has good performances for both polarizations (PDL $<$ 0.5 dB) as shown in Figure 16. The proposed triplexer provides a cost-effective and good performance solution for FTTH

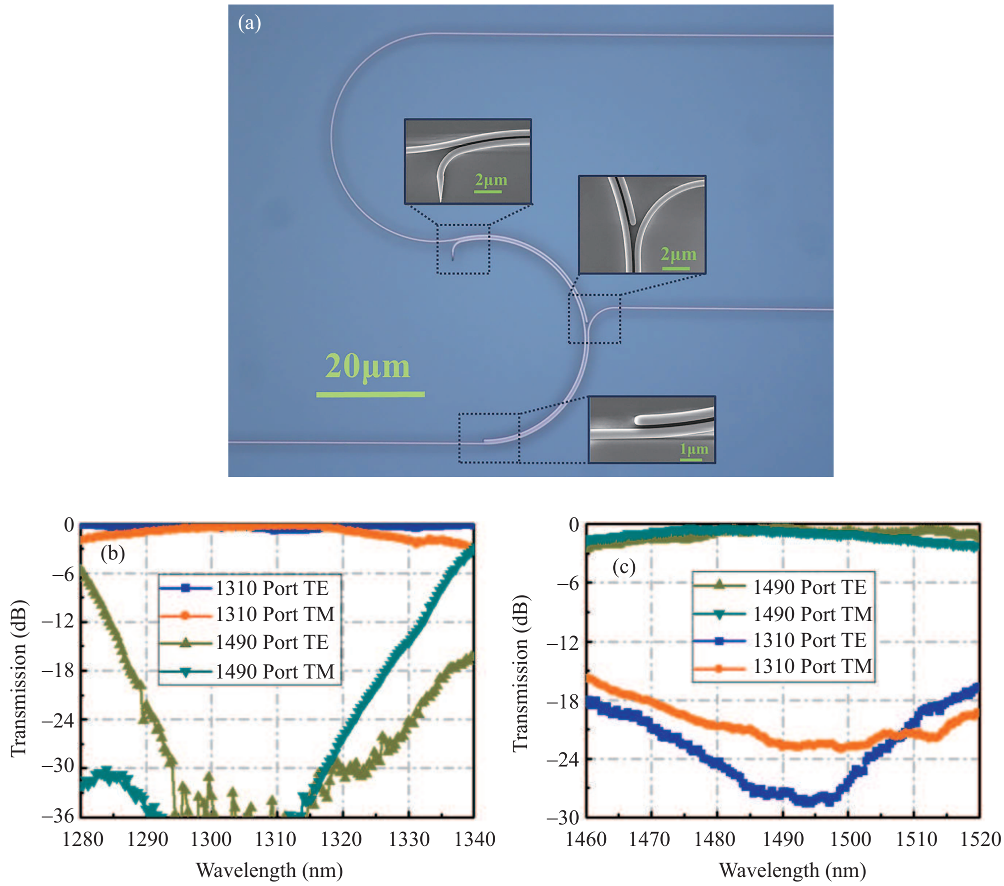

Figure 14 (Color online) (a) The optical microscope image and enlarged SEM images of the fabricated device. The measured transmission spectra of the fabricated devices at (b) 1310 nm band and (c) 1490 nm band for both polarizations [64] @Copyright 2017 IEEE.

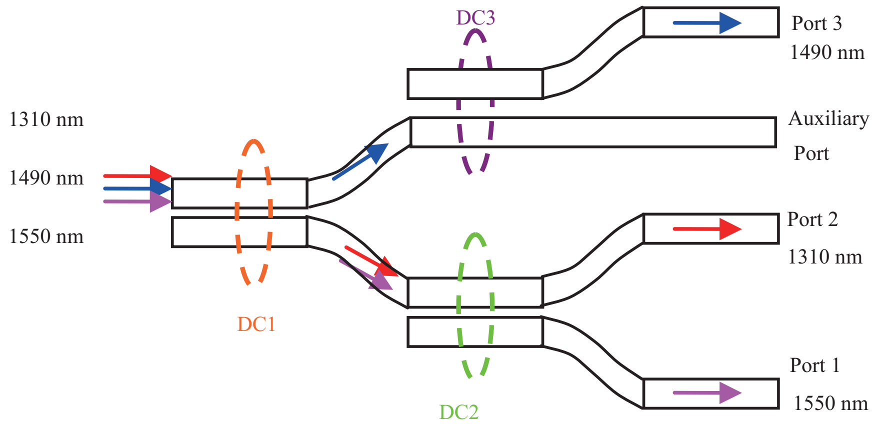

Figure 15 (Color online) Schematic configuration of the polarization insensitive triplexer based on cascaded DCs [65] @Copyright 2009 IEEE.

network systems.

Here, a comparison is given in Table 2 for the polarization-insensitive duplexers/triplexers based on different structures presented previously.

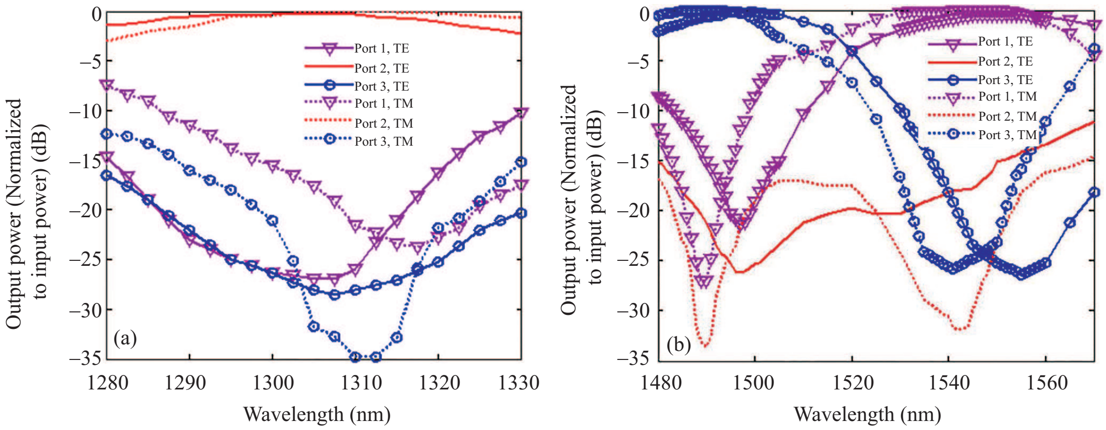

Figure 16 (Color online) Output powers (normalized to the input power) at the three output ports as the wavelength varies [65] @Copyright 2009 IEEE. (a) 1310 nm band and (b) 1490/1550 nm bands.

Table 2 Comparison of polarization-insensitive duplexers/triplexers based on different structures

Structures	Insertion loss (dB)	PDL (dB)	Crosstalk (dB)	3dB bandwidths (nm)	Length (μm)
Rib MMI [62]	< 0.5	NA	< -25	NA	667
Sandwiched MMI [63] (simulated)	0.4	0.3	−22	~ 45	360
Bent DC [64]	0.6	1	−27	~ 35	40
DC [65] (simulated)	0.5	0.2	−25	~ 30	400

4 Conclusion

In conclusion, we have given a review on silicon integrated photonics devices for on-chip two/three wavelengths (de)multiplexers. Wavelength division multiplexers are significantly utilized to increase the number of information channels. Ultra-compact silicon on-chip diplexers/triplexers have been realized with various structures, such as MMI, PhC, DC, etc. Novel structures such as asymmetrical DC and bent DC are utilized to decrease device footprints and have better performance (low insertion loss and crosstalk). The discussed polarization-insensitive (de)multiplexers are also important in practical applications. The dual/triple wavelength (de)multiplexer is one of the key components for optical network units. However, how to obtain ultra-compact devices with higher performance (lower insertion loss and crosstalk) and large fabrication tolerance is still under investigation. As discussed at the last sections, it is urgent to develop simple structures to realize silicon based (de)multiplexers with low PDL for all (de-)multiplexed two/three wavelengths bands. Furthermore, the integration of the on-chip two/three wavelengths (de)multiplexers extensively with the laser diodes and the photodetectors, which are working to transmit/receive optical signals at the same time, is still very promising.

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References

1 Song J H, Kim K-Y, Cho J, et al. Thin film filter-embedded triplexing-filters based on directional couplers for FTTH networks. IEEE Photon Technol Lett, 2005, 17: 1668–1670

2 Yamada Y, Suzuki S, Moriwaki K, et al. Application of planar lightwave circuit platform to hybrid integrated optical WDM transmitter/receiver module. Electron Lett, 1995, 31: 1366–1367

3 Kudo K, Koyabu K, Ohira F, et al. A thin-filter insertion machine for optical wdm transceiver modules. Precision Eng, 1999, 23: 34–38

4 Yanagisawa M, Inoue Y, Ishii M. Low-loss and compact TFF-embedded silicawaveguide WDM filter for video distribution services in FTTH systems. In: Proceedings of Optical Fiber Communication Conference, Los Angeles, 2004. TuI4

5 Luo L W, Ophir N, Chen C P, et al. WDM-compatible mode-division multiplexing on a silicon chip. Nat Commun, 2014, 5: 3069
6 Dai D. Silicon nanophotonic integrated devices for on-chip multiplexing and switching. J Lightw Technol, 2015, 35: 572–587
7 Dai D, Bowers J E. Silicon-based on-chip multiplexing technologies and devices for Peta-bit optical interconnects. Nanophotonics, 2014, 3: 283–311
8 Dai D, Fu X, Shi Y, et al. Experimental demonstration of an ultracompact Si-nanowire-based reflective arrayed-waveguide grating (de)multiplexer with photonic crystal reflectors. Opt Lett, 2010, 35: 2594
9 Dai D, Liu L, Wosinski L, et al. Design and fabrication of ultra-small overlapped AWG demultiplexer based on α-Si nanowire waveguides. Electron Lett, 2006, 42: 400–402
10 Driscoll J B, Chen C P, Grote R R, et al. A 60 Gb/s MDM-WDM Si photonic link with < 0.7 dB power penalty per channel. Opt Express, 2014, 22: 18543–18555
11 Wang J, Chen S, Dai D. Silicon hybrid demultiplexer with 64 channels for wavelength/mode-division multiplexed on-chip optical interconnects. Opt Lett, 2014, 39: 6993–6996
12 Blauvelt H, Benzoni A, Byrd J, et al. High performance planar lightwave circuit triplexer with passive optical assembly. In: Proceedings of Optical Fiber Communication Conference, Anaheim, 2005. 4: 3–4
13 Han Y T, Park Y J, Park S H, et al. A PLC-based optical sub-assembly of triplexer using TFF-attached WDM and PD carriers. ETRI J, 2006, 28: 103–106
14 Chang H H, Kuo Y, Jones R, et al. Integrated hybrid silicon triplexer. Opt Express, 2010, 18: 23891
15 Zou J, Le Z, Hu J, et al. Performance improvement for silicon-based arrayed waveguide grating router. Opt Express, 2017, 25: 9963–9973
16 Zou J, Le Z, He J J. Temperature self-compensated optical waveguide biosensor based on cascade of ring resonator and arrayed waveguide grating spectrometer. J Lightw Technol, 2016, 34: 4856–4863
17 Zou J, Lang T, Le Z, et al. Ultracompact silicon-on-insulator-based reflective arrayed waveguide gratings for spectroscopic applications. Appl Opt, 2016, 55: 3531–3536
18 Zou J, Xia X, Chen G, et al. Birefringence compensated silicon nanowire arrayed waveguide grating for CWDM optical interconnects. Opt Lett, 2014, 39: 1834–1837
19 Zou J, Jiang X X, Xia X, et al. Ultra-compact birefringence-compensated arrayed waveguide grating triplexer based on silicon-on-insulator. J Lightw Technol, 2013, 31: 1935–1940
20 Lang T, He J J, He S. Cross-order arrayed waveguide grating design for triplexers in fiber access networks. IEEE Photon Technol Lett, 2006, 18: 232–234
21 Li X, Zhou G-R, Feng N-N, et al. A novel planar waveguide wavelength demultiplexer design for integrated optical triplexer transceiver. IEEE Photon Technol Lett, 2005, 17: 1214–1216
22 Yang M, Li M, He J. Polarization insensitive arrayed-input spectrometer chip based on silicon-on-insulator echelle grating. Chin Opt Lett, 2017, 15: 081301
23 Mu G, Huang P, Wu L, et al. Facet-rotated echelle grating for cyclic wavelength router with uniform loss and flat passband. Opt Lett, 2015, 40: 3978–3981
24 Ma X, Li M Y, He J J. CMOS-compatible integrated spectrometer based on echelle diffraction grating and MSM photodetector array. IEEE Photonics J, 2013, 5: 6600807
25 Shi Z M, He J J, He S. A hybrid diffraction method for the design of etched diffraction grating demultiplexers. J Lightw Technol, 2005, 23: 1426–1434
26 Bidnyk S, Feng D, Balakrishnan A, et al. Silicon-on-insulator-based planar circuit for passive optical network applications. IEEE Photon Technol Lett, 2006, 18: 2392–2394
27 Li Y P, Henry C H, Laskowski E J, et al. Monolithic optical waveguide 1.31/1.55 μm WDM with −50 dB crosstalk over 100 nm bandwidth. Electron Lett, 1995, 31: 2100–2101
28 Lee T, Lee D, Chung Y. Design and simulation of fabrication-error-tolerant triplexer based on cascaded mach-zehnder inteferometers. IEEE Photon Technol Lett, 2008, 20: 33–35
29 Truong C D, Hoang V C. A triplexer based on cascaded 2×2 butterfly MMI couplers using silicon waveguides. Opt Quantum Electron, 2014, 47: 413–421
30 Hong J K, Lee S S. 1×2 wavelength multiplexer with high transmittances using extraneous self-imaging phenomenon. J Lightw Technol, 2007, 25: 1264–1268
31 Hong J K, Lee S S. PLC-based novel triplexer with a simple structure for optical transceiver module applications. IEEE Photon Technol Lett, 2008, 20: 21–23
32 Yokote R, Kojima Y, Yokoi H. Waveguide optical triplexer with cascaded multimode interference couplers. In: Proceedings of the 18th OptoElectronics and Communications Conference and Photonics in Switching, Kyoto, 2013. TuPL_12
33 Fan S-H, Guidotti D, Chien H-C, et al. A novel compact polymeric wavelength triplexer designed for 10Gb/s TDM-PON based on cascaded-step-size multimode interference. In: Proceedings of the 59th Electronic Components and Technology Conference, San Diego, 2009. 220–223
34 Le Z C, Yin L X, Huang S G, et al. The cascaded exponential-tapered multimode interference couplers based triplexer design for FTTH system. Optik-Int J Light Electron Opt, 2014, 125: 4357–4362
35 Zhang L, Chen P, Shi Y. Design and experimental verification of all waveguide type triplexers using cascaded MMI couplers. Opt Quant Electron, 2015, 47: 1151–1156
36 Hu Y, Jenkins R M, Gardes F Y, et al. Wavelength division (de)multiplexing based on dispersive self-imaging. Opt

Lett, 2011, 36: 4488–4490
37 Nedeljkovic M, Khokhar A Z, Hu Y, et al. Silicon photonic devices and platforms for the mid-infrared. Opt Mater Express, 2013, 3: 1205–1214
38 Hu Y, Li T, Thomson D J, et al. Mid-infrared wavelength division (de)multiplexer using an interleaved angled multimode interferometer on the silicon-on-insulator platform. Opt Lett, 2014, 39: 1406–1409
39 Hu Y, Gardes F Y, Thomson D J, et al. Interleaved angled MMI CWDM structure on the SOI platform. In: Prcoceedings of IEEE 10th International Conference on Group IV Photonics, Seoul, 2013. 21–22
40 Hu Y, Gardes F Y, Thomson D J, et al. Coarse wavelength division (de)multiplexer using an interleaved angled multimode interferometer structure. Appl Phys Lett, 2013, 102: 251116
41 Littlejohns C G, Hu Y, Gardes F Y, et al. 50 Gb/s silicon photonics receiver with low insertion loss. IEEE Photon Technol Lett, 2014, 26: 714–717
42 Chen J, Liu P, Shi Y. An on-chip silicon compact triplexer based on cascaded tilted multimode interference couplers. Optics Commun, 2018, 410: 483–487
43 Ling W, Qiu C, Li H, et al. A compact triplexer using grating-assisted multimode interference coupler based on silicon nanowire waveguide. In: Proceedings of Asia Communications and Photonics Conference, Guangzhou, 2012. 1–3
44 Ling W, Sheng Z, Qiu C, et al. Design of compact bi-directional triplexer based on silicon nanowire waveguides. Chin Opt Lett, 2013, 11: 041301
45 Chen J, Zhang Y, Shi Y. An on-chip triplexer based on silicon bragg grating-assisted multimode interference couplers. IEEE Photon Technol Lett, 2017, 29: 63–65
46 Song J H, Lim J H, Kim R K, et al. Bragg grating-assisted WDM filter for integrated optical triplexer transceivers. IEEE Photon Technol Lett, 2005, 17: 2607–2609
47 Xu H, Shi Y. On-chip silicon triplexer based on asymmetrical directional couplers. IEEE Photon Technol Lett, 2017, 29: 1265–1268
48 Chen J, Shi Y. An ultracompact silicon triplexer based on cascaded bent directional couplers. J Lightw Technol, 2017, 35: 5260–5264
49 Chien F S S, Hsu Y J, Hsieh W F, et al. Dual wavelength demultiplexing by coupling and decoupling of photonic crystal waveguides. Opt Express, 2004, 12: 1119–1125
50 Shi Y, Dai D, He S. Novel ultracompact triplexer based on photonic crystal waveguides. IEEE Photon Technol Lett, 2006, 18: 2293–2295
51 Chen H M, Jin X J, Wang J L. Photonic crystal four wavelength division multiplexing based on multimode interference theory. In: Proceedings of the 10th International Conference on Optical Communications and Networks (ICOCN 2011), Guangzhou, 2011. 395–398
52 Rajarajan M, Rahman B M A, Grattan K T V. A rigorous comparison of the performance of directional couplers with multimode interference devices. J Lightw Technol, 1999, 17: 243–248
53 Dai D, He S. Optimization of ultracompact polarization-insensitive multimode interference couplers based on Si nanowire waveguides. IEEE Photon Technol Lett, 2006, 18: 2017–2019
54 Karthik U, Das B K. Polarization-independent and dispersion-free integrated optical MZI in SOI substrate for DWDM applications. In: Proceedings of the International Society for Optics and Photonics (SPIE), San Francisco, 2013. 8629: 862910
55 Dai D, He S. Proposal for diminishment of the polarization-dependency in a Si-nanowire multimode interference (MMI) coupler by tapering the MMI section. IEEE Photon Technol Lett, 2008, 20: 599–601
56 Fujisawa T, Koshiba M. Theoretical investigation of ultrasmall polarization-insensitive 1/spl times/2 multimode interference waveguides based on sandwiched structures. IEEE Photon Technol Lett, 2006, 18: 1246–1248
57 Darmawan S, Lee S Y, Lee C W, et al. Transition and comparison between directional couplers and multimode interferometer based on ridge waveguides. In: Proceedings of the International Society for Optics and Photonics (SPIE), Beijing, 2005. 5644: 52–65
58 Xiao Z, Luo X, Lim P H, et al. Ultra-compact low loss polarization insensitive silicon waveguide splitter. Opt Express, 2013, 21: 16331–16336
59 Hao R, Du W, Li E P, et al. Graphene assisted TE/TM-independent polarizer based on Mach-Zehnder interferometer. IEEE Photon Technol Lett, 2015, 27: 1112–1115
60 Feng N-N, Feng D Z, Liang H, et al. Low-loss polarization-insensitive Silicon-on-insulator-based WDM filter for triplexer applications. IEEE Photon Technol Lett, 2008, 20: 1968–1970
61 Zhang Q, Fu S, Man J, et al. Low-loss and polarization-insensitive photonic integrated circuit based on micron-scale SOI platform for high density TDM PONs. In: Proceedings of Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, 2017. Th2A.5
62 Paiam M R, MacDonald R I. Polarisation-insensitive 980/1550 nm wavelength (de)multiplexer using MMI couplers. Electron Lett, 1997, 33: 1219–1220
63 Shi Y, Anand S, He S. A polarization-insensitive 1310/1550-nm demultiplexer based on sandwiched multimode interference waveguides. IEEE Photon Technol Lett, 2007, 19: 1789–1791
64 Chen J, Liu L, Shi Y. A polarization-insensitive dual-wavelength multiplexer based on bent directional couplers. IEEE Photon Technol Lett, 2017, 29: 1975–1978
65 Shi Y C, Anand S, He S. Design of a polarization insensitive triplexer using directional couplers based on submicron silicon rib waveguides. J Lightw Technol, 2009, 27: 1443–1447