Low-loss silicon 2 × 4λ multiplexers composed of on-chip polarization-splitter-rotator and 2 × 2 and 2 × 1 Mach-Zehnder filters for 400GbE

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Abstract: 2×4λ Si-photonics multiplexers for 400GbE composed of Mach-Zehnder filters and a polarization-splitter-rotator are proposed and experimentally demonstrated for the first time. Relative spectral position of two filters is locked by using 2×2 and 2×1 configurations.

1. Introduction

To cope with the rapid increase of data traffic between and within data centers, 400GbE has been standardized in 2017 [1]. Especially, 400GBASE-FR8 and -LR8, which use single-mode fibers (SMFs) as a transmission medium are attractive for data center transmission due to their longer transmission distance. For these standards, eight wavelength-division-multiplexing (WDM) with the frequency spacing of 800 GHz (LAN-WDM) including one guard band was employed around 1.3-μm band. Therefore, an eight-wavelength (8λ) multiplexer (MUX) or two 4λ MUXs are essential in a transmitter. So far, various O-band 4λ MUXs have been studied for 100GbE, such as 1by4 MMI couplers [2] with a 6-dB insertion loss and two-stage Mach-Zehnder (MZ) MUXs [3–5], which have no intrinsic loss. In two-stage MZ MUXs, MZ filters with free spectral range (FSR) of 3200 GHz and 1600 GHz are cascaded and multiplex four wavelengths with 800-GHz spacing. The problem of the two-stage MZ MUXs is the control of peak wavelength position. A slight deviation in the arm waveguide width and delay line length (ΔL) of MZ filters results in the peak wavelength fluctuation. In our previous study [6], the 1600-GHz filter of two-stage MZ MUX, which has the severe fabrication-tolerance, is replaced with broadband asymmetric directional coupler (ADC) and rib-waveguide type TE_1-TM_0 mode converter (MC). And low-loss 4λ MUX based on Si-photonics platform was demonstrated. However, the peak wavelength fluctuations of two 3200-GHz filters still remain, and the peak wavelength of these filters have to be tuned separately.

In this paper, we propose and experimentally demonstrate two silicon 4λ MUXs for 400GbE using two MZ filters and an on-chip polarization-splitter-rotator (PSR) based on an ADC and a TE_1-TM_0 MC using tapered rib waveguide [7]. Two 4λ MUXs are designed at 1.28 and 1.3 μm bands (we refer them as 4λ MUX#1 and 4λ MUX#2). By using 2 × 2 and 2 × 1 MZ filters for the 3200-GHz filters, the relative position of peak wavelengths between two filters are automatically locked [8]. Therefore, the peak wavelength fluctuations of two filters caused by the fabrication error in waveguide width are identical and the tuning of the peak wavelength position is considerably simplified compared with conventional multi-stage 4λ MUXs [3–6]. Furthermore, in principle, only one heater is necessary for tuning the peak position of these two filters. The averaged insertion loss of 8λ in the proposed devices is 1.86 dB without current injection, and this is the first time to demonstrate 8λ (2×4λ) MUX for 400GbE based on Si-waveguide.

2. Operation principle and results

Table 1 shows the eight lanes specified in 400GbE. Eight wavelengths from lane 0 (L0) to L7 with 800-GHz spacing are used with one guard band between L3 and L4 and they must be multiplexed at the transmitter side. Fig. 1 (a) shows a concept of conventional two-stage MZ MUXs [3–5]. Although L4 to L7 are indicated in the figure, the situation is the same for L0 to L3. It consists of two 3200-GHz MZ filters and a 1600-GHz MZ filter. The problem of this configuration is in the control of filter peak wavelength. A slight deviation in the arm waveguide width and ΔL in the MZs results in a fluctuation of the peak wavelength positions. Fig. 1 (b) shows the concept of the 4λ MUX considered here. Two 3200-GHz filters are placed in parallel, and the 1600-GHz filter in Fig. 1 (a) is replaced with ADC and TE_1-TM_0 MC, which have broadband transmission spectra. Although the control of peak wavelength of 1600-GHz filter is difficult, it is excluded in this configuration. Instead, two of lanes are multiplexed as TM_0 modes. In our previous work [6], we used directional coupler and ADC for 3200-GHz filters. Here, we use 2×2 and 2×1 MZ filters to ease the tuning of filter peak wavelengths as shown below.

Top panel of Fig. 2 shows a schematic view and operation principle of proposed two 4λ MUXs. They consist of MZ-A, MZ-B, ADC and TE_1-TM_0 MC. Si-wire waveguides and Si rib waveguide with SiO_2 cladding are used. The thickness of Si is h = 210 nm and etching depth for the rib waveguide is d = 140 nm. At port-1 to -4, the Si core width is w_1 = 400 nm. The width for MZ-A is tapered up to w_2 = 824 nm. The output of MZ-B is coupled to MZ-A side via ADC. The gap of ADC is 150 nm, and the coupling lengths of ADC are 35.4 µm and 30.3 µm in 4λ MUX#1 and 4λ MUX#2 respectively. After the ADC, Si-wire waveguide is connected to the rib waveguide, and then, the width is tapered down to w_1. Finally, the rib waveguide is again connected to Si-wire waveguide. The taper lengths from w_1 to w_2 and connection lengths from Si-wire to rib waveguide are all 100 µm.

Table 1. The eight lanes specified in 400GbE

	L0	L1	L2	L3		L4	L5	L6	L7
Frequency [THz]	235.4	234.6	233.8	233.0		231.4	230.6	229.8	229.0
Wavelength [nm]	1273.5	1277.9	1282.3	1286.7		1295.6	1300.1	1304.6	1309.1

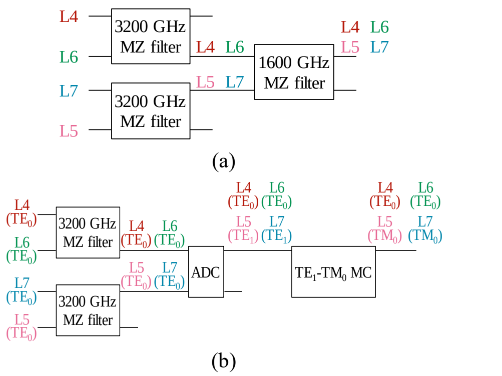


Fig. 1 Concept of (a) conventional two-stage MZ MUX and (b) proposed structure.

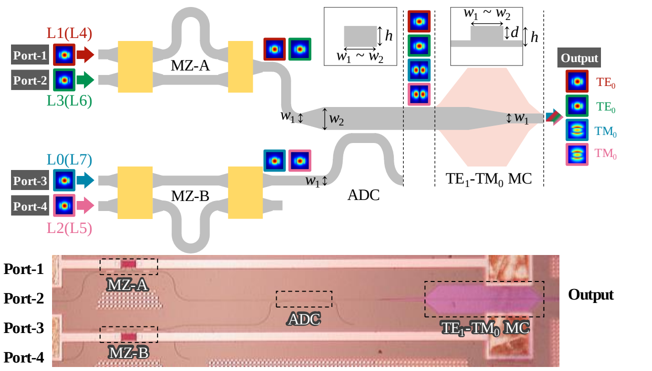


Fig. 2 (top) Schematic view and operation principle of proposed two 4λ MUXs and (bottom) micrograph of 4λ MUX#1.

The operation principle of the device is as follows. In 4λ MUX#1 (4λ MUX#2), two wavelengths: L1 and L3 (L4 and L6) are multiplexed by MZ-A filter as TE_0 mode. Since the frequency spacing between L1 and L3 (L4 and L6) is 1600 GHz, the FSR of MZ-A has to be 3200 GHz. Other two lanes of L0 and L2 (L5 and L7) with 1600-GHz spacing are multiplexed by MZ-B filter as TE_0 mode by setting the FSR to 3200 GHz. They are coupled as TE_1 mode of upper waveguide by ADC. In ADC, the TE_0 mode of the lower waveguide satisfies a phase matching condition with the TE_1 mode of the upper waveguide. After the ADC, four wavelengths are multiplexed as two TE_0 modes and two TE_1 modes, and then, TE_1 modes are converted to TM_0 modes by TE_1-TM_0 MC because SMF transmission is necessary in our target standards. Since the ADC and TE_1-TM_0 MC, which work as O-band PSR, are broadband [6], the spectral tuning is not required as for the 1600-GHz filter used in conventional two-stage MUXs. Once two 4λ multiplexing are achieved by 4λ MUX#1 and #2, 8λ multiplexing can be done by using free space optics [9].

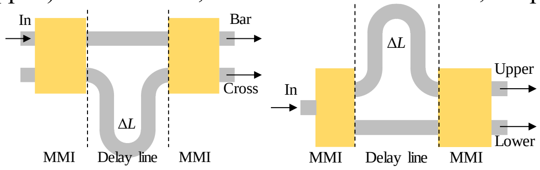
Coupled mode theory and beam propagation method are used for the design of MZ-A, MZ-B, ADC and TE_1-TM_0 MC. Fig. 3 shows the schematic of 2×2 and 2×1 MZ filters and their structural parameters. For 4λ MUX#1, the length of 2×2 and 2×1 MMI are 13 µm and 10.5 µm, the width of MMI is 3 µm for both MMIs. For 4λ MUX#2, the length of 2×2 and 2×1 MMI are 12.8 µm and 3.4 µm, and the width of MMI are 3 µm and 2 µm. ΔL is set to 21.5 µm and 22 µm for 4λ MUX#1 and #2, respectively, to obtain 3200-GHz FSR. The output powers of Bar and Cross ports in the 2×2 MZ filter shown in Fig. 3 (a) is given by transfer matrix analysis as

$$\left[|\mathrm{Bar}|^2 \quad |\mathrm{Cross}|^2\right]^{\mathrm{T}} = \left[\sin^2\frac{\varphi}{2} \quad \cos^2\frac{\varphi}{2}\right]^{\mathrm{T}} \tag{1}$$

where, $\varphi = \beta\Delta L$ (β is the propagation constant of arm waveguides). Similarly, the output power of Upper and Lower ports in the 2×1 MZ filter shown in Fig. 3 (b) are given by

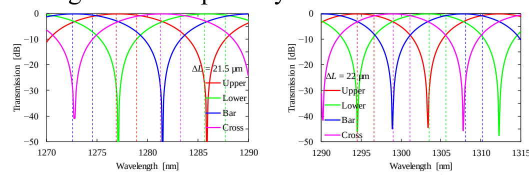
$$\left[|\mathrm{Upper}|^2 \quad |\mathrm{Lower}|^2\right]^{\mathrm{T}} = \left[\cos^2\frac{(\varphi-\pi/2)}{2} \quad \sin^2\frac{(\varphi-\pi/2)}{2}\right]^{\mathrm{T}} \tag{2}$$

From equations (1) and (2), the transmission spectra of the 2×2 and 2×1 MZ filters can be obtained. It can be seen that the phase of the output of 2×1 MZ filter is $\pi/2$ delayed compared with the 2×2 MZ filter. In conventional two-stage MZ 4λ MUXs, since two 2×2 MZ filters are used for the 3200 GHz filters, ΔL values have to be slightly changed [3] to tune this $\pi/2$-phase difference between 3200-GHz MZ filters. In addition, the external spectral tuning in two 3200-GHz MZ filters has to be done separately because their peak wavelength fluctuations caused by the fabrication error in the waveguide width are different. Figs. 4 (a) and (b) show the calculated transmission spectra of 2×1 and 2×2 MZ filters designed for 1.28 µm and 1.3 µm bands. The vertical dashed lines show the wavelength range for each lane specified in 400GbE and each color corresponds to the wavelength outputted from four ports. The peak wavelength positions of 2×1 MZ filter (Upper and Lower) are exactly at the center of two adjacent peak wavelengths for 2×2 MZ filter due to the $\pi/2$-phase difference included in equation (2). This is a great advantage for the MUX. Since ΔL is the same for two filters, the design is considerably simplified and the spectral tuning is easy. Furthermore, the peak wavelength fluctuations for two filters are the same. Therefore, in principle, only one tuning element is necessary for this MUX (in that case, the positions of delay line waveguide with ΔL in Fig. 2 have to be flipped). In this work, for flexible measurement, we prepare the tuning element separately for MZ filters.



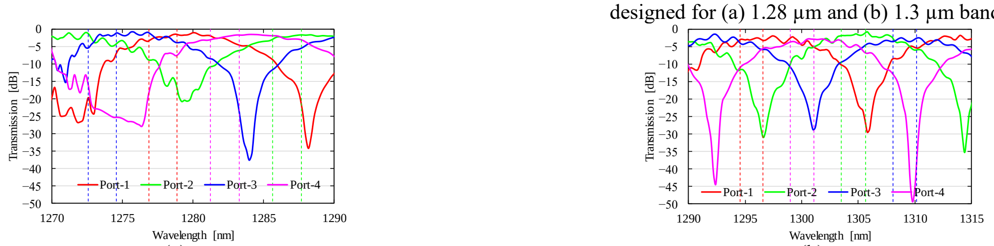
(a) (b)

Fig. 3 Schematic of (a) 2×2 and (b) 2×1 MZ filters.



(a) (b)

Fig. 4 Calculated transmission spectra of 2×1 and 2×2 MZ filters designed for (a) 1.28 µm and (b) 1.3 µm bands.



(a) (b)

Fig. 5 Measured transmission spectra of (a) 4λ MUX#1 and (b) 4λ MUX#2.

We fabricated designed two silicon 4λ MUXs by standard CMOS process and photolithography. The micrograph of 4λ MUX#1 is shown in the bottom panel of Fig. 2. The positions of four-input and one-output ports, MZ-A, MZ-B, ADC, and TE_1-TM_0 MC are denoted. TiN heaters are integrated on the delay line of MZ-A and MZ-B. TE_0 or TM_0 light from 1.3-µm ASE light source via PBS is launched to the fabricated waveguide through a lensed fiber and inverse taper spot size converter [10]. Outputted light is measured by an optical spectrum analyzer and continuously measured 10 times and adopt the average. From the measured spectra, the transmission of the straight Si-wire waveguide fabricated on the same chip is subtracted to exclude the coupling and waveguide losses.

We measured the characteristic of the two 4λ MUXs fabricated on the same chip as DeMUX. TE_0 or TM_0 light is launched from output-port side and the transmission spectra from Port-1 to Port-4 at the other side are measured. Fig. 5 (a) shows the measured transmission spectra of 4λ MUX#1. 3200-GHz FSR filter transmission and π/2-phase differences between MZ-A (Port-1 and -2) and MZ-B (Port-3 and -4) can be seen as designed. Compared with calculated spectra, the peak wavelength positions are slightly shifted to longer wavelength side, but approximately agree with the 4λ grids thanks to the nearly flat-top spectra of 3200-GHz filter. In MZ-A side, when TE_0 mode is launched, Port-1 and -2 can be used for multiplexing L1 and L3 and the excess losses are 1.33 dB and 1.63 dB. In MZ-B side, when TM_0 mode is launched, Port-3 and -4 can be used for L0 and L2 and the excess losses are 1.46 dB and 1.66 dB. The averaged loss of 4λ MUX#1 is only 1.52 dB, without current injection. Fig. 5 (b) shows the measured transmission spectra of 4λ MUX#2. Like 4λ MUX#1, the characteristic of 3200-GHz FSR and π/2-phase differences are achieved as designed. Port-1 and -2 can be used for multiplexing L4 and L6 and the excess losses are 2.41 dB and 1.17 dB when TE_0 mode is launched from output-port side. Port-3 and -4 can be used for L7 and L5 and the excess losses are 2.47 dB and 2.75 dB respectively when TM_0 mode is launched. Without current injections, the averaged loss of 4λ MUX#2 is 2.20 dB and that of 8λ for 400GbE is only 1.86 dB. The losses of TM_0 mode input are larger than that of TE_0 mode input. This probably comes from the fabrication error in the waveguide width in ADC [6]. The fabrication tolerance of ADC can be improved by using tapered ADC [11] or one-side rib waveguide [12]. The heaters on MZ-A and MZ-B can be used for tuning spectral positions although they are not used this time.

3. Conclusion

We theoretically and experimentally demonstrated two silicon 4λ MUXs for 400GbE using two MZ filters and a PSR based on ADC and TE_1-TM_0 MC. By using 2×1 and 2×2 MZ filters, the relative wavelength position is locked, and it eases the tuning of filters. Fabricated devices exhibit successful two 4λ multiplexing in 1.28 and 1.3 µm bands. The averaged loss of 8λ is 1.86 dB and very small. The proposed device is useful for 400GbE transmitter.

4. Reference

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