LETTER

High-tolerance CWDM4 wavelength multiplexer based on $2\times 2/2\times 1$ MZ filters with polarization multiplexing

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Abstract A novel Si four-wavelength multiplexer (MUX) for CWDM system composed of two types of Mach-Zehnder (MZ) MUX, and a polarization splitter rotator (PSR) based on a tapered asymmetric directional coupler (ADC) and TE_1 - TM_0 mode converter (MC) is proposed and experimentally demonstrated. To make the ADC fabrication-tolerant and broadband, a new design method is proposed, in which waveguide width dependence is taken into account. Although due to the waveguide width change during the fabrication process, the loss of the fabricated ADC is relatively large, a proof-of-concept four wavelength multiplexing is experimentally demonstrated.

Keywords: CWDM4, four-wavelength MUX, O-band, high tolerance

Classification: Optical hardware (fiber optics, microwave photonics, optical interconnects, photonic signal processing, photonic integration and modules, optical sensing, etc.)

1. Introduction

The wavelength division multiplexing (WDM) is a promising technology to enhance optical communication capacity. Coarse WDM4 (CWDM4) [1] is an optical communication standard for client-side networks, such as optical Ethernet [2]. Due to the relatively broad wavelength spacing (20 nm), uncooled light sources [3, 4, 5, 6, 7] will be used, and therefore, the devices become low-cost, compared with those of semi-cooled system such as, LAN-WDM (wavelength spacing is 4.5 nm) [2], which is one of the most important features in the client-side network devices. In CWDM4, four wavelengths around 1.3 μm with 20-nm wavelength spacing are used. So far, various O-band four-wavelength MUXs for LAN-WDM and CWDM4 have been demonstrated on various platforms, such as, free-space optics [8, 9], and chip-based photonic integrated circuits (PIC) [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. Especially, PIC-based MUX is suitable for reducing the device size, which is essential for recent small-form-factor optical transceivers, such as SFP (Small Form-factor Pluggable) transceivers [25].

So far, various PIC-based O-band four-wavelength MUX has been reported such as 1×4 multimode interference (MMI) coupler, two-stage MZ-MUXs, etc. Among them, a two-stage MZ-MUX, which has no intrinsic loss, is a promising candidate for four wavelengths MUX of CWDM4

and LAN-WDM standards. Especially, MZ-MUX based on Si-photonics technology attracts a lot of attention and a two-stage MZ-MUX with the flat-top design was proposed for CWDM4 [18, 19].

One of the problems of two-stage MZ-MUX is in the control of peak wavelength position. In two-stage MZ MUXs, MZ filters with free spectral range (FSR) of 80 nm and 40 nm are cascaded and they multiplex four wavelengths with 20-nm wavelength spacing. A slight deviation in the arm waveguide width and delay line length (ΔL) of MZ filters results in the peak wavelength fluctuation. Especially, the second MZ filter has severe fabrication tolerance compared with the first MZ filters due to its narrow FSR. If the peak wavelength positions of the first and second filters do not match, the resulting spectrum is deformed.

Recently, four wavelength MUX using polarization multiplexing (pol-MUX) for LAN-WDM was proposed [24]. In [24], two wavelengths are multiplexed as TE mode and the other two wavelengths are multiplexed as TM mode (The use of TM mode does not matter if single-mode fiber (SMF) is the transmission medium). The pol-MUX was implemented by using ADC and TE_1 - TM_0 MC [26]. In [24], the wavelength range covered by the system is narrow (about 15 nm), the ADC was composed of simple straight waveguides. However, for the CWDM system, more broadband and fabrication-tolerant design are necessary due to its broad wavelength range.

In this paper, we propose a novel PIC-based four-wavelength MUX for CWDM. The proposed device is composed of two-types of MZ filters and PSR based on tapered ADC and TE_1 - TM_0 MC. We present a new design method for tapered ADC to make it broadband and fabrication-tolerant. Furthermore, we used 2×2 MZ and 2×1 MZ filters for two-wavelength MUXs. Since the output of these MZ-MUXs has a 90-degree phase shift [27, 28], the relative spectral position between them can be fixed without changing delay line length, leading to a high tolerance configuration in terms of peak wavelength position.

Although due to the waveguide width deviation during the fabrication process, the loss of the fabricated tapered ADC is relatively large, a proof-of-concept four wavelength multiplexing is experimentally demonstrated.

2. Operation principle and experimental results

Figure 1 shows the schematic of our proposed four-wavelength MUX. It is composed of two types of MZ-

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MUXs (MUX1 and MUX2), TE₀-TE₁ tapered ADC, and TE₁-TM₀ MC. Four-lane signals are launched from left side in Fig. 1 as TE₀ mode. Two wavelength signals are launched to port3 and port4, and they are multiplexed by MUX1 and outputted as TE₀ mode through tapered ADC and TE₁-TM₀ MC. The other two wavelength signals are launched to port1 and port2, and they are multiplexed by MUX2. After that, these signals are coupled to the output (bus) waveguide of MUX1 as TE₁ mode by tapered ADC. Finally, these TE₁ modes are converted as TM₀ mode in TE₁-TM₀ MC. In this section, we explain the design principle and show experimental results of each component of the proposed four-wavelength MUX.

Fig. 1 The schematic of proposed four-wavelength MUX.

2.1 Design of tapered ADC

Here, we explain the design principle of tapered ADC. In the proposed device, tapered ADC acts as a TE₀-TE₁ mode coupler. To cover the broad wavelength range used in CWDM, the device should be broadband. At the same time, the device should be fabrication-tolerant to make the yield high. Figure 2 shows the schematic of the tapered ADC. It consists of the upper bus and the lower access waveguides. The width of the bus waveguide is w_2 . The width of the access waveguide is tapered from $w_1 + 2\Delta w$ to $w_1 - 2\Delta w$. The length of coupling region is L and the space between the access and the bus waveguide at the center of the coupling region is gap . S-bend waveguides are added to the access waveguide.

Fig. 2 The schematic of TE₀-TE₁ tapered ADC.

In [29], the broadband design method of tapered ADC based on the coupled-mode theory (CMT) was presented. First, we design ADC without S-bend waveguides. If we fix w_1 , w_2 , and gap , the design parameters are Δw and L . We evaluate following maximum deviation with changing the wavelength (MD_λ) for the broadband design.

$$MD_\lambda = \max\{|T(\lambda) - 1.0|\} \quad (1)$$

where $T(\lambda)$ is the transmission of TE₁ mode at port 4 at the three wavelengths ($\lambda = 1291, 1311, 1331$ nm), when the TE₀ mode is launched from port 1. Therefore, the structure with minimum MD_λ will have broadband characteristics. Here, we set $w_1 = 400$ nm, $w_2 = 824$ nm, $gap = 150$ nm. Figure 3(a) shows the MD_λ as a function of Δw and L . From this graph, MD_λ is minimum at $\Delta w = 6$ nm and $L = 79$ μ m, where the broadband operation is expected. However, the design does not guaranty the tolerance to the waveguide width variation. Therefore, to make the device fabrication tolerant, we evaluate following maximum deviation with changing the wavelength and the waveguide width ($MD_{\lambda w}$), considering the waveguide width variations.

$$MD_{\lambda w} = \max\{MD_\lambda(\Delta w_t)\} \quad (2)$$

where $MD_\lambda(\Delta w_t)$ is MD_λ given by Eq. (1) with the waveguide width deviations ($\Delta w_t = -10, 0, +10$ nm). If $\Delta w_t = 0$, above waveguide parameters (data are shown in Fig. 3(a)) are used. If Δw_t is not 0, Δw_t is added to w_1 and w_2 and subtracted from gap . Figure 3 (b) shows $MD_{\lambda w}$ as a function of Δw and L . $MD_{\lambda w}$ is minimum when $\Delta w = 7$ nm and $L = 73.1$ μ m, which is different from those of Fig. 3(a). Therefore, to make the device broadband as well as fabrication tolerant, the evaluation of Eq. (2) is useful.

Fig. 3 Calculated (a) MD_λ and (b) $MD_{\lambda w}$.

Figure 4 shows the calculated transmission spectra for several waveguide width variations of straight, tapered ADC1 (optimal design based on Eq. (1)), and, tapered ADC2 (optimal design based on Eq. (2)) without S-bend waveguides using CMT. In the graphs, ADC with the optimized width parameters is denoted as 0 nm. For other lines, the value of the waveguide with deviation is used as the legends. In this paper, ADC composed of simple straight waveguides ($\Delta w = 0$ nm) is named as “straight ADC”. The optimized straight ADC parameters are $w_1 = 400$ nm, $w_2 = 824$ nm, $gap = 200$ nm, $L = 66.4$ μ m, which is equivalent to the

ADC used in [28]. As shown in Fig. 4, the transmission of straight ADC is strongly affected by waveguide width deviation. If the waveguide width is reduced by 10 nm, the transmission is reduced more than -30 dB. On the other hand, two types of tapered ADC have a stronger tolerance for the waveguide width deviation than that of straight ADC. Especially, tapered ADC2 has the strongest tolerance to the waveguide width deviation. The worst transmission deviations between 1270 to 1330 nm for ± 20 nm deviations, are -2.5 dB for tapered ADC1 and -1.7 dB for tapered ADC2. From these results, we employ tapered ADC2 for CWD4 MUX.

Fig. 4 Calculated transmission spectra for several waveguide width variations of (a) straight, (b) tapered ADC1, and (c) tapered ADC2 without S-bend waveguides.

Since the above calculation does not include the coupling in the S-bend waveguides, we performed beam propagation analysis [30, 31] to take into account the coupling in the S-bend region and modify structural parameters. Final optimized parameters of tapered ADC2 are $w_1 = 400$ nm, $w_2 = 824$ nm, $gap = 150$ nm, $\Delta w = 7$ nm, $L = 30$ μm , $sep = 2$ μm , and, $L_r = 30$ μm .

Figure 5 shows the calculated transmission, T , (TE_0 mode in port 1 to TE_1 mode in port 4) and XT (TE_0 mode in port 1 to TE_0 mode in port 3) spectra for several waveguide width variations of tapered ADC2 with S-bend waveguides. In the graphs, ADC with the optimized parameter is denoted

as 0 nm. For other lines, the value of the waveguide width deviation is used as the legends. If the waveguide width varies ± 10 (± 20) nm, the transmission between 1270 to 1330 nm only deviates from -1.02 (-3.48) to -2.81 (-6.06) dB.

Fig. 5 Calculated transmission spectra for several waveguide width variations of tapered ADC2 with S-bend waveguides.

Fig. 6 Micrographs of (top) the fabricated tapered ADC and (bottom) two-cascaded tapered ADC.

2.2 Experimental results of tapered ADC

Figure 6 shows micrographs of the fabricated tapered ADC. For the fabrication, we used multi-project wafer (MPW) service. We fabricated three tapered ADCs with the designed waveguide width, and ± 10 nm from the designed value. Fig. 7 shows measured transmission spectra. For the measurement, TE-polarized light is coupled to port 1 of the chip through an inverse taper spot size converter [32] fabricated at both edges of the chip. Transmitted light is received by an optical spectrum analyzer. The transmission is measured by subtracting the transmitted power of a reference straight waveguide fabricated in the same chip. We measured the transmission characteristics of the two cascaded TE_0 - TE_1 tapered ADC as shown in the bottom panel of Fig. 6. By using this structure, the transmission characteristics of the TE_1 mode (port 1 to port 4) using TE_0 mode. Also, in the following, the received power from port 1 to port 3 (the power which is NOT converted to TE_1 mode) is labeled as “ XT ”. According to Fig. 7, T of the designed structure around 1320 nm is about -3.4 dB and T of $+10$ nm is -0.61 dB. This is probably because, in the fabrication process, there was a fabrication error in the waveguide width. Since the power of $T + XT$ is almost unity for all ADCs, the insertion loss itself is not so large. Therefore, we believe that the degradation comes from a waveguide width variation rather than a line edge roughness. From the comparison between calculated (Fig. 5) and measured results (Fig. 7), it is expected that the waveguide width of the fabricated device is reduced by 20

Fig. 7 Measured T and XT spectra for several waveguide width variations of the fabricated tapered ADC.

Fig. 8 Schematic of (left) 2×2 and (right) 2×1 MZ filters.

nm from the designed values (T of 20 nm in Fig. 5 agree well with that of 0 nm in Fig. 7).

2.3 Design of MZ filters

Figure 8 shows the schematics of MZ filters. The left panel is a MUX2 and the right panel is MUX1 in Fig. 1. The port numbers are the same as the fabricated device (Fig. 10). These filters are composed of two 3-dB MMI and delay line waveguides between them. We use CMT and BPM for designing these devices. Assuming MMI as a wavelength-insensitive 3-dB coupler, the operation principles of these MZ filters are expressed as Eqs. (3) and (4)

$$\begin{bmatrix} |T_{\text{Port2}}|^2 & |T_{\text{Port3}}|^2 \end{bmatrix}^T = \begin{bmatrix} \sin^2 \frac{\varphi}{2} & \cos^2 \frac{\varphi}{2} \end{bmatrix}^T \quad (3)$$

$$\begin{bmatrix} |T_{\text{Port4}}|^2 & |T_{\text{Port5}}|^2 \end{bmatrix}^T = \begin{bmatrix} \cos^2 \frac{(\varphi - \pi/2)}{2} & \sin^2 \frac{(\varphi - \pi/2)}{2} \end{bmatrix}^T \quad (4)$$

where, $\varphi = \beta \Delta L$ (β is a propagating constant of light propagating in delay line). FSR of MZ filter is expressed as Eq. (5)

$$\text{FSR} = \left| \frac{2\pi}{d\beta(\lambda_0)/d\lambda \cdot \Delta L} \right|. \quad (5)$$

If we use two 2×2 filters for MUX1 and MUX2, ΔL has to be changed to tune $\pi/2$ -phase difference between the two filters, which increases the design parameters. In addition, the external spectral tuning has to be done separately because their peak wavelength fluctuations caused by the fabrication error in the waveguide width are different due to different values of ΔL . In the proposed MZ filters, $\pi/2$ -phase difference is automatically satisfied by using 2×1 and 2×2 MZ filters as in Eqs. (3) and (4). Therefore, ΔL of two MZ filters is the same, and in principle, the spectral tuning can be done at the same time for both filters, which simplifies the peak wavelength tuning.

The calculated ΔL for 80-nm FSR is 4.93 μm . Solid lines in Fig. 9 show the transmission spectra of MUX1 and MUX2 by CMT. The positions of peak transmission for the 2×1 MZ filter are exactly at the center of the 2×2 MZ filter.

Fig. 9 Calculated transmission spectra of MUX1 and MUX2.

Although we do not use the flat-top design [18, 19], which needs multiple phase adjusting sections in the MZ filter, the spectra are already very flat, due to the removal of the second MZ filter with the FSR of 40 nm.

2.4 Experimental results of four-wavelength MUX

We fabricated the four-wavelength MUX designed in 2.1 and 2.3 in the same MPW service for tapered ADC shown in 2.2. Figure 10 shows a micrograph of fabricated four-wavelength MUX. TiN heaters are separately placed on the delay lines of MUX1 and MUX2. For the measurement, TE(TM)-polarized light is coupled to port1 of the chip through an inverse taper spot size converter fabricated at both edges of the chip. When TE_0 mode is launched to port1, the majority of the outputs come from port4(5). When TM_0 mode is launched to port1, the majority of the outputs come from port2(3). Black solid lines in Figs. 11 (a), (b), (c), and (d) show the measured T spectra without tuning for port 2, 3, 4, and 5, respectively. The loss of tapered ADC2 (Fig. 7) is subtracted for clarity for Figs. 11 (a) and (b). Filtering spectra with almost 80-nm FSR can be seen. The peak wavelength position of MUX2 (1300 nm) is in the middle of those of MUX1 (1280 and 1315 nm), showing the effect of 2×2 and 2×1 configuration. The deviation of FSR from 80 nm probably comes from the waveguide width fabrication error. The waveguide width deviation makes the value of group delay in Eq. (5) different, leading to the deviation of FSR. Also, the huge waveguide width change increases the loss of MMI and makes the splitting ratio of 2×2 MMI unequal. Probably due to these reasons, the relative peak wavelength positions of 2×2 MZI is not at the center of those of 2×1 MZI. Colored lines in Fig. 11 are transmission spectra with tuning current to TiN heater. As the injection current increase, the peak wavelength positions are shifted to a longer wavelength side. For the same tuning current, the spectral shift is almost the same for MUX1 and MUX2, showing the possibility of tuning two MUXs with one heater.

Figure 12 shows the tuned transmission spectra of four-wavelength MUX. The tuning currents for MUX1 and MUX2 are 20 and 28 mA. Since the FSR is deviated from 80 nm, we cannot make the wavelength spacing 20 nm. The tuning was done to see four wavelength MUX can be seen in the range of 1270 to 1330 nm. For MUX1, the loss of tapered ADC is subtracted for clarity. Clear four wavelength MUX operation can be seen, showing the proof-of-concept of the device. Relatively large loss around 1330 nm and oscillating spectra around 1270 nm come from the limited

Fig. 10 Micrographs of fabricated four-wavelength MUX.

Fig. 11 The measured T spectra for different injection currents of the fabricated four-wavelength MUX for (a) Port2, (b) Port3, (c) Port4, and (d) Port5.

Fig. 12 Transmission spectra of four-wavelength MUX.

bandwidth of our ASE light source.

As explained above, the waveguide width error in the fabrication process was expected to be ~ 20 nm. The insertion loss shown in Figs. 11 and 12 may come from 1×2 and 2×2 MMI due to the waveguide width deviations. Considering the waveguide width control in standard Si-photonics lithography technique (± 10 nm [33]), the deviation in the MPW process used here is too huge. Therefore, if the waveguide width can be controlled within standard value, the performance can be improved as designed.

3. Conclusion

We theoretically and experimentally demonstrated four-wavelength MUX for CWDM4 using two types of MZ filters and a PSR based on tapered ADC and TE_1 - TM_0 MC. The new design method of tapered ADC considering fabrication-tolerance is presented. Fabricated device exhibits proof-of-concept characteristics. The proposed MUX configuration is useful for low-cost CWDM4 MUX.

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