Proposal for a polarization-insensitive and fabrication-tolerant CWDM (de)multiplexer based on cascaded silicon nitride Mach-Zehnder interferometers

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***Abstract*—We propose a polarization-insensitive coarse wavelength division multiplexing (de)multiplexer with large fabrication-tolerance. This device uses a two-stage-MZI coupler with multi-mode waveguide to reduce the phase error, and a two-sections phase-shifter for polarization dependent dispersion engineering. Simulation results show low polarization dependent losses (<0.05dB) within a fabrication-error range of 30 nm.**

Keywords—wavelength division multiplexing, optical filters, Mach-Zehnder interferometers, integrated optics, polarization-insensitive, fabrication-tolerant

I. Introduction

Wavelength division multiplexing (WDM) technology can effectively expand the communication bandwidth by transmitting multiple wavelength carrier channels in single-mode fiber[1]. WDM technology is considered to be a promising technology in large link capacity interconnection scenarios such as modern data centers and 5G fronthaul. Coarse wavelength division multiplexing (CWDM) with channel spacing of 20 nm can relax the accuracy of laser oscillation wavelength and reduce the temperature sensitivity of the whole WDM system. It is a cost-effective WDM system.

WDM (de)multiplexer is the core device to realize CWDM system. In recent years, a large number of on-chip CWDM (de)multiplexers have been reported, including multiplexers based on arrayed waveguide gratings (AWGs)[2], Mach-Zehnder interferometers (MZIs)[3]–[6], Bragg gratings (BGs)[7], [8], and multi-mode interferometers (MMIs)[9]. The cascaded MZIs are utilized to achieve a four-channel CWDM filter with low insertion loss, low crosstalk and flat pass-band. The MZI filter is basically composed of a series of directional couplers (DCs) and phase shifters (PSs). Therefore, the performance of CWDM filter based on MZI is closely related to the coupling ratio dispersion in DCs and the phase error in PSs. Due to the birefringence effect of the material, the dual polarization state will produce polarization-dependent errors in both the splitter and the phase-shifter. There are currently two solutions to solve this problem: one is to use a square waveguide cross-section structure[10], but this method is obviously sensitive to the fabrication-errors. The other is to insert a polarization rotator in the phase shifter[4], but this polarization rotator device is also very sensitive to the fabrication error and will introduce additional insertion loss.

In this work, we propose a polarization-insensitive four-channel CWDM (de)multiplexer with large fabrication-tolerance based on cascaded MZI in 800nm Silicon nitride on insulator (SNOI) waveguides. We introduce a two-stage-MZI coupler instead of the conventional DC to obtain a uniform splitting ratio for a large bandwidth range. A two-sections phase-shifter based on multi-mode waveguide is used for reducing the phase errors and engineering polarization-dependent dispersion.

II. Theory

For a MZI with two-sections PS, as shown in Fig. 1 (a), the central wavelength phase shift (Δφ) can be written as :

$$\Delta\varphi = \frac{2\pi}{\lambda_0}\cdot\left(n_{eff1}L_N - n_{eff2}L_S\right) \qquad (1)$$

where n_{eff1}, n_{eff2}, L_N and L_S are the effective indices and effective phase-shift length of the two waveguides with $width = w_1, w_2$ respectively, and λ_0 is the working wavelength. Considering the dispersion between TE_0 and TM_0 modes we can obtain:

$$\Delta\varphi_{TEM} = \frac{2\pi}{\lambda_0}\cdot\left(\Delta n_{eff1}L_N - \Delta n_{eff2}L_S\right) \qquad (2)$$

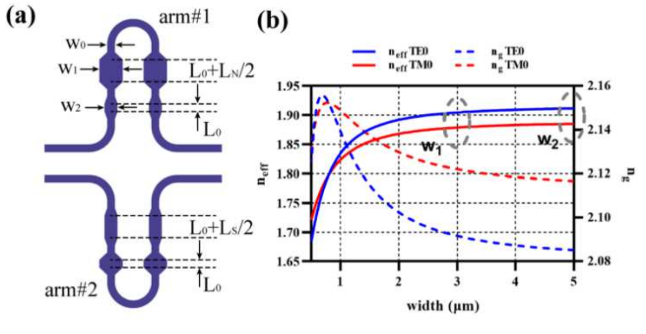

Fig. 1. (a) Schematic configuration of the proposed two-sections PS with key parameters labled. (b) The calculated effective index (n_{eff}) and group index (n_g) dispersion curves for TE_0 and TM_0 modes in 800nm SNOI waveguides.

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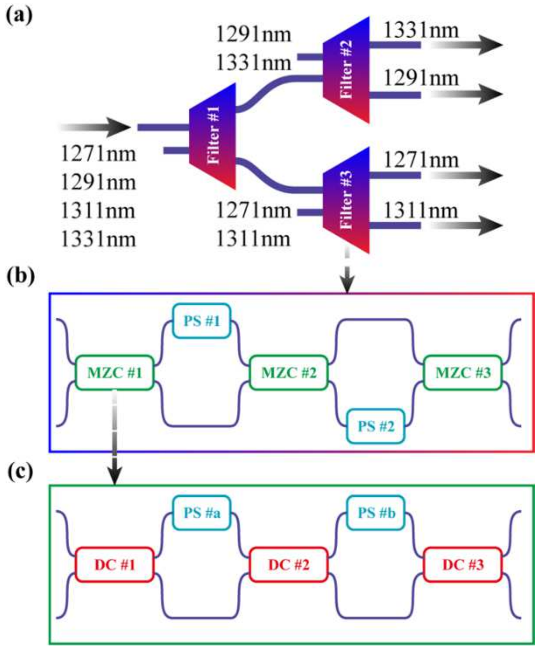

Fig. 2. (a) Illustration for the 4 chennal demultiplexer based on cascaded MZIs. (b) The Schematic layout of the cascaded MZIs with two-stage-MZI coupler. (c) The Schematic layout for the two-stage-MZI coupler with conventional DC.

where $\Delta\varphi_{TEM}$ represents the polarization-dependent phase error, and Δn_{effi} represents the refractive index difference of TE$_0$ and TM$_0$ modes for the waveguide with $width = w_i$ respectively. In order to achieve polarization-insensitive phase-shifting characteristics, the above equation needs to be equal to 0, that is, the effective phase-shifting length of the waveguides needs to meet:

$$\frac{L_S}{L_N} = \frac{\Delta n_{eff1}}{\Delta n_{eff2}} = \eta \tag{3}$$

where η is a scale factor solely determined by the width of the waveguide. We introduce the concept of joint effective index ($n_{eff,j}$) and joint group index ($n_{g,j}$). The phase shift of the PS can be expressed in a simpler way:

$$\Delta\varphi = \frac{2\pi}{\lambda_0} \cdot n_{eff,j} L_N \tag{4}$$

$$n_{eff,j} = n_{eff1} - \eta \cdot n_{eff2} \tag{5}$$

$$n_{g,j} = n_{g1} - \eta \cdot n_{g2} \tag{6}$$

$$L_N = \frac{\lambda_0}{FSR \cdot n_{g,j}} \tag{7}$$

Thus, the PS can be designed to obtain polarization-insensitivity with a large fabrication tolerance. Applying such PS to the MZI couplers and multiplexers, a polarization-insensitive CWDM (de)multiplexer with large fabrication tolerance can be obtained.

III. Design and Simulation

The proposed (de)multiplexer is composed of three cascaded MZI filters connected in binary tree form in 800nm SNOI platform, as shown in Fig. 2 (a). Four channels of light enter the filter #1 are divided into two groups to filter #2 and filter #3, respectively. Each filter adopts the same cascaded MZI structure[11], as shown in Fig. 2 (b), where the splitter is a two-stage-MZI coupler to achieve a uniform splitting ratio with large bandwidth[12], as shown in Fig. 2 (c). We choose the waveguide width $w_0 = 0.7\mu m$ and $gap = 0.5\mu m$ in the coupling region to obtain a same odd-even symmetry mode effective index difference for TE$_0$ and TM$_0$ modes at the central wavelength, which ensures that the DC exhibits similar splitting for TE$_0$ and TM$_0$ modes, as shown in Fig. 3 (e).

To obtain a larger fabrication tolerance, we choose the width of the multi-mode waveguide as $w_1 = 5\mu m$ and $w_2 = 3\mu m$. The stability of the PS not only determines the fabrication tolerance, but also affects the polarization sensitivity. The length scale factor of the PS under this width selection can be calculated by Eq. (3): $\eta = 1.024$, and the joint effective index and group index can be calculated. The relationship between the splitting ratio and the phase shift of the two PS arms φ_a, φ_b and the relationship between the splitting ratio dispersion and the phase shift are calculated using the transfer matrix method (TMM), as shown in Fig. 3 (a-d). We choose the splitting ratio as 50:50, 29:71, 8:92 for each two-stage-MZI coupler to meet flat-top transmission requirement and the phase shifts are listed in TABLE I. to ensure uniform splitting ratio in a wide bandwidth range for both TE$_0$ and TM$_0$ modes as shown in Fig. 3 (f).

TABLE I. The Phase Shifts And Waveguide Lengths Of The Two-Stage-MZI Coupler

	φ_a	$L_{Na}(\mu m)$	$L_{Sa}(\mu m)$	φ_b	$L_{Nb}(\mu m)$	$L_{Sb}(\mu m)$
50:50	2.1	-11.0	-11.3	0	0	0
29:71	2.1	-11.0	-11.3	0.5	-2.6	-2.7
8:92	1.9	-10.0	-10.2	1.1	-5.8	-5.9

The negative length indicates that the waveguide is on the other side arm.

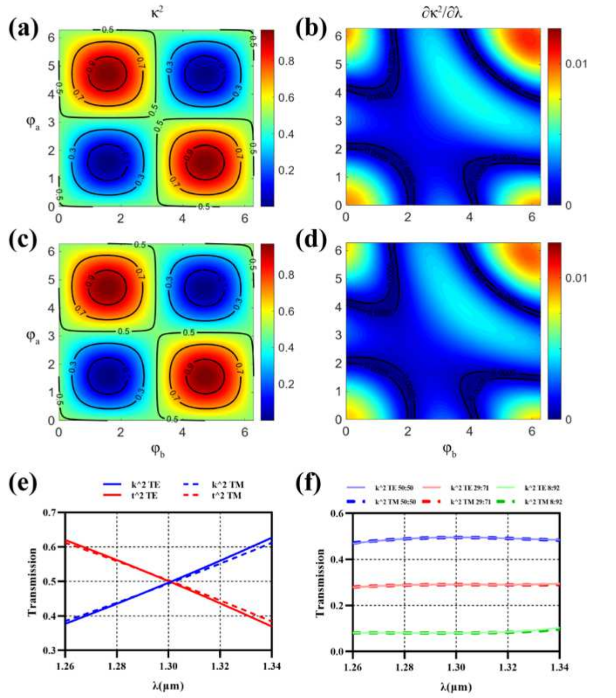

Fig. 3. The calculated (a, c) coupling ratios (κ^2) and (b, d) coupling-ratio dispersions (∂κ^2/∂λ) for a two-stage-MZI coupler with varied phase shifts (φ_a, φ_b) for TE$_0$ (a, b) and TM$_0$ (c, d) modes. (e) The calculated coupling ratio spectra for the directional coupler. (f) The calculated coupling ratio spectra for the optimized two-stage-MZI couplers (MZC #1-3) with splitting ratio of 50:50, 29:71, 8:92.

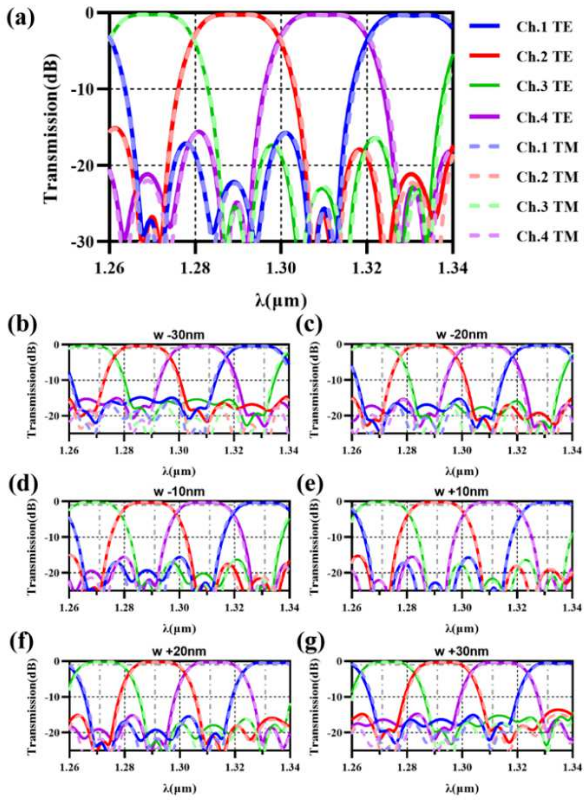

Fig. 4. (a) The calculated transmittance spectra for the optimized CWDM (de)multiplexer. (b-g) The calculated transmittance spectra with width deviations from −30 nm to +30 nm.

TABLE II. THE PHASESHIFTER LENGTHES OF THE CASCADED MZI FILTERS

	$L_{N1}(\mu m)$	$L_{S1}(\mu m)$	$L_{N1}(\mu m)$	$L_{S2}(\mu m)$
Filter #1	-774.4	-793.3	-1390.0	-1423.9
Filter #2	-416.4	-426.6	-674.0	-690.4
Filter #3	-408.2	-418.2	-657.6	-673.6

The negative length indicates that the waveguide is on the other side arm.

According to the Eq. (7), the length of PS #1 and PS #2 are calculated, where $L_{N2} = 2 * L_{N1}$, it should be noted that the two-stage-MZI coupler do not have a phase difference of $\pi/2$ as the DC for all wavelengths. The PS lengths need to be fine-tuned based on the calculation result. The final PS lengths are listed in TABLE II.

IV. RESULTS AND DISCUSSION

We then calculate the transmission spectrum of the 4-channel CWDM multiplexer. As shown in Fig. 4 (a), the crosstalk of the four channels is less than -22dB for both TE_0 and TM_0 modes, and does not introduce additional insertion loss caused by devices such as polarization rotator. The polarization dependent loss is less than 0.03dB. In terms of fabrication tolerance, the broadening of the waveguide does not affect the polarization-related central wavelength deviation, and the crosstalk gradually deteriorates as the broadening becomes larger. In the broadening range of 30nm (−10nm ~ +20nm), the crosstalk can be controlled near −20dB for TE_0 and TM_0 modes. The proposed multiplexer reduces the requirement of fabrication accuracy as much as possible while ensuring polarization insensitivity. The previous works have only optimized to achieve polarization insensitivity without considering the difficulty of fabrication.

V. CONCLUSIONE

We proposed a CWDM (de)multiplexer based on cascaded Mach-Zehnder interferometers with dispersion-engineered phase-shifters and two-stage-MZI couplers. The polarization-dependent dispersion is engineered by using a two-sections phase-shifter with multi-mode waveguide. From the simulation results, the insertion loss of the device is less than 0.5dB, the crosstalk is less than -22dB, the 1dB bandwidth is 13.4nm, and the polarization dependent loss is less than 0.03dB. In the range of 30 nm fabrication tolerance, the crosstalk is kept near -20 dB, and the polarization dependent loss is not affected.

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