A tunable mode divider based on wavelength insensitive coupler using thermo-optic effect for gain-equalization in MDM network

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Abstract: A tunable TE_0-TE_1 mode divider based on wavelength-insensitive-coupler is experimentally demonstrated for the first time. Arbitrary branching ratios can be realized by using thermo-optic heaters. The proposed device is useful for gain-equalization in MDM networks.

1. Introduction

A mode-division-multiplexing (MDM) technique has attracted a lot of attention to increase the capacity of optical fiber transmission system. To construct MDM system, various mode processing devices are necessary, such as mode multi/demultiplexers [1,2], mode converters [3], and few-mode amplifiers [4]. Especially, few-mode (FM) amplifiers based on EDFA are indispensable building blocks for long-haul MDM systems. One of the problems in FM-EDFA is the mode-dependent gain (MDG). To compensate for the MDG, a mode-gain-equalizer is necessary. For single mode waveguide, the gain-equalizer is usually constructed based on free-space optics [5] and dynamic gain equalization for wavelength is possible. As well, a MDG equalization method based on free-space optics for FM-EDFAs [6] also has been proposed. However, if the free-space optics components are used, the size becomes large. Therefore, using an integrated waveguide platform, such as Si photonics is preferable.

To construct the mode-gain-equalizer in the integrated waveguide platform, a broadband mode divider with an arbitrary branching ratio is necessary, as shown later in Fig. 1. In the mode divider, the input mode is divided into the original mode and desired different mode. Recently, we proposed broadband mode divider based on wavelength-insensitive-coupler (WINC) [7], and the branching ratio was changed by adjusting the length of the delay line. However, to construct the dynamic gain equalization function, the tunability is essential.

In this work, an ultra-small tunable TE_0-TE_1 mode divider based on multimode WINC using Si-photonics platform is experimentally demonstrated for the first time. The device is composed of two 3-dB mode dividers and delay lines between them. By properly choosing the length of the delay lines, the broadband mode dividing with arbitrary branching ratio is possible. Branching ratio can be further tuned by using thermo-optic heaters and > 50% branching ratio tuning is demonstrated. Proposed devices were fabricated in CMOS platform and measured spectra are in good agreement with theory. These results indicate that the proposed device is useful for flexible and various mode manipulations, such as dynamic gain equalization.

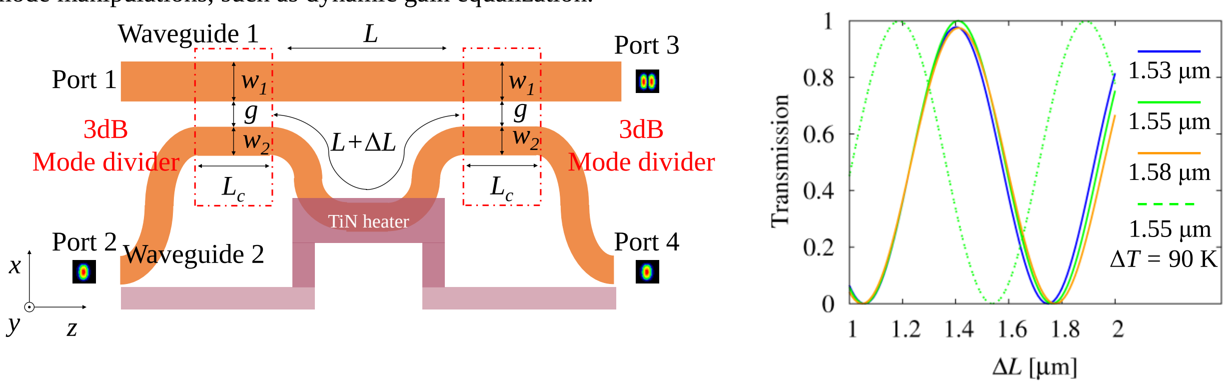

Fig. 1 (a) The schematic of a mode divider with arbitrary branching ratio based on multimode WINC. (b) Transmission (port2 to port3) as a function of ΔL for L = 20 μm.

Fig. 2 A micrograph of (left) the fabricated mode divider with arbitrary branching ratio based on multimode WINC and (right) two-cascaded mode divider.

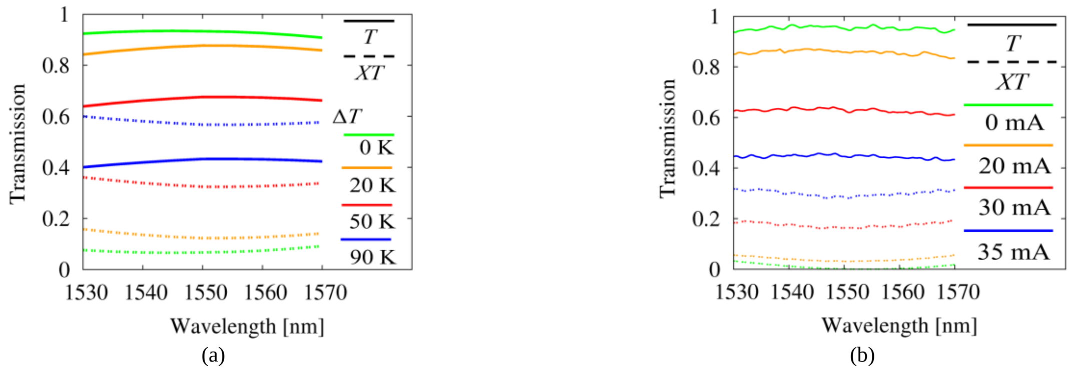

Fig. 3 (a) Calculated transmission (T) and XT spectra for 0 K to 90 K. (b) The measured T and XT spectra for different injection currents of the fabricated mode divider.

2. Operation principle and results

Figure 1 (a) shows the schematic of the mode divider considered in this paper. It is composed of two straight 3-dB mode dividers and delay line waveguides. In the first straight 3-dB mode divider, input TE_0 mode from port 2 is equally divided to TE_1 and TE_0 mode in waveguides 1 and 2 at the center wavelength, and TE_0 mode in the waveguide 2 has additional phase delay in the delay line waveguide. Then, two modes are combined in the second straight 3-dB mode divider and outputted to either port with arbitrary branching ratio depending on the phase difference. The widths of the waveguides 1 and 2 are w_1 and w_2 respectively, and the height of the waveguide is h. For straight 3-dB mode dividers, the spacing between the waveguides is g, and the coupling length is L_c. For delay line waveguides, the lengths of waveguides 1 and 2 are L and $L + \Delta L$ respectively. The refractive indices of the core and the cladding are assumed to be 3.476 (silicon) and 1.444 (silica). We set w_1 = 837 nm, w_2 = 400 nm, g = 200 nm, h = 210 nm. L_c = 9.09 µm, which is the half of coupling length at 1.55 µm.

Solid lines in Fig. 1 (b) show the calculated transmission, T, (TE_0 mode in port 2 to TE_1 mode in port 3) as a function of ΔL calculated by coupled mode theory (CMT) [8] for three wavelengths (λ = 1.53, 1.55, and 1.57 µm). We set L = 20 µm for delay line waveguides. For λ = 1.55 µm, since it is the center wavelength for the design, the transmission is changed from 0 to 1. Although the wavelength dependence can be seen in the transmission, in the range from ΔL = 1 to 1.4 µm, the transmission is almost the same for all three wavelengths and broadband operation can be expected. Also, the transmission is sinusoidally changed with ΔL. It implies that by changing the refractive index of one of the delay line waveguides, the transmission of the mode divider can be tuned. To compose tunable mode divider, on top of the cladding, approximately 2-µm above the Si core, a TiN heater is placed on the delay line waveguide 2 as shown in Fig. 1(a). By injecting the current to the heater, the refractive index of the delay line waveguide 2 is changed by the thermo-optic effect, and the output ratio of the mode divider can be adjusted. In Fig. 1(b), the transmission of the mode divider when the temperature of the Si core in the waveguide 2 is increased by 90 K is also shown as a dashed line for 1.55 µm. For the calculation, the propagation constant of the delay line waveguide is given by

$$\beta' = \beta + k_0 \frac{\delta n}{\delta T} \Delta T \qquad (1)$$

where β is the propagation constant of Si-wire waveguide at room temperature (RT;300K), k_0 is the wavenumber, ΔT is the temperature deviation from RT, $\delta n/\delta T$ is the thermo-optic constant of Si and is 1.86×10^{-4} K^{-1}[9]. The transmission for ΔT = 90 K is significantly changed compared with that of RT, resulting in the tunable operation.

The left panel of Fig. 2 shows the micrograph of the fabricated tunable mode divider. For the measurement, TE-polarized light is coupled to the port 2 of the chip through inverse taper spot size converter [10] 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 mode dividers as shown in the right panel of Fig. 2. By using this structure, the transmission characteristics of the TE_1 mode (port 2 to port 4) as TE_0 mode. Also, in the following, the received power from port 2 to port 5 (the power which is NOT converted to TE_1 mode) is labeled as "*XT*". Figure 3 (a) shows the calculated *T* and *XT* spectra for 0 K to 90 K and Fig. 3 (b) shows measured *T* and *XT* spectra for the injection currents of 0 to 35 mA of the fabricated mode divider. For ΔL = 1.35 μm, almost all the input TE_0 mode is multiplexed as TE_1 mode when no current is injected. By increasing the current, the transmission to TE_1 mode is reduced and *XT* is increased, showing the tunable mode dividing operation. The measured results are in good correspondence with the calculated results.

Figure 4 shows *T* and *XT* as a function of the injection current for the wavelength of 1.55 μm. The results of the mode dividers with ΔL =1.05 to 1.35 um are shown. By changing the value of ΔL, the starting point of the transmission can be changed. For ΔL =1.05, 1.15, 1.25, and 1.35 μm, the transmissions without current injection are 95.1%, 85.5%, 40.7%, and 10.1%. By injecting current, the ratio between *T* and *XT* is changed for all ΔL and arbitrary branching ratio can be achieved.

Finally, Fig. 5 (a) shows the concept of mode-gain-equalizer by using the tunable mode divider for the two-mode case. The signals of TE_0 and TE_1 mode are amplified by a FM-EDFA (and their optical powers are different). After the EDFA, the two modes are demultiplexed as TE_0 modes by using, for example, an asymmetric directional coupler. Then, if the power of the TE_0 signal is larger, the TE_1 mode is transmitted as the demultiplexed TE_0 mode. The original TE_0 mode signal is inputted to the add waveguide of the TE_0-TE_1 mode divider and multiplexed as TE_1 mode and the multiplexed power is adjusted by the mode divider, resulting in the power equalization (at the same time, the mode is exchanged). Figure 5(b) shows the schematic of the three-mode case. Three modes are demultiplexed as TE_0 mode after the EDFA, and for example, the original TE_2 mode signal is transmitted as TE_0 mode. The original TE_1 mode signal is multiplexed by the tunable mode divider with adjusting the power as TE_1 mode. The original TE_0 mode is multiplexed by the tunable mode divider with adjusting the power as TE_2 mode. Although in this work, only TE_0-TE_1 mode divider is demonstrated, the design of TE_0-TE_2 mode divider can be designed as well.

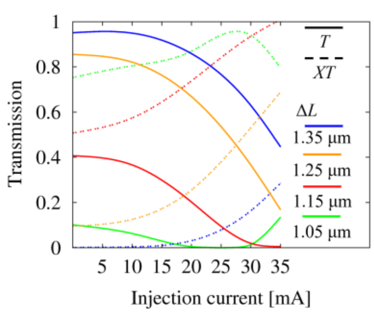

Fig. 4 The measured *T* and *XT* as a function of the injection current at ΔL =1.05 to 1.35 μm for the wavelength of 1.55 μm

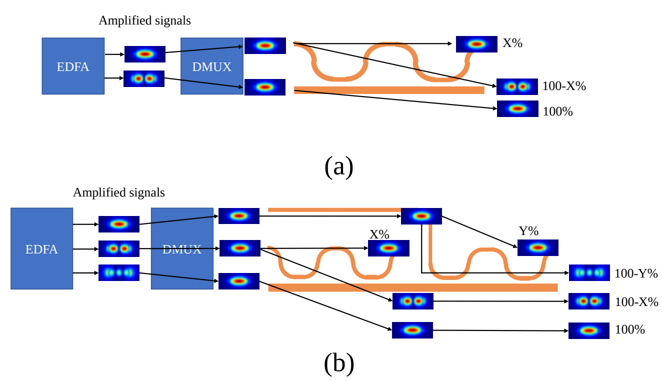

Fig. 5 The concept of mode-gain-equalizer by using the tunable mode divider for (a) two-mode case and (b) three-mode case

3. Conclusion

An ultra-small tunable mode divider based on multimode WINC using the thermo-optic effect was, for the first time, demonstrated on the Si-photonics platform. The measured results are in good correspondence with the calculated results, and the transmission of the output port can be adjusted by changing the temperature of one of the delay lines. The proposed device is useful for constructing a more flexible and functional MDM system, such as gain-equalization.

4. Referense

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