Passive ring-assisted Mach-Zehnder interleaver on silicon-on-insulator

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Abstract: A passive ring-assisted Mach-Zehnder interferometer optical interleaver comprising a Y-bench, a 3-dB directional coupler , a ring-resonator, and a delay line is proposed. The interleaver is fabricated with 300 nm \times 300 nm silicon wires on silicon-on-insulator. The fabricated interleaver demonstrates a flat-top spectral response. The measured free-spectral range is ~4 nm, the insertion loss is ~ -8 dB, and the crosstalk is <-10dB. Both the experimental and simulation results are in good agreement.

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1. Introduction

Optical interleavers/de-interleavers are key components for increasing data transmission rate in optical fiber communication [1-4].Commonly, interleaver divides odd and even number of channels in to two waveguides. This character is applied to increase the channel spacing. Therefore Wavelength-Division Multiplexing (WDM) functional device can be used on Dense Wavelength-Division Multiplexing (DWDM) system. Optical interleavers/de-interleavers have been designed and implemented in many varieties, such as Michelson Gires-Tournois Interferometer (MGTI) [5, 6], bulk birefringent crystal [7, 8], fiber [9-11], and Planar Lightwave Circuit (PLC) [12-19]. However, the MGTI, the bulk birefringent crystal, and the fiber based cannot be integrated with other devices on a chip with the standard complementary metal oxide semiconductor (CMOS) technology. On the contrary, fabrication of the PLC based can be compatible with the CMOS technology. Furthermore, the PLC based interleavers are compact and cost-effective. They are attractive candidates for the DWDM applications.

Typically, an interleaver requires a flat-top and box-shaped spectral response. Jinguji et. al. [12, 13] have proposed a cascade structure to realize an arbitrary filtering response. However, as they used multiple stages for the structure, the design and fabrication were complicated. Oguma et al. used only two stages in the lattices to realize 50-GHz spacing on a 102-channel WDM filter with the insertion loss of 4 dB and the 1-dB bandwidth of 30 GHz [14]. Bidnyk et al. [15] reported a design of a DWDM interleaver based on planar echelle gratings, but the gratings were difficult to deliver a flat-top response. We have designed and fabricated a compact Ring-Resonator Mach-Zehnder Interferometer structure [16], which only comprised a ring and a 3-dB directional coupler (DC). Oda et. al. proposed a guided-wave multi/demultiplexer with ring resonator structure [17], which Madsen and Zhao [4] named as Autoregressive Moving Average (ARMA) filter. Wörhoff et. al. [18, 19] also demonstrated an interleaver with approximately rectangular spectral response. The interleaver comprised an asymmetric Mach-Zehnder Interferometer (MZI) in which a ring resonator was coupled to one of the branches of the MZI. Similarly, Wang et al. [20] presented an ultra-compact optical interleaver based on a two micro-rings assisted MZI on the silica platform. Although the device exhibited a flat and nearly box-shaped pass band, a phase difference had to be introduced externally and the circumference of the micro-rings had to be controlled exactly as two times of the length of the delay line. In fact, an MZI with one delay line can fully function as interleaver [21], and a ring resonator can be employed to flatten the top of the pass band spectrum.

As we mentioned, the previous ARMA structure needs an external phase shift which is commonly realized with a thermo-optical method. In this letter, we will modify the ARMA

filter by using a Y-branch to replace the 3-dB coupler; as a result, the external phase shift will be omitted and the fabrication process will be simplified. We will investigate the new structure both theoretically and experimentally. The reliance on heaters for thermo-optical structures has two purposes: introduce the π or half of π phase shift and increase the fabrication tolerance. As our structure introduces a fixed phase shift to realize the interleaver function, it is a purely passive device. However, this does not mean that a heater is useless to our device. The heater can provide fine tuning and compensation of fabrication tolerance for our future integrated interleavers.

2. RA-MZI structure and optimization



Fig. 1 Schematic of the ARMA, which comprises an asymmetric MZI structure with two 3-dB DCs and a ring resonator. (a). An external phase shift π introduced in the ring resonator. (b). An external phase shift $\pi/2$ introduced in an arm of the MZI. The yellow regions in (a) and (b) denote the external phase shifts. (c). Schematic of the RA-MZI, which comprises a 1×2 asymmetric MZI structure in which a ring resonator is coupled with an arm of the MZI.

The ARMA structure, comprising an asymmetric MZI and a ring, is shown in Fig. 1 (a). The asymmetry is introduced by the delay line in an arm of the MZI. The length of the delay line determines the free-spectral range (FSR), and the length of the optical path (total phase shift) of the R-R should be two times of that of the delay line. To realize the interleaver function, we need to add an external phase shift π in the ring. Alternatively, the external phase shift can be allocated to one of the arms of the MZI, shown in Fig. 1(b), but the shift should be changed as $\pi/2$ correspondingly, because the length of the optical path of the ring-resonator (R-R) is equivalent to two times of that of the delay line. It is known that an inherent $\pi/2$ phase difference between two output waveguides of any directional coupler will be induced. If we use a Y-branch to replace the 3-dB DC in the input port of the interleaver, the external phase shift exerted on the arm of the MZI or the ring can be removed. We name the modified structure as Ring-Assisted Mach-Zehnder Interferometer (RA-MZI) interleaver, as shown in Fig. 1(c). Obviously, the RA-MZI interleaver is a fully passive device.

The transmission functions of Leads A and B in the RA-MZI are described in equation (1) [22]:

$$\begin{cases} H^{(A)} = \frac{\sqrt{2}}{2} \left[H^{(R)} + i \exp\left(i\frac{\theta}{2}\right) \right] \\ H^{(B)} = \frac{\sqrt{2}}{2} \left[iH^{(R)} + \exp\left(i\frac{\theta}{2}\right) \right] \end{cases}$$
(1)

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#92834 - \$15.00 USD (C) 2008 OSA where, *H* denotes the transfer function, and $H^{(R)} = \frac{t - p^2 \gamma exp(i\theta)}{1 - t \gamma exp(i\theta)}$ is transfer function of

light passing through the R-R, a ratio between the input and the output wave functions. θ is the total phase shift for light that runs one round in the ring and can be described as: $\theta = n_r L_c k_0 = n_r L_c \omega/c$. Since θ is a function of frequency ω , we will not distinguish θ and ω in the following discussion. L_c is the circumference of the ring, k_0 is the wave number of vacuum, and *c* is light velocity in vacuum. We define the amplitude loss coefficient as $\gamma = exp(-n_i L_c k_0)$, where n_r and n_i are the real and imaginary parts of the effective refractive index, respectively. We assume that the self coupling coefficient (*t*) and cross coupling coefficient (κ) are constant in the two coupled points of the R-R, and $t^2 + \kappa^2 = 1$. Figure 2 shows comparison of calculated results of ARMA and RA-MZI. Both results are alike except a π shift between them.



Fig. 2. calculated results of the ARMA and RA-MZI. t=1/3.

For an interleaver, the pass band spectrum should be flat. Theoretically, for the lossless case, when t=1/3, the pass band is the flattest. Figure 3(a) shows the response of an interleaver varying with the coupling coefficient *t*. If *t* is near zero, the response will resemble that of a general asymmetric MZI. When *t* is near 1/3, the response flattens, for t=1/2, the red line in Fig. 3(a), the ripples of top are less than 0.006. And when *t* is greater than 0.7, the response ripples obviously. However, when *t* approaches 1, the response will have steep lobes. At $\Delta \theta = -2\pi$ and 0π , the responses display like Fano resonance.

The group delay time is defined as: $\tau = -\frac{\partial \phi}{\partial \omega} = -T_c \frac{\partial \phi}{\partial \theta}$, where T_c is the time of light running a full round in a ring, and the group delay time is dependent on T_c . And we have equation:

$$\frac{\partial \phi}{\partial \theta} = \frac{1}{4} + \frac{1 - t^2}{2 \left\lceil 1 - 2t \cos(\theta) + t^2 \right\rceil}$$
(2)

For the lossless situation, the related group delay is described in equation (2). The influence of varying *t* on the group delay time is shown in Fig. 3(b). In the middle of the 3-dB pass band ($\Delta\theta$ is between -2π and 0π), the group delay time will decrease with increasing *t*, but at -2π and 0π , the situation is reversed. As we mentioned above, the length of the optical path of the R-R must be equivalent to two times of that of the delay line. Thus, if a subtle mismatch between them occurs, the symmetry between their responses will be destructed. Figure 3(c) shows this trend. *v* is the optical path, an asymmetry in the crosstalk will be still observable. The crosstalk deteriorates with increasing $\Delta\theta$. Another important factor that influences the crosstalk is the 3-dB DC. Commonly, transmissions of the bar and the cross outputs of a DC can be described as $cos^2(\theta_{DC})$ and $sin^2(\theta_{DC})$, respectively, where $\theta_{DC}=KL$, *K* is the coupling coefficient of the DC, and L is the effective length of the DC. *K* is a function of

the structure size and the wavelength. For the 3-dB DC, θ_{DC} should be odd multiple of $\pi/4$. If there is a slight deviation, for example, $\theta_{DC}=\pi/4+\eta\Delta\theta$, where $\eta=0.01$, we can see clearly from Fig. 3(d) that the crosstalk deteriorates with increasing $\Delta\theta$.



Fig. 3. (a). Characteristics of the pass band with different coupling coefficient *t*. *t* is from 0.1 to 0.9. (b). Characteristics of related group delay time with different *t*. (c). Characteristics of the response spectrum with different *v*. t=1/3. (d). Characteristics of the response spectrum for 3-dB DC, where $\eta=0.01$.

3. Fabrication and characterization

The fabrication process is the same as in [16]. We start the fabrication on a commercial 200 mm SOI wafer with 400-nm-thick top silicon and 2-µm-thick buried silicon dioxide. We oxidize and thin the top silicon to 300 nm and then use 248 nm deep UV lithography to transfer the pattern to the wafer. Then, we use inductively coupled plasma etching system to dry etch the patterned silicon layer. To decrease waveguide surface roughness, we further thermally oxidize 5 nm-thick silicon. Finally, we deposite 3 µm-thick silicon dioxide with plasma-enhanced chemical vapor deposition process on the wafer. The SEM pictures for the etched structures are shown in Fig. 4. Figure 4(a) is a full view of the RA-MZI. The full length of the device is 3 mm. The cross-section of the silicon wire is \sim 300 nm \times 300 nm. Figure 4(b) shows a fabricated 3-dB DC. The coupling gap is 300 nm and the coupling length is 11.27 µm. Figure 4(c) shows the optical delay line (ODL). The RA-MZI has two ODLs, each of which comprises two 180° bends. The radius of the bends is $10 \,\mu\text{m}$. The total length of the ODL is equivalent to that of the two rings. Figure 4(d) is the ring coupled with an arm of the MZI. The gap between the ring and the arm waveguides determines the coupling coefficient. Figure 4(e) is a spot-size converter (SSC). The tip width of the SSC is 150 nm, and the length is 200 µm. As the optical path of the R-R should be equal to two times of that of the ODL, we set the radii of the R-R as 40 µm.



Fig. 4. (a). SEM picture of the RA-MZI. (b). the 3-dBDC, where the coupling length is 11.27 μ m, and the coupling gap is 300 nm. (c). Optical delay line. The diameter of the bend is 20 μ m. (d). the R-R coupled with a waveguide. The coupling gap is ~280 nm. (e). SEM of the SSC, where the tip width is 150 nm, and the length is 200 μ m.

In the measurements, the insertion loss (IL) was recorded as the fiber to fiber loss, which included the device transmission loss and the coupling loss between a fiber and an SSC. Two lensed polarization-maintaining fibers are coupled with the input and the output silicon wires, respectively. We use a polarization controller to choose a quasi-TE mode (electric field parallel to the substrate plane) from an ASE (Amplified Spontaneous Emission) light source. Firstly, we connect a broadband light source, a polarization controller, and an optical spectrum analyzer with polarization maintaining fibers, and then measure the IL at TE polarization, which is set by the polarization controller. The measured IL is saved as reference for the following measurements._Then, we deduct the polarization IL from the following measurements. Figure 5(a) presents ILs of the bar and the cross waveguides of the 3-dB DC at wavelengths from 1570 nm to 1590 nm. Both the ILs of the bar and the cross waveguides are roughly at the same magnitude. Figure 5(b) is the response spectral of the RA-MZI, where the blue and the red lines are the responses of Leads A and B, respectively, and the blue and the red dashed lines denote the respective fitting results. The measured crosstalk was <-10 dB. Furthermore, we scan sequentially with lights of four polarization orientations for wavelengths from 1570 to 1590 nm (EXFO IQS-12004B) to obtain the minimum and the maximum ILs of the interleaver structure. Figures 5 (c) and (d) show the minimum ILs, the maximum ILs, and the ILs for the TE modes in Leads A and B of the DC, respectively. In the pass bands, the ILs for the TE modes are approximately equal to the minimum ILs. The RA-MZI also demonstrates strong polarization dependence. In the pass bands, the polarization dependence losses are ~5 dB.



Fig. 5. (a). Measured IL for the TE mode of the DC. (b). Measured ILs and their fittings. The blue and the red lines are for Leads A and B, respectively, and the blue and the red dashed lines for the fitting results, respectively. (c). Measured minimum and maximum ILs and the IL for the TE mode in Lead A. (d). Measured minimum and maximum ILs and the IL for the TE mode in Lead B. In (c) and (d), the blue, the green and the red lines denote the minimum ILs, the maximum ILs for the TE modes, respectively.

4. Conclusion

We have demonstrated an RA-MZI interleaver, which comprises a 1×2 asymmetric MZI and a ring resonator. The interleaver works without introducing an external phase shift and is fully passive. We have fabricated the device with 300 nm \times 300 nm silicon wires on SOI. The measured insertion loss is ~-8 dB, the crosstalk is <-10 dB, and the FSR is ~4 nm. Although the performance of the proposed interleaver is not as good as the silica based interleaver [20], whose crosstalk improves from -10dB to -30dB after the thermal tuning, we believe that the performance of our structure would also improve remarkably after a thermal tuning is applied. The heater can be applied to the ring-waveguide coupling region to adjust the coupling coefficient *t*, so the passband of the ring resonator would be flatter. Similarly, the heater can be applied to the 3-dB coupling region to balance the output powers, thus the crosstalk would be reduced significantly.