Broadband SiN Interleaver With a Ring Assisted MZI Using a Tapered MMI Coupler

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***Abstract*—We present an interleaver using a Ring-Assisted Mach-Zehnder Interferometer (MZI) where the ring is coupled to one arm of the MZI through a linearly tapered multimode interferometer (MMI), harnessing the advantages of both the MMI coupler and ring assisted MZI to optimize performance. The tapered MMI coupler extends the operational bandwidth of the interleaver over more than 85 nm due to its wavelength-insensitive response and precisely tailored coupling ratio. Furthermore, it removes the need for thermal tuning of the coupling region, which reduces the power consumption and overall size of the device. The experimental performance of a silicon nitride based interleaver with a channel spacing of 0.8 nm in L-band is reported. The device shows a crosstalk level below 15 dB over a wavelength range of 85 nm.**

***Index Terms*—Interleaver, multimode interferometer (MMI) coupler, silicon nitride.**

I. Introduction

INTERLEAVERS are optical elements utilized to either split or merge closely spaced wavelength channels, which find applications in wavelength routing and (de)multiplexing. Interleavers should be wideband and have a flat and low-loss passband with a rapid roll-off at the band edges [1]. Mach-Zehnder Interferometers (MZIs) are one of the most important building blocks in photonics and their interference-based nature can provide a periodic frequency response suitable for interleaving applications [2]. However, a single MZI cannot deliver a flat-top response. Multiple stages can provide an arbitrary filtering response [3] at the expense of a larger footprint and introducing complexity in both the design and fabrication processes.

Compared to conventional cascaded MZI interleavers, ring-assisted MZI (RAMZI) interleavers provide a simplified device structure and a more box shaped spectral response [4]. They are the most used design in silicon photonic interleavers [5], [6], [7], [8], [9], [10]. However, their spectral range of operation and their crosstalk level are limited by their sensitivity to fabrication imperfections, especially in the coupling region between the ring and the arm of the MZI. In conventional designs, ring resonators are coupled to the short arm of the MZI using directional couplers (DCs). However, the coupling ratio of DCs varies significantly as the spectrum considered broadens, and as a result the response of the device deteriorates when the wavelength deviates from the center frequency. Furthermore, their coupling coefficients are greatly affected by fabrication imperfections. Thermo-optic tuning can be used to mitigate the effects of fabrication variations but this leads to a higher power consumption and a larger footprint to accommodate the wires and connection pads of the heaters. Couplers with a phase compensation capability were employed in [9], [11] as the input and output couplers of the MZI to implement a fully passive device. However, this approach remains sensitive to fabrication variations in the coupling region.

In contrast to directional couplers, multimode interferometers (MMIs) [12] exhibit a remarkable resilience to fabrication variations. This inherent robustness arises from the self-imaging phenomenon within MMIs, which allows them to maintain a consistent output regardless of small deviations in device dimensions or refractive indices. They also enable a consistent performance and coupling ratio over a wider bandwidth than DCs. MMI-Coupled Ring Resonators (MMI-RR) have been introduced in [13], [14], [15] to achieve a broader bandwidth and larger quality factor.

Here, we leverage the advantages of MMI-RR for designing a broadband interleaver. We study the design and optimization of a silicon nitride (SiN) based RAMZI that utilizes a linearly tapered MMI coupler in the coupling region for the integration of the ring resonator within the MZI. A fabrication-robust broadband interleaver design can be achieved making it a viable approach for wavelength division multiplexing (WDM) systems. We designed and utilized a linearly tapered MMI that can provide an arbitrary coupling ratio in order to achieve a flat top response with a high extinction ratio. Unlike other silicon [10] or silicon nitride [16] interleavers, the coupling region of the proposed device does not need to be tuned. Only the ring or the long arm of the MZI should be heated for compensating the phase mismatch between them. This method provides a wideband response and improves the device performance by reducing the power consumption and minimizing its footprint.

Furthermore, eliminating the requirement for thermal tuning of the coupling between the ring and the MZI simplifies the control of the device. Lastly, our experimental results demonstrate a significantly broader bandwidth of over 85 nm with our

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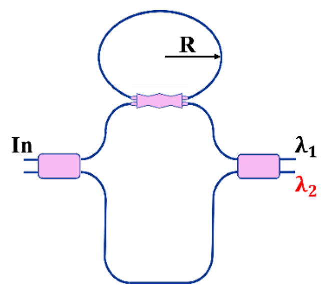

Fig. 1. Schematic of the proposed interleaver.

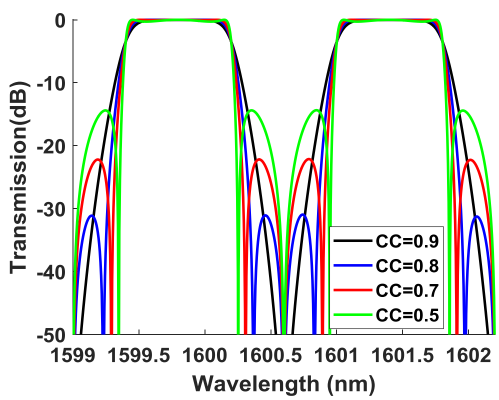

Fig. 2. Transmission response of a conventional ring assisted MZI for different cross-coupling coefficients between the ring and the MZI.

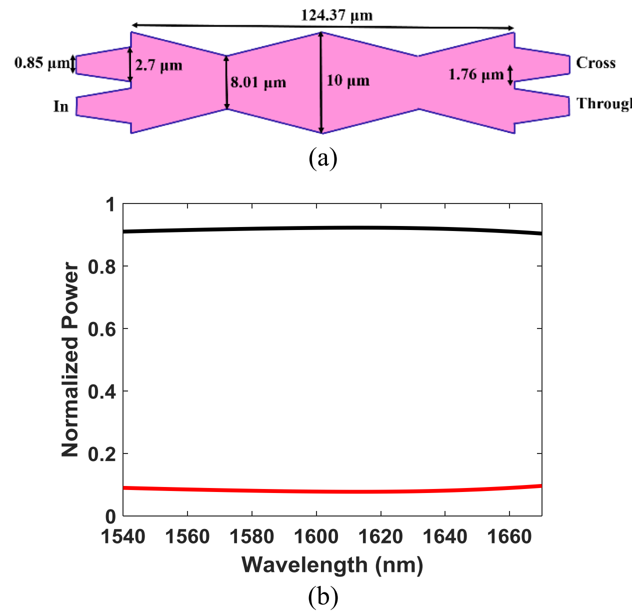

Fig. 3. (a) Schematic of the MMI coupler and (b) its coupling coefficients as a function of wavelength.

SiN prototype, surpassing the bandwidth reported in [17] for a RAMZI with an InP MMI coupler.

The remainder of this article is organized as follows. Section II details the design, Section III describes the fabrication process, and Section IV presents the experimental results. This is followed by a conclusion.

II. Design

A schematic of the proposed design is shown in Fig. 1. It consists of a ring resonator that is coupled to the short arm of the MZI through a linearly tapered MMI coupler. The MZI uses two rectangular 3-dB MMIs as the input and output couplers. Trapezoidal SiN strip waveguides with side-wall angles of 86°, a base width of 850 nm and a height of 435 nm are used to implement the device. The thickness corresponds to the one used in the fabrication process of our industrial collaborator, and the width is the largest possible that ensures single mode operation. Having wide waveguides help to mitigate the sensitivity to fabrication variations. Because of the birefringence of the waveguides, the device is optimized only for the TE polarization over a wavelength range corresponding to the L-band.

The transmission response of the interleaver for different ring coupling coefficients is presented in Fig. 2. The results were obtained using the transfer function of ring-assisted MZI [18] and computed with MATLAB. Wavelength-independent coupling coefficients have been considered in this analysis. As can be seen in Fig. 2, there is an obvious tradeoff between the maximum extinction coefficient and obtaining a box-like response. Larger coupling coefficients lead to a better crosstalk level at the expense of a smaller stopband width, which results in a smaller shape factor. It has been shown that for lossless ring resonators the maximum flatness of the response is achieved when the self-coupling coefficient (SC) is near 0.3 (i.e., corresponding to a cross-coupling coefficient (CC) of 0.7) [9], [11]. Decreasing the cross-coupling coefficient below this value reduces the flatness of the passband and ripples start to appear. Therefore, the coupling coefficient must be selected according to the requirements of the targeted application with regards to crosstalk, the shape of the wavelength response and the flatness of the passband. To demonstrate the potential of MMI-coupled RAMZIs as interleavers, we focus here on minimizing crosstalk and hence implement a linearly tapered MMI with a splitting ratio of 92:8.

The splitting ratio of MMIs can be arbitrarily adjusted by tapering linearly the multimode section to create what looks like a double butterfly shape, as shown in Fig. 3(a) [19]. The multimode section is divided into two equal sections of linearly down and upward tapered regions to carefully control phase dynamics while adhering to the self-image condition. The design process involves initial analytic calculations [19], followed by refinement through numerical optimization using VarFDTD. The dimensions and coupling coefficient of the optimized MMI in the L-band are presented in Fig. 3. It shows a constant splitting ratio over the entire L-band, which helps create an interleaver with a wavelength invariant response. However, the loss at the cross port increases outside the L-band and changes the crosstalk level of the interleaver.

As shown in Fig. 1, the linearly tapered MMI was used as a coupler between the ring resonator and MZI to realize the interleaver. The free-spectral range (FSR) of the ring resonator is

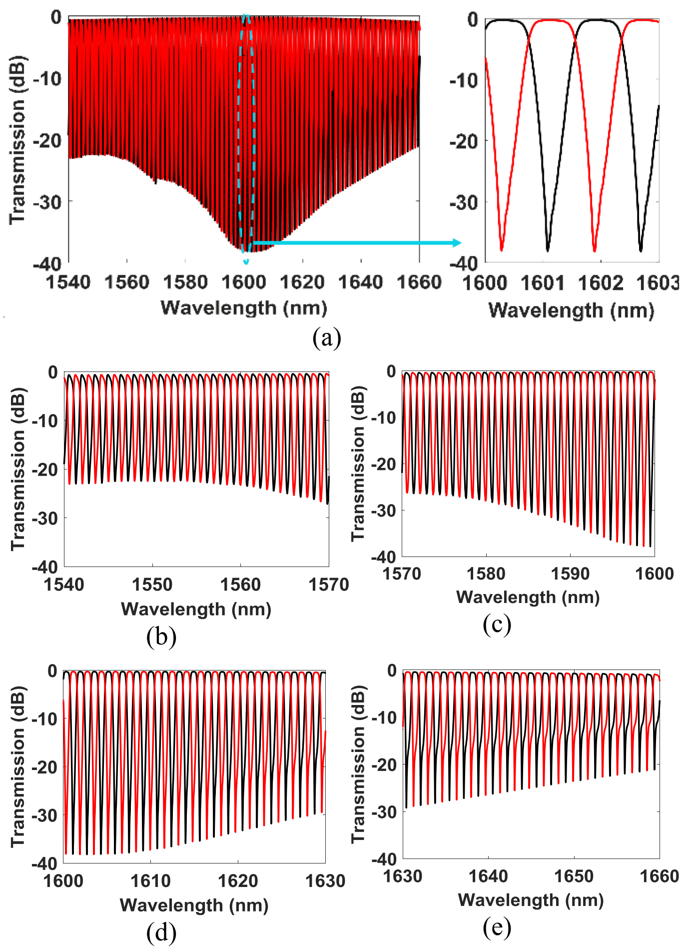

Fig. 4. (a) Simulated transmission response of the MMI-RR based interleaver with a butterfly MMI providing a 92:8 splitting ratio, (b)–(e) zoomed-in plots for different wavelength spans.

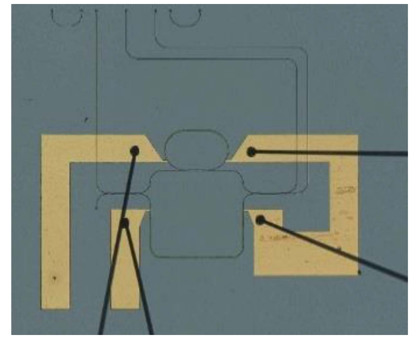

Fig. 5. Wire-bonded fabricated device.

calculated using the equation $FSR = \lambda^2/n_g L$, where L and n_g are the ring circumference and the group index of the waveguide, respectively. However, the length of the long arm of the MZI must be equal to half the circumference of the ring to obtain the desired phase shifts and interference effects, which is called the antiresonance condition [18], and hence is also a function of the FSR. A racetrack ring resonator with a radius of 181.44 um was coupled to the MZI. The length of total length of MMI coupler, which is 184.37 um. The calculated FSR of the interleaver is 1.6 nm at a wavelength of 1.6 um. Since the MMI is part of the ring resonator, the exact value for the length of the long arm of the MZI was obtained from simulations performed with Ansys Lumerical Interconnect in order to accurately account for the phase change accumulated during the propagation inside the MMI.

Simulation results of the interleaver over the wavelength range of 1540–1660 nm are shown in Fig. 4(a). The figure also presents zoomed-in plots for different wavelength spans. The device has crosstalk levels better than 22 dB over the entire 120 nm wavelength range considered here. The lower crosstalk level at the extremity of the range is attributed to the higher coupling loss of the MMI coupler at those wavelengths, as mentioned above. The Shape Factor (SF), defined as the ratio of the 1-dB bandwidth over the 10-dB bandwidth, has an average value of 0.61. Ultimately, the wavelength range is limited by dispersion in the waveguide. As the signal moves further away from the central design wavelength, crosstalk increases and the SF decreases, in particular for shorter wavelengths. This is because the antiresonance condition is no longer fulfilled. However, the response of the interleaver can be optimized for a different wavelength by tuning the phase difference between the ring and the long arm of the MZI with heaters.

III. Fabrication

The fabrication process began with a TEOS Low-Pressure Chemical Vapor Deposition (LPCVD) of a 3.5 μm thick SiO_2 layer on a silicon wafer. Next, a 435 nm SiN layer was deposited using LPCVD at a pressure of 150 mTorr, utilizing DCS, NH_3, and N_2 gases at a temperature of 820 °C. The SiN waveguide pattern was defined through electron beam lithography with a MaN-2403 negative resist, followed by plasma etching to transfer the pattern onto the SiN film. The optimization of the etching recipe is described in [20]. After annealing at 1000 °C, a 3.5 μm thick SiO_2 cladding was deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD). A second annealing at 1000 °C for 40 minutes in a nitrogen environment was performed before the fabrication of the electrodes. The heaters and bonding pads were defined using a lift-off process with Cr/Au films deposited by e-beam evaporation. Finally, the heaters were wire-bonded to a PCB for control by current sources. A top-view microscope image of the fabricated device that is wire-bonded is shown in Fig. 5.

IV. Results and Discussions

To characterize the device, TE-polarized light from a tunable laser source (EXFO T100S-HP) was coupled using a surface grating to the input port of the interleaver through a fiber array. The fiber array was precisely aligned at the angle of 8° with respect to the surface gratings. The input and the output ports were connected to different fibers in the array, which allowed to measure the transmitted spectrum with a component tester (EXFO CT440). The measurement results are normalized with respect to the response of the grating couplers to remove the

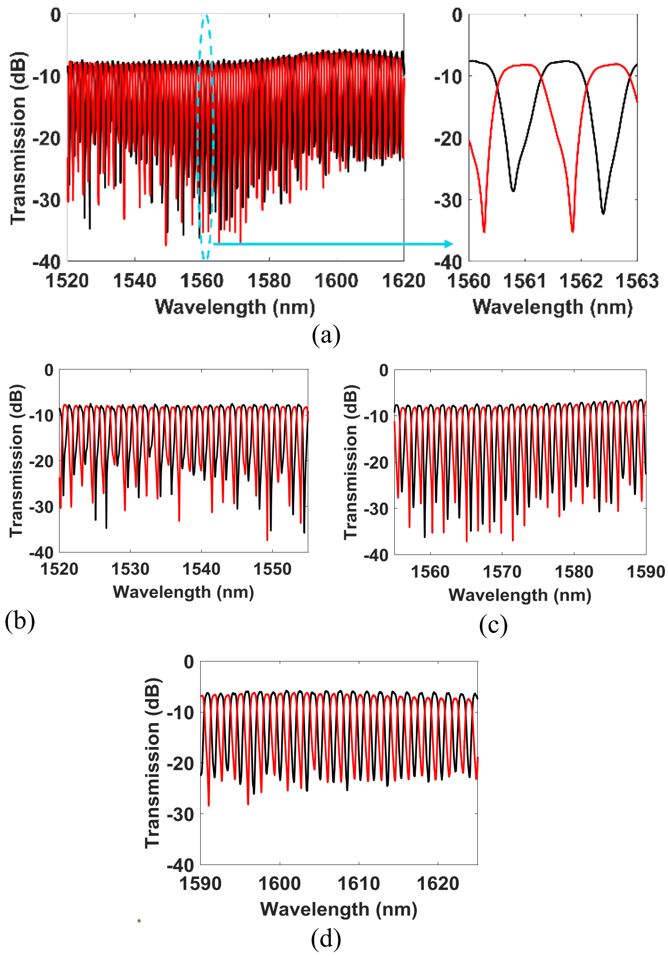

Fig. 6. (a) Measured transmission response of the interleaver after thermal tuning, (b)–(d) zoomed-in plots for different wavelength spans.

wavelength dependent coupling losses. The initial measurements showed that the passband of the device is not flat. Thus, there is a phase mismatch between the ring resonator and the long arm of the MZI.

By applying voltage to the heaters on top of the ring or the long arm of the MZI, we can compensate this mismatch. Fig. 6 shows the transmission response of the device after tuning. The total power consumption required for thermal tuning is 100 mW, which is applied only to the long arm of the MZI. Thermal tuning improves the flatness of the passband whereas the crosstalk does not change significantly. This is in contrast to conventional interleaver designs that employs either DC or a thermo-optically tunable symmetric MZI coupler that provides full control over the coupling coefficient [6], [7], [16].

The experimental transmission spectrum has a flat-top response over the range from 1540 nm–1625 nm. As mentioned earlier, the waveguide dispersion, which leads to a phase mismatch between the signal in the ring resonator and the one in the lower arm of the MZI, restricts the device bandwidth at the lower end of the wavelength spectrum. Furthermore, the tunable laser covers the wavelengths between 1500 nm to 1625 nm, which set the upper limit of the measurements. The SF of the measured transmission response is 0.52 on average. The crosstalk is better than 15 dB over the entire bandwidth. The discrepancy from the expected simulation results is attributed to the higher loss observed in the fabricated MMI within the coupling region, which causes an imbalance in power between the arms of the MZI. Considering the measured propagation loss of 2 dB/cm to remove the loss due to the routing waveguides, the insertion loss of the interleaver is between 6 to 8 dB across the entire measured wavelength range. It is mainly caused by the MMIs (i.e., around 1.2 dB for the input and output MMIs, and 2 dB for the MMI in the coupling region). Therefore, improving the resolution of the MMIs by increasing their width could significantly reduce the insertion loss of the interleaver. However, this would result in longer MMIs that could be challenging to integrate in the MZI. Furthermore, the propagation losses are high for SiN waveguides. This is most likely caused by surface roughness at the core interfaces. Hence, improving the fabrication process could significantly reduce losses.

Previous demonstrations of RAMZI interleavers were limited to spectral bandwidths of less than 70 nm due to the use of wavelength-dependent directional couplers [10]. The effort to realize broadband interleavers has resulted in numerous demonstrations [6], [9], [16]. Ultra-broadband 3 dB couplers were developed for an MZI to ensure uniform coupling across wide bandwidths, reaching up to 125 nm in fabricated devices [6], and 100 nm in simulated ones [16]. However, achieving broadband coupling to the ring required thermal tuning of the coupling region. A passive interleaver covering a wavelength range of a 140 nm [9] was demonstrated, but its passband shape varied significantly across channels, indicating inconsistent coupling coefficients over the operational bandwidth. Our fabricated device not only covers a wide wavelength range from 1540 nm to over 1625 nm, but also provides a high shape factor response, can separate closely spaced channels, and requires minimal tuning.

V. Conclusion

We demonstrated a SiN-based interleaver utilizing a RAMZI with an MMI coupler, centered on the L-band. The proposed design leverages the inherent advantages of MMI couplers, such as robust fabrication tolerances, and combines them with the flat-top spectral response characteristic of RAMZI structures. The linearly tapered MMI coupler effectively eliminates the need for thermo-optical tuning in the coupling region, requiring only the ring resonator or the long arm of the MZI to be heated to compensate for phase mismatches due to fabrication variations. This approach reduces power consumption and minimizes the device's overall size. Moreover, by employing a linearly tapered MMI coupler with a coupling ratio of 92:8, the device achieves an extended operating spectral range of 85 nm. Our prototype demonstrates an experimental insertion loss of 6 to 8 dB and maintains a crosstalk level better than 15 dB across the entire bandwidth.

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