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60.5 dB Silicon Mach-Zehnder Interferometer using Self-Optimising Beam-Splitters

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Abstract: We demonstrate an ultra-high extinction MZI on a reconfigurable silicon photonic chip, using a self-optimising approach to adjust variable beam-splitters. This result paves the way for large-scale integrated photonic quantum information applications.
OCIS Codes: (130.3120) Integrated Optics Devices; (130.0130) Integrated Optics

1. Introduction

Integrated photonics is a highly promising platform for a range of quantum information applications, due to its intrinsic phase stability and potential for scalability with the continuous progress in photonics technology. Future practical quantum information applications relying on large-scale quantum photonics devices require nearly perfect fabrication of each component on the device; otherwise, the resource overhead for fault tolerance will not be acceptable. The Mach-Zehnder interferometer (MZI) with a controllable phase shifter is one of the most fundamental components in integrated photonics—it can implement single-qubit operations with extra phase shifters in quantum computation [1–3] or act as an optical switch in quantum communications. The performance of MZIs, given by their extinction ratios, is limited by the splitting ratios of the beam-splitters used in MZIs. An ideal balanced MZI requires the splitting ratio of beam-splitters to be 50:50. However, the beam-splitters fabricated on integrated photonics devices have different splitting ratios than designed and can even be far from 50:50 because of the imperfections in the fabrication process, becoming one of the current obstacles for large-scale quantum integrated photonic devices.

Here we show that a MZI with up to 60.5 dB extinction ratio can be achieved on a silicon photonic chip, using an adaptive self-optimised approach. We use two additional MZIs to act as beam-splitters whose splitting ratios are tunable. The self-optimised approach allows us to adjust the two variable beam-splitters to 50:50 splitting ratio without any calibration, which then implements a high-fidelity MZI.

2. Results

As shown in Fig. 1a and b, the device we used was a standard BOX SOI wafer formed by 248 nm lithography fabricated by the IME foundry. The device consists of 4 MMI (multimode interferometer) beam-splitters and 3 TiN resistive metal phase shifters reliant upon a thermo-optical effect. The MMI beam-splitters possess various splitting ratios that differ from the ideal 50:50 after initial fabrication. We use additional MZIs on both sides as variable beam-splitters whose splitting ratios can be tuned via the phase shifters H1 and H2. We then use a self-adjustment approach [4] to set BSL and BSR to 50:50 splitting ratios, without calibrating any fabricated components— beam-splitters or phase shifters. During the process, we only adjust H1 and H2 to minimize or maximize the detected optical power with phase shifter HMZI correspondingly set to 0 or π phase. The voltage setting of H1 and H2 will converge to an optimized setting after several rounds, obtaining the optimized 50:50 splitting-ratios of the two variable beam-splitters BSL and BSR.

The self-adjustment approach requires no prior knowledge of the fabricated components, and works for imperfect beam-splitters with unbalanced splitting ratios up to 85:15 or 15:85. Using optimized beam-splitters BSL and BSR, we then implement the MZI with the ultra-high extinction ratio of 60.5 dB, making a new record on silicon integrated photonics device. The best previous result reported is 50.4 dB where the device consists of only one variable beam-splitter [5]. Considering the limits of the measurement apparatus in our current experimental setup—the voltage driver's resolution is limited to 0.005V — a more precise result with higher extinction ratio can be obtained using a higher resolution voltage driver.

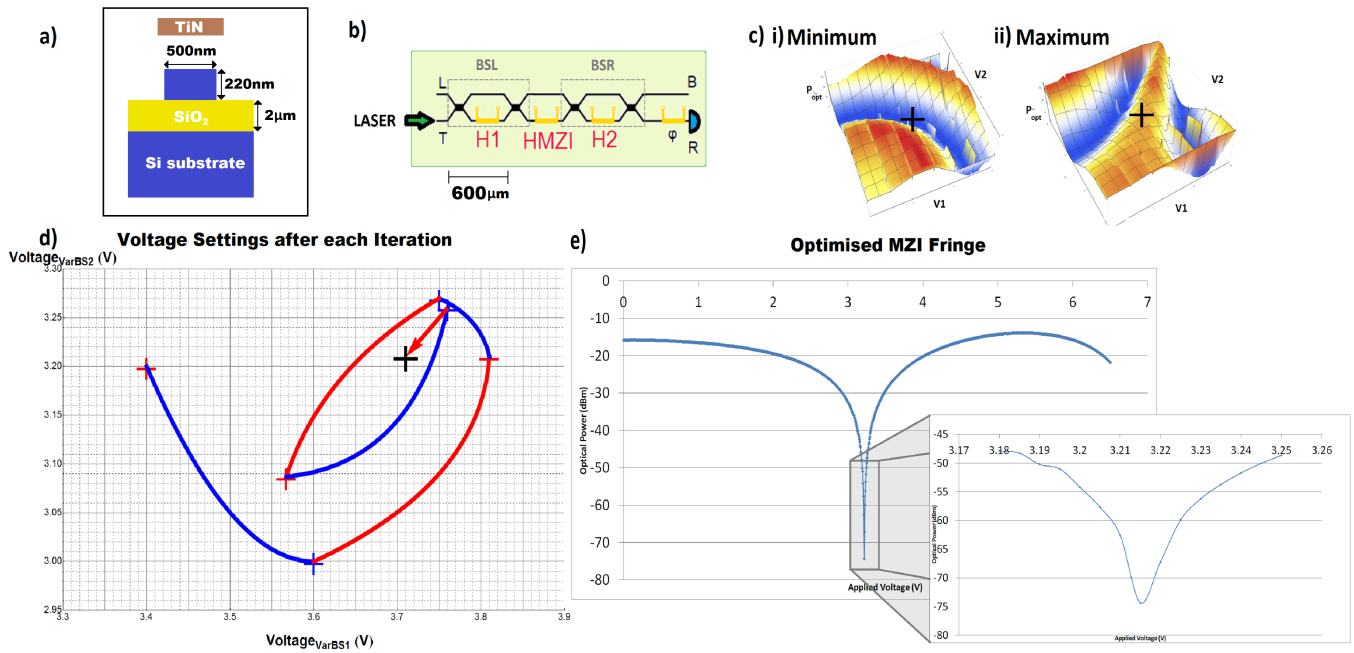

Fig. 1. **a)** Cross-section of a typical deep-edged waveguide on the device. **b)** A schematic of the Si photonic chip used. Bright laser light is injected in to Port T and light is detected at R. The boxed regions, BSL and BSR, are the two variable beam-splitters. HMZI acts like the standard phase shifter in an MZI. **c) i)** and **ii)** The convergence regions for the self-optimising beam-splitters algorithm in the minimum optical power and maximum optical power case respectively. These are 3D data plots of output power measured as a function of the voltages applied to the two phase shifters. The position in (V_1, V_2) space where both **i)** is the global minimum (the regions in blue) and **ii)** is the global maximum (the regions in orange) is the convergence point of the algorithm (indicated by the black cross). At this point, both variable BS are at 50:50 splitting ratio. **d)** Experimental data showing the convergence of voltage settings (and hence reflectivity offsets) to the nearly-50:50 BS case. Each data point represents the voltages obtained after each step of the algorithm. The red (blue) points are the settings obtained when we search for the global minimum (maximum). Rapid convergence takes place after only a few passes of the algorithm. (Lines between points are a guide for the eye.) The system can be seen to be converging iteratively towards the final optimum. **e)** Semi-Logarithmic plot of the 60.5 dB experimental extinction ratio fringe. $P_{max} = -13.9$ dBm. $P_{min} = -74.4$ dBm, showing output power as a function of the voltage V on HMZI. Inset: dip in fringe.

3. Conclusion

We have shown that an ultra-high extinction ratio MZI on a silicon device can be obtained in spite of imperfect fabrication of beam-splitters, by using a self-adjustment approach, without calibrating any components. This dramatically reduces the requirements for fabrication of integrated photonic devices, enabling large-scale integrated photonic devices for future quantum information applications. Furthermore, since the overhead resources required in fault-tolerant linear optical quantum computing decreases with increasing MZI extinction ratio, our result moves a particularly promising step towards integrated photonic quantum computing.

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