Enhanced Operation Range of Silicon MZI Filters Using a Broadband Bent Directional Coupler

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***Abstract*—Mach-Zehnder interferometers (MZIs) are essential components that are used in a variety of wavelength division multiplexing (WDM) systems. Wavelength-sensitive straight directional couplers (DCs) are usually used as the beam splitter and combiner in traditional waveguide-based MZIs, which often limit the operational bandwidth and cause additional insertion loss. To overcome these challenges, we present an MZI based on bent DCs achieving 2.7× increase in operational wavelength range, expanding the bandwidth from 36.7 nm in straight DC-based MZIs to at least 100 nm, while maintaining a large extinction ratio (ER) ≥ 18.4 dB. The proposed MZI is robust across a 300 mm wafer, achieving minimum ER over 100 nm wavelength range of 14.3 ~ 18.4 dB in all the 63 measured dies, significantly outperforming MZIs based on straight DCs, which exhibit minimum ER of 4.2 ~ 6.1 dB. Finally, the proposed MZI is theoretically proven to be highly efficient for more complex WDM systems. Transfer matrix method calculations for 16 −channel MZI-based WDM system demonstrate an improvement of the worst-channel isolation from 5.42 dB to 17.18 dB and the average insertion loss from 1.02 dB to 0.30 dB, as compared to the straight DC based counterpart. This underscores the potential of the proposed MZI to enable scalable and high-performance WDM systems.**

***Index Terms*—Silicon photonics, wavelength division multiplexing, Mach Zehnder interferometer.**

I. Introduction

WAVELENGTH division multiplexing (WDM) filters are crucial in modern optical communication systems, allowing multiple signals to be transmitted over a single optical fiber using different wavelengths. These filters play a crucial role in increasing the bandwidth and capacity of optical networks, making them indispensable in high-speed data transmission and telecommunication applications [1]. Mach Zehnder interferometers (MZIs) are vital optical components that are widely used in various WDM systems, where 2×2 splitters play an essential role in splitting and combining optical signals. In particular, symmetric straight directional couplers (DCs) are typically used in traditional MZIs for their simplicity and ease of fabrication. Nonetheless, MZIs based on straight DCs often suffer from limited bandwidth and increased insertion loss, which can degrade the overall performance of WDM systems. This is mainly due to the wavelength sensitive coupling coefficients of straight DCs, particularly in high-index contrast systems. In order to optimize the performance of MZIs and MZI-based WDM systems, the 2×2 splitters should ideally be broadband, low-loss, robust, and compact. Several approaches have been proposed to achieve highly performing MZIs through the efficient design of 2×2 splitters, including designs based on multi-mode interferometers [2], adiabatic couplers (ADC) [3], [4], DCs with phase control sections [5], subwavelength grating (SWG) based DCs [6], and rib waveguide based DCs [7]. However, these designs are either relatively lossy [2], [4], [5], [7], complex [2], [7], possess a large footprint [3], [7], or introduce additional fabrication complexities [6]. Recently, we experimentally demonstrated that bent DCs serve as robust, low-loss, broadband, and relatively compact 2×2 splitters [8], making bent DC based MZIs viable candidates in MZI systems [9], [10]. However, a robust MZI achieving high ER across a broadband covering the C band without introducing further fabrication complexities or excessive loss has not been reported yet to our best knowledge.

In this Letter, we present an MZI based on bent DCs that can enable scalable and high-performance WDM systems. The proposed MZI expands the operational wavelength range from 36.7 nm using straight DCs to at least 100 nm covering the C band, while maintaining an extinction ratio (ER) ≥ 18.4 dB. Further, the proposed MZI is proven to be suitable for mass production, where wafer-scale measurements over 100 nm wavelength range show minimum ER of 14.3 ~ 18.4 dB across 63 dies, as compared to 4.2 ~ 6.1 dB for the MZI based on straight DCs. The proposed MZI's bent DC achieved a

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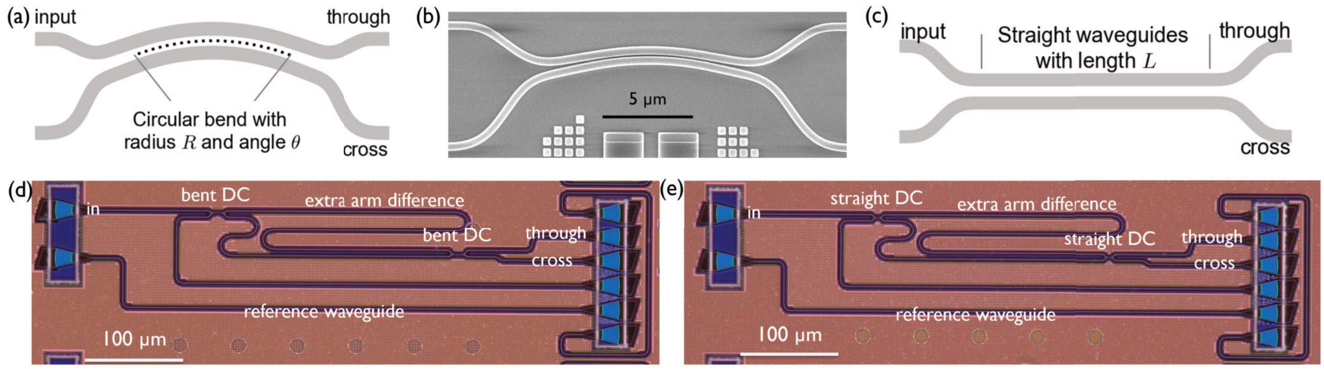

Fig. 1. Schematic (a) and SEM image for the bent DC (b) with R as the coupling radius and θ as the coupling angle. Schematic for the straight DC with L as the coupling length (c). Microscope image for MZI based on bent DCs (d) and based on straight DCs (e). The 0.5 : 0.5 bent DC has an $R = 16$ μm and $\theta = 9.2$ °. The 0.5 : 0.5 straight DC has an $L = 2$ μm. Waveguide material stacks are SOI with silicon oxide as top cladding, using imec iSiPP300 platform. All DCs are based on strip waveguides with nominal silicon thickness of 220 nm, waveguide width of 450 nm, and coupling gap of 100 nm.

low insertion loss of 0.03 ± 0.03 dB, limited by the precision of our measurements, making it the lowest insertion loss for C band 2×2 silicon splitters to our best knowledge, which is a paramount feature for dense WDM systems that often contain several 2×2 splitters. Further, the bent DC is compact with a length of 23 μm. When deployed in a more complex WDM system, transfer matrix calculations of a 16 −channel MZ-based WDM system shows significant improvement of the worst channel isolation and the channels average insertion loss using the proposed MZI as compared to the MZI based on straight DCs, where the worst channel isolation improved from 5.42 dB to 17.18 dB and the average insertion loss decreased from 1.02 dB to 0.30 dB. Overall, these characteristics make the proposed MZI highly competitive and practical design candidate for dense WDM applications.

II. MZI Design and Results

A broadband 0.5 : 0.5 bent DC is used as the 2×2 splitter in the proposed MZI design. The schematic of the bent DC is shown in Fig. 1(a), where the bent DC parameters have been optimized [8] in order to achieve broadband 0.5 : 0.5 coupling over 100 nm covering the C band (Fig. 1(b)). The straight DC is included for benchmarking purposes (Fig. 1(c)). Microscope images of the proposed MZI and the MZI based on straight DCs are shown in Fig. 1(d) and Fig. 1(e), respectively. The fabrication is done using imec's most advanced iSiPP300 platform allowing high waveguide quality and access to feature dimensions well below 100 nm thanks to the 193 nm immersion lithography [11].

The 0.5 : 0.5 bent DC demonstrates significant improvement in coupling variation over 100 nm wavelength range covering the C band (Fig. 2(a)), with a maximum coupling deviation as low as 0.06, compared to 0.23 for the straight DC counterpart (Fig. 2(b)), representing a 3.7× improvement. The bent DC is shown to have robust coupling over the wafer (Fig. 2 (c)), with a maximum cross-coupling shift of 0.039 with respect to the central die at $\lambda = 1.55$ μm over 63 measured dies. Recently invented low loss bends are incorporated in the design, where continuous curvature and curvature derivative are guaranteed at all connections [12] enabling a low insertion loss of

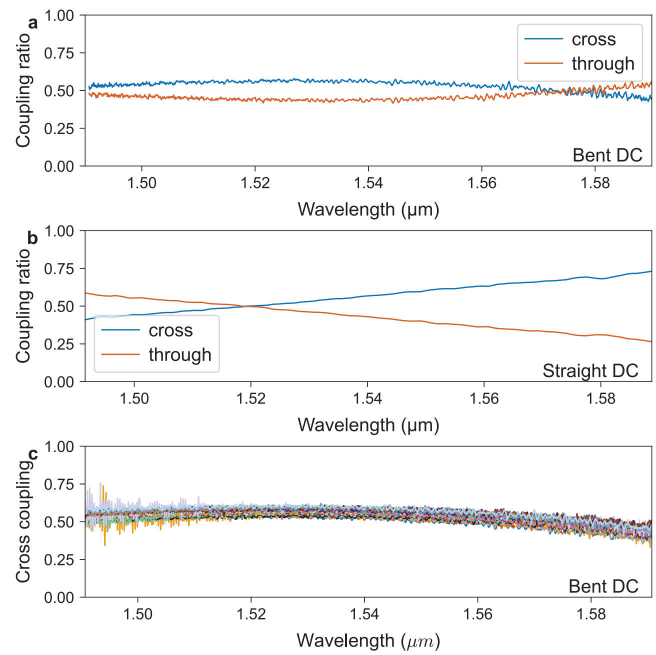

Fig. 2. The measured coupling ratios of the bent DC (a) and straight DC (b) along with the cross coupling spectra for bent DC over 63 measured dies in a 300 mm wafer (c), where each color represents one die. 3.7× less coupling variation is observed in the bent DC as compared to the straight DC. Robust performance of the bent DC is observed over the wafer.

0.03 ± 0.03 dB. The loss is calculated using a sinusoidal fitting for bent DCs with different coupling lengths, where the cutback method is utilized for the optical characterization [8].

The proposed MZI demonstrates a significant improvement in the operational wavelength range with high ER values (Fig 3(a)) as compared to the MZI based on straight DCs (Fig 3(b)). The proposed MZI could operate up to at least 100 nm wavelength range while maintaining an ER $\geq$ 18.4 dB. This represents at least 2.7× increase in the operational wavelength range compared to the MZI based on straight DCs, which could only operate up to 36.7 nm with ER $\geq$ 18.4 dB. It is worth mentioning that the MZI measurements (Fig 3(a, b)) align with the coupling measurements of the DCs

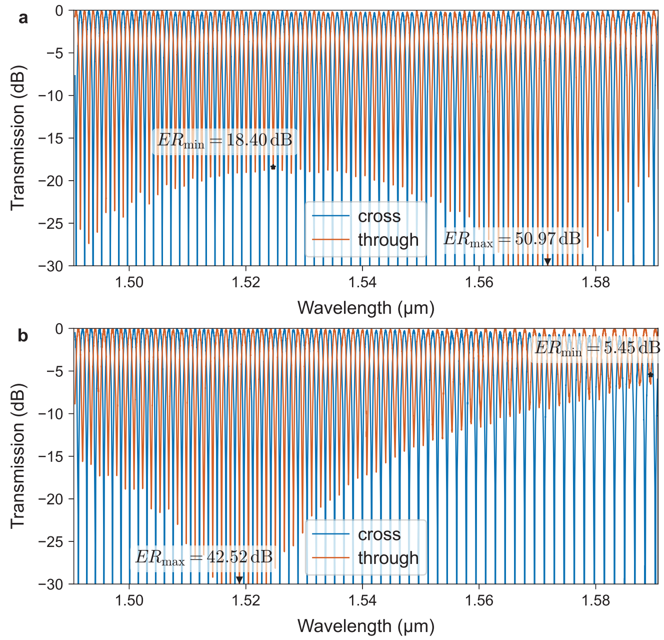

Fig. 3. The proposed MZI spectrum based on bent DCs (a), and the traditional MZI spectrum based on straight DCs (b). Minimum and maximum ER values are marked. At least 2.7× improvement in the ER wavelength operational range for the proposed MZI is shown. The free spectral range for both MZIs is designed to be 100 GHz.

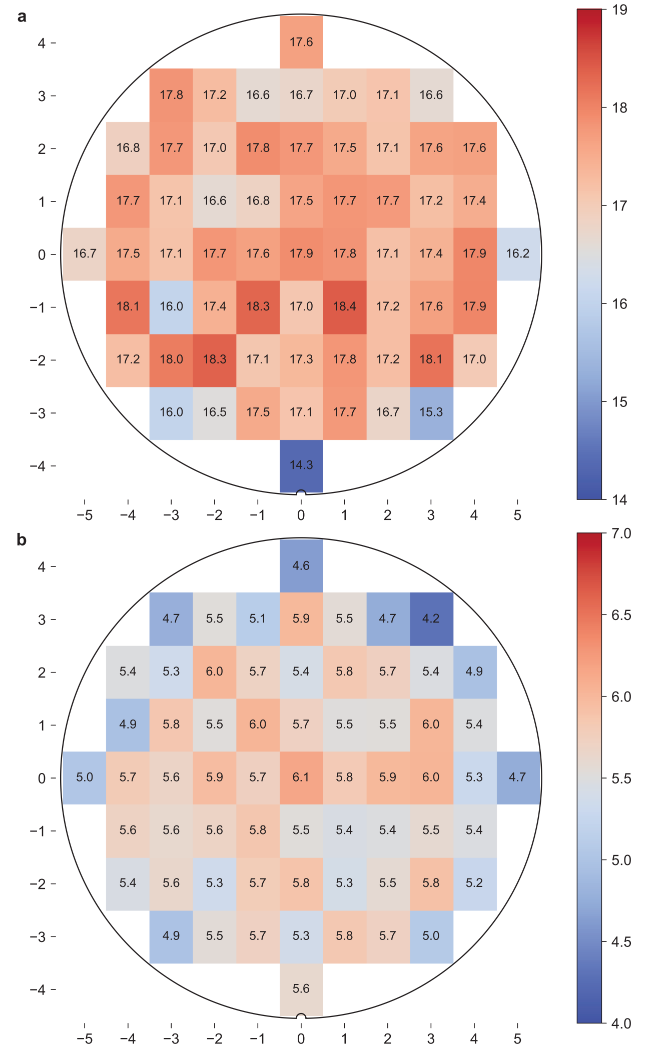

Fig. 4. ER values wafer mapping for the MZI based on bent DCs (a) and the MZI based on straight DCs (b) over the 300 mm wafer. Robust high ER values across the wafer is present in the MZI based on bent DCs, showing the reliability of the design for mass production. The MZI based on straight DCs shows significantly lower ER values across the wafer.

(Fig. 2(a, b)), where the troughs in the spectra are visible around the points close to 0.5 coupling ratios.

Robust ER values are demonstrated based on wafer-scale measurements of the proposed MZI over 100 nm wavelength range covering the C band, where the minimum ER is 14.3 ∼ 18.4 dB across 63 measured dies (Fig. 4(a)). Further, consistent ER enhancement is observed over the wafer using the proposed MZI as compared to the traditional MZI with straight DCs, where the traditional MZI minimum ER is 4.2 ∼ 6.1 dB over the same range. This confirms the proposed MZI is robust and can be reliably used in mass production as indicated by wafer scale measurements on imec's 300 mm platform. It is worth mentioning that variations inherent to wafer-scale fabrication processes lead to minor fluctuations in the DC coupling ratios (Fig. 2(c)), which in turn cause the observed variability in the MZI ERs.

III. 16 Channel MZI WDM System Calculation

The two channel MZI filter is an important building block that is used in different WDM configurations. To demonstrate the effectiveness of the proposed MZI in dense WDM systems, transfer matrix method calculations were performed for a 16-channel cascaded MZI-based WDM system based on measured bent and straight DCs data as shown in the schematic of Fig. 5. Each MZI in the WDM system is composed of two 0.5 : 0.5 DCs. The extra arm length difference in each MZI is configured to achieve 16 channels within the specified wavelength range. In this setup, the extra arm length difference is halved at each subsequent MZI stage relative to the previous stage [13]. The worst channel isolation at central wavelength improved from 5.42 dB to 17.18 dB while the average insertion loss improved from 1.02 dB to 0.30 dB in the WDM system based on bent DCs as compared to the straight DC counterpart Fig. 6(a, b), proving the effectiveness of the proposed MZI for efficient WDM systems.

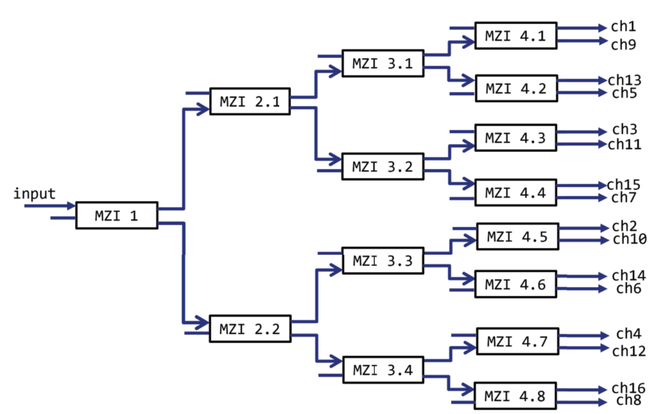

Fig. 5. The schematic of 16 −channel WDM filter based on cascaded MZIs, used in the transfer matrix method calculations. The MZI blocks are as illustrated in Fig. 1(d, e).

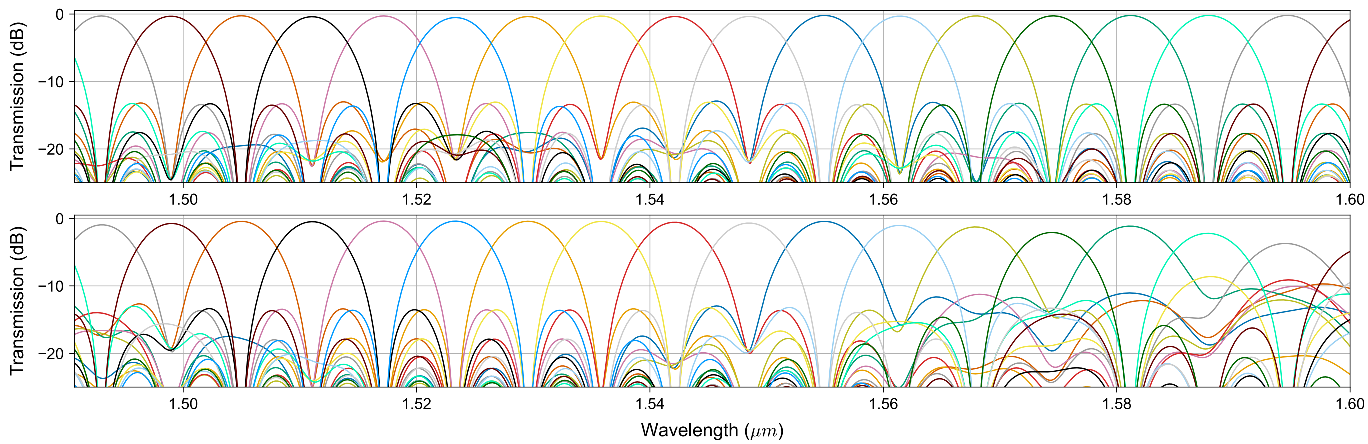

Fig. 6. 16 −channel cascaded MZI WDM spectrum, with 800 GHz channel spacing, based on the measured bent DC (a) and straight DC (b) calculated using the transfer matrix method. Significant improvement is observed in channels isolation and insertion loss for the WDM system based on bent DCs.

TABLE I
COMPARISON OF FABRICATED SILICON UNBALANCED MZIS COVERING THE C BAND

Reference	Splitter structure	Splitter excess loss (dB)	Splitter length (μm)	ER (dB) over 100 nm
[2]	Multi mode interferometer	< 0.45	33.5	> 5.64
[3]	ADC	-	> 200	> 10
[4]	Rib waveguide based ADC	0.23	> 46.7	> 20.21
[5]	DC with phase control section	< 1	31.4	> 15.03
[6]	SWG-assisted ADC	< 0.11	35	> 23.2
[7]	Rib waveguide based DC	0.8	> 475	> 12.52
This work	Bent DC	0.03 ± 0.03	23	> 18.4

IV. CONCLUSION

We have presented a highly efficient, broadband, and robust MZI design that significantly improves the performance of MZI-based WDM systems as indicated by wafer scale measurements over 63 dies on imec's 300 mm platform. Compared to the results reported in the literature (Table I), the proposed MZI shows high ER values ≥ 18.4 dB without introducing further fabrication complexities as in [6], or compromising the excess loss as in [4]. To our best knowledge, the proposed design achieves the lowest insertion loss of 0.03 ± 0.03 dB in silicon 2×2 splitters covering the C band, while maintaining a compact length of 23 μm. Further, the proposed MZI exhibits robust ER values over the wafer, where the minimum ER values ranged between 14.3 dB and 18.4 dB over 63 measured dies. Finally, the transfer matrix method calculations demonstrate significant performance improvement using the proposed MZI in a 16 −channel MZI based WDM system as compared to the MZI based on straight DCs, where the worst channel isolation improved from 5.42 dB to 17.18 dB and the average insertion loss improved from 1.02 dB to 0.30 dB. These results highlight the proposed MZI as a key enabler for scalable and high-performance WDM systems in advanced silicon photonics applications.

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