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Design and numerical simulation of a multi-port 3-dB power splitter based on a hybrid MMI–MZI structure with low-loss waveguide bends and crossings on SOI platform

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Abstract

Multi-directional optical power splitters with compact size and high performance are essential components in modern silicon photonic integrated circuits. However, achieving uniform power distribution across multiple directions while maintaining low loss and minimal crosstalk remains a significant challenge. In this work, a novel multi-directional 3-dB power splitter based on a hybrid multimode interference–Mach-Zehnder interferometer (MMI–MZI) configuration is proposed on a silicon-on-insulator (SOI) platform. The design employs a symmetric four-port architecture that integrates MMI regions with optimised waveguide bends and crossings, enabling simultaneous power splitting and cross routing within a single structure. By exploiting the self-imaging effect in MMI sections, both equal power division and directional signal transfer are realised in a compact footprint. Numerical results indicate that the proposed device achieves low excess loss at a wavelength of around 1.55 µm, with near-equal power distribution between the output ports and suppressed back-reflection. In addition, the structure demonstrates consistent behaviour under different propagation directions, highlighting its inherent symmetry and direction-independent operation. These features make the proposed design suitable for applications in optical interconnects, signal routing, and complex photonic integrated networks.

1. Introduction

High-speed communication systems with ultra-large bandwidth and parallel processing capabilities are desperately needed during the fourth industrial revolution due to the explosive growth of artificial intelligence, big data, cloud computing, and the internet of things (IoT) [1–4]. The low propagation loss, ultra-high data speeds, and scalability of optical networks have made them a fundamental solution. Ultra-wide bandwidth, low loss, and high integration density are enabled by optical signal processing performed directly in the optical domain, thereby eliminating optical-electrical conversions [5–7].

Multiple optical functions can be integrated on a single chip using photonic integrated circuits (PICs), which also improve system reliability and reduce footprint and power consumption. Optical power splitters are crucial for signal distribution and control in interferometric and routing designs, alongside other important components such as multiplexers, switches, and modulators. The system total power uniformity and insertion loss are directly impacted by their performance. Due to its high refractive index contrast, support for dense integration, and compatibility with CMOS technology, the silicon-on-insulator (SOI) platform is widely used for PIC production. This makes it a viable platform for next-generation high-speed optical communication systems, as it enables cost-effective, large-scale manufacturing and smooth integration with electronic circuitry [8].

Within this context, multimode interference (MMI) couplers in silicon photonic waveguides have become essential building blocks for realising advanced photonic devices, including arbitrary-ratio optical power splitters [9, 10], optical logic gates [11, 12], and thermo-optic

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switches [13]. In recent years, MMI-based optical power splitters have attracted significant attention and have been widely utilized in silicon photonic systems due to their compact footprint, fabrication tolerance, and broadband operation [14–16].

A 1 × 2 mode splitter based on an asymmetric MMI coupler is proposed, demonstrating low insertion loss (< 11.62 dB) and crosstalk (< −10.7 dB) over 1530–1625 nm, thereby enhancing the flexibility and integration of mode division multiplexing systems [17]. Reference [14] introduces a compact, low-loss asymmetric 1 × 2 MMI optical power splitter on a SOI platform. Six distinct optical power splitters are designed with unconventional splitting ratios in this paper, which substantiates that the device can achieve any power splitter ratios (PSRs) in the range of 95:5 to 50:50. The dimensions of the multimode section were established at 2.9 × (9.5–10.9) µm. Reference [18] proposes an arbitrary-proportion multi-port power splitter (MAPS) on SOI by optimising its form factor, achieving a small size (6 × 2.7 µm²) and low loss (< 0.5 dB simulated, < 1.3 dB experimental) in the 1500–1600 nm range. In our previous work, a 2×2 optical power splitter based on the restricted interference-multimode interference (RI-MMI) structure was proposed [19].

However, most existing designs mainly focus on conventional configurations such as 1 × 2 or 1 × N splitters with limited routing flexibility, while multi-port or multi-directional power splitting structures remain relatively less explored. Although several studies have reported multi-port MMI devices (e.g., 3 × 3 or 4 × 4 structures), these are often associated with increased complexity, larger footprint, or limited control of phase and power distribution. Therefore, the development of a compact, efficient, multi-directional 3-dB power splitter is of significant interest. Such a device not only enables uniform power distribution across multiple directions but also enhances flexibility in optical routing, making it highly suitable for applications in interferometric networks, optical interconnects, signal processing systems, and next-generation integrated photonic circuits.

The remainder of this paper is organised as follows. Section 2 describes the proposed device structure. Section 3 presents the simulation results along with a detailed discussion. Finally, section 4 summarises the main conclusions of this research.

2. Proposed device structure

Figure 1 illustrates the proposed power splitter structure. Unlike conventional MMI-based power splitters that employ a single interference section to achieve the 3 dB splitting function, the proposed design is constructed as a four-directional symmetric interference network, enabling the simultaneous realisation of power splitting and optical cross-transmission within a single integrated structure. The device consists of four MMI sections, S-bend waveguides, crossing regions, and straight interconnecting waveguides. All components are symmetrically arranged along four directions – East, West, South, and North – as indicated in Fig. 1. Each key functional block is highlighted with enlarged views in Fig. 1 to clearly illustrate the geometric configuration. The detailed geometrical parameters of the entire device are summarised in Table 1.

Each MMI section in the proposed structure is designed with two input ports and two output ports. These ports employ tapered waveguides to improve coupling efficiency and reduce reflections at the interface between single-mode waveguides and the multimode region. The input width is set to 0.45 µm, ensuring excitation of only the fundamental transverse electric (TE_0) mode in the silicon photonics platform. The MMIs are implemented using the RI-MMI configuration, operating based on the self-imaging principle in the multimode region. According to self-imaging theory [20], when the length of the MMI section equals L_π, the optical field at the input is reproduced at the cross port, meaning that the entire optical power is transferred to the diagonally opposite output. In contrast, when the MMI length is $L_\pi/2$, the interference process generates two symmetric images with equal amplitudes at the two output ports, corresponding to a 3-dB power splitter.

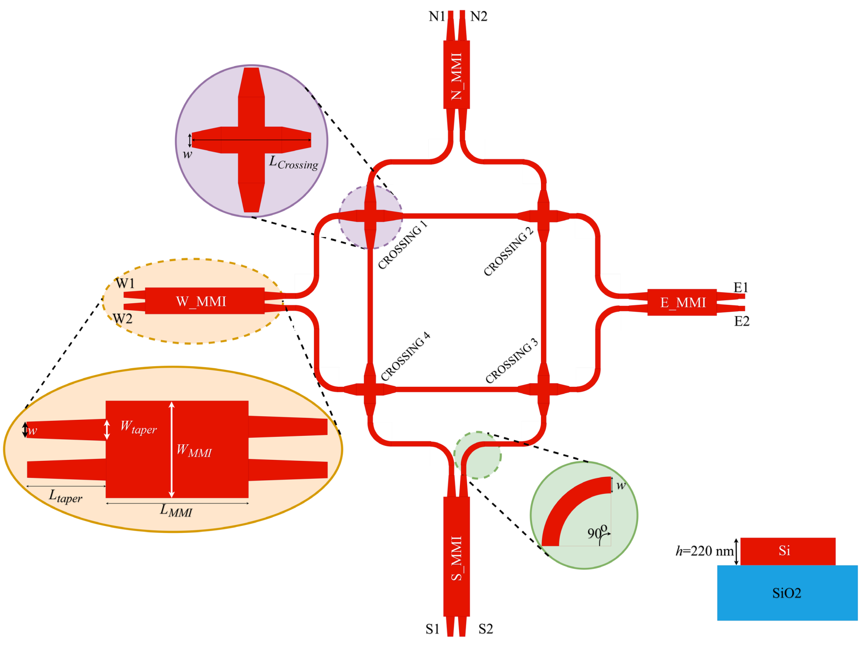

Fig. 1. Structural diagram of the proposed optical power splitter.

Table 1.
Initial parameters of the proposed design.

Parameter	Symbol	Value
Width of input/output waveguide	w	450 nm
Waveguide thickness (Si)	h	220 nm
Refractive indices of the silicon core layer	n_r	3.47
Refractive indices of the cladding oxide layer	n_c	1.444
RI-MMI		
Length of taper	L_{taper}	15 µm
Width of taper	W_{taper}	900 nm
Width of MMI	W_{MMI}	5.4 µm
Length of MMI	L_{MMI}	34 µm and 68 µm
Crossing waveguide		
Length of crossing waveguide		16 µm
S-bend		
Length of S-bend		50 µm

In the proposed design, the two MMI sections located in the West and South directions are chosen to have a length of L_π, thereby reproducing the optical field at the cross-port, i.e., enabling optical power cross-transmission. The remaining two MMI sections in the North and East directions are designed with a length of $L_\pi/2$, serving as 3-dB power splitters. Previous studies [19] have shown that an MMI length of 34 µm satisfies the $L_\pi/2$ condition, resulting in equal power splitting between the two output ports. Meanwhile, when the MMI length is increased to 68 µm, which corresponds to the L_π condition, the optical power is completely transferred to the cross-port.

S-bend waveguides are employed to smoothly route light between the MMI sections and crossing regions, while preserving the overall structural symmetry. The S-bend design helps minimise bending loss, suppress unwanted mode conversion, and reduce reflections caused by abrupt changes in propagation direction. As a result, light can propagate stably throughout the entire interference network without significantly degrading the overall performance. Crossing waveguide regions enables two waveguides to intersect orthogonally while maintaining low crosstalk. In this four-directional symmetric configuration, the crossings play a crucial role in ensuring equal optical path lengths and maintaining accurate phase relationships among different branches. The geometric design of the crossing regions is carefully optimised to minimise loss and suppress crosstalk within the operating wavelength range.

3. Simulation results and discussion

After completing the device design, numerical simulations are carried out to evaluate its performance. First, each individual component is analysed and characterised separately. Subsequently, all components are integrated to assess the device's overall performance.

Each individual component is characterised in terms of excess loss (EL), as this metric directly reflects the intrinsic loss introduced by each element. For the complete device, the performance is comprehensively evaluated based on EL, balancing factor (BF), and reflection (R). This evaluation framework is adopted to ensure not only a low overall loss but also a uniform power distribution among the output ports and minimal back-reflection. Such criteria are essential for maintaining signal integrity and achieving stable operation in integrated photonic systems. These values may be found using the formulas:

$$\mathrm{EL} = 10\log_{10}\left(\frac{\sum P_{out}}{P_{in}}\right), \quad (1)$$

$$\mathrm{BF} = 10\log_{10}\left(\frac{P_i}{P_j}\right), \quad (2)$$

$$\mathrm{R} = 10\log_{10}\left(\frac{P_{ref}}{P_{in}}\right), \quad (3)$$

where P_{out} and P_{in} are the normalised output and input powers, respectively, P_i and P_j are the two normalised output powers, respectively.

The spectral response of the EL for each component in the proposed design in the wavelength range of 1.5 µm to 1.6 µm is shown in Fig. 2. Passive elements, including the waveguide crossing and S-bend, demonstrate wavelength-independent behaviour with near-zero dB loss. The MMI-based components [multimode interference (West) (MMIW) and multimode interference (East) (MMIE)] also exhibit robust performance. The MMIE achieves a minimum EL of −0.4 dB at 1.55 µm, displaying a typical parabolic loss profile across the bandwidth. Meanwhile, the MMIW shows stable operation between 1.54 and 1.58 µm with a low excess loss (EL) of −0.25 dB, despite the emergence of notable ripples and increased attenuation at wavelengths shorter than 1.53 µm.

Figure 3 presents the performance of the proposed device when light is injected from the West ports (W1 and W2) and propagates toward the East direction (E1 and E2). The device is evaluated in terms of EL, BF, and R. Figure 3(a) shows the EL for the two input ports W1 and W2 over the wavelength range of 1.50–1.60 µm. The EL curves of W1 and W2 almost completely overlap, with

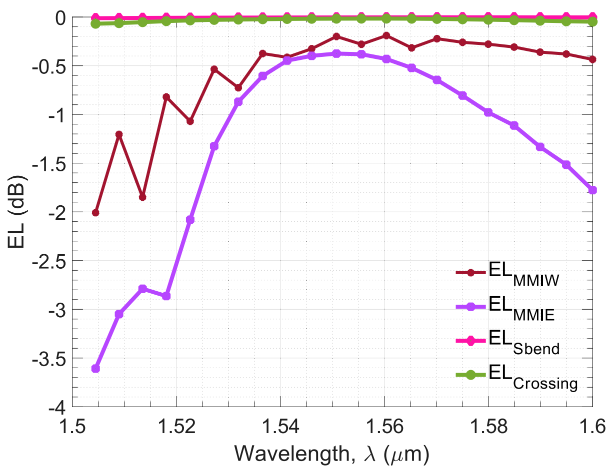

Fig. 2. Simulated excess loss (EL) of individual components as a function of wavelength.

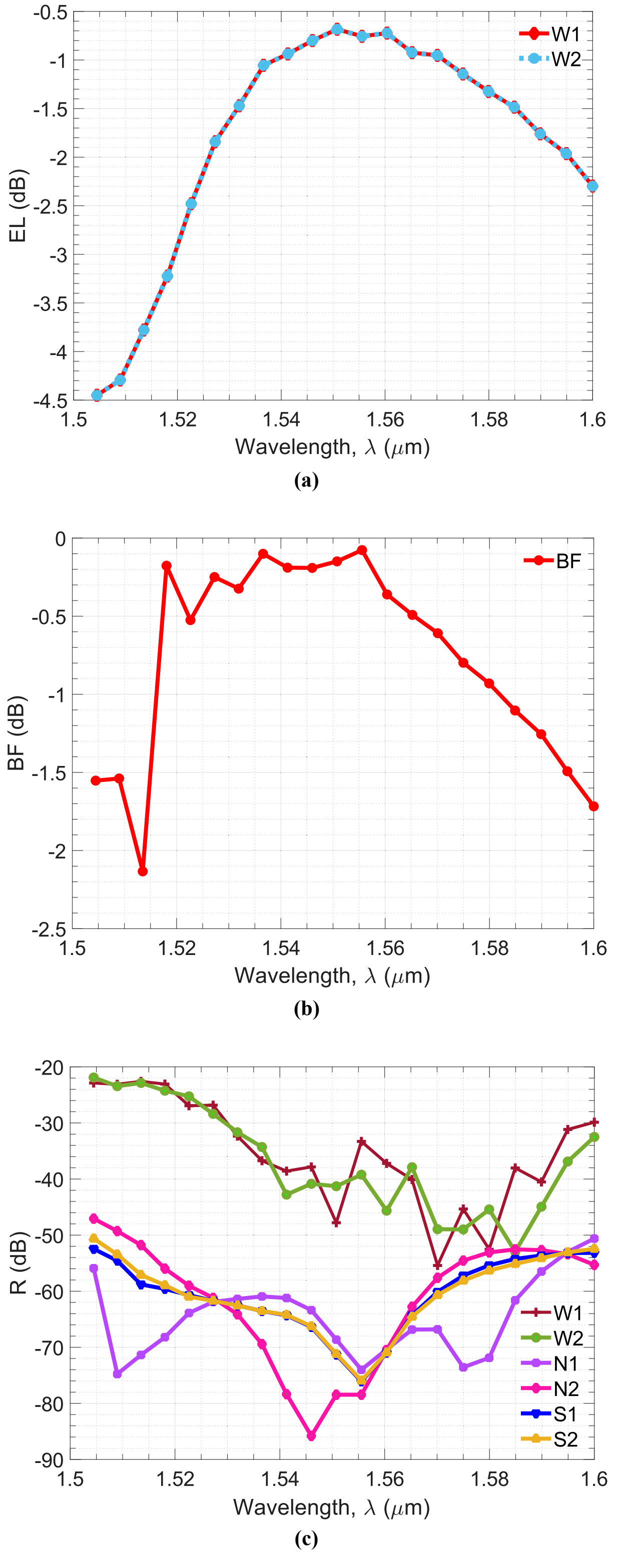

Fig. 3. Simulated performance of the proposed multi-port 3-dB MMI–MZI power splitter under West-to-East excitation: (a) EL for input ports W1 and W2, (b) BF between output ports E1 and E2, and (c) R at all ports.

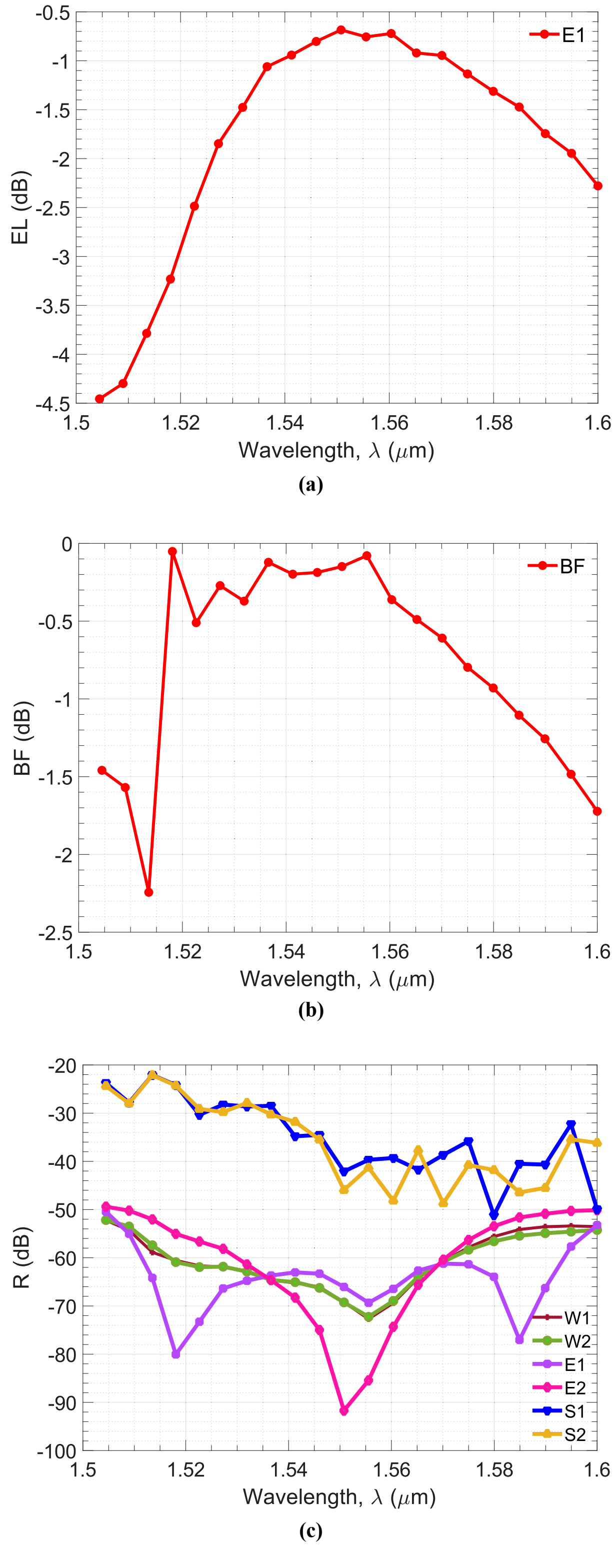

Fig. 4. Simulated performance of the proposed multi-port 3-dB MMI–MZI power splitter under South-to-North excitation: (a) EL for input ports S1, (b) BF between output ports N1 and N2, and (c) R at all ports.

a deviation of less than 0.1 dB, confirming the high structural symmetry and consistent transmission behaviour of the device. Quantitatively, the minimum EL is approximately −0.6 to −0.7 dB in the wavelength range of 1.54–1.56 μm, which represents the optimal operating region. As the wavelength moves away from this region, the EL increases, reaching about −4.4 dB at 1.50 μm and −2.3 dB at 1.60 μm. Notably, within a bandwidth of approximately 20 nm (1.53–1.55 μm), the EL remains above −1 dB, indicating good broadband performance around the design wavelength. Figure 3(b) illustrates the balancing factor between the two output ports E1 and E2. In the central wavelength region (approximately 1.53–1.55 μm), the BF remains close to 0 dB, ranging from about −0.1 dB to

−0.3 dB, indicating excellent power uniformity and confirming effective 3 dB splitting operation. At shorter wavelengths (around 1.51–1.52 µm), the BF shows noticeable degradation, reaching approximately −2.2 dB, while at longer wavelengths it gradually decreases to about −1.7 dB at 1.60 µm. Overall, the device maintains BF better than −0.5 dB within the main operating bandwidth, demonstrating stable and balanced power distribution. Figure 3(c) presents the reflection characteristics at all ports, including the West, North, and South directions. The results show that the reflection at all ports is consistently below −20 dB across the entire wavelength range, indicating low back-reflection and good impedance matching. More specifically, the West ports exhibit reflection levels between −25 dB and −45 dB, while the North and South ports achieve significantly lower reflection, typically in the range of −55 dB to −75 dB, with a minimum reaching approximately −85 dB near 1.55 µm. It is noteworthy that the lowest reflection values occur around the same wavelength region where the EL is minimised and the BF is closest to 0 dB, confirming that the device is well optimised at the design wavelength.

Figures 4 and 5 further evaluate the performance of the proposed device under different propagation directions, confirming its symmetric and reciprocal behaviour. Figure 4 presents the case where light is injected from the South ports and propagates toward the North direction. The results show performance characteristics similar to those observed in Fig. 3, with low EL, a BF close to 0 dB, and R below −20 dB, indicating consistent transmission, good power uniformity, and low back-reflection.

Figure 5 illustrates the reverse propagation scenario, in which light is launched from the East ports toward the West. Despite the opposite propagation direction compared to Fig. 3, the EL characteristics at the output ports remain nearly unchanged, with similar trends and values across the wavelength range. These results collectively demonstrate that the proposed structure maintains stable and uniform performance across multiple propagation directions. The consistent behaviour under both orthogonal and reverse excitations confirms the high structural symmetry and reciprocity of the device, making it highly suitable for multi-port and bidirectional photonic integrated circuit applications.

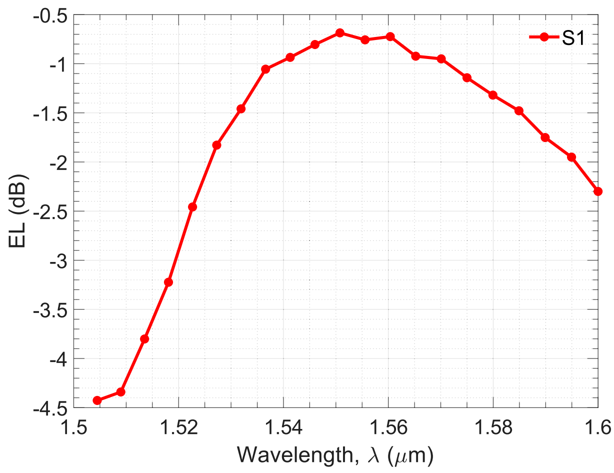

Fig. 5. Simulated excess loss of the proposed multi-port 3-dB MMI–MZI power splitter for input ports E1 under East-to-West excitation.

4. Conclusions

In this work, a multi-port 3-dB optical power splitter based on a hybrid MMI–MZI architecture has been proposed and numerically investigated on a SOI platform. The device is designed using a symmetric four-directional configuration, integrating multiple MMI sections, S-bend waveguides, and optimised waveguide crossings to simultaneously achieve power splitting and optical cross-transmission within a compact footprint. Simulation results demonstrate that the proposed device achieves low EL, with a minimum value of approximately −0.6 dB around a design wavelength of 1.55 µm. The BF remains close to 0 dB within the main operating bandwidth, indicating excellent power uniformity between output ports. In addition, the reflection at all ports is maintained below −20 dB, with significantly lower values observed near the optimal wavelength, confirming effective suppression of back-reflection. Furthermore, the device exhibits consistent performance under different propagation directions, including orthogonal and reverse excitations, validating its high structural symmetry and reciprocal behaviour. This direction-independent operation makes the proposed design highly suitable for multi-port and bidirectional photonic integrated circuits. Overall, the proposed multi-directional 3-dB power splitter offers a promising solution for efficient optical signal distribution in advanced silicon photonics applications, such as optical interconnects, interferometric systems, and integrated optical networks.

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