

## Design and demonstration of a compact silicon photonic 3-dB power and quadrature phase splitter using 2×2 RI-MMI coupler

Tran Thi Thanh Thuy<sup>1\*</sup>, Nguyen Tan Hung<sup>2</sup>, Truong Cao Dung<sup>1\*</sup>

<sup>1</sup>Posts and Telecommunications Institute of Technology, 96A Tran Phu, Ha Dong, Hanoi, Vietnam;

<sup>2</sup>Advanced Institute of Science and Technology, The University of Danang, 41 Le Duan, Hai Chau, Danang, Vietnam.

\*Corresponding author: thuyttt@ptit.edu.vn and dungtc@ptit.edu.vn

Received 03 Mar. 2026; Revised 21 May 2026; Accepted 15 Sep. 2026; Published 15 Oct. 2026.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.114.2026.88-96>

### ABSTRACT

*Multimode interference (MMI) waveguides are widely used in silicon photonics for their broadband operation and low loss. We present a compact and high-performance 2×2 restricted-interference MMI (RI-MMI) optical power splitter on a silicon-on-insulator platform. By optimizing input positions and interference length, the device footprint is reduced to 6 μm × 65 μm without compromising optical performance. Simulations via 3D-BPM and 3D-FDTD show low excess loss (< 4.3 dB), minimal phase difference (< 2%), coupling ratio variation (-0.09 to 0.05 dB), and excellent balance (< -17 dB) across 1500–1600 nm. Two designs (32.5 μm and 34 μm lengths) were fabricated using 193 nm DUV lithography. The 34 μm device exhibited < 5 dB insertion loss and < -23 dB reflection in the C-band. These results demonstrate the RI-MMI splitter's suitability for integration in advanced photonic circuits, including phasor signal generation, QPSK modulation, and OFDM processing.*

**Keywords:** 3-dB power and quadrature phase splitter; Restricted interference (RI); MMI coupler; Silicon-on-insulator; Silicon photonic fabrication; High- performance.

### 1. INTRODUCTION

Silicon photonic integrated circuits (PICs) have become a key platform for high-speed optical communication, supporting data center interconnects, FPGA-based processing, WDM, spatial mode multiplexing, photonic neural networks [1] and quantum system [2]. Their compatibility with CMOS/VLSI technology enables monolithic integration of photonic and electronic components on Silicon-on-Insulator (SOI) wafers with a standard 220-nm silicon layer, reducing device footprint, power consumption, and optical loss while supporting large-scale, cost-effective manufacturing [3]. Optical power splitters are essential components in photonic integrated circuits, forming the basis of devices such as Mach–Zehnder modulators (MZMs) and N×N optical switches, which rely on equal optical paths, optical coupling, and phase shifting. There are multiple approaches for designing optical power splitters on the silicon photonic platform. Y-junction couplers, for instance, offer a simple geometric structure but present challenges such as intricate mask designs and significant scattering losses at the junction interfaces [4]. Adiabatic and directional couplers provide low-loss performance; however, they require highly precise control over the coupling gap dimensions to ensure optimal performance [5].

Recently, two promising methods have emerged for achieving broadband and highly compact 3-dB power splitters: subwavelength grating-assisted silicon waveguides [6] and inverse design optimized through deep learning techniques [7]. While these approaches offer significant advantages in terms of footprint reduction and enhanced bandwidth, they introduce additional challenges. Subwavelength gratings necessitate high-resolution lithographic fabrication to accurately define nanoscale grating structures, whereas inverse-designed photonic devices require extensive computational resources and training time for AI-driven optimization. Moreover, the intricate and compact nature of these designs contributes to increased mask patterning complexity

and elevated fabrication costs [8]. In silicon photonic waveguides, multimode interference (MMI) couplers serve as fundamental building blocks for a wide range of functional devices, including optical logic gates [9], thermo-optic switches [10], and, most notably, arbitrary-ratio optical power splitters [11]. A recent development in this domain is a  $1 \times 2$  MMI-based 3-dB power splitter designed to operate at dual-band wavelengths of 1.55  $\mu\text{m}$  and 2  $\mu\text{m}$  [12]. However, a major limitation of this design is that it only supports a single input port, restricting its applicability in more complex optical signal processing systems.

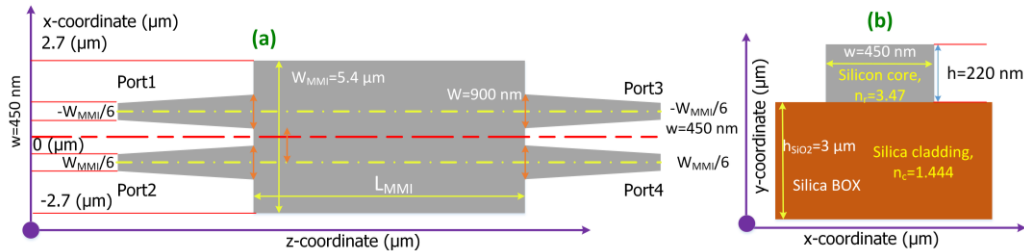


**Figure 1.** The design structure of the 3-dB power splitter based on a  $2 \times 2$  RI-MMI using silicon-on-insulator waveguide platform: (a) Schematic diagram; (b) Cross-sectional view.

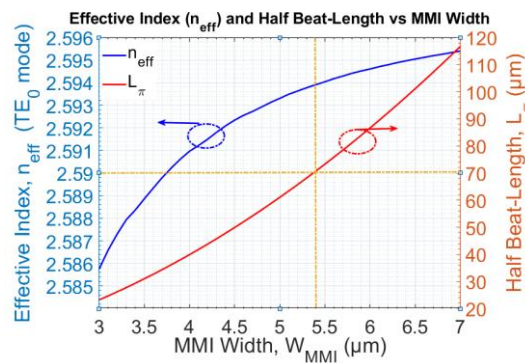


**Figure 2.** Effective index  $n_{\text{eff}}$  and half-beat length  $L_{\pi}$  as functions of MMI width.

MMI couplers are widely used in photonic integrated circuits (PICs) due to their compactness and fabrication tolerance. However, conventional MMIs operating in the general interference regime require relatively long devices and mainly support equal power splitting from a single input. Many photonic applications, such as phasor generation, QPSK modulation, and OFDM [13], require compact multi-input splitters with equal-power outputs and  $90^\circ$  phase shifts. Numerical methods, including 3D-BPM and FDTD, are commonly employed for silicon photonic design, with BPM offering high computational efficiency and FDTD providing greater accuracy. In this work, a compact 3-dB optical power splitter based on a  $2 \times 2$  MMI operating in the restricted interference regime is proposed to reduce the multimode interaction length. The device is analyzed using both 3D-BPM and FDTD simulations, demonstrating low insertion loss (IL) and balanced power splitting over a broad wavelength range. The design is further validated through fabrication using 193-nm DUV photolithography and experimental comparison with simulation results.

## 2. OPTIMIZED DESIGN AND CHARACTERISTIC SIMULATION

Figure 1 shows the schematic diagram of a 3-dB optical power splitter based on a  $2 \times 2$  MMI coupler operating under TE polarization. Specifically, Figure 1(a) shows the side view of the proposed 3-dB splitter. In this design, 15- $\mu\text{m}$ -long tapers are employed as the input and output ports instead of conventional rectangular access waveguides. This aims to improve the coupling efficiency between the access single-mode waveguides and the multimode region [5]. The entire

device is constructed on a SOI material platform, featuring a silicon (Si) guiding layer with a thickness of  $h = 220$  nm and a  $3\text{ }\mu\text{m}$ -thick buried oxide (BOX) layer of silica ( $\text{SiO}_2$ ), derived from a standard SOI wafer using CMOS technology. The refractive indices of the silicon core and the cladding oxide layer are considered constants at  $n_r = 3.47$  and  $n_c = 1.444$ , respectively, as determined by the Sellmeier model [14], within the third telecom window [15]. In the central section of the device, the  $2\times 2$  MMI coupler has an initial multimode region width  $W_{\text{MMI}} = 5.4\text{ }\mu\text{m}$ .

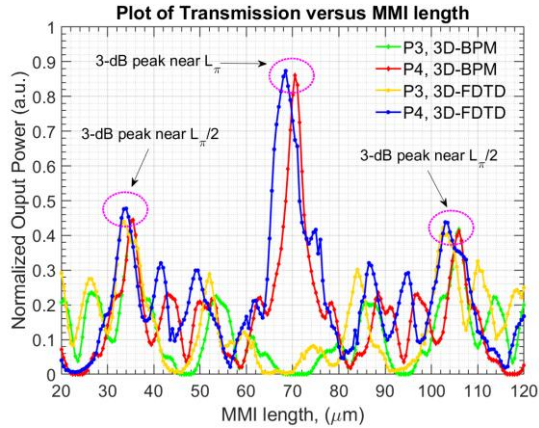


**Figure 3.** Normalized output power transmission characteristic dependence on the MMI length is swept in the range from  $20\text{ }\mu\text{m}$  to  $120\text{ }\mu\text{m}$ .

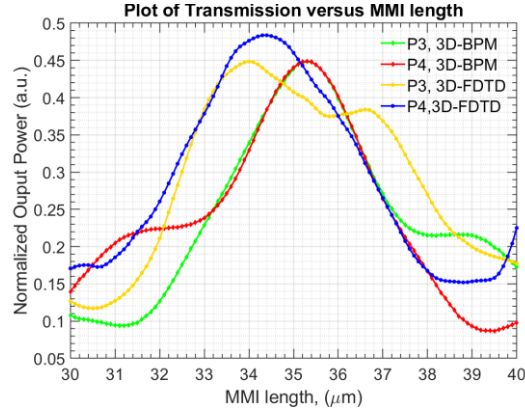


**Figure 4.** High-resolution swept transmission spectra of outputs depend on the MMI length at the operation wavelength of  $1550\text{ nm}$ .

To reduce the multimode length required to generate two mirrored fold-images, this paper proposes using a restricted interference regime where the input and output ports are positioned at approximately  $y = \pm W_{\text{MMI}}/6$  [16]. According to the restricted interference theory, at these positions, the overlap between the symmetric input field and the antisymmetric mode fields vanishes. This results in the periodic and paired reproduction of single images of the input field at the MMI region as much as multiple of a critical length,  $L = p(L_\pi)$ , with  $p = \{0, 1, 2, \dots\}$  as a non-negative integer, where the critical length  $L_\pi$  is the half-beat length of the MMI coupler [16].

Following the restricted interference theory, the single fold-images (direct or inverted images) are reproduced at the length  $L_{\text{MMI}} = p(L_\pi)$ , with  $p$  is a positive integer. In addition, the paired interference regime also exhibits two differently mirrored images at minimal lengths of the multimode region  $L_{\text{MMI}} = L_\pi/2$  and  $L_{\text{MMI}} = 3L_\pi/2$ . In addition, in a  $2\times 2$  RI-MMI coupler, each even mode leads its odd partner by a phase difference of  $\pi/2$ , from a subtraction between the phase angle of the mirrored output port (Port4) and the phase angle of the straightforward output port (Port3), at the position  $z = L_\pi/2$  (referred to as the 3-dB length [16]).

The numerical simulation methods used in the design were the three-dimensional beam propagation method (3D-BPM) and 3D finite-difference time-domain (3D-FDTD), both of which are reliable, accurate, and efficient techniques for modeling optical waveguides and photonic structures. These methods were employed to analyze and characterize the guided-wave propagation and optical performance of the proposed  $2\times 2$  MMI coupler [17].

Figure 2 presents the effective index and half-beat length as functions of the MMI width ( $W_{\text{MMI}}$ ) at  $1550\text{ nm}$ , obtained using 3D-BPM simulations. For  $W_{\text{MMI}} = 5.4\text{ }\mu\text{m}$ , the effective index is approximately 2.59, giving  $L_\pi \approx 70.8\text{ }\mu\text{m}$ . The MMI length was then swept from  $20$  to  $120\text{ }\mu\text{m}$  ( $0.5\text{-}\mu\text{m}$  resolution) under TE excitation at Port 1. As shown in Figure 3, both 3D-BPM and 3D-FDTD simulations identified two equal-splitting regions at approximately  $30\text{--}40\text{ }\mu\text{m}$  and  $100\text{--}110\text{ }\mu\text{m}$ , while a mirrored image was observed near  $71\text{ }\mu\text{m}$ . Accordingly, an MMI length of  $30\text{--}40\text{ }\mu\text{m}$ ,

close to  $L_{\pi}/2$ , was selected for the proposed design.

To determine a more precise MMI length, we performed a parameter sweep from 30  $\mu\text{m}$  to 40  $\mu\text{m}$  with a resolution of 0.1  $\mu\text{m}$ . Figure 4 presents the simulated transmission characteristics of output ports Port3 and Port4 as a function of MMI coupler length near  $L_{\pi}/2$ . The simulation results indicate that transmission peaks at approximately 45% when  $L_{MMI} = 35.4 \mu\text{m}$  for both 3D-BPM and 3D-FDTD simulations.

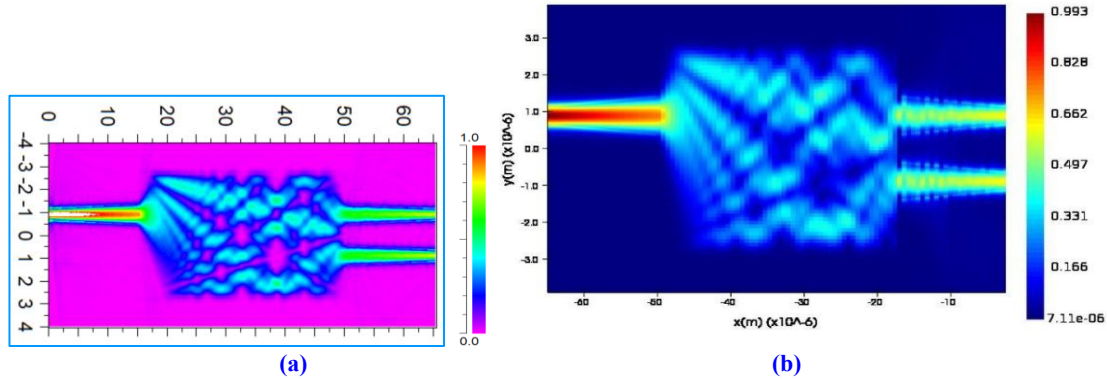


**Figure 5.** Simulation of the electric field distributions under TE mode of the power splitter at the wavelength of 1550 nm for: (a) at  $L_{MMI} = 35.4 \mu\text{m}$  (3D-BPM); and (b) at  $L_{MMI} = 33.5 \mu\text{m}$  (3D-FDTD).

In the 3D-BPM simulation, the transmission characteristics of the two output ports remain nearly identical within the range 33.2–37.4  $\mu\text{m}$ , forming a symmetrical parabolic shape centered at 35.4  $\mu\text{m}$ , with transmission values ranging from 25% to 45%. This suggests a 3-dB bandwidth extending  $\pm 2.1 \mu\text{m}$  around the central length of 35.3  $\mu\text{m}$ . For the 3D-FDTD simulation, the output port transmissions are nearly identical within 32.5–33.5  $\mu\text{m}$  and again intersect at 36  $\mu\text{m}$ . The highest transmission level, approximately 44%, is observed at 33.5  $\mu\text{m}$ . Based on these findings, we selected  $L_{MMI} = 35.4 \mu\text{m}$  (for 3D-BPM) to achieve the highest transmission and  $L_{MMI} = 33.2 \mu\text{m}$  (for 3D-FDTD) to obtain a more precise 50:50 splitting ratio, with transmission around 40%. These values were chosen for further analysis as they correspond to points where the transmission curves intersect, ensuring balanced optical power distribution.

### 3. SIMULATION BASED-DEVICE PERFORMANCE CHARACTERIZATION

Figure 5 presents the top-view electric field patterns of the device, corresponding to simulations using 3D-BPM with an MMI region length of 35.4  $\mu\text{m}$  (Figure 5(a)) and 3D-FDTD with an MMI region length of 33.2  $\mu\text{m}$  (Figure 5(b)). The electric field evolution diagrams confirm that the incident light waves are evenly split. Notably, the main section of the proposed power splitter, based on the designed 2×2 MMI coupler, occupies a compact footprint of 6  $\mu\text{m} \times 65 \mu\text{m}$ , making it well-suited for large-scale integration.

To evaluate the device performance, we also calculated the excess loss (EL) and the IL at each output port using the following relations [12]:

$$EL = 10 \log_{10} (P_{out} / P_{in}) + 3 = IL + 3 \quad (1)$$

where  $P_{out}$  and  $P_{in}$  correspond to the output and input powers, respectively. The constant quantity of 3 dB in Eq. (1) implies that the input light wave is divided into two output ports with a splitting ratio of 50:50. Moreover, a 3-dB power splitter for applications in advanced photonic circuits, such as quadrature phase-shift keying loaded-modulation, should maintain the phase difference between the two output ports ( $\Delta\Phi = \Phi_4 - \Phi_3$ ) as a constant of 90 degree, ensuring minimal fluctuation of the phase difference. As shown in Figure 6(a), for the 3D-BPM simulation, the excess losses at both

output ports remain consistently similar and exhibit smooth variations across a broad wavelength range of 100 nm, from 1500 nm to 1600 nm. The device demonstrates ultra-low loss over this range, with a minimum excess loss of 0.48 dB at 1546 nm and a maximum of 2.7 dB at 1600 nm. At the central wavelength of 1550 nm, the excess loss is measured at 0.5 dB. In contrast, for the 3D-FDTD simulation, the excess losses at both output ports remain closely matched but within a narrower wavelength range of 1540 nm to 1560 nm. The excess loss for the two output ports reaches a maximum of 4.3 dB at a wavelength of 1500 nm and a minimum of 0.2 dB at a wavelength of 1585 nm. Moreover, the excess losses in the 3D-FDTD case are higher than those in the 3D-BPM case in the operating wavelength region of 1550 nm because FDTD simulations provide a more rigorous analysis. Unlike BPM, FDTD accounts for additional loss mechanisms, including scattering and reflection effects, leading to greater overall loss accumulation. Simulation results obtained by 3D-BPM simulation show that the phase difference varies very slightly, from  $88.4^\circ$  to  $91.9^\circ$ , resulting in a relative phase deviation of less than 2% around the desired phase difference value of  $90^\circ$  over a broad spectrum up to 100 nm, as seen in Figure 6(b). It is evident that the  $35.4\text{ }\mu\text{m}$ -length device exhibits significant performance in terms of excess loss and phase difference, making it an appealing choice for a variety of sophisticated functional photonic integrated circuits.

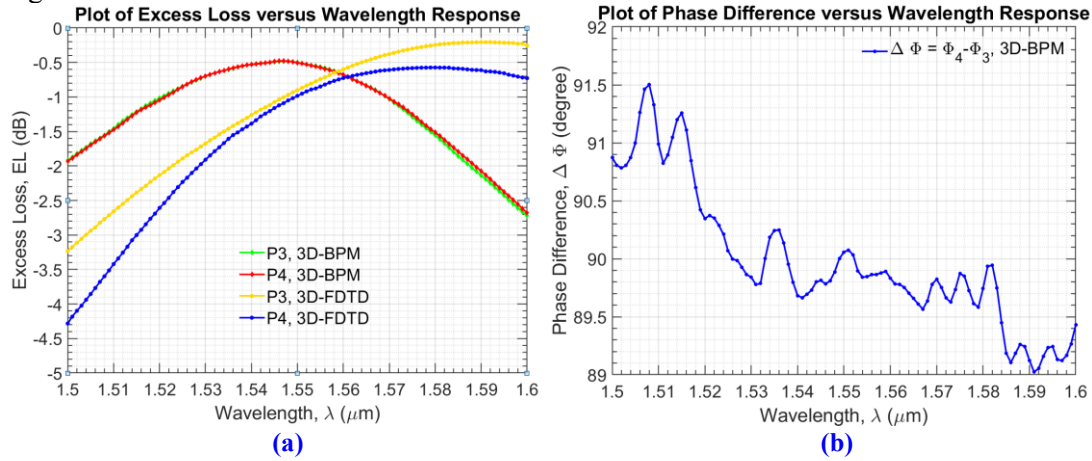


**Figure 6.** Optical performance wavelength-dependence of the designed 3-dB power splitter based on RI-MMI coupler in 100-nm spectrum for two output ports: (a) EL; and (b) Phase difference.

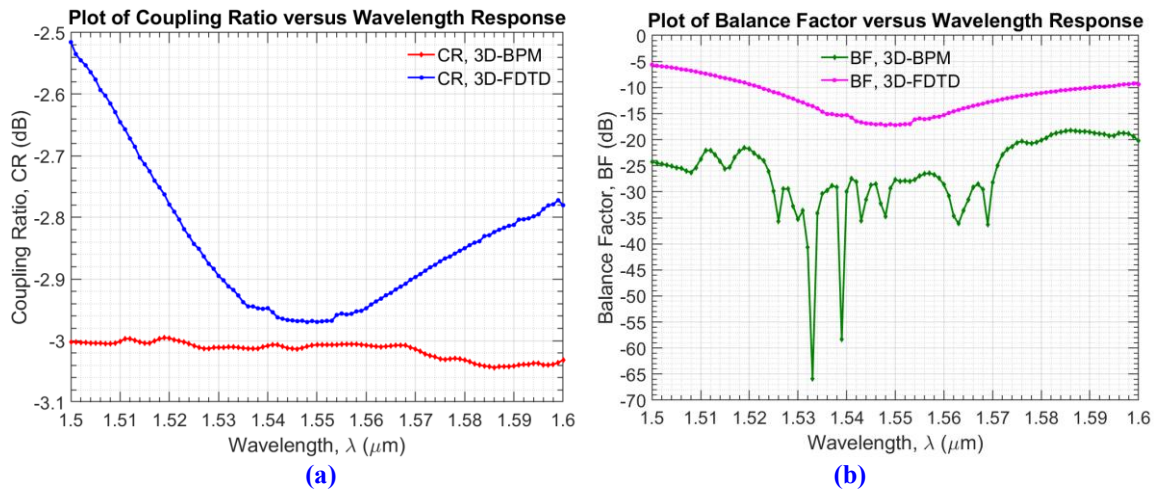


**Figure 7.** Wavelength response characteristics of the proposed power splitter ranging from 1500 nm to 1600 nm: (a) Coupling ratio; (b) Balance factor.

Subsequently, we employed standardized equations to ascertain the coupling ratio and the balance factor of the devices, facilitating the identification of those achieving optimal 50:50 power splitting. The coupling ratio (CR) and the balance factor (BF) are described as follows:

$$CR = 10 \log_{10} \left( \frac{P_{out3}}{P_{out3} + P_{out4}} \right) \quad (2)$$

$$BF = 10 \log_{10} \left( \left| \frac{P_{out3}}{P_{out4}} - 1 \right| \right) \quad (3)$$

where  $P_{out3}$  and  $P_{out4}$  correspond to the output power of the Port3 and Port4, respectively. The CR quantifies the percentage of input power delivered to each output port, while the BF measures the power difference between the output ports, indicating the uniformity of power distribution in optical splitters and couplers. Figure 7(a) shows the simulation results of the coupling coefficient CR as a function of wavelength. The results show that the coupling coefficient varies slightly in the range from -0.09 dB to 0.05 dB over a wide spectral range up to 100 nm. In addition, BF defined in Equation (3) is used to evaluate the power balance between the two output ports of the proposed splitter. In this definition, a lower BF value indicates a smaller power difference between Ports 3 and 4. Ideally, for a perfect 3-dB splitter, the optical powers at both output ports should be identical, resulting in BF approaching negative infinity. Figure 7(b) shows the simulation results of the BF according to the wavelength response from 1500 nm to 1600 nm. The simulation results show that the balance of the two ports, due to the limited interference characteristics of the device is very high because, on the decibel scale, BF is small, fluctuating only from the highest value of -17 dB to the lowest value of -41 dB. A BF value below -17 dB indicates that the proposed RI-MMI splitter achieves an excellent output power balance, with the power difference between the two output ports being less than approximately 2%. At the center wavelength of 1550 nm, the balance level is very high because BF = -31 dB (less than 0.1%).

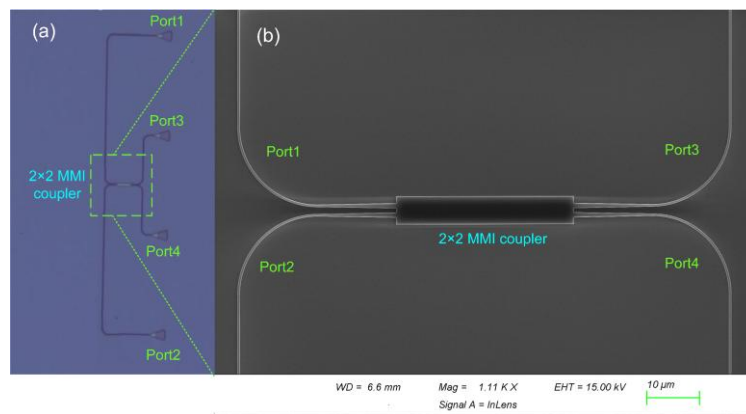


**Figure 8.** Microscope images of the fabricated devices (top-view) at the MMI length of 34  $\mu\text{m}$ : (a) The entire device featuring four subwavelength grating couplers connected to two input and two output ports; (b) SEM image of a magnified view of the 2 $\times$ 2 MMI silicon chip.

The discrepancy between the 3D-BPM and 3D-FDTD results mainly arises from their different numerical approaches. The 3D-BPM method uses the paraxial approximation and considers mainly forward propagation, enabling fast computation and efficient MMI optimization, but it may not fully account for higher-order mode coupling, back reflections, and scattering effects. In contrast, 3D-FDTD directly solves Maxwell's equations, providing a more rigorous full-wave analysis of interference, reflection, and diffraction phenomena. Therefore, slight differences in the optimal MMI lengths are observed, although both methods show consistent trends and validate the feasibility of the proposed RI-MMI design.

#### 4. EXPERIMENTAL FABRICATION AND CHARACTERIZATION

Based on the simulation results, the optimal RI-MMI length for the two-port optical splitter was determined to be 32.5–35.5  $\mu\text{m}$ . Accordingly, devices with MMI lengths of 32.5  $\mu\text{m}$  and 34  $\mu\text{m}$  were fabricated for experimental validation. The devices were patterned by electron beam lithography (EBL), followed by a single etching process and deposition of a 1- $\mu\text{m}$ -thick  $\text{SiO}_2$  cladding using PECVD. Fabrication was carried out through a Multi-Project Wafer (MPW) service using 193-nm deep ultraviolet (DUV) photolithography. Figure 8 shows microscope and SEM images of the fabricated 34- $\mu\text{m}$  device with grating couplers for fiber-chip coupling. Optical characterization was performed using a Keysight N7711A tunable C-band laser and a Newport 818-IR-L-FC/DB photodetector. Light was coupled through grating couplers with single-mode fibers, and the measured spectra were calibrated using on-chip reference waveguides to eliminate coupling losses.

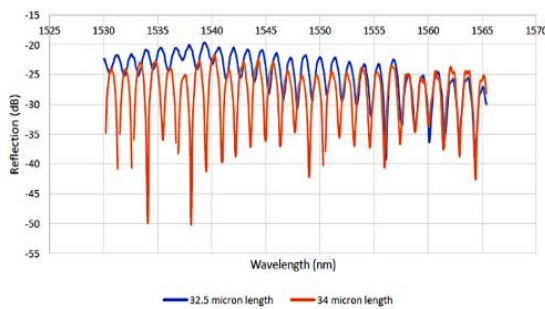


**Figure 9.** Reflection dependence on the wavelength response in the C-band for two cases of 32.5  $\mu\text{m}$  and 34  $\mu\text{m}$  MMI lengths.

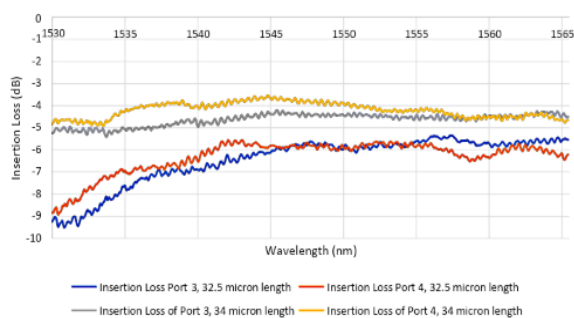


**Figure 10.** IL dependence on the wavelength response in the C-band for two cases of MMI lengths: 32.5  $\mu\text{m}$  and 34  $\mu\text{m}$ .

Figure 9 illustrates that the reflections at Port2 for both the 32.5  $\mu\text{m}$ - and 34  $\mu\text{m}$ -length devices remain below -23 dB, indicating minimal impact on overall performance. In Figure 10, it is evident that the 32.5  $\mu\text{m}$ -length device experiences significantly higher IL compared to its 34  $\mu\text{m}$ -length counterpart. Specifically, for the 34  $\mu\text{m}$ -length device, IL between the two output ports remains consistently low, staying below -5 dB across the C-band (1530 nm–1565 nm). In simulation, the EL is approximately -0.5 dB, corresponding to the IL ( $IL = EL - 3$  (dB)) of about -3.5 dB. However, the experimentally measured IL is below -5 dB, indicating an additional loss of approximately -1.5 dB. This discrepancy mainly originates from fabrication imperfections, including lithography errors and material absorption in the fabricated device. Moreover, the reported IL values do not include the loss contribution from the grating couplers. The device reaches a minimum loss of -4.5 dB near 1560 nm while maintaining a well-balanced splitting ratio over a 10 nm range from 1555 nm to 1565 nm. These characteristics make it a promising candidate for optical switching applications and other advanced photonic integrated circuits. However, as depicted in Figure 10, the 32.5  $\mu\text{m}$ -length device exhibits an optimal and stable 3-dB splitting ratio over a narrower spectral window, ranging from 1545 nm to 1555 nm.

Based on the overall evaluation, the 34- $\mu\text{m}$  MMI operating at 1560 nm was selected to achieve stable 50/50 power splitting with low IL and minimal spectral ripples. Although the measured IL is slightly higher than the simulated result due to fabrication imperfections and measurement uncertainties, both results show good agreement, confirming the feasibility and robustness of the proposed RI-MMI design for PICs.

#### 5. CONCLUSIONS

In conclusion, we present a numerically optimized design for a silicon 2×2 RI-MMI-based 3-dB optical power and quadrature phase splitter. Numerical simulations using both 3D-BPM and

3D-FDTD methods identify the optimal MMI lengths as 35.4  $\mu\text{m}$  and 33.2  $\mu\text{m}$ , respectively. In general, both simulation methods demonstrate excellent optical performance for the designed 2×2 RI-MMI coupler, exhibiting low excess loss ( $< -4.3$  dB), a small relative phase difference ( $< 2\%$ ), a near-ideal coupling ratio of around -3 dB with a minimal variation of -0.09 to 0.05 dB, and a high balance factor ( $< -17$  dB) over a broad 100 nm bandwidth. Furthermore, the main section of the proposed power splitter is accommodated within a compact footprint of 6  $\mu\text{m} \times 65 \mu\text{m}$ . Two silicon photonic chip samples were fabricated using 193 nm DUV photolithography with MMI lengths of 32.5  $\mu\text{m}$  and 34  $\mu\text{m}$ . Measurement results for both samples indicate minimal reflection below -23 dB in the C-band. Additionally, for the 34  $\mu\text{m}$ -length device, the IL between the two output ports remains consistently low, staying below 5 dB across the C-band. These exceptional characteristics position the proposed device as a promising candidate for very large-scale photonic integrated circuits and photonic neural networks in telecom applications.

**Acknowledgement:** This research is sponsored by the Posts and Telecommunications Institute of Technology under project code 03–2026–HV–KTDT1. Thuy Tran Thi Thanh was funded by the PhD Scholarship Program of Vingroup Innovation Foundation (VINIF), VinUniversity, code VINIF.2025.TS70.

## REFERENCES

- [1]. E. Paolini, L. De Marinis, M. Cococcioni, L. Valcarenghi, L. Maggiani, and N. Andriolli, “Photonic-aware neural networks”, *Neural Comput. Appl.*, vol. 34, no. 18, pp. 15589–15601, (2022). DOI: 10.1007/s00521-022-07243-z.
- [2]. C. Van Toan et al., “A solution for analyzing and evaluating quantum communication networks through simulation”, *J. Mil. Sci. Technol.*, no. IITE, pp. 3–11, (2025).
- [3]. L. Sun, Y. Zhang, Y. He, H. Wang, and Y. Su, “Subwavelength structured silicon waveguides and photonic devices”, *Nanophotonics*, vol. 9, no. 6, pp. 1321–1340, (2020). DOI: 10.1515/nanoph-2020-0070.
- [4]. Y. Zhang et al., “A compact and low loss Y-junction for submicron silicon waveguide”, *Opt. Express*, vol. 21, no. 1, p. 1310, (2013). DOI: 10.1364/oe.21.001310.
- [5]. Y. Luo, Y. Yu, M. Ye, C. Sun, and X. Zhang, “Integrated dual-mode 3 dB power coupler based on tapered directional coupler”, *Sci. Rep.*, vol. 6, pp. 1–7, (2016). DOI: 10.1038/srep23516.
- [6]. Z. Liu, Y. Dong, Y. Xu, B. Zhang, and Y. Ni, “Low loss and ultra-broadband design of an integrated 3 dB power splitter centered at 2  $\mu\text{m}$ ”, *Appl. Opt.*, vol. 63, no. 3, p. 662, (2024). DOI: 10.1364/ao.510814.
- [7]. Z. Li et al., “The Intelligent Design of Silicon Photonic Devices”, vol. 2301337, pp. 1–42, (2024). DOI: 10.1002/adom.202301337.
- [8]. L. Zheng et al., “UV-LED projection photolithography for high-resolution functional photonic components”, *Microsystems Nanoeng.*, vol. 7, no. 1, (2021). DOI: 10.1038/s41378-021-00286-7.
- [9]. E. G. Anagha and R. K. Jeyachitra, “Review on all-optical logic gates: design techniques and classifications – heading toward high-speed optical integrated circuits”, *Opt. Eng.*, vol. 61, no. 06, pp. 1–31, (2022). DOI: 10.1117/1.oe.61.6.060902.
- [10]. S. Pal and S. Gupta, “Proposal and Analysis of a Silicon MMI Coupler-Based Electronically Controllable Photonic Switch”, *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 6, pp. 141–154, (2016). DOI: 10.1109/JSTQE.2016.2545239.
- [11]. Z. Li et al., “Ultra-compact low-loss variable-ratio 1×2 power splitter with ultra-low phase deviation based on asymmetric ladder-shaped multimode interference coupler”, *Opt. Express*, vol. 28, no. 23, p. 34137, (2020). DOI: 10.1364/oe.405449.
- [12]. Qiyuan Yi, Guanglian Cheng, Zhiwei Yan, Qiyuan Li, Fanglu Xu, Yongchao Zou, Ting Li, Yuhua Sun, Yi Zou, Yu Yu, and L. S., “Silicon MMI-based power splitter for multi-band operation at the 1.55 and 2  $\mu\text{m}$  wave bands”, *Opt. Lett.*, vol. 48, no. 5, pp. 1335–1338, (2023). DOI: 10.1364/OL.486428.
- [13]. N. Van Vinh, D. T. Hai, P. N. Thang, and N. Q. Binh, “Reducing the effect of the nonlinear distortion in 16-APSK OFDM system by pilot-based automatic phase shift”, vol. 95, pp. 12–19, (2024).
- [14]. S. Zollner et al., “Thin-film metrology of silicon-on-insulator materials”, *Appl. Phys. Lett.*, vol. 76, no. 1, pp. 46–48, (2000). DOI: 10.1063/1.125651.

- [15]. S. Dwivedi et al., “Experimental Extraction of Effective Refractive Index and Thermo-Optic Coefficients of Silicon-on-Insulator Waveguides Using Interferometers”, J. Light. Technol., vol. 33, no. 21, pp. 4471–4477, (2015). DOI: 10.1109/JLT.2015.2476603.
- [16]. L. B. Soldano and E. C. M. Pennings, “Optical Multi-Mode Interference Devices Based on Self-Imaging: Principles and Applications”, J. Light. Technol., vol. 13, no. 4, pp. 615–627, (1995). DOI: 10.1109/50.372474.
- [17]. Y. Jiao, Y. Shi, D. Dai, and S. He, “Accurate and efficient simulation for silicon-nanowire-based multimode interference couplers with a 3D finite-element mode-propagation analysis”, J. Opt. Soc. Am. B, vol. 27, no. 9, p. 1813, (2010). DOI: 10.1364/josab.27.001813.

### TÓM TẮT

#### Thiết kế và thực nghiệm bộ chia công suất 3 dB và chia pha vuông góc quang tử silic kích thước nhỏ gọn sử dụng bộ ghép 2×2 RI-MMI.

Ổng dẫn sóng giao thoa đa mode (MMI) được sử dụng rộng rãi trong quang tử silic nhờ khả năng hoạt động băng rộng và suy hao thấp. Chúng tôi trình bày một bộ chia công suất quang 2×2 dựa trên MMI giao thoa hạn chế (RI-MMI) có kích thước nhỏ gọn và hiệu năng cao trên nền tảng silicon-on-insulator (SOI). Bằng cách tối ưu vị trí đầu vào và chiều dài vùng giao thoa, kích thước thiết bị được giảm xuống còn  $6\ \mu\text{m} \times 65\ \mu\text{m}$  mà không làm suy giảm hiệu năng quang học. Kết quả mô phỏng bằng phương pháp 3D-BPM và 3D-FDTD cho thấy suy hao dư thấp ( $<4,3\ \text{dB}$ ), sai lệch pha tối thiểu ( $<2\%$ ), tỷ lệ ghép nối biến thiên trong khoảng  $(-0,09\ \text{đến}\ 0,05\ \text{dB})$  và độ cân bằng công suất tốt ( $<-17\ \text{dB}$ ) trong dải bước sóng 1500–1600 nm. Hai thiết kế với chiều dài 32,5  $\mu\text{m}$  và 34  $\mu\text{m}$  đã được chế tạo bằng công nghệ quang khắc DUV 193 nm. Thiết bị có chiều dài 34  $\mu\text{m}$  đạt suy hao chèn  $<5\ \text{dB}$  và phản xạ  $<-23\ \text{dB}$  trong băng C. Các kết quả này chứng minh bộ chia RI-MMI phù hợp để tích hợp trong các mạch quang tử tiên tiến, bao gồm tạo tín hiệu phasor, điều chế QPSK và xử lý OFDM.

**Từ khoá:** Bộ chia công suất 3 dB và chia pha vuông góc; Giao thoa hạn chế (RI); Bộ ghép MMI; Silicon-on-insulator; Chế tạo quang tử silic; Hiệu năng cao.