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Simultaneous mode conversion and wavelength routing in an SOI photonic integrated circuit

<https://doi.org/10.1515/joc-2026-0321>

Received July 17, 2026; accepted September 14, 2026;

published online October 1, 2026

Abstract: This paper proposes a multifunctional device integrating mode conversion and wavelength routing on a single chip. The device passively processes four wavelength–mode channels formed by two modes (TE_0 and TE_1) at two wavelengths (1,490 nm and 1,550 nm), which can be selectively routed to the device's four different output ports. The device is built on a Silicon-on-Insulator (SOI) platform, including two main functional blocks: a mode conversion block using multimode interference ($MMI-1 \times 3$ and $MMI-3 \times 2$), and a wavelength routing block based on two butterfly structures ($MMI-1 \times 2$). Structural parameters are refined using the three-dimensional beam propagation method (3D-BPM) to achieve suitable insertion loss and crosstalk performance. Simulation results show that at a wavelength of 1,490 nm, insertion loss and crosstalk are approximately 1.6 dB and -13 dB, respectively, while the corresponding values at 1,550 nm are approximately 1.7 dB and -15 dB. Furthermore, the device has a compact size of only $3.6 \times 344.5 \mu m^2$. Fabrication tolerance analysis confirms that the device maintains stable operation for $\pm 20\%$ variations in the investigated input-waveguide length (L_{in}) and width (W_{in}). The proposed passive device could be potentially suitable for CMOS-compatible photonic integrated circuits in MDM–WDM hybrid systems.

Keywords: mode conversion; wavelength routing; SOI; MMI; MDM–WDM; PICs

1 Introduction

In recent years, high-speed and broadband optical fiber communication systems have been rapidly developed to meet the increasing demand for data transmission and multimedia services. Although the optical domain offers extremely large bandwidth approximately 10 thousand times higher than that of the electrical domain thanks to the use of optical carriers around 200 THz [1], its efficient utilization remains limited. This limitation is mainly attributed to the reliance on optical–electrical (O/E) and electrical–optical (E/O) conversions, which introduce bottlenecks in processing speed and system capacity.

To overcome these challenges, recent research has focused on all-optical switching technologies combined with wavelength division multiplexing (WDM) and mode division multiplexing (MDM), forming MDM–WDM systems [2–6]. In such systems, the total transmission capacity is proportional to the product of the number of wavelengths and the number of modes per wavelength, significantly enhancing system throughput without expanding spectral bandwidth.

Figure 1 illustrates a typical unidirectional MDM–WDM system, where two wavelengths are multiplexed/demultiplexed, each carrying multiple spatial modes (mode 0, mode 1, and mode 2). In these hybrid systems, photonic integrated circuits (PICs) have gradually become a potential solution for high-speed connections in data-center interconnects [7, 8]. In particular, PICs designed on silicon substrates, with their advantages of large bandwidth, low loss, high integration density, and especially compatibility with CMOS fabrication technology, are a preferred choice for these optical link applications [9, 10].

Various photonic components have been proposed for MDM–WDM systems, including mode multiplexers/demultiplexers, mode converters, mode routers, and wavelength routers. Among these, multifunctional integrated devices capable of simultaneously performing mode conversion and wavelength routing have attracted significant attention thanks to their ability to enhance on-chip transmission capacity without increasing footprint, making them suitable for optical network-on-chip (ONoC) architectures.

Previous studies have investigated mode conversion [11, 12], mode routing [13, 14], and multifunctional mode manipulation devices based on mode exchange [15]. Several

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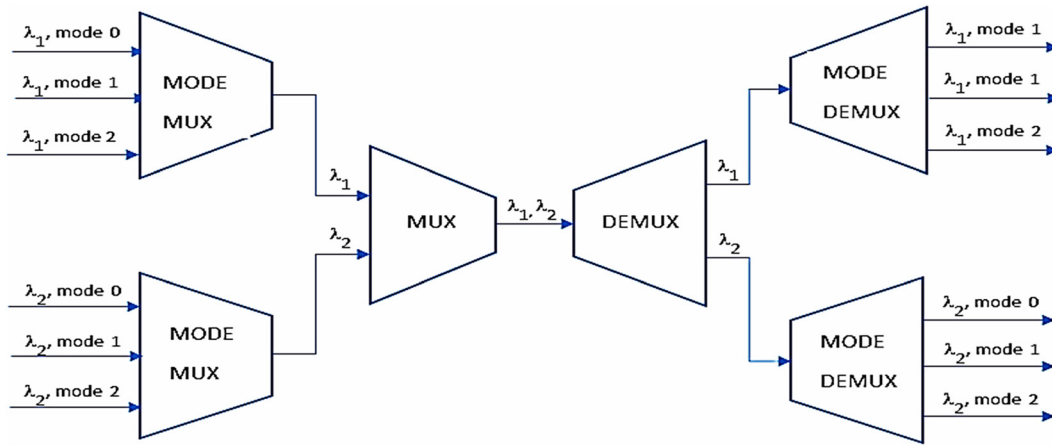


Figure 1: Schematic diagram of the wavelength division multiplexing and mode division multiplexing (MDM-WDM) system.

silicon photonic switching architectures capable of jointly manipulating optical modes and wavelengths have also been reported in [16–18]. Stern et al. [16] demonstrated an integrated switch capable of simultaneously supporting wavelength-division multiplexing (WDM) and mode-division multiplexing (MDM), achieving crosstalk levels from -16.8 to -24.0 dB. However, the implementation relies on resonant switching elements and a relatively complex switching architecture, increasing design complexity and control requirements. Han et al. [17] proposed a wavelength and mode-selective silicon photonic switch for WDM-MDM networks, providing flexible wavelength and mode routing functionalities, but requiring multiple thermo-optic tuning elements. More recently, Liu et al. [18] reported a demultiplexing-free WDM-compatible multimode optical switch assisted by mode exchangers. Although the device enables simultaneous wavelength and mode switching, its architecture relies on multiple mode exchangers, microring resonators, and thermal control units, resulting in increased structural complexity and insertion losses of up to 8.7 dB.

In contrast, the present work employs a passive MMI-based architecture to integrate mode conversion and wavelength routing without active thermal/electrical tuning or resonant switching elements. It exhibits a low insertion loss of ~ 1.7 dB, crosstalk around -13 dB, a footprint of $3.6 \times 344.5 \mu\text{m}^2$, and stable simulated performance for $\pm 20\%$ variations in the investigated input-waveguide length (L_{in}) and width (W_{in}). Although its crosstalk is higher than that reported in [16], the passive architecture offers a compact footprint and simpler implementation without active tuning. It should be emphasized that the present study is a numerical investigation of a passive SOI photonic device. The demonstrated operation is restricted to two spatial modes (TE_0 and TE_1) and two operating wavelengths (1,490 and 1,550 nm).

The remainder of this paper is organized as follows. Section 2 presents the device structure and operating principle. Section 3 evaluates device performance and discusses the results. Finally, Section 4 concludes the paper.

2 Device structure and operating principle

2.1 Device structure

Figure 2 depicts the schematic diagram of the proposed DEMUX device, which consists of two main functional blocks: a mode converter and a wavelength router. The mode converter consists of two rectangular multimode interference couplers ($\text{MMI1-}1 \times 3$ and $\text{MMI2-}3 \times 2$) and a phase shifter (PS). The wavelength router consists of two butterfly $\text{MMI-}1 \times 2$ structures (MMI3 and MMI4) used to separate and route signals at 1,490 nm and 1,550 nm. The phase shifter introduces a π -phase shift between the two branches, enabling interference within MMI2 to direct the signal to the desired output. The two MMIs in the mode converter have the same width ($W_{\text{MMI1}} = W_{\text{MMI2}}$). However, the length of the multimode interference MMI2 (L_{MMI2}) is twice that of MMI1 (L_{MMI1}). Meanwhile, the size and shape of the two butterfly-shaped MMI structures, MMI3 and MMI4 , are the same, differing only in the position of the input waveguide. Additionally, trapezoidal tapers are used to connect the straight waveguides to the MMI blocks, thereby enhancing light coupling between them.

The proposed device is implemented on a Silicon-on-Insulator (SOI) rib waveguide platform with a silicon core ($n_{\text{core}} = 3.46$) on a silicon dioxide (SiO_2) substrate ($n_{\text{clad}} = 1.44$). The silicon core thickness is $H = 0.5 \mu\text{m}$, including a slab

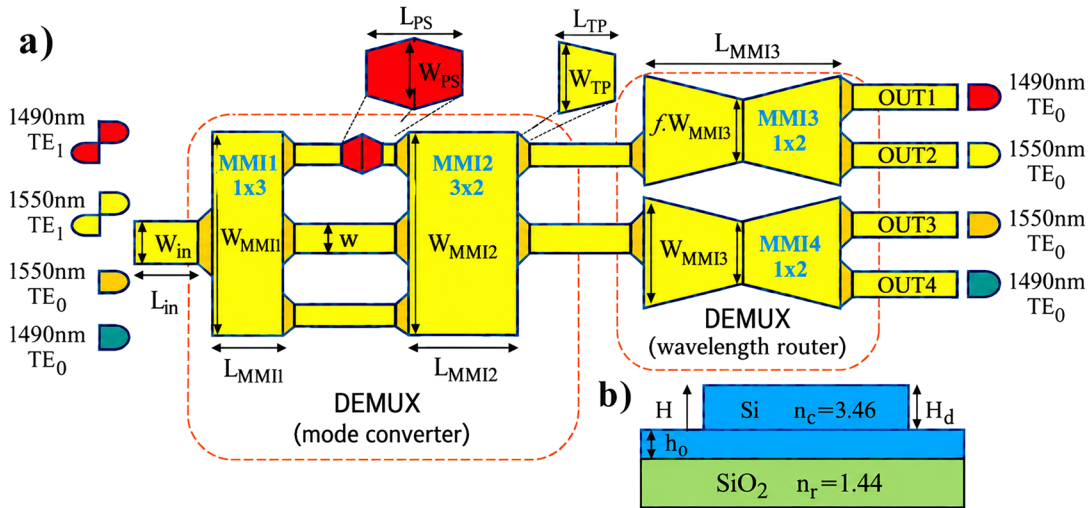


Figure 2: Schematic diagram of the proposed device for simultaneous mode conversion and wavelength routing. (a) Schematic diagram of the proposed device; (b) cross section of the waveguide.

height of $h_0 = 0.22 \mu\text{m}$ and an etched height of $H_d = 0.28 \mu\text{m}$, which supports stable propagation of both TE₀ and TE₁ modes.

2.2 Operating principle

The device is designed to handle four input signal cases, including TE₁/1,490 nm, TE₁/1,550 nm, TE₀/1,550 nm, and TE₀/1,490 nm. When a TE₁ mode signal at 1,490 nm/1,550 nm is launched into the device, the mode converter converts it to a TE₀ mode signal in the outer waveguide branch, maintaining the same wavelength. Conversely, if the device's input signal is in TE₀ mode, the output signal in the middle branch of the mode converter remains in TE₀ mode. These TE₀ mode signals at the output of the mode converter are then launched into one of the two MMI structures, MMI3 or MMI4. If the input signal is TE₀ at 1,490 nm or 1,550 nm from the outer waveguide branch, it will be routed to the device's output ports OUT1 and OUT2. Similarly, the two TE₀/1,550 nm and TE₀/1,490 nm signals in the middle waveguide will be routed to ports OUT3 and OUT4, respectively. The routing order of signals to the four output ports described above is strongly dependent on the geometrical configuration and dimensions of the MMI components within the device. The chosen routing scheme ensures structural simplicity while optimizing performance by exploiting the interference and self-imaging properties of TE₀ modes in MMI couplers.

Figure 3 illustrates the optical field distribution and propagation paths within the device when the TE₁ mode signal at 1,490 nm is injected. The input TE₁/1,490 nm signal passes through MMI1; there, it is converted into two

TE₀/1,490 nm modes propagating along the first and third branches at the MMI1 output. Although these two TE₀ mode signals are initially in phase, a relative phase shift of 180° is introduced between them by the phase shifter. These two out-of-phase signals then enter MMI2, where they interfere and combine into a single TE₀/1,490 nm signal that emerges from MMI2's output port 1. This signal is then fed into MMI3 and routed to the OUT1 output port. The optical signal path in the mode-conversion function block is similar when the input signal is TE₁ at 1,550 nm.

However, the signal is routed out at the device's OUT2 port (Figure 4).

Similarly, Figures 5 and 6 show optical field distribution and propagation paths through the chip for TE₀/1,550 nm and TE₀/1,490 nm signals at the device input. The TE₀ mode propagates without mode conversion but will be routed along a vertical axis of the central waveguides as it passes through the two MMI structures, MMI1 and MMI2. Here, the TE₀/1,550 nm mode signal will be routed to OUT3 and the TE₀/1,490 nm signal will be routed to OUT4.

Table 1 summarizes the mode conversion and wavelength routing processes for the four output ports under different input signal conditions.

The geometrical parameters of the proposed device were determined through a combination of analytical MMI self-imaging relations and numerical simulations using the RSoft BeamPROP software [19]. Three-dimensional beam propagation method (3D-BPM) was employed to simulate the optical-field evolution in the cascaded SOI rib-waveguide and MMI structures. The simulations used spatial discretization steps of $\Delta x = \Delta y = 0.01 \mu\text{m}$ and $\Delta z = 0.02 \mu\text{m}$. The computational domain extends from -5.64 to $4.14 \mu\text{m}$ in the

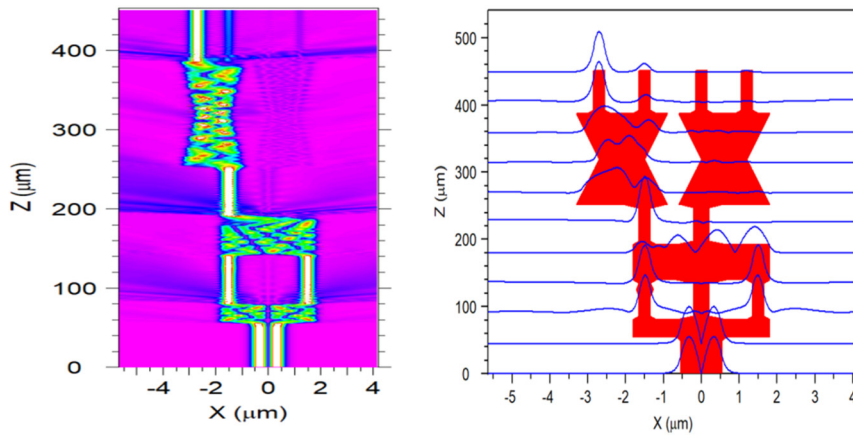


Figure 3: Optical field distribution and propagation paths through the chip for $TE_1/1,490$ nm input.

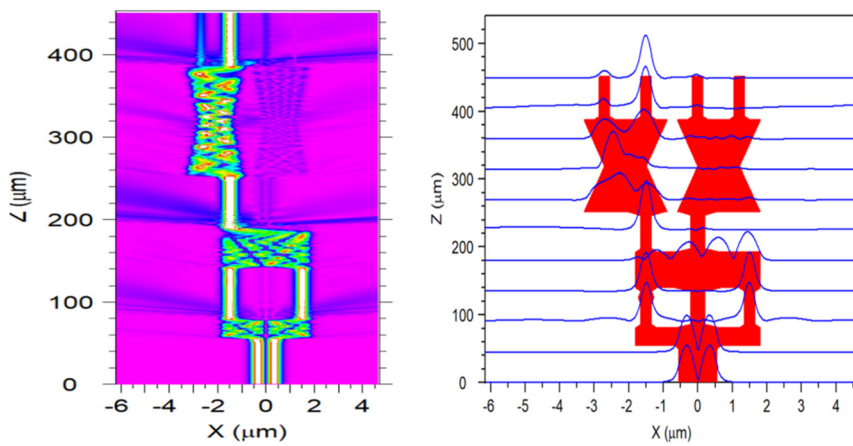


Figure 4: Optical field distribution and propagation paths through the chip for $TE_1/1,550$ nm input.

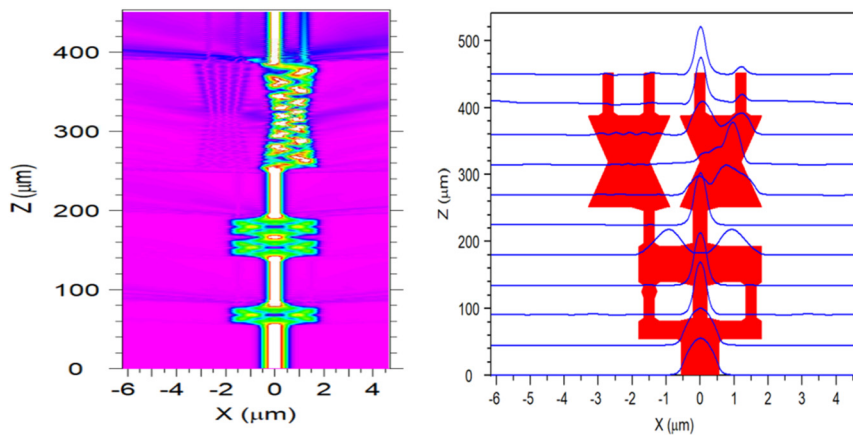


Figure 5: Optical field distribution and propagation paths through the chip for $TE_0/1,550$ nm input.

transverse x -direction and from 0 to $451.5 \mu\text{m}$ in the longitudinal z -direction, fully encompassing the waveguide structure and the surrounding cladding region. Absorbing boundary conditions were applied at the outer boundaries to suppress artificial reflections. The refractive indices $n_{\text{core}} = 3.46$ and $n_{\text{clad}} = 1.44$ were kept constant throughout the simulations. The output powers were extracted using the MOST Scanner and subsequently processed in MATLAB

to calculate IL and CrT. The analytical MMI relations were used to estimate the initial geometrical parameters, which were subsequently refined through systematic 3D-BPM parameter sweeps rather than an automated optimization algorithm. A mesh-convergence check using different spatial discretizations showed negligible variations in IL and CrT, confirming sufficient numerical convergence of the adopted mesh.

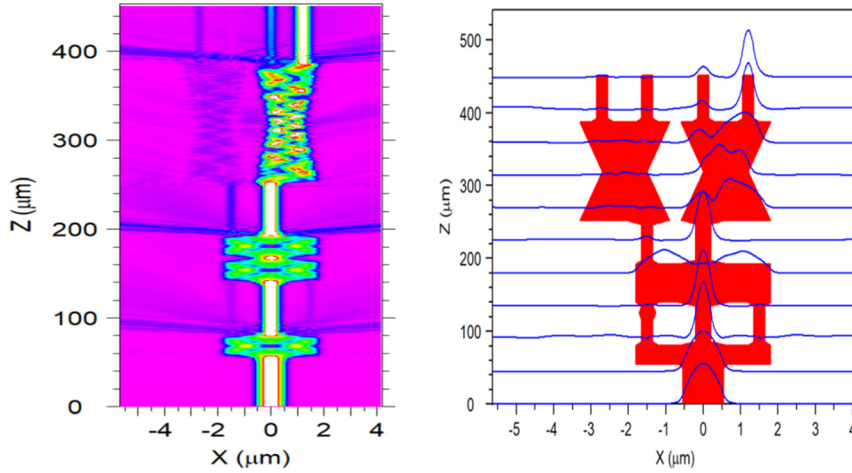


Figure 6: Optical field distribution and propagation paths through the chip for $TE_0/1,490$ nm input.

Table 1: Mode conversion and wavelength routing at four output ports.

Input signal	Mode conversion	Wavelength (nm)	Output mode	Output port
$TE_1/1,490$ nm	$TE_1 \rightarrow TE_0$	1,490	TE_0	OUT1
$TE_1/1,550$ nm	$TE_1 \rightarrow TE_0$	1,550	TE_0	OUT2
$TE_0/1,550$ nm	None	1,550	TE_0	OUT3
$TE_0/1,490$ nm	None	1,490	TE_0	OUT4

The dimensions of the MMI structures are determined by two parameters: L_{MMI} and W_{MMI} . The lengths L_{MMI1} and L_{MMI2} of the rectangular MMI structures are initially estimated using the following relations [20]:

$$L_{MMI2} = 2L_{MMI1} = 3 \frac{L_{\pi(\lambda)}}{2} \quad (1)$$

where L_{π} denotes the beat length of the two lowest-order modes in the MMI region and it is given by:

$$L_{\pi(\lambda)} = \frac{4n_e W_e^2}{3\lambda} \quad (2)$$

With:

$$W_e = W_{MMI1} + \frac{\lambda}{\pi} (n_{core}^2 - n_{clad}^2)^{-0.5} \quad (3)$$

Equations (1)–(3), based on the conventional MMI self-imaging principle, were used only to estimate the initial MMI dimensions. For the central input waveguide, symmetric interference was considered, whereas the side input waveguides were designed using the general interference condition. The final dimensions listed in Table 2 were subsequently refined and verified by 3D-BPM simulations using the actual SOI rib-waveguide geometry.

The initial value of L_{MMI3} is estimated using the following relation [21]:

Table 2: Key design parameters of the proposed device.

No.	Symbol	Value	Description
1	n_{clad}	1.44	Refractive index of SOI substrate
2	n_{core}	3.46	Refractive index of SOI core
3	H	$0.5 \mu\text{m}$	Silicon core thickness
4	h_0	$0.22 \mu\text{m}$	Slab height
5	H_d	$0.28 \mu\text{m}$	Etched height
6	L_{in}	$50 \mu\text{m}$	Input waveguide length
7	W_{in}	$1.1 \mu\text{m}$	Input waveguide width
8	L_{MMI1}	$25.5 \mu\text{m}$	Length of MMI1 (1×3)
9	W_{MMI1}	$3.6 \mu\text{m}$	Width of MMI1 (1×3)
10	L_{MMI2}	$51 \mu\text{m}$	Length of MMI2 (3×2)
11	W_{MMI2}	$3.6 \mu\text{m}$	Width of MMI2 (3×2)
12	L_{MMI3}	$67.5 \mu\text{m}$	Length of MMI3 and MMI4 (1×2)
13	W_{MMI3}	$2.4 \mu\text{m}$	Width of MMI3 and MMI4 (1×2)
14	L_{PS}	$10 \mu\text{m}$	Phase shifter length
15	W_{PS}	$0.45 \mu\text{m}$	Phase shifter width
16	f	0.5	Width factor of butterfly structure

$$L_{MMI3} = \frac{1}{2} (3mL_{\pi(1490 \text{ nm})}) = \frac{1}{2} (3nL_{\pi(1550 \text{ nm})}) \quad (4)$$

For the butterfly MMI wavelength-routing section, Eq. (4) was used to obtain an initial length satisfying the self-imaging conditions at the two operating wavelengths. The resulting butterfly-MMI dimensions were subsequently refined by 3D-BPM simulations to obtain the required wavelength-dependent power distribution at the output ports.

The phase shifter is implemented as a fixed passive waveguide section whose phase shift is determined by its geometrical parameters W_{PS} and L_{PS} . In the present design, $W_{PS} = 0.45 \mu\text{m}$ and $L_{PS} = 10 \mu\text{m}$ provide an approximate π -phase shift required for the intended mode-conversion operation. A tunable phase shifter could be considered in future implementations when reconfigurable phase control is required. Table 2 summarizes the key design parameters

of the proposed device obtained from the analytical estimates and subsequent 3D-BPM refinement.

Based on the design parameters listed in Table 2, the overall footprint of the proposed device is approximately $(3.6 \mu\text{m} \times 344.5 \mu\text{m})$. The results indicate that the proposed device exhibits a compact footprint, making it well suited for photonic integrated circuit (PIC) applications.

3 Performance evaluation and discussion

The electromagnetic field distribution images in Figures 3–6 demonstrate the successful operation of mode conversion and wavelength routing within a single chip. However, these light-field distribution images do not quantitatively represent the signal conversion efficiency between the device's input and output. For a more accurate assessment, we use numerical simulation to evaluate the performance using two parameters: insertion loss and crosstalk.

$$\text{IL (dB)} = 10 \log_{10} \left(\frac{P_{\text{TE}_0(\lambda_k), \text{OUT}_q}}{P_{\text{TE}_i(\lambda_k), \text{IN}}} \right) \quad (5)$$

$$\text{CrT (dB)} = 10 \log_{10} \left(\frac{\sum P_{\text{TE}_{j \neq 0}(\lambda_k), \text{OUT}_q}}{P_{\text{TE}_0(\lambda_k), \text{OUT}_q}} \right) \quad (6)$$

Where $i = 0, 1; j = 0, 1, 2, \dots; q = 1, 2, 3, 4; \lambda_k = 1,490 \text{ nm}$ and $1,550 \text{ nm}$; $P_{\text{TE}_i(\lambda_k), \text{IN}}$ is the input signal power of mode TE_i at the wavelength λ_k ; $P_{\text{TE}_0(\lambda_k), \text{OUT}_q}$ is the desired output signal power of mode TE_0 at the wavelength λ_k and at the q -th port; and $P_{\text{TE}_{j \neq 0}(\lambda_k), \text{OUT}_q}$ is the power of the unwanted output signal TE_j (with $j \neq 0$) considered at the output port OUT_q , which appears at the output port with the desired signal TE_0 .

3.1 Insertion loss analysis

Figure 7 shows the variation in insertion loss (IL) as a function of wavelength over $(1,490\text{--}1,550) \text{ nm}$ for four input signal cases: $\text{TE}_0/1,490 \text{ nm}$, $\text{TE}_1/1,490 \text{ nm}$, $\text{TE}_0/1,550 \text{ nm}$, and $\text{TE}_1/1,550 \text{ nm}$. The results indicate that the proposed device achieves low insertion loss. The TE_0 and TE_1 mode signals at $1,490 \text{ nm}$ wavelength exhibit insertion losses of approximately -1.6 dB (points A and B). Moreover, at $1,550 \text{ nm}$, the corresponding values for $\text{TE}_0/1,550 \text{ nm}$ and $\text{TE}_1/1,550 \text{ nm}$ are around -1.7 dB (points C and D).

3.2 Crosstalk analysis

Figure 8 depicts the variation of crosstalk (CrT) versus wavelength over the range $(1,490\text{--}1,550) \text{ nm}$ for four input

signal cases. The results demonstrate that the proposed device achieves low crosstalk levels. The crosstalk characteristics are further evaluated in Figure 8. At $1,490 \text{ nm}$, the $\text{TE}_0/1,490 \text{ nm}$ and $\text{TE}_1/1,490 \text{ nm}$ signals exhibit crosstalk values of approximately -13 dB (points N and M). At $1,550 \text{ nm}$, the corresponding crosstalk values for $\text{TE}_0/1,550 \text{ nm}$ and $\text{TE}_1/1,550 \text{ nm}$ are approximately -15 dB (points P and Q). The simulated CrT ranges from approximately -15 dB to -13 dB over the two operating wavelengths, with the worst-case value occurring at $1,490 \text{ nm}$.

The difference in CrT between $1,490$ and $1,550 \text{ nm}$ is mainly attributed to the wavelength-dependent propagation constants and self-imaging conditions in the MMI sections. Since the device geometry is fixed, the accumulated phase and self-imaging conditions are slightly different at the two wavelengths, resulting in different power levels at the desired and undesired output ports.

3.3 Fabrication tolerance analysis

To evaluate the fabrication robustness of the proposed device for integrated mode conversion and wavelength routing, the investigated geometrical parameters (L_{in}) and (W_{in}) are varied by $\pm 20\%$ around their design values for the TE_0 mode at $1,490 \text{ nm}$. As shown in Figure 9, when L_{in} varies from $40 \mu\text{m}$ to $60 \mu\text{m}$ ($50 \mu\text{m} \pm 20\%$), the insertion loss (IL) changes only slightly from -1.408 dB to -1.395 dB , while the crosstalk (CrT) remains between -14.56 dB and -14.24 dB .

Similarly, Figure 10 shows that when W_{in} varies from $0.88 \mu\text{m}$ to $1.32 \mu\text{m}$ ($1.1 \mu\text{m} \pm 20\%$), the IL is maintained within a narrow range of -1.410 dB to -1.395 dB , whereas the CrT exhibits a negligible variation from -14.564 dB to -14.558 dB . Overall, the maximum fluctuations in IL and CrT are limited to 0.015 dB and 0.32 dB , respectively, indicating stable simulated performance under dimensional variations in the investigated input-waveguide length (L_{in}) and width (W_{in}). A more comprehensive fabrication-tolerance analysis involving etching depth, silicon thickness, and other process variations will be considered in future work.

3.4 Performance comparison and discussion

Compared with the devices summarized in Table 3, the main distinction of the proposed design is the integration of mode conversion and wavelength routing in a passive MMI-based SOI structure without active thermal/electrical tuning or resonant elements. The proposed design, therefore, represents a trade-off between crosstalk performance, passive

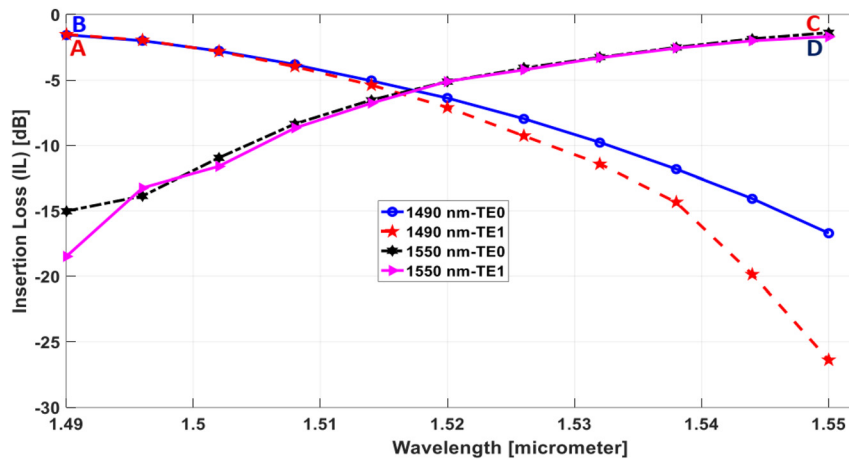


Figure 7: Insertion loss (IL) as a function of wavelength for four input signal cases.

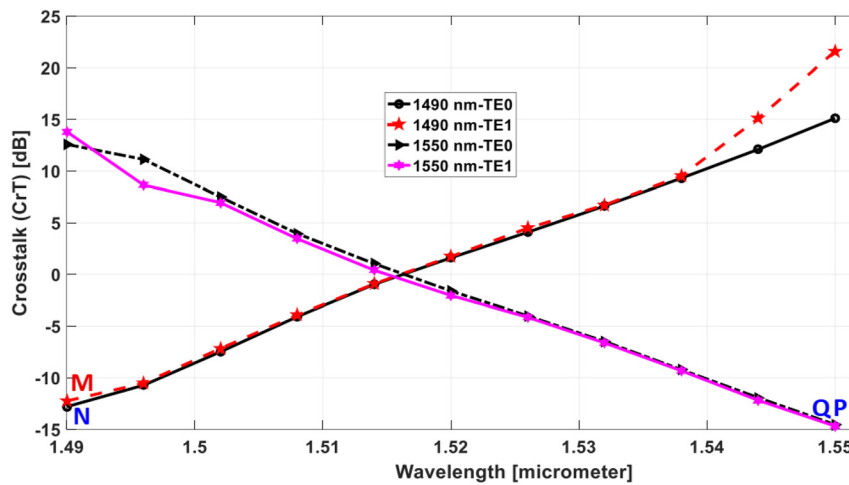


Figure 8: Crosstalk (CrT) as a function of wavelength for four input signal cases.

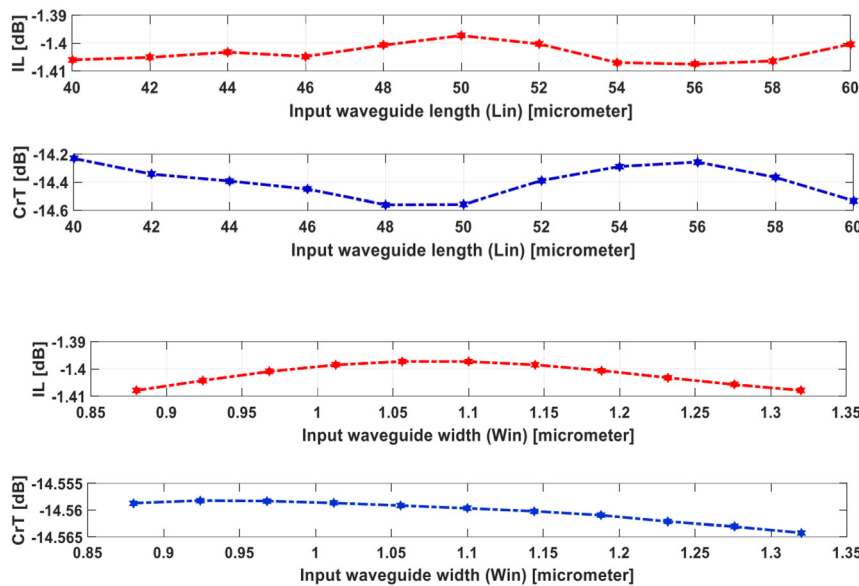


Figure 9: Variation of IL and CrT versus input waveguide length (L_{in}) for $TE_0/1,490$ nm input signal case.

Figure 10: Variation of IL and CrT versus input waveguide width (W_{in}) for $TE_0/1,490$ nm input signal case.

Table 3: Performance comparison with previously reported integrated devices.

Ref.	Function	Mode/wavelength	IL (dB)	Crosstalk (dB)	Footprint	Tuning/mechanism	Tolerance
[16]	WDM-MDM switch	TE ₀ , TE ₁ /2 λ ; 4 channels	(5.4–9.1) ^a	–16.8 to –24.0	<0.07 mm ²	Thermo-optic MRRs	NR
[17]	Wavelength/mode selective switch	2 modes/WDM channels	NR	NR	2.3 $\times$ 1.4 = 3.22 mm ²	Thermo-optic, 20 elements	NR
[18]	WDM-compatible multimode switch	TE ₀ , TE ₁ /1,551 nm	<8.7	NR	0.87 $\times$ 0.52 = 0.452 mm ²	Thermo-optic MRRs	NR
This work	Integrated mode conversion + wavelength routing	TE ₀ , TE ₁ /1,490, 1,550 nm; 4 channels	(1.6–1.7)	–13 to –15 dB	3.6 $\times$ 344.5 = 1,240.2 μ m ² = 0.00124 mm ²	Passive; no active tuning	$\pm$ 20 % (Lin and Win only)

^aMeasured insertion loss including on- and off-chip coupling losses. NR, not reported.

operation, and structural compactness. A more comprehensive evaluation of practical implementation aspects is beyond the scope of the present numerical study and requires further investigation.

4 Conclusions

In this work, a compact passive SOI photonic integrated device integrating mode conversion and wavelength routing has been proposed and numerically investigated. The device processes four wavelength–mode channels formed by the TE₀ and TE₁ modes at 1,490 and 1,550 nm. The 3D-BPM simulation results show insertion losses of approximately 1.6–1.7 dB and crosstalk levels of –13 to –15 dB, with a compact footprint of 3.6 $\times$ 344.5 μ m². The tolerance analysis also indicates stable simulated performance for $\pm$ 20 % variations in the investigated input-waveguide length and width. These results demonstrate the potential of the proposed passive MMI-based architecture for integrated MDM–WDM applications. Extension to additional wavelengths or higher-order modes may be possible through further design optimization and validation.

Acknowledgments: The authors gratefully acknowledge Dr. Thang Duy Dao, Silicon Austria Labs (SAL), for his valuable technical discussions and support with the computational analysis carried out in this work.

Research ethics: Not applicable.

Informed consent: Not applicable.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission. Conceptualization: N. V. Tuan; Methodology and Simulation: N. V. Tuan and N. T. Hung; Validation and Data Analysis: T. A. Hoang; Writing – original

draft preparation: H. H. Q. Hieu; Writing – review and editing: H. D. T. Linh.

Use of Large Language Models, AI and Machine Learning

Tools: An AI-based tool was strictly limited to secondary proofreading of English grammar and syntax to ensure linguistic clarity. The core scientific ideas, theoretical formulations, 3D-BPM numerical models, performance evaluations, and all academic conclusions were entirely conceived, developed, and verified by the authors without the assistance of any automated tools.

Conflict of interest: The authors state no conflict of interest.

Research funding: None declared.

Data availability: Not applicable.

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