Compact, Highly Efficient, and Controllable Simultaneous $2 \times 2$ Three-Mode Silicon Photonic Switch in the Continuum Band

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ABSTRACT Multimode switch (MMS) allows realizing multimode optical communication enabling high-speed communication. However, to develop such an ultrafast switch for simultaneous multimode with a compact size is very challenging. In this paper, we design and demonstrate a compact multimode $2 \times 2$ MMS based on numerical simulation methods using silicon $\Psi$-junctions and multimode interference (MMI) couplers. The switch is controlled by thermal-optic phase shifters which is able to switch simultaneously states of the optical signal between three quasi-transverse electric modes. The MMS exhibits a low insertion loss from $-1.5$ dB to $-3$ dB, low crosstalk below $-22$ dB, and high extinction ratio larger than $22$ dB in 40-nm bandwidth in the third telecom window from 1520 to 1560 nm, respectively. With a compact footprint of $12 \mu m \times 1300 \mu m$, the MMS exhibits relatively large dimensional tolerances. Besides, the MMS provides total electric power consumption levels smaller than 103 mW at an ultrafast switching time of 4.4 $\mu s$ without the impact of the plasmonic effect. Furthermore, the conceptual principle of the proposed MMS can be reconfigurable and scalable in dimensional multifunctional on-chip mode-division multiplexing optical interconnects and promising potential for photonic large scale integration circuits in the continuum band.

INDEX TERMS Silicon photonics, multimode waveguide switch, thermo-optic effect, controllable, $\Psi$-junctions, MMI couplers, optical interconnects, numerical simulation, continuum band.

I. INTRODUCTION
The recent rapid capacity growth in widely various services in the era of the fourth industrial revolution (industry 4.0) such as data sciences based on machine learning and deep learning, 5G mobile system, video on demands, is now becoming a critical issue in optical fiber communication systems and optical interconnects [1]–[4]. Besides, the explosion of big data processing systems and high-power computational systems results in the increased bandwidth in data centers [5]. However, once the data rate speeds up, the optical communication bandwidth is limited due to the optical nonlinearity [6]. The mode-division multiplexing (MDM) technique has recently become an attractive solution for on-chip networks to enhance the optical transmission capacity with a single laser source for each individual wavelength.

This method allows each carrier multiplexed in a spatial mode to behave as an independent channel without suffering nonlinear interactions from the fiber media. Thus, when many guided modes are associated with an independent wavelength in a wavelength division multiplexing (WDM) system, they may significantly increase the channel capacity in short reach optical communications systems and optical interconnects where modal crosstalk can be negligible.

The data rate can obtain up to Tb/s when MDM and WDM techniques are combined [7], [8] on a general platform. Such a hybridization has been suggested in some recent works [8]–[10]. A mode-division reconfigurable and controllable multimode switch are vital to realizing flexible and complex photonic network-on-chip systems [11]–[13]. Currently, MDM systems based on silicon waveguides are the most preferable for photonic integrated circuits due to wideband, high confinement of optical field, large compact size, low absorption loss, low bending loss, and especially CMOS-
compatible manufacturing process [14]. To date, optical switches in silicon photonics are now facing a significant challenge in multimode optical communication and interconnect systems, where multimode guided waves in an integrated silicon waveguide need to be simultaneously switched for all different order modes in the reconfigurable switching system [15], [16]. Silicon mode simultaneously selective switches used in MDM networks have been reported by using various techniques. Conventionally, the fundamental and higher-order modes in a multimode waveguide are demultiplexed and converted into single modes at first via a mode demultiplexer and mode-order converters. Then, a spatial switching mechanism is applied to switch these fundamental modes. Some various approaches for switching multimode have been proposed and demonstrated via photonic integrated circuits, such as microrings-based switch [17], [18], silicon adiabatic couplers-based switch [19]–[22], and multimode interference coupler-based switch [23]–[25]. However, such structures either need many asymmetric adiabatic couplers for deploying the (de)multiplexing functionalities before the switching operation or use indispensable waveguide crossing elements. Other approaches utilize the Benes topology by cascading multistage, leading to large footprints and comparatively complicated mechanisms [9], [26], [27].

This paper proposes a compact 2 \times 2 three-mode optical switch design allowing the simultaneous switching operation of three modes without needing mode multiplexers and fundamental mode switches. The proposed switch utilizes four \( \Psi \)-junction couplers and 2 \times 2 multimode interference couplers constructing on the silicon-on-insulator platform. This structure is similar to the recently published version of the four-mode switch [28]. However, in this version dedicated to the simultaneous three-mode switching function, we engineered the mode sorting differently with fewer bridges playing the roles of crossovers to accommodate the three-mode switching operation. In addition, in this work, we additionally consider optical performances in terms of extinction ratio for evaluating the operation ability of the designed switch. The simultaneously switchable operation for three modes is executed by using controllable phase shifters under the thermo-optic effect impact, realizing a three-mode waveguide switch’s function. The optimization and characterization of the device are implemented via numerical methods from RSoft’s commercial simulation software tools showing a compact footprint and highly efficient optical performances in a continuum band. Grating couplers [29], [30], or edge-coupler [31] are indispensable elements to couple high-order modes from few-mode fibers to the silicon waveguides for applications.

II. OPERATION PRINCIPLE AND DESIGN OPTIMIZATION

Fig. 1(a) presents the conceptual design diagram of a 2 \times 2 three-mode switch. The proposed switch consists of two inputs and two outputs of multimode waveguides placed in the symmetric structure. The switch is based on silicon-on-insulator (SOI) channel waveguides that can be patterned from a standard 220-nm top layer thickness SOI wafer utilizing the photolithography process or the electron-beam writing technique as seen in Fig. 1(b). Refractive indices of the silicon core layer and the cladding silica layer in the central wavelength 1550 nm of the C-band window are \( n_r = 3.465 \) and \( n_c = 1.444 \), respectively. For the designed switch, inputs and outputs are constructed from triple-branch waveguide whose bus waveguide widths at the cutoff point are \( W_0 = 1.08 \, \mu m \) enabling the guidance of three exciting modes TE_0, TE_1, TE_2 of transverse polarizations, which are shown in Fig. 1(c). Exhibited results of guided modes are solved by the mode solver using the three-dimensional beam propagation method. The triple-branch middle output waveguide has the width of \( W_\phi = 0.5 \, \mu m \) for satisfying the single-mode condition [32]. Two S-bent waveguides on the left side and the right side have the same width of \( W_0 \). Besides, the bus waveguide and S-bent waveguide lengths in the propagation direction of the \( z \)-coordinate are correspondingly defined as \( L = 20 \, \mu m \) and \( L_\phi = 250 \, \mu m \), respectively.

According to the phase-matching condition, the input optical modes in the bus waveguide can be perfectly coupled to two fundamental modes in two outer arms (upper and lower arms of the \( \Psi \)-junction) if the effective index of the input mode is appropriate to the effective index of the fundamental mode in the access arms at outputs. This means the coupling efficiency between the guided mode at the bus waveguide and the local super-mode at the output branches will reach the maximal value if the phase-matching condition occurs. This principle accords to the mode-sorting theory that evolves into the mode of the output arm with the closest effective index by
the mode conversion factor (MCF) given as follows [33]:

$$\text{MCF}_{ij} = \frac{|\beta_i - \beta_j|}{\theta_{ij} \gamma_{ij}}$$  \hspace{1cm} (1)

where \( i \) and \( j \) denote the orders of output arms and \( \theta_{ij} \) is the divergence angle between them; \( \gamma_{ij} \) is the conversion factor given by:

$$\gamma_{ij} = \frac{1}{2} \left[ (\beta_i + \beta_j)^2 - (2k_0 n)^2 \right]^{1/2}$$  \hspace{1cm} (2)

here \( n \) is the refractive index between output arms and \( k_0 = 2\pi/\lambda_0 \) is the free-space wave number, \( \lambda_0 \) is the operation wavelength. The performance of a multi-junction with \( N \) output arms can then in part be modeled by minimizing the multi output factor (MOF) which is defined as follows:

$$\text{MOF}_{ij} = \sum_{j \neq i}^N \left| \frac{1}{\text{MCF}_{ij}} \right| = \sum_{j \neq i}^N \left| \frac{\theta_{ij} \gamma_{ij}}{\beta_i - \beta_j} \right|$$  \hspace{1cm} (3)

An ideal mode-sorter should have a MOF of zero. The excitation of higher-order modes within the output arms is avoided as long as the maximum significant value of the minimum mismatch between the stem mode and the fundamental mode during a specific output arm is significantly smaller than the tiniest mismatch between a mode within the stem and a higher-order mode in an output arm. To study the phase-matching condition between the fundamental mode \( \text{TE}_0 \) in the single-mode access waveguide and different order modes in the input bus waveguide, we investigate the coupling efficiency of the transformed mode power instead of minimizing the MOF parameters. We consider the convolutional process of the amplitude dynamics of local modes along the propagation direction, which is described by the following relation [34]:

$$\frac{da_j}{dx} = -i \beta_j a_j = \sum_k C_{jk} a_k$$  \hspace{1cm} (4)

where \( a_j \) and \( a_k \) are amplitudes of different supermodes, \( C_{jk} \) is the supermode coupling coefficients expressed by the coupled supermode theory as follows:

$$C_{jk} = \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \frac{k_0}{4} \frac{1}{\beta_j - \beta_k} \int_{A(x,z)} e_j^* e_k \frac{\partial n^2}{\partial x} dA$$  \hspace{1cm} (5)

where \( \varepsilon_0 \) and \( \mu_0 \) are the vacuum permittivity and vacuum permeability, \( \beta_j \) and \( \beta_k \) are the propagation constants of different supermodes relating to the effective refractive index \( n_{eff} \) by the equality \( \beta = n_{eff} k_0 \), \( e_j \) and \( e_k \) are the electric fields of the supermodes, \( n(x,y,z) \) is the refractive index on the dependence the position in three-dimensional space. Due to the symmetry of the triple-branch structure, following the coupled supermode theory, if the width of outer arms is larger than the width of the inner center arm \( (W_b > W_d) \), then the fundamental mode \( \text{TE}_0 \) at the bus waveguide will be overlapped on two outer arms and become larger than on the inner center arm. In contrast, the mode \( \text{TE}_2 \) will be coupled to the fundamental mode \( \text{TE}_0 \) much more than that of the inner center arm and vice versa for the condition \( W_b < W_d \). Whereas, the first-order mode \( \text{TE}_1 \) is always coupled to two outer arms with the same of supermode coupling coefficients but contradictory phases. By means of using the numerical simulation method of finite difference beam propagation method (FD-BPM), the coupling coefficient of local supermodes at the outer arms and the inner arm of the triple-branch structure is investigated by varying the width of \( W_b > 0.5 \mu m \). As a result, the phase-matching condition is relatively excellent at the width of \( W_b = 0.6 \mu m \). If we inject three exciting modes of \( \text{TE}_0, \text{TE}_1, \text{TE}_2 \) into the stem of the input port, two lowest modes of \( \text{TE}_{0,1} \) will be confined in two outer branches of outputs of triple-branch waveguide while the \( \text{TE}_2 \) mode will be only localized in the inner central line of the output of the \( \Psi \)-junction waveguide. Fig. 2 shows the contour maps of electric field distributions and three spectrums of guided modes when propagating through the triple-branch coupler. For the modes \( \text{TE}_0 \) and \( \text{TE}_1 \), the high transmission (propagation loss \(<0.5\text{dB}) \) throw the outer arms (port1 and port3), while for the mode \( \text{TE}_2 \), the transmission occurs in the center arm (port2). We observed a very high extinction (crosstalk \(<-30\text{dB}) \) for unwanted output ports in the 40-nm continuum range within 1520-1560 nm.

The proposed switch consists of four types of fundamental multimode interference (MMI) couplers, namely MMI-(A, B, C, D), playing roles as bridged couplers. In detail, these couplers include two MMI-A, four MMI-B, four MMI-C, and two MMI-D couplers. Functionally, MMI-A and MMI-B types play the role of crossover couplers (also called X-couplers), while MMI-C and MMI-D types substitute 3-dB couplers, as seen in Fig. 1(a). In this design,
MMI couplers are properly chosen in general interference regimes with different widths and lengths of the multimode region. The operation principle of MMI couplers is based on Talbot’s effect [35]. Following this effect, the optical field will be reproduced periodically along the guided-wave propagation direction according to the length of the multimode region [36]. Self-imaging will be mirrored through the $2 \times 2$ MMI coupler central line if the multimode region length satisfies the condition $L_{\text{MMI}} = 3L_{\pi}$. In contrast, the $2 \times 2$ MMI coupler will divide the optical input field into two equal parts (3-dB coupler) when the multimode length is equal to $L_{\text{MMI}} = 3L_{\pi}/2$. Here, $L_{\pi}$ is the half-beat length defined as follows:

$$L_{\pi} = \frac{4n_{\text{eff}} W_e^2}{3\lambda}$$

where

$$W_e = W_{\text{MMI}} + \frac{\lambda}{\pi} \left( n_{\text{eff}}^2 - n_c^2 \right)^{-0.5}$$

for TE polarization

where $W_e$ is the effective width of the multimode region, $\lambda$ is the operation wavelength, $n_{\text{eff}}$ is the effective index of the core layer, $n_c$ is the refractive index of the cladding layer.

As can be seen, MMI-A and MMI-B exhibit the role of crossover couplers (Fig. 3a&b), and MMI-C and MMI-D exhibit the 3-dB couplers (Fig. 3c&d). Besides, subfigures of Fig. 3 (a’, b’, c’, d’) show the wavelength response of those multimode couplers. All optimized couplers have a low propagation loss lower than 3 dB and a high extinction ratio in a relatively wide band of 40-nm wavelength bandwidth from 1520 nm–1560 nm.

In the configuration of three controllable phase shifters placed at the positions in Fig. 1, we assume that all three controllable phase shifters are simultaneously handled by only one external source, such as a voltage-driven thermal source with the same phase angle of $\Delta\Phi$. By using the transfer matrix relations in symmetric $\Psi$-junction couplers and $2 \times 2$ MMI couplers via simple algebra transformations, optical fields combined at output ports are reformed to original modes like input modes that are determined by the following expression:

$$P_{m,n}(\Delta\Phi) = P_{in,m}\eta_{m,c}10^{-\alpha L}\sin^2 \left( \frac{\Delta\Phi}{2} \right)$$

where $m = \{0, 1, 2\}$ stands for the order of the switched mode; $n = \{1, 2\}$ is the symbol of output ports; $P_{in,m}$ is the input power of the $m$-order mode; $P_{out,m}$ is the reformed output power of the $m$-order mode; $\eta_{m,c}$ is the accumulative coupling efficiency of the $m$-order mode when propagating through the device; $\alpha$ is the attenuation factor of the silicon core at the wavelength of 1550 nm, typically $\alpha$ in the decibel unit is approximate 1 dB/cm; $L$ is the propagation length of the device in the $z$-direction; $\Delta\Phi$ is the common phase shift of the controllable phase shifters. Eq. (8) indicates that all, mathematically, three modes of TE$_0$, TE$_1$, and TE$_2$ polarization states will be simultaneously switched to the cross output port if the phase difference $\Delta\Phi = 0$ radian and switched to the bar port if the phase difference $\Delta\Phi = \pi$ radian.

To obtain the switching operation simultaneously, we need to use a number of controllable phase shifters. There are amounts of phase shifters designed and used in a variety of scientific reports to drive the switching function, i.e., thermo-optic phase shifter (TOPS), electro-optic phase shifter, charge-carrier effect phase shifter. Among those, integrated optical metal-strip micro-heaters are widely applied for reconfigurable silicon photonics due to the sizeable thermo-optic coefficient of the bulk silicon crystal as well as the easy compatibility with CMOS manufacturing technology. Some other requirements should be optimized here regarding the metal-strip micro-heaters to achieve the best performances of the product of $\tau P_{\pi}$ for each the fixed-length $L_{PS}$ of the TOPS, such as the high figure-of-merit (FOM) quality, the miniature of design footprint, the minimization of crosstalk, and short switching time. In which, $\tau$ and $P_{\pi}$ are switching time relating to the thermal response time and electrical power supplied in the phase shifter to reach the required amount of phase shift equally $\tau$, respectively [37]. Microheater-based phase shifters can reach a short switching time only a few $\mu$s and a relatively low electrical power.

**FIGURE 3.** Contour map-based distributions of the transmission characteristics and wavelength-dependent spectra simulated numerically for different types of $2 \times 2$ MMI couplers: (a, a’) for MMI-A, (b, b’) for MMI-B, (c, c’) for MMI-C, and (d, d’) for MMI-D.
consumption for several tens of mW. Therefore, these properties premise an important role of microheaters-based controllable phase shifters compared to other kinds, such as carrier effect-based phase shifters [38]. Hardly can the multimode switch be recognized by our proposed device without the principle working of three TOPSs, which we called PS$_1$, PS$_2$, and PS$_3$ as shown in Fig.1, with the same structure. By utilizing the thermo-optic (TO) effect, we can adjust and fine-tune refractive index of the silicon core layer under the influence of the Ti-heater leading to the phase changes. This effect is dominated by the following heat transfer equation [38]:

$$\nabla(-\kappa_e \nabla T) + DC_p \frac{\partial T}{\partial t} = Q$$

where $\kappa_e$ is the thermal conductivity, $D$ is the density, $C_p$ is the specific heat capacity, $T$ is the temperature, $t$ is the time, and $Q$ is the heat source which can be determined by the following ohmic relations:

$$Q = \frac{P}{V} = \rho_{Ti}\frac{I^2}{S^2}$$

where $P$ and $V$ stand for the electric power applied to the heater and the volume of the Ti-microheater, $\rho_{Ti}$ is the Ti-heater resistivity, $I$ is the flow current of the heater and $S$ is the area of Ti-heater.

The area change can be calculated from the difference of index by [39]:

$$\Delta \Phi = kL_h \Delta n = kL_h \frac{dn}{dT} \Delta T$$

where $L_h$ is the heater length to obtain the required phase shift of $\Delta \Phi$, $k = 2\pi/\lambda$ is the wavenumber, $\Delta n$ is the total index change of the silicon material, $dn/dT$ is the thermal coefficient that is considered as a constant in the telecom C-band of $1.84\times10^{-4}$ K$^{-1}$.

The TOPS in this designed multimode switch comprises a thin metal film of the titanium (Ti) metal playing a vital role in making a heat source. The Ti heater has a thickness of $\delta_{Ti} = 100$ nm, a width of $W_{PS} = 1.5$ µm, and a length of $L_{PS} = 250$ µm. The whole structure of the designed microheater can be sputtered on the top of the SOI structure by using fast ions to eject Ti particles from a Ti target. This heater is far from the silicon core layer in the vertical direction by the installed gap of $h_{SOx} = 0.7$ µm, as plotted and described in Fig. 4(a), (b). Fig. 4(c) and Fig. 4(d) present simulated results for two states “OFF” and “ON” under the operation of the Ti-heater thanks to the use of the finite-element method (FEM). The heat distribution in the cross-section for the steady-state in Fig. 4(d) shows that the thermal conductivity of Ti-heater is not relevant and heat-spread across the claddings is a negligible difference, thus resulting in terms of heat distribution and propagation. Consequently, the required phase change difference only belongs to the supplied heat power without depending on the heater metal material. Fig. 4(e) and (f) show distributions of the temperature rise ($\Delta T$) and the index change ($\Delta n$) in the silicon core layer at the switching state “ON” when the electric power is applied to reach a required phase difference of $\pi$ radian. Fig. 4(g) presents the shifted phase angle as a linear function of the temperature rise ($\Delta T$) under the influence of the TOPS simulated and characterized by using the Rsoft’s commercial multi-physics tool. The required temperature increase by about 58 K for reaching the phase difference of $\pi$ radian. This result agrees with the dependent relation expressed in Eq. (11). Also, the dependence of the output power for three guided modes on the shifted phase angle is plotted in Fig. 4(h). It can be seen that there is a harmonic form, thus agreeing with the theoretical relationship analyzed in Eq. (8). This reason can be knowable because all three guided modes are identical wavelengths. Furthermore, one can see that the higher-order mode is, the lower its transmission is. Here, the higher-order modes have gradual reduction efficiencies since their power portions leaked and radiated to the cladding layer increase gradually.

### III. DEVICE CHARACTERIZATION AND DISCUSSION

Fig. 5 shows electrical field patterns under contour maps of guided modes implemented by numerical simulation for all switching states of three guided modes at the central wavelength of 1550 nm in the bar and cross directions. The proposed switch operates at two states: ON and OFF for BAR and CROSS operations, respectively. In the ON state, each mode entering one input port is switched to equivalent order mode on the BAR side at the corresponding output port, Fig. 5(a), (b), and (c). In the OFF state, input modes are simultaneously switched to the CROSS side at the output port as seen in Fig. 5 (a’), (b’), and (c’).
In a silicon photonic device, three critical parameters for evaluating the optical performance are insertion loss (I.L), crosstalk (Cr.T), and extinction ratio (E.R). In general, these quantities can be defined for each guided mode by the following expressions:

\[
I.L_{m,n} = 10\log_{10} \left( \frac{P_{m,n}}{P_{in,m}} \right) \tag{12}
\]

\[
Cr.T_{m,n} = 10\log_{10} \left( \sum_{k \neq m} P_{k,n} \right) \tag{13}
\]

\[
E.R_{m,n} = 10\log_{10} \left( \frac{P_{\text{max}}}{P_{\text{min}}} \right) \tag{14}
\]

where \(P_{in,m}\) is the input power of the \(m\)-order mode; \(P_{m,n}\) is the output power at the desired output port \(n\) (\(n = \{1, 2\}\)) of the \(m\)-order mode (\(m = \{0, 1, 2\}\)); \(\sum_{k \neq m} P_{k,n}\) is the total output power at undesired output ports leaked to the desired output port; \(P_{\text{max}}\) and \(P_{\text{min}}\) are the power transmitted between the ON and OFF states, respectively.

It is worth to note that the broadband optical field guided in a silicon waveguide has suffered a variety of optical effects such as chromatic dispersion, mode coupling, and mode confinement for different wavelengths. In order to get the visual observation and the accurate evaluation, we will represent the optical performance parameters in terms of I.L, Cr.T, and E.R. As can be seen, the variation of I.L is in the relatively narrow scope from \(-1.5\) dB to \(-3\) dB, while the variation of Cr.T is in the range from \(-22\) dB to \(-34\) dB, and the variation of E.R is in the range from \(-22\) dB to \(-32\) dB for both cases of ON and OFF states. These high contrasts between insertion loss and crosstalk lead to the excellent quality for the optical signal to noise (OSNR) of the proposed multimode switch in a relatively wide bandwidth of 40-nm as well as demonstrate the promising application potential of the device in terms of low loss, low crosstalk, and wideband. Also, a high difference between ON and OFF states (larger than 22 dB) which is originated from an excellent E.R enabling an extension for sensitivity of the receiver as well as system margin in a broad band of 40-nm. Optical performance parameters in this proposed multimode switch are reasonable and remarkable when compared to related works in the C band [20], [24], [40]–[42].

Fabrication tolerances play an important role in the field of photonic integrated circuits, especially for simulation-based designs. Because material, as well as geometrical parameters, strongly affect the optical performances. For example, the quality of the SOI wafer, the surface roughness, the purity of silicon crystallinity, etc. Besides, the accuracy of the fabricated product depends strongly on patterning and etching techniques. Furthermore, the simulation method also contributes to generating errors due to the different accuracy between numerical simulation algorithms. Therefore, in this paper, we investigated geometrical tolerances in terms of the waveguide height and the waveguide width. The height tolerances of \(\Delta h\) are shown in Fig. 7 (a, b) for two outputs...
corresponding to the ON and OFF states when the guided modes are injected into the input I1 with a change of the width within ±8 nm. Simulated data show that I.L fluctuation is small value around −1.5 dB to −2.5 dB while the change of Cr.T is smaller than −25 dB for all guided modes. Also, the width tolerances, ΔW, presented in Fig. 7 (c, d) show that I.L is almost unchanged at a value around −1.5 dB and Cr.T is less than −21 dB for both switching states as ON and OFF in the variation equally as ±10 nm. Such relatively high tolerances on the aspects of geometrical dimensions are possible thanks to the current advancement of fabrication technology in the-state-of-the-art such as electron-beam writing.

Normally, in a TOPS we expect to obtain the product of $P_\pi, \tau = H, \Delta T_\pi$ as an optimal value during the operation process of the optical switch [39]. Here, $H$ is the heat capacity, $\Delta T_\pi$ is the temperature change from a cold state to a hot state to attain the expected phase shift of $\pi$, and $\tau = 0.35/(\Delta f_{3-dB})$ (f3−dB is the frequency at the 3-dB bandwidth) is the switching time related to the fall time or the rise time in the phase shifter temporal response [43]. $P_\pi$ is the power consumption needed to have $\pi$ phase shift. To reduce power consumption, one needs to increase the size of the phase shifter and the switching time. Also, a small power consumption should be attained at an acceptable level when the gap between the metallic heater and the silicon core $h_{SiO_2}$, as shown in Fig. 4(a), is small enough to avoid the influence of the plasmonic effect on the lightwave propagation in terms of phase shift and optical loss. Because, if the $h_{SiO_2}$ is very small in several nanometers, the plasmonic effect strongly hybridizes photonic modes in the silicon core layer with plasmonic modes near the metal-dielectric interface due to the phase-matching condition of guided-wave momentums. Fig. 8 presents mode profiles of both TE and TM polarization states simulated by the finite element method (FEM) for several gaps of $h_{SiO_2}$. Herein, Fig. 8(a) and Fig. 8(b) plot the mode distributions corresponding to photonic modes of TE (specified by the electric field element of $|E_z|$) and TM (specified by the electric field element of $|E_y|$) polarization states along the propagation direction, showing a perfect distribution for each mode. Fig. 8 (c-l) successively present the mode distributions of $|E_z|$ under the active region covered by the Ti-thin film for both TE and TM polarization states at different gaps of $h_{SiO_2}$ corresponding to 700 nm, 100 nm, 50 nm, 30 nm, and 10 nm at the operation wavelength $\lambda_0 = 1550$ nm. Simulated results show the plasmonic-hybrid photonic mode is significant when $h_{SiO_2} \leq 100$ nm for the TM mode and when $h_{SiO_2} \leq 30$ nm for TE modes. This is not surprising because the optical field in the p-polarized state (TM mode) is hybridized much stronger than the optical field in the s-polarized state (TE mode). Besides, when optical fields are in the plasmonic mode, the imaginary part of the dielectric constant becomes more extensive, leading to a larger conductive absorption. Therefore, the plasmonic effect restricts the propagation length of the optical fields in the photonic device if the gap between the metal and the dielectric interface is small enough. In the proposed optical switch, which was designed for the operation of TE modes aiming to conform with most of the standard process design kit (PDK) elements provided by silicon photonics foundries with the gap $h_{SiO_2} = 700$ nm, the impact of the plasmonic effect is negligible because optical fields always preserve in photonic modes.

Trade-offs between power consumption and switching speed and between integration size and long-range propagation distance are unavoidable. For the optical switch based on the TO effect, the switching time should be desirable for only a few microseconds aiming to serve for a lot of ultrafast and wideband applications, and therefore the electric power consumption should be kept in several tens of mW [27]. The switching consumption power is a specific parameter representing the power efficiency, which can be determined thanks to the utilization of a modified two-dimensional treatment of the heat flow on the lateral spreading as follows [44]:

$$P_\pi = \frac{\lambda_0 k_{SiO_2} \left( \frac{W_{PS}}{h_{SiO_2}} + 0.88 \right)}{\frac{\partial n}{\partial T}}$$

(15)

where $k_{SiO_2} = 1.4$ W/(m.K) is the thermal conductivity of SiO2, and $W_{PS}$ is the width of the Ti-metal film on the lateral direction. Whereas, the switching time characterized by the response time of the TO phase shifter has a direct relation to the cut-off frequency by $\tau = \frac{1}{\epsilon f_{cut-off}}$. In which the cut-off frequency is directly related to the switching power as follows [45]:

$$f_{cut-off} = \frac{P_\pi}{\pi \lambda_0 \rho_{SiO_2} C_{SiO_2} A \partial T}$$

(16)

where $\rho_{SiO_2} = 2.203$ g/cm$^3$ is density of silica, $C_{SiO_2} = 0.703$ J/(g.K) is specific heat capacity, and $A$ denotes the effectively heated cross-section area relating to the geometry parameters of the TO phase shifter. Fig. 9 plots the simulation results of the electric power consumption and the switching time as a function of the gap $h_{SiO_2}$. As one can see, the switching time and the required power to achieve a phase shift of $\pi$-radian are progressive functions to the variable of $h_{SiO_2}$. 

![FIGURE 8. Mode profiles of both TE and TM polarization states simulated by the finite element method (FEM) for several gaps of $h_{SiO_2}$: (a, b) photonic modes at the silicon core layer, (c-l) plasmonic hybridized-modes under the influence of the plasmonic effect for several gaps.](image-url)
At the selected gap of \( h_{\text{SiO}} = 700 \) nm, the power \( P_{\pi} \) obtains a relatively small value of \( \sim 27 \) mW, for the width of the silicon core \( w_a = 0.5 \) μm, and 38 mW for the width of the silicon core \( w_b = 0.6 \) μm, respectively, with an ultrafast switching time of 4.4 μs. Noted that results analyzed here are concerned in the case of a single thermo-optic phase shifter. Assuming that all of the three guided modes are simultaneously injected into the proposed switch in a full-load traffic configuration, to switch three TE modes from the “ON” state to the “OFF” state, all TOPSs must be used (as referred in Fig. 4) giving a total electric power consumption of 103 mW \( (2 \times 38 + 27) \) as measured by Fig. 9.

Finally, optical performances of the switch depend strongly on the accuracy of the control process relating to the temperature or the thermal source supplied to the Ti-metal heater which is fed by a direct current or a direct voltage. Fig. 10(a) and (b) show the simulated optical performance of the multimode switch for three modes according to the temperature tolerance \( (\Delta T_P) \) and the electric power tolerance \( (\Delta P_{\pi}) \). The insertion loss exhibits a flat behavior at about \( -2 \) dB while the crosstalk is smaller than \( -20 \) dB in the temperature tolerance level of \( \pm 4 \) K, as exhibited in Fig. 10(a). We obtained the same level of insertion loss in the power tolerance of \( \pm 2 \) mW but is a bit higher for the crosstalk which is below \( -18 \) dB, as seen in Fig. 10(b). These tolerances are feasible in practice due to the high resolution of direct current electric sources.

For the further discussion, the proposed device has demonstrated the \( 2 \times 2 \) three-mode silicon photonic switch’s functionalities that enable the simultaneously switched three-mode operation in a multimode waveguide for both MDM and hybrid WDM-MDM applications. For use in the single MDM system, a grating coupler [30] or an edge-coupler [46] needs be utilized to guide high-order modes from a few-mode fiber (FMF) to a silicon waveguide to recognize the functionality of a few-mode fiber coupler switch. For use in the WDM-hybridized MDM, subwavelength gratings (SWG) consisting of periodically arranged dielectric particles can be utilized for highly efficient coupling from single-mode fibers to a silicon photonic chip [47], [48] at first. Then, fundamental modes in single-mode silicon waveguides are multiplexed into a multimode waveguide and vice versa by adiabatic couplers [49] before connecting to the multimode switch. Finally, single-mode optical fibers are coupled to the WDM system via the WDM multiplexer following the ITU-T G.694.1 recommendation to complete a hybrid WDM-MDM system for the applied potential of the proposed multimode switch.

In another WDM-MDM scenario, first, single-mode optical fibers carrying each dedicated wavelength are coupled to each dedicated silicon single-mode waveguide via curved Bragg gratings that allow the light propagation onto the third telecom spectrum of 1550-nm. Second, a set of individual wavelengths is multiplexed into a single-mode silicon waveguide carrying the total WDM-channels traffic via an arrayed waveguide grating (AWG) [50]. Next, each group of the single-mode silicon waveguide is multiplexed to a three-mode bus waveguide employing the phase-matched technique as adiabatic couplers [49]. Finally, three groups into a three-mode waveguide are connected to an input/output port of the designed \( 2 \times 2 \) three-mode switch. The constructed structure can permit the switching operation of three WDM groups in the \( 2 \times 2 \) switching configuration.

Compared to some related works on multimode switches, our proposed switching device supports three guided modes operation rather than two guided modes [17], without requiring complicated space switching and mode division multiplexing mechanisms like reports presented in [19], [27]. Our proposed switch also has a much simpler design and more compact than those reported elsewhere [21], [23]. The device enables switching simultaneously three guided modes of transverse electric polarization states that only use optics interference mechanisms and the mode-sorting principle in \( \Psi \)-junctions to realize a simultaneous silicon photonic multimode-waveguide switch. Therefore, the proposal device can apply not only for dedicated MDM systems but also for hybrid WDM-MDM systems. Besides, the proposed optical switch can operate as a multifunctional-multimode processing device, like an arbitrary ratio multimode power splitter that may be realized by just one control mechanism for adjusting the multimode power splitting ratio simultaneously. Finally, the proposed structure is capable of enlarging blocks to upscale the number of guided modes as well as scalable to the multi-input-multi-output (MIMO) configuration via the concatenation of \( 2 \times 2 \) switching fundamental units in the configuration of the Benes topology to construct a \( 2N \times 2N \) multimode silicon photonic switch.
IV. CONCLUSION

In conclusion, we designed and optimized a novel 2 × 2 simultaneous three-mode switch based on four symmetric Ψ-junction couplers and three kinds of 2 × 2 MMI couplers on SOI material using numerical simulations. The working principle of the proposed was relatively simple based on the mode sorting technique in Ψ-junctions and combined optical paths in 2 × 2 MMI couplers without needing the space division switching mechanism, mode (de)multiplexing element. The designed multimode switch could operate in a 40-nm continuum band from 1520 to 1560 nm with a low insertion loss fluctuation smaller than 1.5 dB (from −1.5 dB to −3 dB), a low crosstalk below −22 dB, and a high extinction ratio larger than 22 dB, respectively. The device also had relatively large geometry tolerances corresponding to ±20 nm and ±8 nm of width and height tolerances, respectively. Besides, the MMS possessed a total reasonable electric power consumption level under 103 mW (smaller than 38 mW for each thermo-optics phase shifter) and exhibited an ultrafast switching time of 4.4 μs. Furthermore, the device footprint was very compact with a small size of 12 μm × 1300 μm, offering great potentials for applications in very large-scale integrated photonic circuits and WDM-MDM switching systems, and providing the fundamental cells to scale up to higher-connection multimode switches or multimode photon-on-chip networks.

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