Reconfigurable optical add-drop multiplexers for hybrid mode-/wavelength-division-multiplexing systems

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Abstract. Dealing with the increase in data workloads and network complexity requires efficient selective manipulation of any channels in hybrid mode-/wavelength-division multiplexing (MDM/WDM) systems. A reconfigurable optical add-drop multiplexer (ROADM) using special modal field redistribution is proposed and demonstrated to enable the selective access of any mode-/wavelength-channels. With the assistance of the subwavelength grating structures, the launched modes are redistributed to be the supermodes localized at different regions of the multimode bus waveguide. Microring resonators are placed at the corresponding side of the bus waveguide to have specific evanescent coupling of the redistributed supermodes, so that any mode-/wavelength-channel can be added/dropped by thermally tuning the resonant wavelength. As an example, a ROADM for the case with three mode-channels is designed with low excess losses of < 0.6 dB, 0.7 dB and 1.3 dB as well as low crosstalks of < −26.3 dB, −28.5 dB and −39.3 dB for the TE\textsubscript{0}, TE\textsubscript{1} and TE\textsubscript{2} modes around the central wavelength of 1550 nm. The data transmission of 30 Gbps/channel is also demonstrated successfully. The present ROADM provides a promising route for data switching/routing in hybrid MDM/WDM systems.

Keywords: reconfigurable, hybrid multiplexing, subwavelength grating, silicon photonics.

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1 Introduction

The ever-growing data traffic has become a severe problem as cloud computing and artificial intelligence developed in the past decades, leading to an increasing demand of high-capacity transmissions\textsuperscript{1,2}. A key is exploiting optical interconnects to enhance the link capacity, which exhibit potential of high speed, broad bandwidth and low power consumption\textsuperscript{3–5}. To realize high-capacity optical communications, multiplexing techniques have been widely investigated and utilized, including wavelength-division multiplexing (WDM)\textsuperscript{6–8}, polarization-division multiplexing (PDM)\textsuperscript{9–12} and mode-division multiplexing (MDM)\textsuperscript{13–15}. Among them, the MDM technique has attracted substantial attention as it leverages multiple orthogonal spatial modes as
the carrier to transmit massive data in parallel within a single wavelength, which is promising to meet the rapidly increasing demand for high-capacity and low-cost optical interconnects\textsuperscript{16,17}.

With the development of the multiplexing technologies, multi-dimensional multiplexing systems have also gained their popularity and hybrid MDM-WDM-PDM devices have been intensively investigated\textsuperscript{18–20}. For example, a WDM-compatible MDM system was carried out by employing singlemode microring resonators (MRRs) to couple different spatial modes into a multimode waveguide\textsuperscript{21}. Later, an on-chip mode-division multiplexing switch was proposed with full flexibility to enable networks with many nodes connected by high-bandwidth multimode links to dynamically allocate bandwidth, which is scalable with more mode-/wavelength-channels\textsuperscript{22}. A mode-selective modulation is realized by combining silicon MRRs and the mode multiplexer based on asymmetric directional couplers (ADCs), in which way the mode carriers in the multimode bus waveguide can be selectively modulated\textsuperscript{23}. In recent years, reconfigurable optical add-drop multiplexers have been widely proposed and demonstrated to enable any mode-/wavelength-channel to be switched and routed flexibly\textsuperscript{24–26}.

Despite that great efforts have been made so far, the selective manipulation of individual optical carriers is still of particular interest, which aims at accessing a particular individual channel without introducing any undesired influences on other channels. In other words, any desired channels are able to be selectively added/dropped to/from the multimode bus waveguide. In 2021, an MDM switch was demonstrated so that any mode-/wavelength-channels can be directly accessed, but additional mode conversion devices are required to convert each mode into the highest-order mode supported by the multimode bus waveguide, which therefore increases the complexity\textsuperscript{27}. In 2022, a three-mode (de)multiplexing device was demonstrated by introducing multimode MRRs, in which case the fundamental mode in the bus waveguide is evanescently
coupled to the TE$_1$ mode in the Euler-based MRR$^{28}$. Nevertheless, it suffers from the excess loss and the crosstalk, hindering its practical applications. Recently, an MZI-based mode-sensitive phase shifter was proposed by using subwavelength grating (SWG) structures to have varied temperature coefficient for different modes, which provides a new way for realizing the mode-selective phase manipulation with high extinction ratios$^{29}$. So far, it still remains challenges to selectively add/drop the target optical mode-channel individually without influencing the undesired channels flexibly.

In this paper, we propose a reconfigurable optical add-drop multiplexer (ROADM) for hybrid MDM/WDM systems by utilizing the modal field redistribution to enable the efficient selective access of any mode-/wavelength-channels based on our previous work$^{30}$. With the assistance of SWG structures to engineer the refractive index, the launched modes are redistributed to be the supermodes localized at different regions of the multimode bus waveguide. In this way, the evanescent coupling of the desired mode-channel can be enhanced while the undesired mode coupling can be suppressed significantly. MRR-based wavelength-selective switches are placed at the side of the bus waveguide to have specific evanescent coupling for the corresponding redistributed supermodes. By tuning the resonant wavelength of the MRRs, any wavelength-channels can be switched flexibly and accessed selectively. With such devices, any target mode-/wavelength-channels can be easily added/dropped without affecting the other non-target channels.

As an example, we design a ROADM with three mode-channels, which have low excess losses (ELs) of $<0.6$ dB, 0.7 dB and 1.3 dB and low intermode crosstalks of $<-26.3$ dB, $-28.5$ dB and $-39.3$ dB around the resonant wavelength of $\sim1550$ nm. For the fabricated device, the ELs for TE$_0$, TE$_1$ and TE$_2$ modes ranging from 0.6-2.7 dB over a broad wavelength range of 1530-1605 nm. The intermode crosstalks are less than $-23.9$ dB, $-18.5$ dB and $-19.4$ dB, respectively. Finally, the
data transmission of 30 Gbps/channel is demonstrated successfully. The proposed ROADM is promising for data switching and routing in hybrid MDM/WDM systems in the future.

2 Principle and design

Here we propose a ROADM utilizing the scheme of redistributing the modal field in the multimode bus waveguide (MBW), as proposed in our previous work, which enables the simultaneous manipulation of the evanescent coupling for all the mode-/wavelength-channels considered. In this case, we design a ROADM with three TE mode-channels as an example, and the schematic configuration is shown in Fig. 1. The proposed ROADM consists of an SWG-structure-assisted MBW and three MRR-based wavelength-selective switches. As shown in Fig. 1, the SWG structure embedded in the MBW is used to engineer the equivalent refractive index profile, so that the launched TE$_0$, TE$_1$ and TE$_2$ modes are converted to the TE$_{0B'}$, TE$_{1B'}$ and TE$_{2B'}$ supermodes whose modal fields are redistributed to be localized at regions #0, #1 and #2, respectively. Since these supermodes are orthogonal with different effective indices, they can be maintained across the SWG MBW without cross-coupling. Note that the supermodes are localized in the corresponding region with only one major peak. In this way, the coupling of the non-target mode-channels can be suppressed significantly while that of the target mode can be enhanced. Particularly, an adiabatic SWG taper is introduced to realize efficient mode conversion from the uniform MBW to the coupling region with SWG structures. The MRR wavelength-selective switches #0, #1 and #2 are then placed at the corresponding side of the MBW to have efficient evanescent coupling for the target supermodes (TE$_{0B'}$, TE$_{1B'}$ and TE$_{2B'}$ modes), so that any mode-channels can be added/dropped selectively and flexibly. By tuning the resonant wavelengths of the MRRs, different wavelength-channels can be switched and accessed selectively. Here micro-heaters are introduced for thermally tuning the resonant wavelength of each MRR switch. For
switches #0, #1 and #2, data carried by different wavelength-channels ($\lambda_1, \lambda_2, \ldots, \lambda_N$) of three mode-channels in the MBW can be dropped selectively. Similarly, the local data carried by different wavelength-channels ($\lambda_1, \lambda_2, \ldots, \lambda_N$) can also be added from the add port of the corresponding MRR switch to the target mode-channel in the MBW. With such a ROADM, one can selectively add/drop any mode-/wavelength-channels to/from the MBW by simply tuning the resonant wavelength of the MRR switch, which is promising to be further used for other applications in hybrid MDM/WDM systems. Notably, it is possible to be scaled for working with more mode-channels, because higher-order modes are with weaker mode confinement and thus are easier to be added/dropped when using optimally-designed ADCs. Besides, it is also possible to develop ROADMs working with the mode-channels of dual polarizations (including both TE$_i$ and TM$_i$ modes) according to the operation mechanisms of the adiabatic SWG tapers and the MRRs.

![3D illustration of the proposed ROADM utilizing the scheme of redistributing the modal fields. Here the launched TE$_0$, TE$_1$ and TE$_2$ modes are converted to the TE$_{0B'}$, TE$_{1B'}$ and TE$_{2B'}$ supermodes whose modal fields are redistributed to be localized at regions #0, #1 and #2, respectively.](image)

Here the present ROADM is designed on the silicon-on-insulator (SOI) platform with a 220-nm-thick top-silicon layer and a 2-μm-thick buried oxide layer. The operation wavelength is
around 1550 nm, and the corresponding refractive index of silicon and silica are \(n_{Si}=3.476\) and \(n_{SiO2}=1.444\), respectively. The key parameters of the MRR switch are shown in Fig. 2(a), where the Ti/W alloy heater is deposited on the silica upper-cladding above the MRRs for tuning the resonant wavelength, as shown in Fig. 2(b).

![Fig. 2 Details of the MRR. (a) Coupling region of the thermally-tunable MRR switch. (b) Cross section of the SOI photonic waveguide with a micro-heater on the top.](image)

The MBW width \(w_b\) is chosen as 1.5 \(\mu\m\) to support the TE\(_0\), TE\(_1\) and TE\(_2\) modes. The period and the duty cycle of the SWG structure are chosen as \(\Lambda=210\) nm and \(f=0.5\) according to the subwavelength-regime condition\(^3\) and the requirement of the fabrication process. The end widths \((w_0, w_1, w_2)\) of regions #0, #1 and #2 are respectively chosen as \((0.4\ \mu\m, 0.3\ \mu\m, 0.8\ \mu\m)\), so that the redistributed supermodes are localized at the desired local regions of the MBW\(^{30}\). Figures 3 (a)-(c) show the simulated light propagation in the SWG mode evolution region and the redistributed modal fields of the TE\(_{0B'}\), TE\(_{1B'}\) and TE\(_{2B'}\) supermodes, respectively. It can be seen clearly that these three supermodes are localized well at regions #0, #1 and #2 in the MBW as desired.
Fig. 3 Design of the SWG mode evolution region. Simulated light propagation in the SWG MBW and the redistributed modal fields of the TE_{0B'} (a), TE_{1B'} (b) and TE_{2B'} (c) supermodes, respectively.

The coupling region of the MRR switches are designed carefully, so that different mode-/wavelength-channels can be selectively added/dropped. Figure 4(a) shows the calculated effective index of the modes as the width \( w_r \) of the microring waveguide varies. The width \( w_r \) and the access-waveguide width \( w_a \) for switches #0, #1 and #2 are chosen as 476 nm, 410 nm and 300 nm according to the phase-matching condition given as \( n_{\text{eff}}(\text{TE}_{EB'}) = n_{\text{eff}}(\text{TE}_{0A-E}) \), respectively. In particular, the race-track MRRs are used for the flexible manipulation of the coupling ratios. The 3-dB bandwidth is chosen to be as large as 0.8 nm (100 GHz), so that data transmission of up to 100 Gbps/channel can be achieved potentially. Accordingly, the power coupling coefficient \( \kappa \) is optimally chosen as ~0.16 based on the transfer matrix method (TMM). Figure 4(b) shows the calculated power coupling coefficients \( \kappa \) for three MRRs as the coupling length \( L_c \) varies. The length of the coupling region is defined as \( L_c = NA \), where \( N \) is the period number of the grating. Here the widths \( w_{g2} \) of the gaps between the access waveguide and the ring waveguide are respectively chosen as 0.20 \( \mu \)m, 0.315 \( \mu \)m and 0.43 \( \mu \)m for the three channels, which are sufficiently large for fabrication ease. Correspondingly, the coupling lengths \( L_g \) are chosen as 6.30 \( \mu \)m, 8.82 \( \mu \)m and 1.05 \( \mu \)m to achieve the optimal coupling ratio, respectively. Similarly, the widths \( w_{g1} \) of the gaps between the MBW and the microring waveguides are chosen as 0.195 \( \mu \)m, 0.290 \( \mu \)m and 0.305 \( \mu \)m to realize the optimal coupling ratio.
Fig. 4 Design of the microring waveguide. (a) Calculated effective indices of the supermodes and the fundamental modes of each MRR waveguide as \( w_r \) varies. (b) Calculated power coupling coefficient for three MRRs as the coupling length \( L_c \) varies. Here the coupling length is defined as \( L_c = N \Lambda \), where \( N \) is the period number of the grating.

The free spectral range (FSR) of the present MRR is given by

\[
FSR = \frac{\lambda}{n_g (2nR + 2L_c)},
\]

(1)

where \( \lambda \) is the operating wavelength, \( n_g \) is the group index of the guided-mode, and \( R \) is the bending radius of the resonator. The bending radius \( R \) should be chosen optimally to achieve low ELs and large FSRs. Notably, the bending radius for the MRR should be minimized to maximize the FSR so that more wavelength-channels are available, while it is limited due to the bending loss. As a trade-off, the FSR is designed to be \( \sim 15.8 \) nm to cover four wavelength-channels with a channel spacing of 400 GHz (\( \Delta \lambda = 3.2 \) nm) by choosing the bending radius \( R \) of the three MRRs as 3.94 \( \mu \)m, 3.21 \( \mu \)m and 5.62 \( \mu \)m, so that their central resonant wavelengths are aligned to 1550 nm. All the designed key parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( R ) (( \mu )m)</th>
<th>( w_r ) (nm)</th>
<th>( w_g ) (nm)</th>
<th>( w_{g1} ) (nm)</th>
<th>( w_{g2} ) (nm)</th>
<th>( L_c ) (( \mu )m, ( N )= )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE(_0)</td>
<td>3.94</td>
<td>476</td>
<td>476</td>
<td>195</td>
<td>200</td>
<td>6.30 (30)</td>
</tr>
<tr>
<td>TE(_1)</td>
<td>3.21</td>
<td>410</td>
<td>410</td>
<td>290</td>
<td>315</td>
<td>8.82 (42)</td>
</tr>
<tr>
<td>TE(_2)</td>
<td>5.62</td>
<td>300</td>
<td>300</td>
<td>305</td>
<td>430</td>
<td>1.05 (5)</td>
</tr>
</tbody>
</table>

Table 1 Structure parameters.
A three-dimensional finite-difference time-domain (3D-FDTD) method is used to simulate the transmission and light propagation of the MRR switches. For switches #1 and #2 used for the TE\(_1\) and TE\(_2\) mode-channels, the MRRs are placed at the sides of regions #1 and #0, respectively, as shown in Fig. 1. Figures 5(a)-(c) show the simulated light propagation for the designed switch \(i\) \((i=0, 1\) and 2\) (including the mode conversion region and the mode coupling region) at the resonant wavelength of 1550 nm when the TE\(_i\) \((i=0, 1\) and 2\) mode is launched in the MBW, respectively.

It is clear that the mode profile of the launched TE\(_i\) mode is redistributed and finally converted to supermodes TE\(_{iB}\) localized at region \(i\) of the MBW \((i=0, 1, \text{and } 2)\). The supermodes launched at the input end of the corresponding switch are selectively evanescent coupled to the corresponding MRR with different resonant wavelength-channels. It can be seen that the designed ROADM works well with all the desired mode-/wavelength-channels.

Figures 5(d)-(f) show the calculated transmissions at the drop port of the whole ROADM structure for the TE\(_0\), TE\(_1\) and TE\(_2\) mode-channels. It shows that the switch has a low EL of \(<0.6\) dB, 0.7 dB and 1.3 dB and low intermode crosstalk of \(<–26.3 \text{ dB}, –28.5 \text{ dB and } –39.3 \text{ dB}\) for the TE\(_0\), TE\(_1\) and TE\(_2\) mode-channels around the central resonant wavelength of 1550 nm. These mode-channels have ELs of \(<0.6 \text{ dB}, 0.8 \text{ dB and } 1.7 \text{ dB}\) and intermode crosstalk of \(<–24.7 \text{ dB}, –25.2 \text{ dB and } –31.3 \text{ dB}\) in the wavelength range of 1500-1590 nm, respectively. Notably, the FSRs of these MRRs are as large as 15.72 nm, 15.08 nm and 16.60 nm for switch #0, #1 and #2, respectively, which are slightly different from the designed values. The intermode crosstalk can be further reduced by carefully optimizing the waveguide width and the gap width of the MRRs, for maximizing the mode mismatch and lowering the evanescent coupling for those mode-channels which are undesired to be added/dropped.
Fig. 5 Simulation results for the designed switches. (a)-(c): Simulated light propagation for switch #0 (a), #1 (b) and #2 (c) at the resonant wavelength of 1550 nm when the TE\(_0\), TE\(_1\) and TE\(_2\) mode is launched in the MBW, respectively. Here the mode conversion region and the mode coupling region are included. (d)-(f): Calculated transmissions at the drop port of the whole ROADM structure for the TE\(_0\) (d), TE\(_1\) (e) and TE\(_2\) (f) mode-channels.

The fabrication tolerance of the designed MRR switches is also analyzed by varying the core width \(w_r\) of the MRR waveguides, as shown in Figs. 6(a) and 6(b). Consider that the simulation for the whole ROADM structure is time-consuming when using the 3D-FDTD method, the TMM method is chosen to be used here for the analysis. The simulation result indicates that there is no notable deterioration on either the EL or the intermode crosstalk for these MRR switches. By utilizing the modal field redistribution method, the undesired mode coupling can be suppressed significantly and any target mode-/wavelength-channels can be selectively added/dropped by simply placing the optimized MRR at the corresponding side of the MBW.
Fig. 6 Fabrication tolerance analysis. Analysis of the fabrication tolerance for switches #0, #1 and #2 when assuming that the core width $w_r$ of the ring waveguide has a variation of $\pm 10$ nm. (a) EL, (b) Intermode crosstalk.

3 Fabrication and measurement

The designed ROADM chip was fabricated at Applied Nanotools on the SOI platform with a 220-nm-thick top-silicon layer and a 2-μm-thick buried oxide layer. The SOI waveguides were fabricated with the electron beam lithography (EBL) followed by an inductively coupled plasma (ICP) dry-etching process. A 1.5-μm-thick $\text{SiO}_2$ thin film was deposited above the silicon core layer as the upper-cladding by utilizing the plasma enhanced chemical vapor deposition (PECVD) process. Then the 200-nm thick titanium-tungsten (Ti/W) alloy micro-heater was deposited on top of the cladding. Figure 7(a) shows the microscope image of the whole fabricated photonic integrated circuit (PIC) with grating couplers at both input and output ends for efficient fiber-chip coupling, and the enlarged views of switches #0, #1 and #2 are shown in Figs. 7(b)-(d). Here the micro-heaters were placed away from the coupling region of the MRRs and thus the temperature variation has little impact to the evanescent coupling. In order to (de)multiplex the TE$_0$, TE$_1$ and TE$_2$ mode-channels, a pair of three-channel mode (de)multiplexer based on dual-core adiabatic tapers$^{32}$ were used. For the characterization of the fabricated PIC, a broadband amplified spontaneous emission (ASE) light source was used as the source and an optical spectrum analyzer (OSA) was used to record the transmission spectrum. The spectral response of the PIC was characterized by launching the light from input port $I_i$ ($i=0$, 1, and 2, corresponding to the TE$_0$, TE$_1$, and TE$_2$ mode-channels) and monitoring the transmission at the drop port $D_i$ ($i=0$, 1, and 2). Here we mainly characterize the transmission from input port $I_i$ to drop port $D_i$ as well as the transmission from add port $A_i$ to output port $O_i$. 

11
Fig. 7 Microscope image of the fabricated devices. (a) The whole fabricated PIC for switches #0, #1 and #2. (b)-(d): The enlarged view of MRR switches #0 (b), #1 (c) and #2 (d).

Figures 8(a)-(c) show the measured transmission spectra at drop port $D_i$ in the wavelength range of 1530-1605 nm when light is launched from port $I_i$ ($i=0$, 1, and 2), respectively. The transmission is normalized with a straight singlemode waveguide fabricated on the same chip. Note that there are some wavelength deviations, which might be due to the fabrication imperfectness. Here the resonant wavelengths of the three MRRs are thermally tuned to be 1554.3 nm accordingly. The fabricated device shows a low EL of 0.6-2.7 dB over a broad wavelength range of 75 nm for all the channels. As shown in Figs. 8(a)-(c), the FSR of the fabricated MRRs are ~14.76 nm, 14.65 nm and 16.14 nm and the slight difference is mainly caused by the fabrication deviation. The measured intermode crosstalk is $<-23.9$ dB, $-18.5$ dB and $-19.4$ dB for switches #0, #1 and #2, respectively. As a comparison, we also characterize the performance of the back-to-back dual-core adiabatic-taper mode (de)multiplexers when the $TE_0$, $TE_1$ and $TE_2$ modes are excited, as shown in Figs. 8(d)-(f). It can be seen that the intermode crosstalks of the mode (de)multiplexer are measured to be lower than $-21.6$ dB, $-20.8$ dB and $-21.4$ dB in the wavelength range of 1530-1605 nm, which works well with the present design.
Fig. 8 Measured transmission results for the switches and the dual-core adiabatic-taper mode (de)multiplexer. (a)-(c): Normalized transmission spectra at drop port D$_i$ covering a bandwidth of 1530-1605 nm when light is launched from port I$_i$ ($i=0$ (a), 1 (b) and 2 (c)), respectively. (d)-(f): Normalized transmission spectra at output port O$_i$ of the back-to-back dual-core adiabatic taper mode (de)multiplexer when light is launched from port I$_i$ ($i=0$ (d), 1 (e) and 2 (f)).

Figures 9(a)-(c) show the transmission spectra of switches #0, #1 and #2 when the resonant wavelengths are thermally tuned with a channel spacing of $\Delta \lambda = 0.8$ nm, 1.6 nm and 3.2 nm. It can be seen that when $\Delta \lambda$ is chosen as 3.2 nm, the crosstalks of the adjacent wavelength-channels are $-17.8$ dB, $-15.9$ dB and $-10.1$ dB, respectively. One might notice that the measured 3-dB bandwidth of switch #2 is larger than the simulation result, which might probably be caused by the increased coupling coefficients of MRRs due to the fabrication variation. The desired 3-dB bandwidth can be achieved by updating the design and the fabrication when needed. The wavelength-channel crosstalks can also be reduced by introducing the design of higher-order microrings, which enables box-like responses with lowered inter-channel crosstalk. Figure 10(a) shows the measured transmission at drop port D$_1$ of switch #1 when different electric power is
applied for the tuning of MRRs. The tuning efficiency of the MRRs is calculated and shown in Fig. 10(b). The wavelength-tuning efficiency is measured to be $\approx 0.141$ nm/mW, and the whole FSR can be covered completely within the wavelength-tuning range. Compared with the designs that can selectively access mode-/wavelength-carriers reported previously\textsuperscript{27,28}, the present ROADM utilizing the modal field redistribution scheme possesses advantages of low insertion losses and low intermode crosstalk while no additional mode conversion devices are needed.

**Fig. 9** Wavelength crosstalk measurement of the switches. (a)-(c): Transmission spectra of switches #0 (a), #1 (b) and #2 (c) when the resonant wavelengths are thermally tuned with a channel spacing of $\Delta \lambda = 0.8$, 1.6 and 3.2 nm.

**Fig. 10** Characterization of the thermal tuning performance. (a) Measured transmission of drop port $D_1$ when different electric powers are applied for the MRR tuning. (b) Calculated tuning efficiency of the MRRs.

Furthermore, the experiment of data transmission in the fabricated PIC was carried out by using the setup shown in Fig. 11(a). Two wavelength-channels ($\lambda_1$, $\lambda_2$) are modulated by a high-speed electro-optic modulator, where the pulse pattern generators (PPGs) provide non-return-to-zero (NRZ) pseudo random binary sequence signals to generate non-identical data with a bit rate of 30 Gbps for each wavelength-channels. The two modulated channels passed through a polarization controller (PC) respectively, and then multiplexed into a singlemode fiber by a 3-dB...
coupler. The data carried by two wavelength-channels are then coupled into the fabricated chip from input port $I_i$ ($i=0$, 1, and 2) through the grating coupler. In this way, the device was characterized with one of the mode-channels. As an example, here we choose to input the two-wavelength data ($\lambda_1$, $\lambda_2$) from port $I_0$ corresponding to switch #0. Unfortunately, the characterization for the chip when operating with the three mode-channels simultaneously haven’t been carried out because the 3-channel fiber array with channel spacing of 40 $\mu$m is not available in the lab. As a result, the eye-diagram is given when operating with a single mode-channel. In a practical MDM transmission link, the intermode crosstalk is the main contribution for deteriorating the communication quality, which affects the quality of the eye diagram and the bit-error-rate (BER)\textsuperscript{33}. When multiple mode-channels are involved simultaneously, there is about 0.1-2 dB power penalty introduced, corresponding to the intermode crosstalk of $-15$-$25$ dB\textsuperscript{21,34-36}. Figure 11(b) shows the clear eye diagrams of switches #0, #1 and #2 for the TE\textsubscript{0}, TE\textsubscript{1} and TE\textsubscript{2} mode-channels when operating at the wavelength of 1554.3 nm, respectively. Here the eye diagram of a straight singlemode waveguide is also shown as a reference. It can be seen that the measured eye diagrams of the three mode-channels are similar to that of the straight waveguide, indicating that the data pass through each mode-channel with high quality. The measured extinction ratios (ERs) are 9.0 dB, 7.4 dB, 6.4 dB and 5.5 dB, while the measured signal-noise-ratios (SNRs) are 12.0 dB, 8.8 dB, 7.0 dB and 5.6 dB, for the reference, switches #0, #1 and #2, respectively. Figure 11(c) shows the eye diagram of switch #0 as data carried by two wavelength-channels with a channel spacing of $\Delta\lambda=0.8$ nm, 1.6 nm and 3.2 nm. Compared with the single wavelength-channel, the quality of the eye diagram is improved as the channel spacing increased. The measured ERs are 5.9 dB, 6.5 dB and 6.8 dB, while the measured SNRs are 4.9 dB, 7.4 dB and 7.9 dB for the cases of $\Delta\lambda=0.8$ nm, 1.6 nm and 3.2 nm, respectively. Consider the case with three mode-channels and
four wavelength-channels, an aggregate data of 0.36 Tbit can be realized with a total of twelve-channels. As demonstrated in Fig. 11, the present ROADM is promising for data switching and routing in hybrid MDM/WDM systems in the future.

Fig. 11 Data transmission experiment. (a) Data transmission setup including tunable lasers, polarization controllers (PCs), modulators (MODs), pulse pattern generators (PPGs), device under test (DUT), Erbium-doped fiber amplifier (EDFA), optical receiver (Recv.) and digital communication analyzer (DCA). (b) Measured eye diagrams for data carried by each mode-channels, where a reference eye diagram of a straight singlemode waveguide is also shown. (c) Measured eye diagram when the input data is carried by two wavelength-channels with $\Delta \lambda = 0.8$ nm, 1.6 nm and 3.2 nm simultaneously.

4 Conclusion

In summary, we have proposed and demonstrated a silicon ROAM for hybrid MDM/WDM multiplexing by utilizing the special modal field redistribution. In particular, subwavelength grating structures have been utilized to engineer the refractive index, so that the launched TE$_0$, TE$_1$ and TE$_2$ modes are redistributed to be supermodes localized at different regions of the multimode bus waveguide. MRR wavelength-selective switches have been designed carefully and are placed at the corresponding side of the bus waveguide to selectively add/drop the target mode-channels.
By tuning the resonant wavelength of each MRRs, any wavelength-channels can also be switched and accessed selectively. With such devices, one can easily add/drop any mode-/wavelength-channels without affecting the other non-target channels. The simulated results show that the ELs are lower than 0.6 dB, 0.7 dB and 1.3 dB and the intermode crosstalks are lower than –26.3 dB, –28.5 dB and –39.3 dB for three mode-channels around the central wavelength of 1550 nm. The fabricated device shows low ELs ranging from 0.6-2.7 dB for the TE$_0$, TE$_1$ and TE$_2$ modes at the resonant wavelength over a broad wavelength range of 75 nm. The intermode crosstalks are <–23.9 dB, –18.5 dB and –19.4 dB, respectively. The data transmission experiment of 30 Gbps/channel have also been demonstrated successfully. It is expected that proposed ROADM provides an attractive route for data switching/routing in hybrid MDM/WDM systems.

Disclosures

The authors declare no conflicts of interest.

Code, Data, and Materials Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

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**Caption List**

**Fig. 1** 3D illustration of the proposed ROADM utilizing the scheme of redistributing the modal fields.

**Fig. 2** Details of the MRR.

**Fig. 3** Design of the SWG mode evolution region.

**Fig. 4** Design of the microring waveguide.

**Fig. 5** Simulation results for the designed switches.

**Fig. 6** Fabrication tolerance analysis.

**Fig. 7** Microscope image of the fabricated devices.

**Fig. 8** Measured transmission results for the switches and the dual-core adiabatic-taper mode (de)multiplexer.

**Fig. 9** Wavelength crosstalk measurement of the switches.

**Fig. 10** Characterization of the thermal tuning performance.

**Fig. 11** Data transmission experiment.

**Table 1** Structure parameters.