Research Article

Hongnan Xu, Chaoyue Liu, Daoxin Dai and Yaocheng Shi*

Direct-access mode-division multiplexing switch for scalable on-chip multi-mode networks

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Abstract: By leveraging mode-division multiplexing (MDM), capacity of on-chip photonic interconnects can be scaled up to an unprecedented level. The demand for dynamic control of mode carriers has led to the development of mode-division multiplexing switches (MDMS), yet the conventional MDMS is incapable of directly accessing an individual lower-order mode that propagates in a multi-mode bus waveguide, which hinders its scalability and flexibility. In this paper, we propose and demonstrate the first direct-access MDMS as a novel platform for scalable on-chip multi-mode networks. At first, the highly efficient mode exchangers are developed for TE₀–TE₂ and TE₁–TE₂ mode swap, which are then employed to realize the direct-access mode add-drop multiplexers with high performances. The direct-access MDMS is then achieved based on the proposed mode add-drop multiplexers, which can be used for dynamically adding and dropping any selected mode carrier in a three-channel MDM. Moreover, the novel direct-access scheme is also adopted to simultaneously harness wavelength and mode carriers, leading to a wavelength/mode-hybrid multiplexing system with an enhanced link capacity of twelve channels. To further verify the utility of the MDMS, a multi-mode hubbed-ring network is constructed, where one hub and three nodes are organized within a ring-like multi-mode bus waveguide. The reconfigurable network traffic of 6 × 10 Gbps data streams are obtained by using three eigen modes as signal carriers. The measurement results show low bit-error rates (<10⁻⁹) with low power penalties (<3.1 dB).

Keywords: mode-division multiplexing; on-chip photonic network; optical switch; silicon photonics.

1 Introduction

The multi-core architecture has become the mainstream in improving performances of modern micro-processors by assembling numerous parallel computational cores on a single chip [1]. In the meantime, the continuous drive towards a highly parallel system has led to the ever-growing bandwidth demand in dense intra-chip data communications and complex on-chip network traffics. Nevertheless, the commonly used on-chip electric interconnects face critical challenges in fulfilling the stringent bandwidth requirement, due to severe power dissipation and significant latency penalties at high frequencies [2]. Recently, on-chip photonic interconnects have emerged as a potential approach to break the performance ceiling, which is promised by the intrinsically large bandwidth and ultra-low propagation losses [3]. Moreover, the parallelism offered by multi-dimensional multiplexing enables the simultaneous transmission of multiple data streams in a single waveguide, so that the link capacity can be efficiently scaled up. The wavelength-division multiplexing (WDM) is to utilize different wavelengths as signal carriers [4, 5]. The WDM technology has been extensively used, especially for long-haul optical communications. However, WDM systems usually require a great number of laser diodes working simultaneously, and it is essential to monitor each wavelength carrier and compensate the wavelength drift caused by thermal effect, which gives rise to power consumption and therefore hinders its applications in power-sensitive on-chip operations.

The power-efficient on-chip photonic interconnects can be realized by adopting mode-division multiplexing (MDM) to boost the capacity within each single-wavelength carrier [6]. The MDM is to use different eigen modes as
signal carriers, and the major advantage of MDM is its excellent scalability, since the channel number of MDM can be increased by simply choosing a wider multi-mode waveguide that supports more eigen modes. Over the recent years, a variety of devices have been reported to facilitate the practical use of MDM, e.g. mode add-drop multiplexers (MADM) [7–9], multi-mode bends [10–12], multi-mode crossings [13–15], multi-mode splitters [16–18] and mode-division multiplexing switches (MDMS) [19–27]. Among them, the MDMS is a key element in MDM, which can be used to add/drop any desired eigen modes and re-allocate them at will, allowing a dynamic manipulation of mode carriers in multi-mode networks with tremendous flexibility. Various MDMSs have been demonstrated in the previous works by leveraging Y-junctions [19–21], asymmetric directional couplers (ADC) [22–24] and asymmetric micro-ring resonators (MRR) [25–27]. Usually, an MDMS is achieved by combining an MADM with a single-mode switch. However, the conventional MADM cannot individually add/drop a single lower-order mode in the multi-mode waveguide unless all the higher-order modes have been demultiplexed, as will be discussed in Section 2. Consequently, the conventional MDMS cannot select an individual mode carrier in a “direct-access” manner; in other words, some unwanted mode carriers also have to be accessed during switching operations. This will lead to a vastly increased device footprint and layout complexity especially when the channel number is large, as will be discussed in Section 2. Up to now, such “direct-access” conundrum has not been properly addressed for all the reported MDMSs.

In this paper, we propose and demonstrate the first direct-access MDMS for scalable on-chip multi-mode networks. We firstly develop two types of novel mode exchangers (MEs) for swapping lower-order modes (i.e. TE₀ and TE₁) with the highest-order mode (i.e. TE₂). The proposed MEs are then employed to implement the direct-access MADM that is capable of directly coupling arbitrary eigen modes to/from a multi-mode bus waveguide. After that, the direct-access MADM is realized by combining the proposed MADMs with Mach–Zehnder switches. Furthermore, the proposed MADMs are also combined with tunable MRRs to manipulate wavelength/mode-hybrid carriers to further enhance the capacity. The reconfigurable multi-mode hubbed-ring network (HRN) is then developed to further prove the utility of the MDMS. For the proposed HRN, multiple eigen modes (i.e. TE₀–₂) rather than multiple wavelengths are used as carriers to organize network traffics with a ring-like topology, based on which, reconfigurable on-chip photonic interconnects between one hub and three nodes can be realized.

2 Design, results and discussion

The direct-access MADM is the footstone for realizing the MDMS. Therefore, it is worthwhile to further explain the “direct-access” conundrum in MADM to clearly show the context of this work. For a multiplexing system, “direct-access” means that only the selected carrier will be added and dropped while the other carriers will pass through without (de)multiplexing. For WDM, this functionality can be quite easy to realize by leveraging optical notch filters, e.g. MRR. However, the scenario is completely different for MDM. A three-channel MDM is discussed here as a proof of concept. The first three TE modes (i.e. TE₀–₂) are employed as carriers, and the corresponding signal channels are denoted as CH₀–₂. Figure 1A illustrates the schematic of conventional MADM. It can be seen that, to add/drop CH₀ (carried by TE₀), all the other higher-order modes (i.e. TE₁–₂) must be sequentially demultiplexed by ADC₂ and ADC₁ and bridged to the other two mirrored ADCs. Consequently, the conventional MADM fails to work in a “direct-access” manner, since idle carriers (i.e. TE₁–₂) are also (de)multiplexed. The underlying cause of this issue is two-fold. Firstly, the mode selectivity of ADC solely relies on the phase-matching between adjacent waveguides [8]. We calculate effective indices of TE₀–₂ modes in a silicon-on-insulator (SOI) waveguide with varied widths and a fixed thickness of \( h_{wg} = 0.22 \mu m \) by using the finite-element method (FEM) (see Figure 1C). For a multi-mode waveguide with \( W_{wg} = 1.2 \mu m \), one can set the access waveguide widths as \( W_{wg} = 0.37 \mu m \) and \( W_{wg} = 0.58 \mu m \) to achieve selective TE₂–TE₀ and TE₁–TE₀ coupling (see the dash lines in Figure 1C). However, the complete coupling of TE₀ requires the same widths between multi-mode and access waveguides. As a result, the undesired TE₁–₂ modes will also be coupled. Secondly, even if the phase-matching condition can be satisfied, it is still challenging to extract lower-order modes (e.g. TE₀) with ADCs due to weak coupling strength. Figure 1D shows the calculated field profiles for TE₀–₂ with \( h_{wg} = 0.22 \mu m \) and \( W_{wg} = 1.2 \mu m \). One can see that, compared with TE₂, the evanescent field is much weaker for TE₀–₁. The coupling strength can be enhanced by choosing a narrower multi-mode waveguide, but higher-order modes will be cut off at a smaller width.

Here, an ME-based configuration is proposed to solve this “direct-access” conundrum, as schematically shown in Figure 1B. The add-drop of CH₀ is considered as an example. The ME is capable of swapping mode carriers between two signal channels. The signal-carrier mapping relation is shown in the inset of Figure 1B. At the input port, the carrier for CH₀ is transformed from TE₀ to TE₂, while the
carrier for CH2 is transformed from TE2 to TE0. Thus, the incident CH0 can be directly dropped by ADC2 through a TE2–TE0 coupling. The carrier for CH2 is reverted from TE0 to TE2 by another identical ME at output port. On the other hand, the launched TE1 mode will pass through ME without any change, and thus CH1 (carried by TE1) will go straight into the output port. For the adding operation, the CH0 signal is firstly loaded onto TE2 mode by ADC2 through a TE0–TE2 coupling. The carrier for CH2 is then converted from TE2 to TE0 by the output ME. For such a design, CH0 can be directly added or dropped without demultiplexing the mode carriers for CH1–2. Furthermore, the mapping relation between CH0 and TE0 can be perfectly maintained at the output port. Here, we take the add-drop of CH0 as an example, but this method should work for all the involved signal channels. The prime advantage for this design is its superior scalability and flexibility. In a conventional MADM, the number of ADCs can be expressed as:

$$N_{\text{ADC}} = \begin{cases} 2(C - M) & \text{for } C > M \\ 2 & \text{for } C = M \end{cases},$$

where $N_{\text{ADC}}$ is the required number of ADCs, $C$ is the largest mode order used in the MDM system, and $M$ is the mode order of carrier to be added or dropped. It is clear that the ADC number will rapidly increase with the channel number of MDM especially when a lower-order mode needs to be added or dropped from a large capacity. In contrast, for the present direct-access MADM, only two ADCs ($N_{\text{ADC}} = 2$) and
two MEs are required, no matter how large the channel number is, and thus the system can be easily scaled up. Moreover, this scheme will not introduce additional ADCs (i.e. $N_{ADC} = 2C$) even if it is necessary to add/drop all the mode carriers. In the following subsections, we will present the realization of MDMS and relevant devices (i.e. ME and MADM) based on the proposed “direct-access” scheme. The fabrication and characterization methods for these devices can be found in Supporting Information, Sections S1 and S2.

### 2.1 Mode exchanger

The previously reported MEs are usually based on free-geometric or sub-wavelength structures with a complex design flow and a lack of universality [28–31]. Here, a simple and general design methodology is present for high-performance MEs, as schematically illustrated in Figure 2A. The proposed structures are based on long-period waveguide gratings (LPWGs). Two different types of MEs are discussed: ME$_{02}$ for TE$_0$–TE$_2$ mode swap and ME$_{12}$ for TE$_1$–TE$_2$ mode swap, as illustrated in the insets of Figure 2A. The sinusoidal functions are utilized to define the shape of LPWGs. The grating structures are applied on both side-walls of ME$_{02}$ since TE$_0$ and TE$_2$ are both symmetric modes. In contrast, for ME$_{12}$, width variations are applied only on a single side-wall and the trajectory of other side-wall is straight and uniform since width variations are applied only on a single side-wall and the grating structures are applied on both side-walls of ME$_{02}$ since functions are utilized to de-swap, as illustrated in the insets of Figure 2A. The sinusoidal functions are utilized to de-swap, as illustrated in the insets of Figure 2A. The sinusoidal functions are utilized to define the shape of LPWGs. The grating structures are applied on both side-walls of ME$_{02}$ since TE$_0$ and TE$_2$ are both symmetric modes. In contrast, for ME$_{12}$, width variations are applied only on a single side-wall and the trajectory of other side-wall is straight and uniform since symmetries of TE$_1$ and TE$_2$ are reversed. Moreover, the waveguide width linearly decreases over $0 \leq L \leq N_{meij}/\Lambda_{meij}/2$ region, while linearly increases over $N_{meij}/\Lambda_{meij}/2 \leq L \leq N_{meij}/\Lambda_{meij}$ region, in order to enhance the working bandwidth:

$$W_{meij}(L) = W_{me,m} + \left[\frac{L - N_{meij}/\Lambda_{meij}/2}{L}\right] (W_{me,M} - W_{me,m}),$$  \hspace{1cm} (2)

where $W_{meij}(L)$ is the width function for ME$_{ij}$, $W_{me,m}$ and $W_{me,M}$ are minimum and maximum widths, $N_{meij}$ is the grating-period number of ME$_{ij}$, and $\Lambda_{meij}$ is the grating pitch of ME$_{ij}$. Thus, the corresponding trajectory functions can be expressed as:

$$Y_{me02,+}(L) = W_{me02}(L)/2 + \Delta_{me02}\sin\left(\frac{2\pi L}{\Lambda_{me02}}\right),$$  \hspace{1cm} (3)

$$Y_{me02,-}(L) = -W_{me02}(L)/2 - \Delta_{me02}\sin\left(\frac{2\pi L}{\Lambda_{me02}}\right),$$  \hspace{1cm} (4)

$$Y_{me12,+}(L) = W_{me12}(L) - W_{me12}(0)/2 + \Delta_{me12}\sin\left(\frac{2\pi L}{\Lambda_{me12}}\right),$$  \hspace{1cm} (5)

$$Y_{me12,-}(L) = -W_{me12}(0)/2,$$  \hspace{1cm} (6)

where $Y_{meij,+}$ denotes trajectory function for ME$_{ij}$, $\Delta_{meij}$ is the grating strength of ME$_{ij}$.

The widths are chosen to be $W_{me,m} = 1.23 \mu m$ and $W_{me,M} = 1.29 \mu m$ as an initial setting. The idea is to use LPWGs to compensate the index mismatch between eigen modes. Therefore, the foremost issue is to determine the grating pitch according to the following equation [32]:

$$\left|n_{TE_i} - n_{TE_m}\right| = \frac{\lambda}{\Lambda_{meij}},$$  \hspace{1cm} (7)

where the left term represents the effective-index difference between $TE_i$ and $TE_m$, and the right term represents the effective-index compensation offered by LPWGs. The effective-index dispersion curves are calculated for TE$_0$–2 at an average width ($W_{eq} = 1.26 \mu m$) by using FEM, as shown in Figure 2B. Thus, grating pitches can be approximately set as $\Lambda_{me02} = 2.65 \mu m$ and $\Lambda_{me12} = 4.1 \mu m$ according to Eq. (7). The index-mismatch compensations for ME$_{02}$ and ME$_{12}$ are shown in Figure 2C and D. One can see that index differences can be perfectly canceled out at the central wavelength of 1.55 $\mu m$ (see intersections between solid lines and dashed lines). The remnant index mismatch at other wavelengths is also quite small. Moreover, the mode swap should occur merely between target eigen modes since required index compensations are distinct between ME$_{02}$ and ME$_{12}$. Here, grating-period numbers are set as fixed values ($N_{me02} = 4, N_{me12} = 3$), and mode-swap efficiencies are calculated with varied grating strengths ($\Lambda_{meij}$) and grating pitches ($\Lambda_{meij}$) by using the finite-difference time-domain (FDTD) method, as shown in Figure 2E and F. For ME$_{ij}$, the mode-swap efficiency (MSE$_{meij}$) is defined as the normalized transmittance of TE$_i$ as TE$_m$ is launched. From the results, near-unity mode-swap efficiencies can be reached for both ME$_{02}$ and ME$_{12}$ (MSE$_{me02} > 0.99$, MSE$_{me12} > 0.99$) with the following optimal parameters: $\Delta_{me02} = 0.22 \mu m$, $\Delta_{me12} = 0.18 \mu m$, $\Lambda_{me02} = 2.65 \mu m$ and $\Lambda_{me12} = 4.325 \mu m$. The light propagation profiles are then calculated for the optimized ME$_{02}$ and ME$_{12}$ by using FDTD, as shown in Figure 2G, where efficient and complete mode-swap processes can be observed. The transmittance spectra are also calculated by using FDTD. The calculation results can be found in Supporting Information, Section S3. The fabrication tolerance analysis for MEs is also obtained (see Supporting Information, Figures S3 and S4). Low IL and XT can still be maintained even with a large width deviation of ±20 nm, indicating outstanding reliability in massive productions.

Two sets of devices (ME$_{02}$ and ME$_{12}$) were fabricated closely on the same chip, as shown in Figure 2H. The cascaded ADCs (CADC) were employed as terminals for (de) multiplexing mode carriers in a multi-mode waveguide. The detailed discussion about CADC can be found in Supporting Information, Section S4. To measure the mapping relation between input TE$_m$ and output TE$_n$ modes for ME$_{ij}$, one can choose $I_{meij,m}$ and $O_{meij,n}$ as input and output ports,
respectively. The transmittance matrices were measured for the fabricated ME02 and ME12 at the central wavelength, as shown in Figure 2I. The calculated transmittance matrices are also given for comparison. It can be found that the measured insertion losses and crosstalk are as low as IL < 0.88 dB, XT < −15.8 dB, respectively. The pure losses of MEs were measured to be IL < 0.4 dB by deducting losses caused by CADCs. We also measured the transmittance spectra over the wavelength range from 1.52 μm to 1.58 μm, as shown in Figure 2J. From the spectra, low crosstalk of XT < −10 dB can be attained over the whole bandwidth (BW > 60 nm). The demonstrated ME02 and ME12 are mainly applicable for a three-channel MDM, but the proposed design methodology should not be hampered by the required channel number or mode orders, since the index compensation between any eigen-mode pair can be easily achieved.

Figure 2: Design and results for mode exchangers (ME).
(A) The schematic configuration of mode exchangers (ME02, ME12) for TE0–TE2 and TE1–TE2 mode swap. The insets show mode-swap processes. (B) The calculated effective-index (n_{eff}) dispersion curves of TE0–2 modes. The index-mismatch (Δn_{eff}) compensations for (C) ME02 and (D) ME12. The calculated mode-swap efficiencies (MSE_{me02}, MSE_{me12}) for (E) ME02 and (F) ME12 with varied grating strengths (Δme02, Δme12) and grating pitches (λme02, λme12). (G) The calculated light propagation profiles for ME02 (left column) and ME12 (right column) as TE0–2 modes are launched. (H) The optical microscope image of fabricated devices with port identifiers labeled. The insets are scanning electron microscope (SEM) images of ME02 and ME12. (I) The calculated (upper row) and measured (lower row) transmittance matrices for ME02 (left column) and ME12 (right column) at the 1.55-μm wavelength. (J) The measured transmittance spectra for ME02 (upper row) and ME12 (lower row). CADC, cascaded asymmetric directional couplers.
by tailoring the grating pitch, which makes it a universal solution to arbitrary mode swap. It should also be noted that the mapping relation for passive ME is fixed once it is designed and fabricated since it is basically a passive device. However, the mode selectivity will not be hindered by the fixed functionality of ME, because the active mode add-drop can be easily obtained by combining MEs with ADCs and single-mode switches, as will be discussed later.

2.2 Direct-access mode add-drop multiplexer

Here, the direct-access scheme presented in Figure 1B is realized by employing the aforementioned MEs. Figure 3A schematically illustrates the proposed structures (MADM) for direct add-drop of CH (carried by TE). Among them, MADM0/MADM1 is formed by combining ME02/ME12 with two ADC (as discussed in Figure 1B), whereas MADM2 is just a pair of mirrored ADC for TE (de)multiplexing. The optimization processes and experimental results for ADC can be found in Supporting Information, Section S4. The mode add-drop processes for MADM0–2 are illustrated in the insets of Figure 3A. We calculate the light propagation profiles for MADM by using FDTD, as shown in Figure 3B. The dropping processes are displayed in the 1st–3rd rows. It can be seen that, for MADM0, only TE is routed into the dropping port with negligible residual power in the multimode bus waveguide, showcasing direct-access operations with high efficiencies and low crosstalk. The 4th row shows

![Figure 3: Design and simulation results for direct-access mode add-drop multiplexers (MADM).](image)

(A) The schematic configuration of mode add-drop multiplexers (MADM0–2) for TE modes add-drop. The insets show mode add-drop processes. (B) The calculated light propagation profiles for MADM0 (left column), MADM1 (middle column) and MADM2 (right column) as TE modes are launched. ME, mode exchanger; ADC, asymmetric directional coupler.
adding operations for $\text{TE}_{0-2}$. The input $\text{TE}_0$ mode is firstly coupled into the multi-mode waveguide and converted to $\text{TE}_2$ through a $\text{TE}_0-\text{TE}_2$ coupling. For MADM$_2$, the excited $\text{TE}_2$ mode goes directly into the output port, whereas for MADM$_{0-1}$, an additional mode-swap process is performed to recover the signal-carrier mapping relation. The transmittance spectra are also calculated by using FDTD. The calculation results can be found in Supporting Information, Section S5.

Three sets of devices (i.e., MADM$_{0-2}$) were fabricated closely on the same chip, as shown in Figure 4A. The CADCs were utilized to (de)multiplex $\text{TE}_{0-2}$ (see Supporting Information, Section S4 for more information). To characterize mode-dropping processes in MADM$_i$, we chose $\text{I}_{\text{madmi}}$ as the input port to excite $\text{TE}_m$, while measured transmittances at $\text{O}_{\text{madmi}}$ (for the output $\text{TE}_n$ mode) and $\text{D}_{\text{madmi}}$ (for the dropped mode carrier). Figure 4B shows the measured transmittance matrices for mode-dropping operations. The measurement results show low losses ($\text{IL} \approx 0.17-1.52 \text{ dB}$) and low crosstalk ($\text{XT} \approx -37.2 \sim -15.4 \text{ dB}$) at the central wavelength, which agrees well with calculation results (see the upper row of Figure 4B). We also measured the transmittance spectra as $\text{TE}_{0-2}$ are dropped, as shown in Figure 4C, where dashed lines highlight dropped mode carriers. The measured crosstalk levels are as low as $\text{XT} < -12 \text{ dB}$ over a 60-nm wavelength span. To characterize mode-adding processes in MADM$_n$, we chose $\text{A}_{\text{madmi}}$ as the input port and measured transmittances at $\text{O}_{\text{madmi}}$ (for the output $\text{TE}_j$ mode). The measured transmittance spectra are shown in Figure 4D. From the spectra, one can find low losses ($\text{IL} < 0.9 \text{ dB}$) and low crosstalk ($\text{XT} < -15 \text{ dB}$) around the central wavelength.

### 2.3 Direct-access mode-division multiplexing switch

The direct-access MDMS can be realized by exploiting the aforementioned MADMs. Here, we propose and demonstrate a cascaded mode-division multiplexing switches.
CMDMS to obtain dynamic switching operations in a three-channel MDM, where three independent MDMSs (i.e. MDMS_{0–2}) are successively cascaded to add/drop TE_{0–2}, as schematically illustrated in Figure 5A. Each MDMS is built by assembling the aforementioned MADM with a Mach–Zehnder switch. Here, a normally-bar switch (NBS) is proposed and demonstrated to enhance the working bandwidth and reduce the power consumption by using bent directional couplers (BDCs) and a multi-sectional phase shifter (PS), as schematically illustrated in Figure 5B. The BDCs can provide a flattened coupling-ratio spectrum to ensure high extinction ratios over a broad bandwidth [33]. The multi-sectional PS is introduced to induce a phase bias at off state [34]:

$$\varphi_{\text{nbs, bias}} = \frac{2\pi}{\lambda} (n_{\text{nbs, 2}} - n_{\text{nbs, 1}}) (L_{\text{nbs, s}} - L_{\text{nbs, r}}),$$

where $\varphi_{\text{nbs, bias}}$ is the phase bias, $n_{\text{nbs, 1}}$ and $n_{\text{nbs, 2}}$ are TE_{0} effective indices with $W_{\text{wg}} = W_{\text{nbs, 1}}$ and $W_{\text{wg}} = W_{\text{nbs, 2}}$, $L_{\text{nbs, s}}$ and $L_{\text{nbs, r}}$ are waveguide lengths of shifting and reference sections. Thus, the bar-coupling can be achieved at off state by properly choosing waveguide widths and lengths of PS to induce a phase bias of $\varphi_{\text{nbs, bias}} = \pi$. More simulation details about BDCs and PS can be found in Supporting Information, Section S6. The phase bias of $\pi$ can be compensated in the switching operation by heating arm #1 (see the yellow region in Figure 5B), leading to the cross-coupling at on state. Figure 5C shows the measured transmittance spectra for the fabricated NBS (see also Figure 11 in Supporting Information). A high extinction ratio (ER > 16.7 dB) was measured at the central wavelength with a switching power of 30.9 mW. The flattened transmittance spectra can be observed over the whole

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**Figure 5:** Design and all-off measurement results for direct-access mode-division multiplexing switches (MDMS). (A) The schematic configuration of cascaded MDMSs (CMDMS). (B) The schematic configuration of normally-bar switch (NBS). (C) The measured transmittance spectra for NBS at off state (upper panel) and on state (lower panel). (D) The illustration of mode add-drop operations. (E) The optical microscope image of fabricated devices with port identifiers labeled. (F) The measured transmittance matrix for CMDMS at all-off state ($\lambda = 1.55 \mu m$). (G) The measured transmittance spectra for CMDMS at all-off state as light was launched from input ports. BDC, bent directional coupler; PS, phase shifter; CADC, cascaded asymmetric directional coupler.
bandwidth at both on and off states. More measurement results and fabrication-tolerance analysis for NBS can be found in Supporting Information, Section S6. Thus, if all the NBSs are at off state, the mode carrier (i.e. TE) dropped by MADM, will be coupled back into the multi-mode waveguide, and thus all the mode carriers will go straight into the output port with the initial signal-carrier mapping relation preserved. On the other hand, if NBS is switched on, the corresponding signal channel Ch (carried by TE) can be added and dropped at Amdms,i and Dmdms,i, as illustrated in Figure 5D. One should note that the cascading configuration is proposed just to verify the direct-access operations for arbitrary mode carriers, and a stand-alone MDMS also works especially when only few mode carriers need to be handled within a large capacity. For example, a separate MDMS0 is fully functional if TE0 is the only mode carrier to be added and dropped.

Figure 5E shows the microscope image of fabricated devices, which consists of two mirrored CADCs for mode (de)multiplexing and a CMDMS in between. One can refer to Supporting Information, Section S4 for more details about CADC. We firstly characterized the transmission responses as all the NBSs were switched off. The TE mode was excited in the multi-mode waveguide by choosing lmdms,i as the input port. The output transmittances of TE were measured at Omdms,i, while the transmittances of dropped mode carrier were measured at Dmdms,i. The transmittance matrix was measured at the 1.55-μm wavelength, as shown in Figure 5F. From the results, the light transmission from lmdms,i to Omdms,i is dominant, whereas the transmittance at Dmdms,i is negligible, indicating that no mode carriers were dropped. Low losses and crosstalk were measured (IL ≈ 1.35–1.56 dB, XT ≈ −28.8 ~ −14.8 dB) at all-off state. We also measured the transmittance spectra over the wavelength range from 1.52 μm to 1.58 μm, as shown in Figure 5G. Over the whole bandwidth, crosstalk levels were measured to be XT < −10 dB. One might find some dense ripples in the measured spectra, which is mainly caused by the interference effect. Specifically, the extinction ratio of NBS is not high enough to fully eliminate cross-coupling, and a weak interference will be accumulated as multiple NBSs are cascaded. The ripples can be depressed by further improving the extinction ratio of NBS (see Supporting Information, Section S6).

Next, dropping operations were conducted by switching on NBS0–2, as shown in Figure 6A. The left panel (i.e. 1st–3rd columns) and right panel (i.e. 4th–6th columns) show the transmittance spectra at output and dropping ports, respectively. For clarity, we only display the measurement results for lmdms,i to Omdms,i and lmdms,i to Dmdms,i transmittances. It can be seen that, when NBSi was switched on, transmittances at the corresponding Omdms,i port were efficiently reduced to a relatively low level (<−15 dB), and the dropped mode carriers were transferred to Dmdms,i with low losses (IL < 1 dB), showcasing dropping
processes of selected mode carriers. After that, we measured the transmittance spectra when light is launched from $A_{\text{mdms},i}$ as NBs, was switched on to verify the adding functionality of CMDMS, as shown in Figure 6B. From the spectra, low losses ($IL < 1$ dB) and low crosstalk ($XT \approx -18 \sim -12$ dB) can be observed for $A_{\text{mdms},i}$ transmissions. We also measured eye-diagrams and bit-error rates (BER) with a 10 Gbps data stream to verify data links built in CMDMS under different states (see Supporting Information, Section S7). Based on the single-port method, wide-opened eye-diagrams with $ER > 10$ dB have been observed. The power penalties were measured to be as low as $=1.2 \sim 2.6$ dB at $BER = 10^{-9}$.

2.4 Direct-access wavelength/mode-division multiplexing switch

The wavelength/mode-hybrid multiplexing has drawn tremendous interests for its ability to push the capacity limit while ensure relatively low cost and power consumption by transmitting signals with both wavelength and mode carriers [35–37]. Thus, it is essential to develop the wavelength/mode-division multiplexing switch (WMDMS) for handling wavelength/mode-hybrid carriers. Here, the cascaded WMDMSs (CWMDMS) are proposed and demonstrated as a proof of concept. In essence, the proposed scheme is just the aforementioned CMDMS with NBs replaced by tunable MRRs, as schematically illustrated in Figure 7A. Three mode carriers (i.e. $TE_{0-2}$) and four wavelength carriers (i.e. $\lambda_0 \approx 1.5445 \mu m$, $\lambda_1 \approx 1.5461 \mu m$, $\lambda_2 \approx 1.5477 \mu m$ and $\lambda_3 \approx 1.5491 \mu m$) are considered in this scheme, and the signal channel carried by $TE_i/\lambda_i$ is denoted as $CH_i$. Thus, totally twelve wavelength/mode-hybrid carriers can be supported. The tunable MRR is realized based on a race-track resonator with a pair of BDCs [38], as shown in Figure 7B. Figure 7C shows the measured transmittance spectra as different electric power is applied onto the tunable MRR (see also Supporting Information, Figure S14). One can see that the utilized wavelength carriers can be totally covered by the wavelength-tuning range with a large wavelength-tuning slope of $=0.095$ nm/mW (see Figure 7D). More details about tunable MRR can be found in Supporting Information, Section S8. The static resonant wavelength of MRR is deviated from the utilized wavelength carriers (i.e. $\lambda_{0-3}$). Thus, at all-off state, the incident $CH_i$ will propagate directly into output ports. To add/drop $CH_i$ (carried by $TE_i/\lambda_i$), one can choose WMDMS to select $TE_i$, while apply the specific electric power ($P_j$) onto MRR, to select $\lambda_j$, as illustrated in Figure 7E. One should note that the proposed scheme is just a proof of concept, and it is unnecessary to cascade all the three WMDMSs if only few wavelength/mode-hybrid carriers need to be added and dropped from a large capacity. For example, one can use a stand-alone WMDMS, to perform the carrier manipulation if $CH_{03}$ is the only signal channel to be handled.

Figure 7F shows the microscope images of fabricated devices. A pair of mirrored CADCs were fabricated at input and output ends of CWMDMS for mode (de)multiplexing (see Supporting Information, Section S4 for more information). Three sets of cascaded MRRs (CMRR) were placed at the output end as four-channel wavelength demultiplexers (see Supporting Information, Section S9 for more information). Thus, to launch $CH_i$ into the multi-mode waveguide, one can choose $I_{\text{wmdms},i}$ as the input port, while align the wavelength of tunable laser to $\lambda_i$. The output transmittances of $CH_i$ can be measured at $O_{\text{wmdms},ij}$. The adding and dropping ports for $CH_i$ are $A_{\text{wmdms},ij}$ and $D_{\text{wmdms},ij}$, respectively. We firstly measured the transmittance matrix as zero electric power was applied (see Figure 7G). It can be seen that the incident $CH_i$ was completely routed to the corresponding output port (i.e. $O_{\text{wmdms},ij}$). The insertion losses and crosstalk were measured to be $IL < 2.25$ dB and $XT < -15.2$ dB for all the signal channels. Figure 7H shows the measured transmittance spectra over the wavelength range from 1.542 $\mu m$ to 1.552 $\mu m$, where low crosstalk ($XT < -15$ dB) can be observed over the whole bandwidth.

We then characterized the transmission responses for dropping operations, as shown in Figure 8A. The left panel (i.e. 1st–3rd columns) shows $I_{\text{wmdms},ij}$ to $O_{\text{wmdms},ij}$ transmittances, while the right panel (i.e. 4th–6th columns) shows $I_{\text{wmdms},ij}$ to $D_{\text{wmdms},ij}$ transmittances. The applied electric power was set as $P_0 = 24.2$ mW, $P_1 = 41.1$ mW, $P_2 = 57.9$ mW and $P_3 = 72.6$ mW for dropping $\lambda_{0-3}$, respectively. From the spectra, when MRR was tuned with electric power of $P_j$, the $O_{\text{wmdms},ij}$ transmittance at $\lambda_i$ was dramatically reduced with $ER > 15$ dB, and the dropped $CH_i$ was efficiently transferred to the corresponding dropping port (i.e. $D_{\text{wmdms},ij}$) with low losses ($IL < 2$ dB). The 3 dB bandwidths are slightly different between tunable MRR and CMRR filter due to fabrication errors, which leads to the notch-like response shown in Figure 8A [27]. The adding operations for $CH_{ij}$ were then conducted by injecting light into $A_{\text{wmdms},ij}$ while applying electric power of $P_j$ onto MRR. The measured transmittance spectra are shown in Figure 8B. The crosstalk levels were measured to be $XT < -15$ dB, while insertion losses were measured to be $IL < 2$ dB. The single-port method was used to measure eye-diagrams and bit-error rates (BER) as a 10 Gbps data stream was
coupled into the device (see Supporting Information, Section S10). Figure S16A shows the measured eye-diagrams, where clear patterns and high extinction ratios (ER > 10 dB) can be observed. From Figure S16B, power penalties were measured to be ≈0.9–2.2 dB to ensure low bit-error rates of BER = 10^{-9}.

2.5 Reconfigurable multi-mode hubbed-ring network

The proliferation of on-chip photonic interconnects has created a rising demand for high-performance optical networks [39]. The hubbed-ring network (HRN) has been...
widely used in optical communication systems (e.g. metropolitan area networks), taking advantage of its outstanding scalability and robustness [40–42]. Typically, an HRN can be built by connecting one central hub and numerous access nodes with a single feeding ring. The network traffic of the HRN is organized on a multi-point-to-point (MP2P) basis. In other words, the optical paths are built merely between one central hub and each access node in a duplex manner, whereas inter-node links are forbidden. Here, an HRN with three access nodes (denoted as nodes #1–3) is investigated as an example, as schematically illustrated in Figure 9A, where there are totally six optical paths contained in a single ring-like bus waveguide. The hub-to-node (H2N) link is supported by paths #1–3 (see solid arrows), while the node-to-hub (N2H) link is supported by paths #1′–3′ (see dashed arrows). One can

Figure 8: Add-drop operation results for direct-access wavelength/mode-division multiplexing switches (MDMSs). (A) The measured transmittance spectra at output ports (left panel) and dropping ports (right panel) as light was launched from input ports while different electric power ($P_{0,3}$) was applied on MRR$_{0,2}$. The dashed boxes and arrows highlight the dropped wavelength/mode-hybrid carriers. (B) The measured transmittance spectra at output ports as light was launched from adding ports and different electric power ($P_{0,3}$) was applied on MRR$_{0,2}$. CWMDMS, cascaded wavelength/mode-division multiplexing switch; MRR, micro-ring resonator.
Figure 9: Design and results for the reconfigurable multi-mode hubbed-ring network (HRN).

(A) The illustration of HRNs based on wavelength-division multiplexing (WDM) and mode-division multiplexing (MDM). (B) The optical microscope image of fabricated HRN. The dashed boxes show enlarged views of cascaded mode add-drop multiplexers (CMADM, upper panel) and cascaded mode-division multiplexing switches (CMDMS, lower panel). The HRN consists of one CMADM as a central hub and three CMDMSs as access nodes #1–3. The port and switch identifiers are also labeled. The illustrations of hub-to-nodes (H2N) and nodes-to-hub (N2H) links for HRN at (C) state A and (D) state B. The shaded boxes illustrate which normally-bar switches (NBS) are turned on. The measured transmittance matrices for the HRN at (E) state A and (F) state B (\(\lambda = 1.55 \mu m\)). The measured transmittance spectra for the HRN at (G) state A and (H) state B. The measured (I) eye-diagrams and (J) bit-error rates (BER) with 10 Gbps data links at \(\lambda = 1.55 \mu m\) using multi-port method. CGMB, curvature-gradient multi-mode bend; B2B, back-to-back.
find that these optical paths overlap with each other, which makes it inevitable to use the multiplexing technology to achieve parallel data transmissions. The conventional HRNs are usually constructed based on WDM [39], as shown in the inset of Figure 9A, which requires a large number of laser diodes with different wavelengths working simultaneously at the central hub. As an improvement, we propose to use MDM to substitute WDM, leading to a novel concept of multi-mode HRN, as shown in the inset of Figure 9A. For this approach, the optical paths in HRN are carried by multiple eigen modes (i.e. TE0,2) rather than multiple wavelengths (i.e. λo,2), in order to improve the power efficiency. The reconfigurability is another desired attribute for HRN, which refers to the ability to deploy the mode carrier for each optical path. It should be noted that there are usually a large number of nodes in HRN and each node only requires a limited number of carriers, which makes it inefficient to add-drop all the mode carriers. Therefore, the aforementioned MDMs should just fit in the application scenario due to its ability to directly access any eigen mode without demultiplexing other idle carriers.

Here, we propose and demonstrate a reconfigurable multi-mode HRN by utilizing the aforementioned MADMs and MDMs. Figure 9B shows the microscope images of fabricated devices. One set of cascaded MADMs (CMADM) was employed as a central hub, while three sets of cascaded MDMs (denoted as CMDMS1–3) were used as three access nodes (i.e. nodes #1–3), as shown in the right panel of Figure 9B. The central hub and access nodes were connected by a ring-like multi-mode bus waveguide with four curvature-gradient multi-mode bends (CGMB) at corners. More details about CGMB can be found in Supporting Information, Section S11. The input/output port at central hub is denoted as H16, while the input/output port at node #i is denoted as N16–i (see the right panel of Figure 9B). One can choose to switch on NBSi (see the left panel of Figure 9B) to select TEi as the mode carrier for path #i(6) between the central hub and access node #i. Two connection states were implemented to verify the reconfigurability of HRN, as illustrated in Figure 9C and D. At state A, we chose to switch on NBS10, NBS20 and NBS30. In this case, mode carriers for paths #1(1), #2(3) and #3(5) were TE0, TE2, and TE3, respectively. The H2N2H links were characterized by choosing H2/N11, H4/N23 and H6/N35 as input ports, while choosing N12/H1, N20/H3 and N30/H5 as output ports. At state B, we chose to switch on NBS20, NBS30 and NBS31. In this case, carriers for paths #1(1), #2(3) and #3(5) were TE2, TE3, and TE5, respectively. The H2N2H links were characterized by choosing H2/N15, H4/N23 and H6/N35 as input ports, while choosing N16/H1, N20/H3 and N30/H5 as output ports. The single-wavelength measurement was firstly performed to obtain transmittance matrices at λ = 1.55 µm for both states A and B, as shown in Figure 9E and F. From the results, it can be seen that optical paths were successfully established for both H2N and N2H links. The measured insertion losses are IL ≈ 1.76–4.17 dB at state A and IL ≈ 1.25–4.05 dB at state B. The crosstalk was also measured to be as low as XT < −17.6 dB. The transmittance spectra were then measured at states A and B, as shown in Figure 9G and H. From the spectra, low crosstalk levels of XT < −10 dB can be achieved over a 45 nm bandwidth. After that, 10 Gbps data streams were injected into each optical path built in the reconfigurable multi-mode HRN to further evaluate its overall performance. Here, the rigorous multi-port method was used to characterize data transmissions in the HRN. Figure 9I shows the measured eye-diagrams at states A and B, where low noises and high extinction ratios (ER > 10 dB) can be observed. The bit-error rates were also measured at the central wavelength, as shown in Figure 9J. Low power penalties of ≈1.9–3.1 dB were experimentally observed under low bit-error rates of BER < 10−9. Thus, the aggregate transmission bandwidth should be 6 × 10 Gbps for parallel transmissions of totally six optical paths in HRN.

The above results for states A and B are present just to show the feasibility, and more connection states can be supported by the reconfigurable multi-mode HRN. Actually, totally M!(M − N)! connection states can be achieved for an HRN with M mode carriers and N access nodes. We believe these experimental results can be a solid demonstration of viability of using the MDMs to build scalable on-chip networks. Moreover, the results shown in Figure 9G and H have demonstrated the broadband characteristic of the HRN, which makes it potential to further expand the capacity and add more access nodes to the network by introducing wavelength/mode-hybrid multiplexing, as discussed in Section 2.4.

3 Summary and conclusion

In conclusion, we have proposed and demonstrated, to the best of our knowledge, the first direct-access MDMs as a novel platform for dynamically controlling mode carriers. In the first place, the ME and MADMs are developed to address the “direct-access” conundrum. The direct-access MDMs is then realized by employing MADMs as a building block. The proposed scheme is a combination of direct-access MADMs and normally-bar switches (NBSs), which is capable of adding and dropping any selected mode carrier in a three-channel mode-division multiplexing system. We have also proposed and demonstrated a
WMDMS by introducing tunable micro-ring resonators (MRRs) to achieve an expanded link capacity with totally twelve wavelength/mode-hybrid carriers. In principle, these proposed schemes are viable for any MDM systems regardless of the channel number. We have summarized and compared the performance of several reported MDMs in Supporting Information, Section S12. It can be found that our proposed MDMS and WMDMS can provide low crosstalk, low losses and small footprint. The device footprint can be further reduced by introducing thermal-isolation trenches [43] and direct thermal contacts [44] to further improve the thermo-optical efficiency of NBSs. A reconfigurable multi-mode hubbed-ring network (HRN) is then constructed based on the developed MADM and MDMS. The mode carriers are utilized to support six parallel optical paths between one central hub and three access nodes with a large bandwidth. The different connection states can be built in the multi-mode HRN, taking advantages of its great reconfigurability. In this work, we have provided a general and systematic solution to how to dynamically control mode carriers in a direct-access manner, which we believe is potential for large-scale on-chip photonic interconnects.

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