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Special Focus on Photonic Devices and Integration

Silicon chip-scale space-division multiplexing: from devices to system

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Abstract Space-division multiplexing (SDM) technique has attracted increasing attentions recently, because it provides an effective way to increase transmission capacity. With the continuous and exponential increase in data demands, high-density integration of silicon photonic components is of significant interest in terms of link price, performance and power consumption. The multimode/mutlicore devices applied to achieve diverse functionalities are key building blocks to construct a chip-scale SDM system based on a silicon on insulator (SOI) platform. This study reviews the recent progress of multimode/multicore devices, which enable coupling, multiplexing/demultiplexing, transmitting switching, as well as modulation and detection. Based on these devices, a complete on-chip SDM system is constructed and discussed.

Keywords integrated optics devices, space-division multiplexing, optical switching devices

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1 Introduction

To satisfy the rapidly increasing demands for high-speed data transfer for cloud computing and data-intensive applications, optical interconnects have attracted considerable attention as a promising candidate for the next-generation solution to alleviate the communication bottleneck and unfavorable power scaling [1, 2]. The silicon on insulator (SOI) platform is attractive for optical interconnects owing to high refraction index contrast, high transparency in telecom wavelength band and compatibility with well-established complementary metal oxide semiconductor (CMOS) processes. In addition, an SOI platform enables highly desirable features such as low cost, low optical loss, compact footprint, and reduced power consumption. In contrast, various advanced multiplexing techniques such as wavelength-division multiplexing (WDM), polarization-division multiplexing (PDM) and space-division multiplexing (SDM) have been utilized to improve the communication capacity. Among them, WDM [3, 4] using varied wavelengths in a shared channel, is one of the most popular techniques in the past decades for both long-haul and short-reach optical interconnects. High-density WDM system illustrates the fundamental commercial promise. Great strides in WDM system have been achieved, benefiting from a wide variety of basic elements such as power splitters, wavelength multiplexers/de-multiplexers (MUXs/DEMUXs), switches, modulators and photodetectors. Over the last decade, silicon photonics integrated circuits (PICs) for WDM system have transitioned from research topics in academic organizations to product development in industrial community [5–10].

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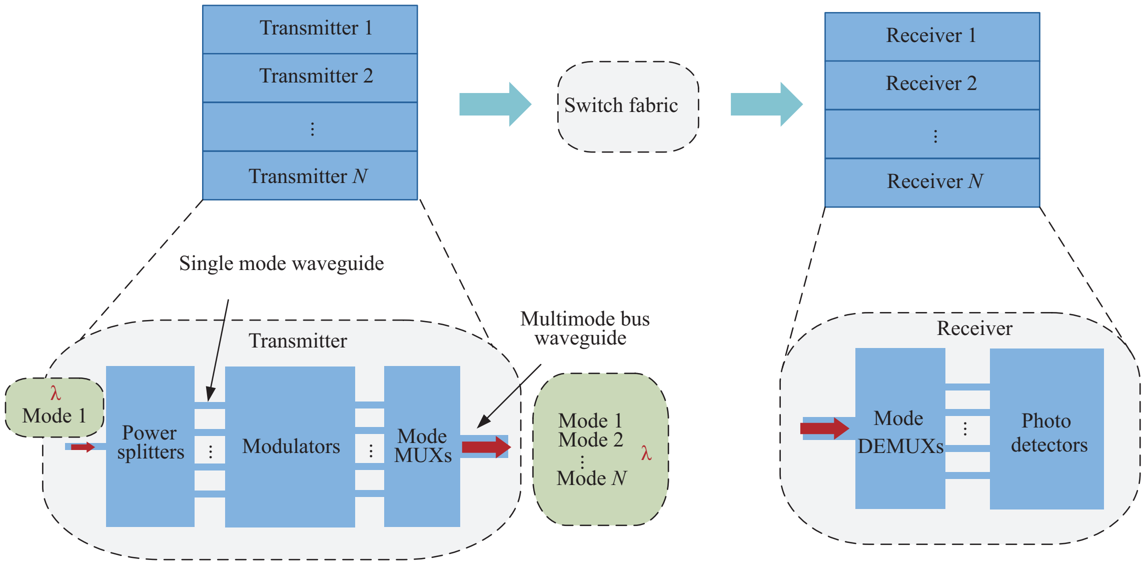

Figure 1 (Color online) The schematic of an SDM system comprising N transmitters, a switch fabric, and N receivers. All the mode channels involved in the SDM system share the same wavelength.

Alternatively, SDM technique including multimode and multicore approaches is emerging because multiple spatial modes/routes can be simultaneously applied to further increase the throughput of a single-wavelength link [11–20]. Although both approaches are very promising for chip-scale optical interconnect, the multimode solution provides more compact footprint because all eigenmodes propagate in a single multimode bus waveguide. In addition, a single waveguide should be very careful to avoid any undesired mode coupling/conversion for the sake of a low crosstalk between the mode channels. Mode-dependent operations such as splitting and switching, which are usually indispensable for reconfigurable PICs, are more realistic to implement in a single waveguide. One can easily combine these two SDM techniques on-demand to construct a hybrid SDM system.

Because all mode channels share the same wavelength emitted from a laser diode, it is an efficient way to decrease cost and power consumption for the hardware. The laser diode is especially attractive for the intra-chip optical interconnect and large-scale integration applications. Resembling the WDM system, a multi-functional SDM system integrating various multimode elements is also highly desired The schematic configuration of an SDM system is shown in Figure 1. The high-performance multimode devices for realizing coupling, (de)multiplexing, connecting/transmitting and switching operations are the major challenges.

In this paper, we review and discuss the recent research progress regarding on-chip SDM system and relevant multimode/multicore photonic integrated devices. After a brief introduction, Section 2 covers fiber-chip couplers for SDM system. Section 3 focuses on the mode MUXs and Section 4 refers to various connecting/transmitting devices. In Section 5, the multimode/multicore reconfigurable devices are reviewed. Then, the high-speed silicon modulators and germanium (Ge) photodetectors used for SDM interconnects are discussed in Section 6, before the prospect of complete chip-scale SDM systems is reviewed. Finally, a conclusion is given.

2 Fiber-chip couplers for SDM

For silicon-integrated devices, gratings for vertical coupling and spot-size converters for edge coupling are key components because they bridge fibers and chips. Previously, the efforts were mainly focused on enhancing the bandwidth, polarization independence and coupling efficiency for grating coupler or misalignment tolerance as well as coupling efficiency for the spot-size converters. As the emerging of SDM technique in today's transmission links, fiber-chip coupling solutions for SDM become nonnegligible

Mode conversion between eigenmodes of planar multimode waveguides and few-mode fibers (FMFs) or multicore fibers (MCFs) is a highly efficient approach for SDM transmission. As shown in Figure 2(a), Lai et al. [21] proposed and demonstrated a scheme comprising two inverse tapers cascaded by a symmetric Y-junction to couple LP_{01} and LP_{11a} modes of an FMF into the chip simultaneously. Also, the operation was achieved by a specially designed two-dimensional (2D) grating coupler [22, 23]. The situation, however, is hard to handle when it comes to high-order modes (HOMs) such as LP_{11b} and LP_{21} modes, because there are no corresponding modes in the planar silicon waveguide (e.g., 220 nm thickness) having only single mode supported in the vertical direction. One efficient way is to seek help for other materials. As reported in [24], a silicon nitride (SiN) strip waveguide that is grown on a SOI platform and supports two modes in vertical direction is used to couple the modes from an FMF. A specially designed silicon mode rotator is used for the connection between multimode silicon waveguide and SiN waveguide. Although additional SiN growth and relatively complicated layout are required, as much as six orthogonal spatial and polarization modes can be supported.

Compared with direct mode conversion between multiple eigenmodes, it is relatively easy to realize mode multiplexing along with coupling from several single-mode waveguides to an FMF. For edge coupling, it is difficult to stack multiple silicon waveguide layers, which requires specific processing and is not compatible with CMOS fabrication to achieve 2D coupling. This is a nonnegligible issue because the edge coupling benefits from many advantages, such as polarization independence and broad bandwidth. The grating coupler for vertical coupling has more flexible arrangements in a 2D plane. Thus, it is possible to independently excite and combine the complete set of eigenmodes of an FMF by a series of reasonably configurated grating couplers without using imaging optics [25, 26]. As illustrated in Figure 2(b), a full six-channel mode in an FMF was independently excited by selectively inputting light with different relative phases to the corresponding grating coupler. Although the required phase shifters increase the complexity, they provide the possibility of achieving other functionalities on the same chip, e.g., switches. Furthermore, a simplified and improved design is demonstrated, which can excite the complete set of eight-channel LP modes in an FMF [27]. Three-dimensional (3D) waveguide having low refraction index materials, instead of planar silicon waveguide, can realize 2D edge coupling. The typical structure is based on photonic-lantern that merges N single-mode waveguides into a few-mode waveguide having a 2D mode pattern [28]. Spin-coating and photolithography or direct laser writing enable the fabrication of such structures [29, 30].

MCF fan-in/fan-out (FI/FO) is an efficient solution for coupling between chip and MCF. The layout of the output grating couplers/waveguide tips corresponds to that of the cores of the MCF. Figure 2(c) shows a seven-core grating coupler based MCF FI/FO fabricated on SOI platform [31]. To further extend this concept, the MCF FI/FO can work together with photonic-lantern structure to combine multimode and multicore SDM techniques [32, 33]. Twenty-one spatial LP modes with both polarizations in a few-mode multicore fiber (FM-MCF) are excited using 3D waveguides and a gross total capacity of 255 Tbit/s is achieved [33].

3 Mode MUXs

Mode MUXs play the most important role in an on-chip SDM system. The purpose of mode MUXs is to excite and combine the complete set of eigenmodes of a multimode bus waveguide independently for multimode system or a densely packed waveguide array (DPWA) for multicore system. A high-performance mode MUX requires low crosstalk, broad bandwidth, low insertion loss and large fabrication tolerance.

3.1 Mode MUXs for multimode

Highly efficient mode conversion from fundamental mode (FM) to the desired HOMs can be achieved, while the converted mode can be combined into the same waveguide with other modes. Many mode MUX

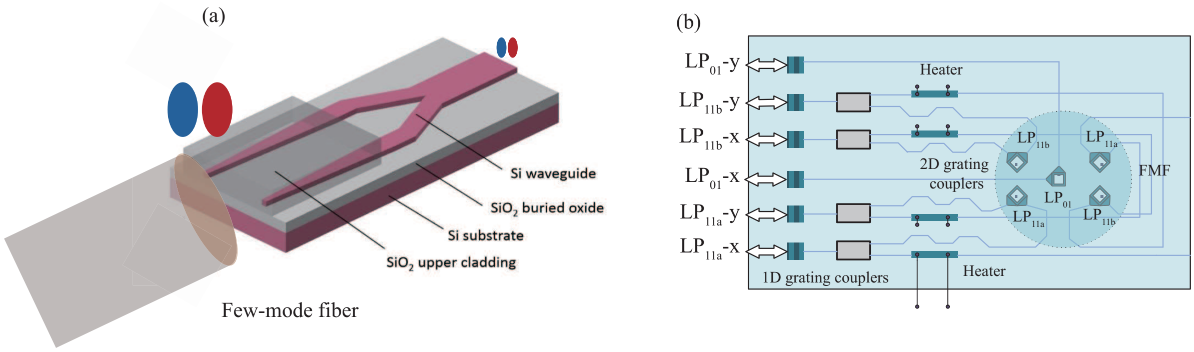

Figure 2 (Color online) (a) Schematic structures of mode converter for fiber-chip coupling [21]; (b) mode MUX for FMF fibers [25]; (c) MCF fan-in/fan-out [31].

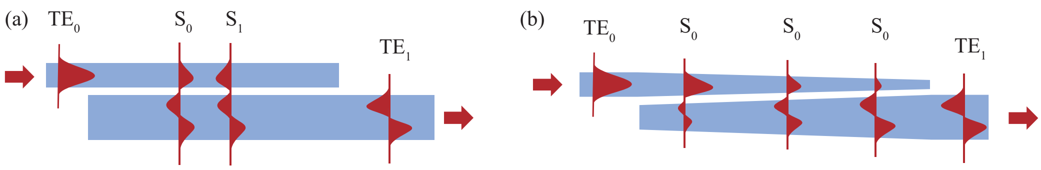

Figure 3 (Color online) Schematic of the two supermodes propagating in (a) ADCs and (b) ACs.

architectures have been proposed and experimentally demonstrated. In general, most of architectures are following three principles: multimode interference (MMI), phase matching, and mode evolution.

The MMI-based mode MUX is relatively complicated, having several MMI couplers and phase shifters that are sensitive to fabrication errors [34–36]. More importantly, the MMI-based device is not easy to incorporate more channels. In contrast, phase matching and mode evolution principles whose typical structures are asymmetric directional couplers (ADCs) and adiabatic couplers (ACs), as shown in Figures 3(a) and (b), respectively, are extensively applied in the design of mode MUXs due to high scalability.

For ADCs, the two modes in the individual waveguides have the same effective refraction index, satisfying phase matching condition. These two waveguides are placed closely to form a coupling system, supporting two supermodes S and S_1. The two supermodes are first excited at the interface of the coupling region due to severe mode mismatch. Subsequently, they interfere in the coupling region and result in the oscillation of field intensity between the two waveguides. By controlling the coupling length, one can achieve complete mode conversion. Benefiting from phase matching, the coupling length of ADCs-based mode MUX is usually short and can easily scale up to HOMs. A dual-mode MUX was presented in [37], which enables a simultaneous two channels add/drop to/from multimode bus waveguide. Furthermore, Dai et al. [38] expanded to four-mode channels having cascaded ADCs, as illustrated in Figure 4(a). However, the precise phase matching condition is required for ADC-based mode MUX. The performance, thus, is normally sensitive to waveguide size variations and the structure is inherently not broadband. An improved scheme based on tapered directional couplers (DCs) was proposed by Ding et al. [39] to relax the fabrication tolerance of conventional ADCs. A large tolerance of >20 nm width deviation is obtained, while it is only a few nanometers for conventional ADCs. To enable WDM grid to be compatible, a micro-ring resonator (MRR) was introduced into ADCs having wavelength-selective features [40–42] as shown in Figure 4(b). Besides, other novel structures based on phase matching condition such as

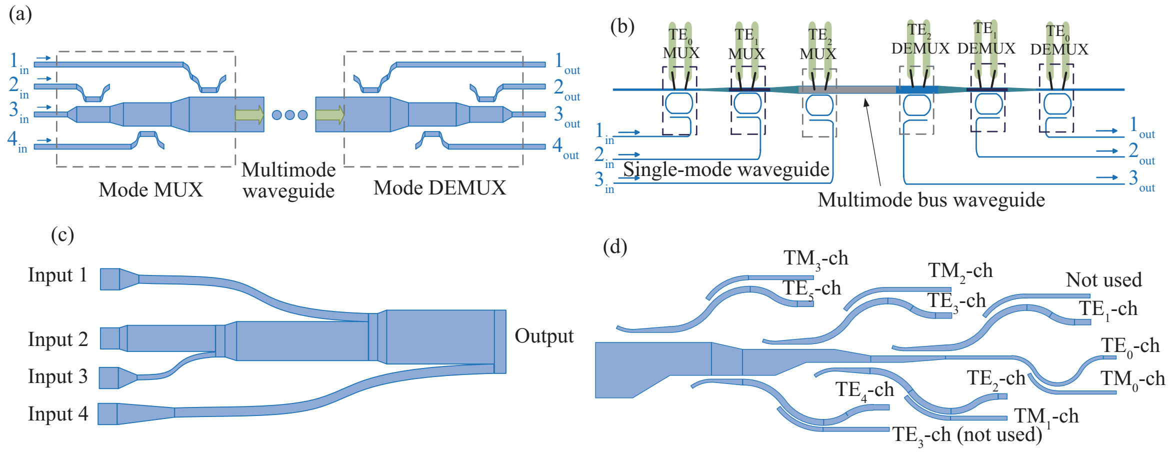

Figure 4 (Color online) Schematics of multimode MUXs based on (a) ADCs [38], (b) MRRs [40], (c) Y-junctions [59], and (d) ACs [68].

grating-assisted couplers are used to realize contra-directional coupling and band-pass filtering [43, 44].

For ACs comprising two waveguides nearby, the geometry or refractive index of at least one waveguide is gradually varied along the propagation direction by tapering or partially etching [39, 45–53]. Although two supermodes are supported in the coupling region, only one can be excited. The supermodes having an initial state of being mainly located in the narrow waveguide is excited due to closely mode distribution. Subsequently, it evolves to the state of being divided into two waveguides having normalized local modes [54, 55]. Finally, the amplitude in the bus waveguide becomes strong and evolves into the HOM smoothly. Unlike ADCs that precise phase matching condition is required in the entire coupling region, the ACs show much more relaxed condition and only a certain position should be phase matched. The mode coupling in ACs is one-to-one without unwanted coupling between the supermodes. Perfect mode conversion is guaranteed when the coupling length is long enough to ensure adiabatic mode evolution. Wang et al. [48] experimentally demonstrated three-channel mode multiplexing based on ACs. Because no precise phase matching is required, the device exhibits a very large −1 dB bandwidth of >180 nm. The performance shows reasonable degradation for large width deviations from −60 to +40 nm. The broad bandwidth covering numerous wavelength channels makes it possible to work together with WDM to realize a hybrid multiplexing that further improves the communication capacity. The large fabrication tolerance gives high reliability and yield. Moreover, the ACs was utilized to achieve efficient one-stop multi-path SDM signals multiplexing simultaneously, avoiding the mode conflict [53].

The asymmetric Y-junction is another structure for mode evolution [56–59]. High scalability for more mode channels is easily fulfilled. Figure 4(c) exhibits a four channels mode MUX based on cascaded asymmetric Y-junctions [59]. However, very precise fabrication is usually required to achieve a low-loss Y-junction corner in practice. The weakness of mode evolution is the relatively long device length that is usually over 100 μm. Shortcuts to adiabaticity that has been developed to optimize the quantum state transfer is successfully applied to reduce the length of mode MUX, while the broadband and robust merits are preserved [60–62]. This approach provides a pathway to design compact and robust photonics integrated devices [63–65].

The SDM can even works together with other multiplexing techniques such as WDM and PDM to construct a multi-dimensional hybrid multiplexing technique [66–69]. The total channel number is doubled to as high as ten using polarization beam splitter/combiner (PBS/PBC) [68], as shown in Figure 4(d). Dai et al. [67, 69] presented a hybrid mode MUX which simultaneously enables four-mode channels and sixteen wavelength channels.

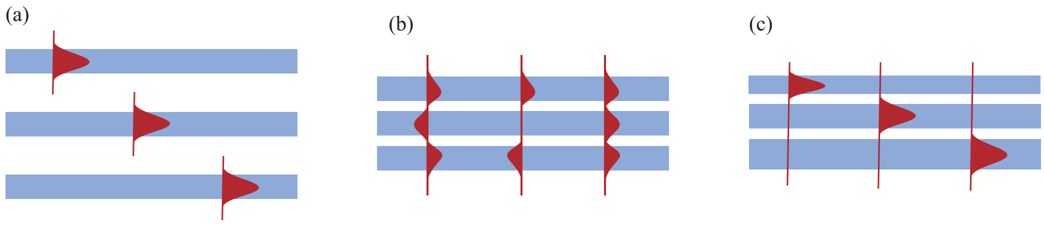

Figure 5 (Color online) Guide modes supported in (a) waveguides far from each other, in (b) waveguides close to each other, and in (c) the proposed DPWA with optimized waveguide widths and separations.

3.2 Mode MUXs for multicore

Multimode solution for massive (>10) mode channels is hard to handle due to the increased crosstalk and the (de)multiplexing complexity. Multicore solution is an attractive alternative to overcome such limitations. Unlike multimode that multiplexed signals are carried on conventional modes in a single wide waveguide, several waveguides having the same widths and spaced in parallel are employed to transmit data for multicore case. As shown in Figure 5(a), the guide modes are separated well with the optical field confined in the respective waveguide provided that the gap is large enough. To enable high-density integration, the waveguides should be placed closely with narrow gaps, forming a DPWA. Due to the reduced spacing, the guided modes turn into supermodes whose transverse distribution extends spatially within the waveguides array, as shown in Figure 5(b). For operation convenience such as multiplexing and bending with reduced crosstalk, the key point is to make supermodes work as conventional modes that are mainly confined on a single waveguide. This can be achieved by breaking the phase matching condition. An efficient approach is to optimize waveguide width and separation to decouple the waveguides while keeping compact footprint, as shown in Figure 5(c).

There are many research efforts involved in multicore mode MUXs. A compact solution of five modes (three transverse electric modes and two transverse magnetic modes) guided is realized in three waveguides having an ultra-narrow gap of 100 nm and a DPWA bus waveguide width of 1.58 μm [70]. Song et al. [71] studied a special waveguide array with sub-array works as the DPWA structure. An eleven-channel mode MUX comprising two sub-arrays of five single-mode waveguides is exhibited. The theoretical framework and design guidelines for DPWAs to generate supermodes having low crosstalk are provided comprehensively [72, 73]. Another possible way to break the phase matching condition is to introduce bent waveguide array where the waveguides have the same width but different bend radius. The phase differences are induced by curvature differences, and it is widely employed to design photonic integrated devices [74–77]. Xu et al. [78] demonstrated an ultra-broadband 16-channel multicore mode MUX utilizing densely packed bent waveguide arrays. Furthermore, a nine-channel hybrid mode MUX comprising ADCs and densely packed multimode waveguide arrays was achieved by combining the advantages of multimode and multicore techniques [79].

4 Connecting/transmitting devices for SDM

With a rapid increase in system complexity and density, the passive devices performing connecting and transmission functionalities are essential for chip-scale layout. For instance, high-performance splitters, filters, waveguide bends and intersections are the indispensable parts to form a complete on-chip circuit. However, typical devices are single-mode and redesign is necessary to accommodate the multimode. In this part, four kinds of representative connecting/transmitting devices including power splitters, mode filters, sharply bend waveguides and waveguide crossings are discussed to address the multimode splitting, filtering, bending and in-plane intersecting issues, respectively.

4.1 Multimode power splitters

The power splitters/couplers are essential components in integrated optical communication systems with many applications. Previously, most efforts were mainly focused on enhancing the bandwidth or realizing polarization independence. Only a few investigations had been carried out on multimode dimension targeting the complicated mode coupling for HOMs. The simplest design for power couplers comprises of two parallel waveguides with a small gap. Generally, the couplers with symmetrical waveguide structure are sensitive to wavelength and coupling length. When HOMs are considered, the sensitivity will be more critical, making the common coupling length for multiple modes to be very long and inapplicable to compact multimode system. To address these issues, Xu et al. [80] demonstrated a scheme composed of two cascaded ADCs and a symmetric Y-junction using multiple mode conversions at the expense of degradation of loss and crosstalk. As shown in Figure 6(a), Luo et al. [81] realized a concise and compact dual-mode 3 dB power coupler based on tapered DCs. Because the coupling length of HOM is more sensitive to width variation, the geometry of taper is optimized to mainly adjust the 3 dB coupling length of HOM, ensuring a short common 3 dB coupling length.

4.2 Mode filters

A mode filter is used to remove unwanted modes while extracting the desired ones. Resembling a wavelength filter for WDM system, a mode filter is foreseen as an important unit for on-chip SDM system in the future. Although an add/drop mode DEMUX can be partially regarded as a mode filter, the drawbacks are the large size and complicated structure. Filtering out a HOM is straightforward due to the weak confinement in a waveguide with a cut-off width for HOM. By tapering the waveguide down to the cut-off width, the HOM tends to be a radiation mode, resulting in a large propagation loss. The filtering effect can be strengthened by appropriately designing waveguide bends [82]. To obtain a HOM pass filter, two mode converters were added to connect an adiabatic tapered single-mode waveguide [83]. The mode converter consists of two Y-junctions and a phase shifter, forming a Mach-Zehnder interferometers (MZI) structure. The Y-junction acts as a power splitter, which splits FM/HOM into two in/anti-phase parts having equal power. The phase shifter induces a π phase difference between the two arms of MZI, leading to the exchange between FM and HOM after propagating through the mode converter. In this way, the HOM is first converted to FM, before traveling through the tapered waveguide smoothly. Finally, it is converted back to the HOM. Figure 6(b) shows a compact HOM pass filter by employing a 1D photonic crystal grating silicon waveguide [84]. The grating is designed to target that the FM lied in the band gap while the HOM is located in the air band of the photonic crystal. As a result, the FM is scattered and/or reflected while the HOM is turned into a Bloch mode in the photonic crystal and propagates through the filter having low insertion loss. By introducing optical phase change materials having externally changeable optical properties such as Vanadium dioxide (VO_2) and chalcogenide alloys (ChAs) that has attracted great attentions recently [85–87], one can obtain reconfigurable mode filters. For example, in a steady state, VO2 acts as an insulator with high transparency at infrared wavelengths. However, it can switch to metallic phase under thermal, electrical, or optical triggering [88].

4.3 Multimode bent waveguides

The sharply bent waveguide is essential for PIC to change the propagation direction of light. Single-mode silicon strip nanowire enables a sharp bend about several microns with low loss [89], because the ultrahigh refraction index contrast as well as eigenmodes in straight and bent waveguides can match very well. However, the situation is quite different for multimode case, where the bend mode is shifted slightly to the outside of the bend and becomes asymmetric. The eigenmode in straight waveguide mismatches with that in sharply bent waveguide severely. As a result, transition loss and inter-mode crosstalk would be induced at the waveguide transition. A conventional way to minimize these issues is to enlarge the bend radius for connection, whereas it goes against high-density integration. An improved scheme was presented to reduce size using a bend section, whose curvature varies from zero to a certain value gradually [41]. Thus, the mode of straight waveguide can be turned into the corresponding eigenmode of the bent waveguide adiabatically.

The refractive index profile of the bent waveguide can be modified using transformation optics theory. Gabrielli et al. [90] designed a sharply bent waveguide having width of 4 μm and radius of 78 μm, transmitting 16 modes with low inter-mode crosstalk. However, complicated fabrications including gray-scale lithography, which are not compatible with mature CMOS technology, should be adopted. Another simple method is to use a vertical multimode waveguide which supports single mode in the lateral direction while supporting HOMs in the vertical direction, which allows micro bend [91]. Nevertheless, such narrow and tall waveguide is not available in common SOI platform. Sun et al. [92] proposed and demonstrated a scheme based on common SOI platform without additional fabrication steps. As shown in Figure 6(c), a compact mode converter was used to connect the multimode straight and bent waveguides, avoiding the mode mismatch. The radii of the bent waveguide can be as small as 5 μm, having an equivalent performance of conventional scheme with 40 μm radii. Also, the objective-first inverse-design algorithm is an efficient way, where an alternative binarization method is introduced to obtain a "binary" structure with two materials only [93]. It has been used in automated design of photonic devices having ultra-compact footprint [94–99]. In addition, compact bend is also achieved for a photonic crystal waveguide with high transmission and suppressed inter-mode crosstalk [100]. Large robustness to fabrication error can be obtained. The major disadvantage is the relatively narrow bandwidth. In addition, sufficient periods of lattice are necessary to obtain low loss and crosstalk, increasing the equivalent footprint.

4.4 Multimode waveguide crossings

Compared with electronic interconnects where electrical routing can be realized flexibly on multiple layers, optical routing is fundamentally limited by layer-to-layer optical coupling and cost control of multi-layer integration. The waveguide crossing is inevitable and becomes one of key building blocks in optical networks. Extensive investigations on single-mode waveguide crossing had been done [101–105]. Unlike single-mode waveguide crossing having almost lossless transmission, it is difficult for multimode waveguide crossing to process multiple modes simultaneously with low loss. The typical solution is based on MMI. Multiple modes are first excited by the input mode through a non-adiabatic process before these modes interfere in the multimode region. By adopting an appropriate coupling length, an image of input mode can be formed at the center of waveguide intersection due to self-imaging effect. This means little light diffracts into side waveguides. Due to the high refraction index contrast of SOI waveguide, the best crossing/intersection points for different modes cannot be overlapped perfectly. One alternative way is to choose the center of intersection regions between two self-imaging positions at the expense of transmission efficiency [106]. To avoid tackling the HOM directly, the HOM can also be converted and processed in the form of FM through a symmetric Y-junction [107], as illustrated in Figure 6(d). In this way, the subsequent cascaded crossings only need to be optimized for the FM, releasing the design difficulty of handling two modes simultaneously.

5 Reconfigurable devices for SDM

Along with the dramatic growth of link capacity, developing data traffic grooming in on-chip system is becoming increasingly important to enhance the efficiency and flexibility of the network. The reconfigurable photonic integrated device is one of building blocks of optical networks that promises high-speed data transmission, low latency and power consumption. They allow dynamic rearrangement and increase the throughput of the communication system.

Previously, many investigations were focused on single-mode systems. Various high-performance single-mode switch elements and fabrics having a high-port-count have been achieved [108–118]. MZIs comprising two power couplers and a phase shifter are extensively applied for broadband switch where many wavelength channels can be switched at the same time. MRR-based switches having wavelength selection can provide more compact footprint and lower power consumption. The switch operating directly

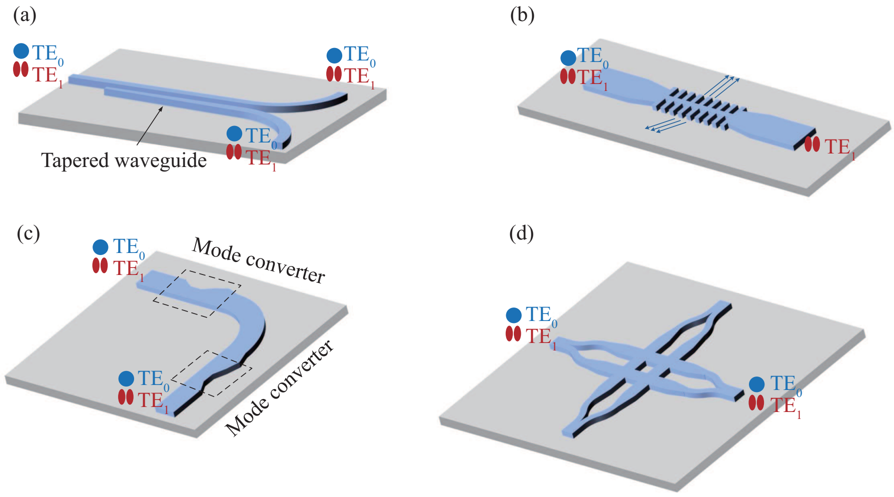

Figure 6 (Color online) Three-dimensional structures of (a) multimode power splitter [81], (b) HOM pass filter [84], (c) multimode sharply bent waveguide [92], and (d) multimode waveguide crossing [107].

on the waveguides can be realized by injecting free carriers into a p-i-n diode based on the free-carrier dispersion effect. It is promising to realize low power and fast (∼ ns) reconfigurable silicon photonic integrated devices and circuits. In addition, silicon has a high heat conductivity (∼149 W/m·K) and a large thermo-optic (TO) coefficient ($\sim 1.8\times10^{-4}$/K @ λ=1.55 μm), enabling efficient switching (∼ μs) with simple fabrication process. To fully excavate the potential of SDM technique, a complete system should be reconfigurable with mode channels being spatially switched/routed.

5.1 Mode-selective switches

Great advances have been made concerning mode-selective switches. Sun et al. [119] demonstrated a dual-channel 1×1 mode-selective switch using a mode-dependent MZI structure, as shown in Figure 7(a). By controlling the phase difference between the two arms of the MZI, the data information carried on two input modes can be exchanged or remain the same. This concept was extended to four-mode channels and the switch manipulated the optical phases of a 3D balanced four-arm waveguide MZI [120]. For the multicore SDM case, a 7×7 single-mode switch fabric and two seven-core fiber couplers were utilized to construct a multicore 1×1 switch [121], as illustrated in Figure 7(b). Compared with the 1×1 switches having only one input and one output, multi-port switches are desired in one-to-many or many-to-many system such as communications between one CPU and multiple memory cores simultaneously. Wu et al. [122] realized 1×3 switch operating with three-mode channels. HOMs in the bus waveguide were converted to FMs in single-mode waveguides by mode DEMUXs. A 3×3 single-mode optical switch was connected to the DEMUXs to transfer the three modes independently to one of the three outputs. To adopt WDM and SDM simultaneously, MRRs were induced to realize wavelength selection to obtain a four-channel (two wavelengths and two modes) 1×2 switch [123], as shown Figure 7(c). Inter-mode and inter-wavelength routing can be fulfilled to either output. Similarly, PDM technique can also work together with SDM. Zhang et al. [124] demonstrated a 1×2 mode- and polarization-selective switch that routes eight data channels on four modes and two polarization states. A 2×2 mode-selective switch is more efficient than a 1×2 case, because it can manipulate two optical links. Jia et al. [125] realized a 2×2 mode-selective switch that supported four-mode channels. For the abovementioned multi-port mode-selective switches, the signals were all demultiplexed to FMs and then handled individually using single-mode elements. Finally, they were restored back to the target output modes. Even though such a DEMUX-processing-MUX procedure is flexible and straightforward, more control electrodes and complicated controls are needed. In contrast, simplified designs of mode-selective switches were proposed to avoid intricate operations [126–128]. The input multiplexed signals can be processed simultaneously and the output signals are both on FMs, which is easy for detection and subsequent processing.

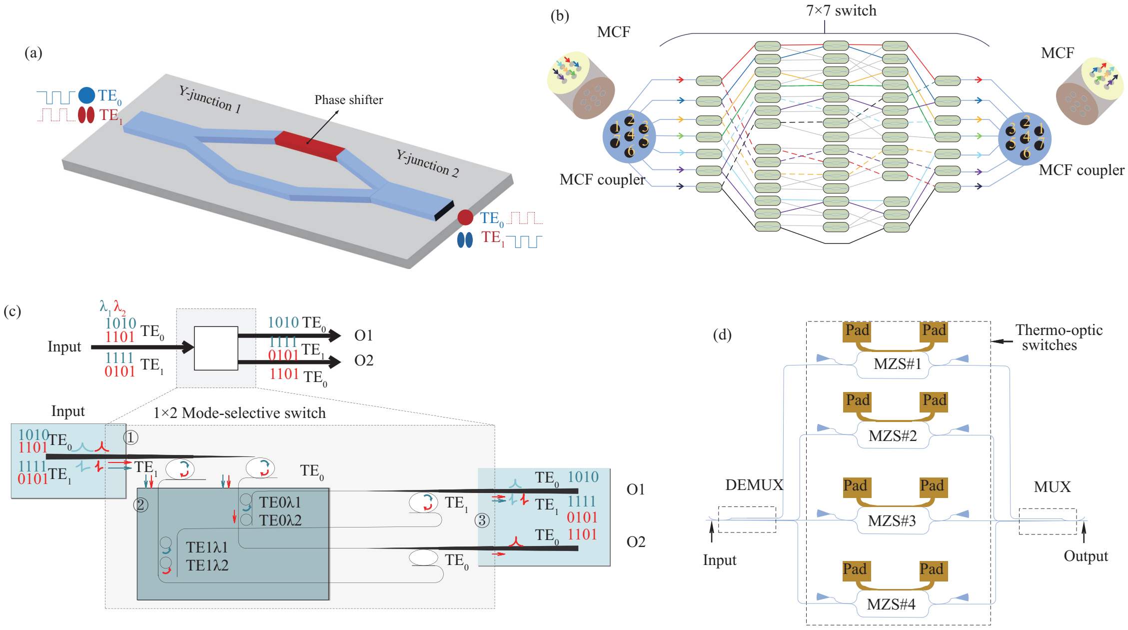

Figure 7 (Color online) Schematic views of (a) dual-channel 1×1 mode-selective switch [119], (b) 1×1 mode-selective switch for seven-core fiber [121], (c) WDM-SDM 1×2 switch [123], and (d) four-channel reconfigurable add-drop multiplexer (ROADM) for multimode SDM [130].

5.2 Reconfigurable add-drop multiplexers

Optical add/drop multiplexers (OADMs), which allow traffic to bypass intermediate nodes, greatly reduce the cost of optical networks without the need to convert all channels into electronics. Reconfigurable OADM (ROADM) further allows convenient expansion of systems by providing desirable flexibility and reconfigurability as needed. It enables users to drop/add data from/to the network on top of the basic communication between networks. Many studies have been conducted on ROADMs for WDM system. For example, a compact ROADM was realized on silicon, which composed of two arrayed waveguide gratings and eight single-mode switches [129]. As for SDM network, Figure 7(d) shows a ROADM having four-mode channels realized by monolithically integrating a four-channel mode DEMUX, a switch array having four identical 2×2 single-mode switches, and a four-channel mode MUX [130]. Furthermore, a ROADM can be a charming solution for grooming data traffic to leverage potential SDM technique and successful WDM technique, as a ROADM for hybrid WDM-SDM systems as demonstrated in [131]. Any wavelength-mode channel can be added/dropped selectively to/from the multimode bus waveguide in the system.

6 High-speed modulators and photodetectors

Although modulators and photodetectors cannot work for HOMs directly, they play irreplaceable roles in a complete SDM system. In this section, recent progress on silicon-integrated modulators and photodetectors are summarized.

The MZI-based silicon optical modulators have achieved a commercial success. Nevertheless, long device lengths in the order of few millimeters are usually required. As a result, a relatively large loss and power consumption are introduced. Low power consumption modulators are highly desired for high-level of integration with numerous channels involved in the future. A resonant or slow light structure can efficiently decrease power consumption by reducing the footprint and/or drive voltage. Using an MRR-based modulator, 60 Gb/s on-off keying transmission was realized [132]. Ultralow power of 1 fJ/bit was also presented at a data rate of 25 Gb/s [133]. However, the issues of high temperature-dependence and narrow bandwidth are inevitable. On the other hand, the advanced modulation schemes such as pulsed amplitude modulation (PAM) and discrete multi-tone, are supported for the modulators [134, 135]. An ultrahigh-speed silicon modulator having 80 Gb/s PAM-4 was reported [135].

Germanium is considered as a representative material for optical detection due to the strong absorption in near-infrared wavelength range (up to ~1.55 μm) and CMOS compatible character germanium [136–140]. Many other materials are also demonstrated, including polycrystalline silicon [141–143], silicon germanium [144], III-V materials [145–147] and two-dimensional materials [148,149] based photodetectors.

To date, germanium photodetectors become one of the most mature devices in silicon photonics, offering comparable performance to their III-V counterparts. However, there are still some challenges to be solved, one of which is to reduce the dark current. Additionally, the co-integration of germanium photodetectors and silicon modulators on the same silicon substrate should also be optimized. The detector responsivity and bandwidth should also be enhanced. The state-of-the-art characteristics include a bandwidth higher than 67 GHz, responsivity higher than 1 A/W, and a dark current lower than 1 μA [136–139].

7 On-chip SDM circuits/systems

Optical interconnects featured with large bandwidth, low power consumption and multiplexing compatibility, have been a disruptive technology. They can be used in diverse scales such as intra-chip interconnects, short-reach communications in datacenters and high-performance computers, as well as long-haul communication networks. High-density photonic integration is the compromise for complexity, performance and power consumption. Multi-functional PICs have been developed to fulfill various communication applications. Over the last decade, there have been ongoing researches to develop and implement transmitting devices, switches, modulators, and detectors for inter-chip and intra-chip interconnect applications, including receivers [6, 150, 151], transmitters [7, 152, 153], and transceiver [154–158]. Figure 8(a) exhibits a 30 Gb/s SDM PIC link using three modes. Furthermore, a functionality of non-invasive monitoring for the SDM system was realized [157], as illustrated in Figure 8(b). By selectively extracting the incoming signals partially through the tunable wavelength and mode-dependent drop filter, the in-line and switchable monitor can discriminate the wavelength, mode and power information of the transmitted signals. However, all the reported PICs so far are restricted to WDM systems or small-scale SDM systems without reconfigurable design.

To achieve a multi-functional and high-density SDM system that supports flexible and reconfigurable operations, the aforementioned SDM devices can be integrated organically. In analogy with a multi-functional WDM system, an SDM system includes transmitters, switch fabrics and receivers. Figure 9 shows the prospect of a reconfigurable SDM system for intra-chip interconnect applications. At the transmitter node, the light from the laser diode is uniformly split into N channels on the FMs using a conventional power splitter. The subsequent modulators are used to independently modulate FM channels, which are then combined into a bus waveguide through the mode MUX. At the receiver terminal, the N-channel data are de-multiplexed and received by an array of photodetectors. The transmitters are connected to the receivers through a switch fabric and other connecting/transmission devices as mentioned in Section 4. The system can also be used for inter-chip optical interconnect (not shown here) through light coupling into/off the chip. For such an on-chip SDM system, it is possible to achieve one-stop solutions for multimode/multicore processing. However, it is not easy to handle more channels simultaneously on a chip, because the increased differences for mode confinement and property. Although the DEMUX-processing-MUX procedure mentioned in Subsection 5.1 can address more modes, it put forward higher requirements for the performances of mode (DE)MUXs in terms of mode crosstalk and insertion loss. The transmission difference including mode dispersion should also be considered, if more modes are utilized. Another challenge is the general architecture for SDM system that is not mature and standardized. Many basic devices and blocks should be redesigned especially for large-scale on-chip circuits Of course, the integration of light source on silicon chip together with other components is still challenging. A complete on-chip SDM system can be expected in the near future, if the aforementioned issues are properly solved.

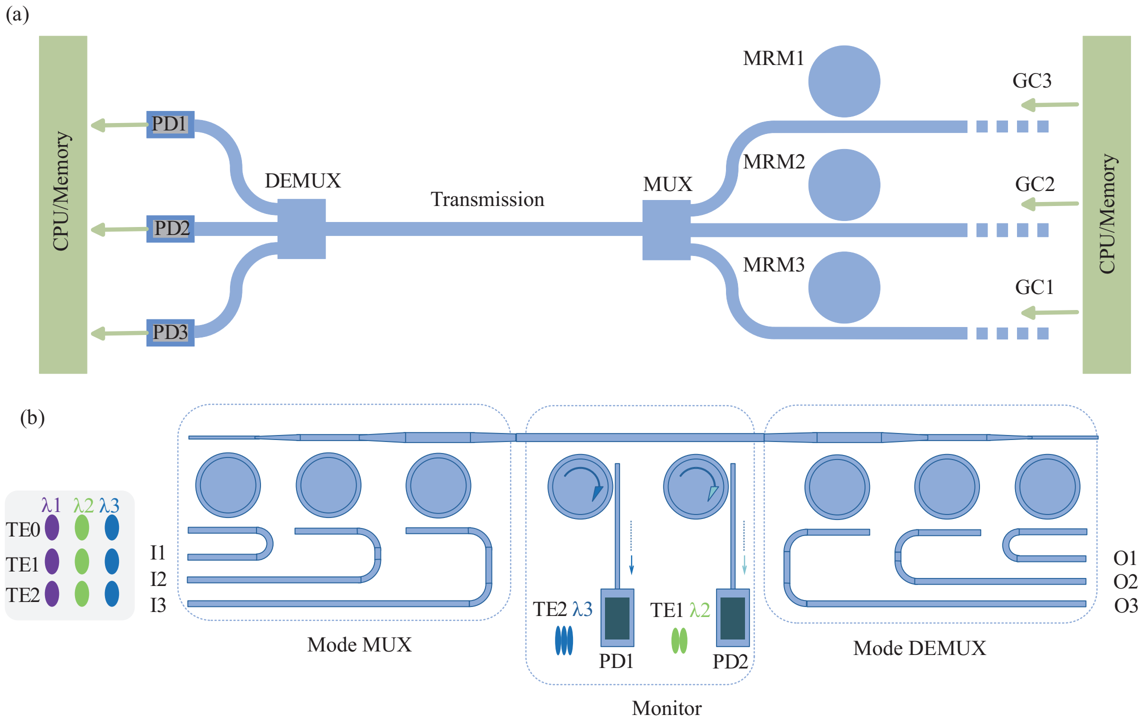

Figure 8 (Color online) (a) Three-channel multimode PIC [145]; (b) non-invasive monitor for three-channel multimode PIC [157].

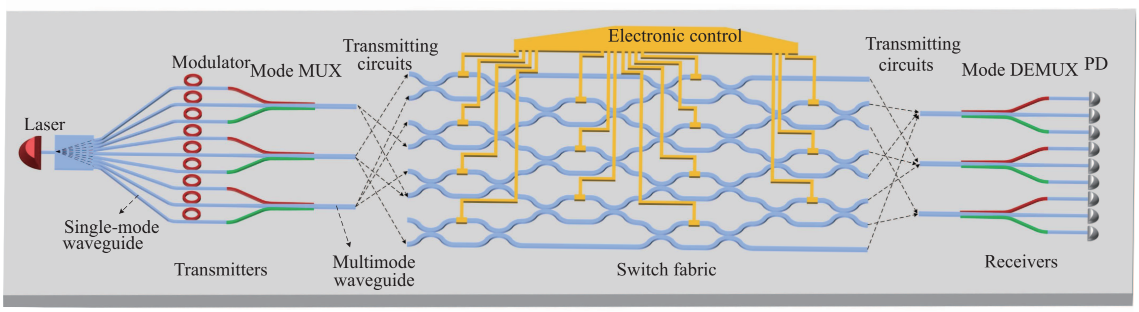

Figure 9 (Color online) Schematic of an on-chip reconfigurable SDM system.

8 Conclusion

In summary, this paper gives a review on recent achievements about multimode/multicore devices for a chip-scale SDM system. The fiber-chip couplers serve as bridges between chips and fibers for the SDM inter-chip interconnect applications. As the most crucial devices, the mode MUXs transfer data from multiple path channels to multiple mode channels, which can increase communication capacity of a single-wavelength link. After the mode MUX, the multiplexed signals usually cascaded by transmitting devices perform a series of subsequent operations such as power splitting, mode filtering, bending as well as crossing. The representatives such as multimode power splitters, mode filters, sharply bent waveguides as well as multimode waveguide crossings are discussed. When a switchable structure such as MZI or MRR is combined to construct a switch, the dynamic and flexible functionalities can be introduced to enhance the efficiency and throughput of the system. By controlling the state of the switch between “ON” and “OFF”, one can selectively route any desired channel. Also, the modulators and photodetectors for conversion between electrical and optical signals are reviewed. Finally, the complete PICs for chip-scale SDM system are discussed. As an outlook, a multi-functional on-chip SDM system which monolithically integrates diverse multimode/multicore devices is highly expected. A high-density integration and multi-functional SDM system will make the SDM technique more promising and practical.

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References

1 Shacham A, Bergman K, Carloni L P. Photonic networks-on-chip for future generations of chip multiprocessors. IEEE Trans Comput, 2008, 57: 1246–1260
2 Miller D. Device requirements for optical interconnects to silicon chips. Proc IEEE, 2009, 97: 1166–1185
3 Nagarajan R, Ziari M, Kato M, et al. Large-scale DWDM photonic integrated circuits. In: Proceedings of IEEE LEOS Annual Meeting Conference, Sydney, 2005
4 Jalali B, Fathpour S. Silicon photonics. J Lightwave Technol, 2006, 24: 4600–4615
5 Narasimha A, Analui B, Liang Y, et al. A fully integrated 4×10-Gb/s DWDM optoelectronic transceiver implemented in a standard 0.13 μm CMOS SOI technology. IEEE J Solid-State Circ, 2007, 42: 2736–2744
6 Doerr C R, Chen L, Buhl L L, et al. Eight-channel SiO_2/Si_3N_4/Si/Ge CWDM receiver. IEEE Photon Technol Lett, 2011, 23: 1201–1203
7 Gill D M, Xiong C, Proesel J E, et al. Demonstration of error-free 32-Gb/s operation from monolithic CMOS nanophotonic transmitters. IEEE Photon Technol Lett, 2016, 28: 1410–1413
8 Dong P, Lee J, Chen Y K, et al. Four-channel 100-Gb/s per channel discrete multitone modulation using silicon photonic integrated circuits. J Lightwave Technol, 2016, 34: 79–84
9 Boeuf F, Cremer S, Temporiti E, et al. Recent progress in silicon photonics R&D and manufacturing on 300 mm wafer platform. In: Proceedings of Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, 2015
10 Orcutt J, Gill D M, Proesel J E, et al. Monolithic silicon photonics at 25 Gb/s. In: Proceedings of Optical Fiber Communications Conference and Exhibition (OFC), Anaheim, 2016
11 Berdagué S, Facq P. Mode division multiplexing in optical fibers. Appl Opt, 1982, 21: 1950–1955
12 Murshid S H, Grossman B, Narakorn P. Spatial domain multiplexing: a new dimension in fiber optic multiplexing. Opt Laser Tech, 2008, 40: 1030–1036
13 Li G F. The future of space-division multiplexing and its applications. In: Proceedings of OptoElectronics and Communications Conference held jointly with International Conference on Photonics in Switching (OECC/PS), Kyoto, 2013
14 Sakaguchi J, Puttnam B, Klaus W, et al. 19-core fiber transmission of 19×100×172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s. In: Proceedings of Optical Fiber Communication Conference, Los Angeles, 2012
15 Koshiba M, Saitoh K, Kokubun Y. Heterogeneous multi-core fibers: proposal and design principle. IEICE Electron Express, 2009, 6: 98–103
16 Ryf R, Randel S, Gnauck A, et al. Space-division multiplexing over 10 km of three-mode fiber using coherent 6×6 MIMO processing. In: Proceedings of Optical Fiber Communication Conference, Los Angeles, 2011
17 Murshid S, Alanzi S, Hridoy A, et al. Combining spatial domain multiplexing and orbital angular momentum of photon-based multiplexing to increase the bandwidth of optical fiber communication systems. Opt Eng, 2016, 55: 066124
18 Murshid S, Iqbal J. Spatial combination of optical channels in a multimode waveguide. In: Proceedings of Frontiers in Optics, Rochester, 2010
19 Hsu R C J, Tarighat A, Shah A, et al. Capacity enhancement in coherent optical MIMO (COMIMO) multimode fiber links. IEEE Commun Lett, 2006, 10: 195–197
20 Tkach R W. Scaling optical communications for the next decade and beyond. Bell Labs Tech J, 2010, 14: 3–9
21 Lai Y X, Yu Y, Fu S N, et al. Efficient spot size converter for higher-order mode fiber-chip coupling. Opt Lett, 2017, 42: 3702–3705
22 Wohlfeil B, Rademacher G, Stamatiadis C, et al. A two-dimensional fiber grating coupler on SOI for mode division multiplexing. IEEE Photon Technol Lett, 2016, 28: 1241–1244
23 Yu Y, Ye M Y, Fu S N. On-chip polarization controlled mode converter with capability of WDM operation. IEEE Photon Technol Lett, 2015, 27: 1957–1960
24 Dai D X, Mao M. Mode converter based on an inverse taper for multimode silicon nanophotonic integrated circuits. Opt Express, 2015, 23: 28376–28388
25 Koonen A M L, Chen H S, van den Boom H P A, et al. Silicon photonic integrated mode multiplexer and demultiplexer. IEEE Photon Technol Lett, 2012, 24: 1961–1964

26 Ding Y H, Ou H Y, Xu J, et al. Silicon photonic integrated circuit mode multiplexer. IEEE Photon Technol Lett, 2013, 25: 648–651
27 Ding Y H, Yvind K. Efficient silicon PIC mode multiplexer using grating coupler array with aluminum mirror for few-mode fiber. In: Proceedings of Lasers and Electro-Optics (CLEO), San Jose, 2015
28 Wu Y F, Chiang K S. Ultra-broadband mode multiplexers based on three-dimensional asymmetric waveguide branches. Opt Lett, 2017, 42: 407–410
29 Riesen N, Gross S, Love J D, et al. Femtosecond direct-written integrated mode couplers. Opt Express, 2014, 22: 29855–29861
30 Dong J L, Chiang K S, Jin W. Mode multiplexer based on integrated horizontal and vertical polymer waveguide couplers. Opt Lett, 2015, 40: 3125–3128
31 Ding Y H, Ye F H, Peucheret C, et al. On-chip grating coupler array on the SOI platform for fan-in/fan-out of MCFs with low insertion loss and crosstalk. Opt Express, 2015, 23: 3292–3298
32 Riesen N, Gross S, Love J D, et al. Monolithic mode-selective few-mode multicore fiber multiplexers. Sci Rep, 2017, 7: 6971
33 van Uden R G H, Correa R A, Lopez E A, et al. Ultra-high-density spatial division multiplexing with a few-mode multicore fibre. Nat Photon, 2014, 8: 865–870
34 Qiu J F, Zhang D L, Tian Y, et al. Performance analysis of a broadband second-order mode converter based on multimode interference coupler and phase shifter. IEEE Photonics J, 2015, 7: 1–8
35 Li Y M, Li C, Li C B, et al. Compact two-mode (de)multiplexer based on symmetric Y-junction and multimode interference waveguides. Opt Express, 2014, 22: 5781–5786
36 Uematsu T, Ishizaka Y, Kawaguchi Y, et al. Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission. J Lightwave Technol, 2012, 30: 2421–2426
37 Greenberg M, Orenstein M. Simultaneous dual mode add/drop multiplexers for optical interconnects buses. Opt Commun, 2006, 266: 527–531
38 Dai D X, Wang J, Shi Y. Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light. Opt Lett, 2013, 38: 1422–1424
39 Ding Y H, Xu J, Da Ros F, et al. On-chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer. Opt Express, 2013, 21: 10376–10382
40 Luo L W, Ophir N, Chen C P, et al. WDM-compatible mode-division multiplexing on a silicon chip. Nat Commun, 2014, 5: 3069
41 Dorin B A, Ye W N. Two-mode division multiplexing in a silicon-on-insulator ring resonator. Opt Express, 2014, 22: 4547–4558
42 Yang Y D, Li Y, Huang Y Z, et al. Silicon nitride three-mode division multiplexing and wavelength-division multiplexing using asymmetrical directional couplers and microring resonators. Opt Express, 2014, 22: 22172–22183
43 Qiu H Y, Yu H, Hu T, et al. Silicon mode multi/demultiplexer based on multimode grating-assisted couplers. Opt Express, 2013, 21: 17904–17911
44 Davis J A, Grieco A, Souza M C, et al. Hybrid multimode resonators based on grating-assisted counter-directional couplers. Opt Express, 2017, 25: 16484–16490
45 Xing J J, Li Z Y, Yu Y D, et al. Design of polarization-independent adiabatic splitters fabricated on silicon-on-insulator substrates. Opt Express, 2013, 21: 26729–26734
46 Xing J J, Xiong K, Xu H, et al. Silicon-on-insulator-based adiabatic splitter with simultaneous tapering of velocity and coupling. Opt Lett, 2013, 38: 2221–2223
47 Xing J J, Li Z Y, Xiao X, et al. Two-mode multiplexer and demultiplexer based on adiabatic couplers. Opt Lett, 2013, 38: 3468–3470
48 Wang J, Xuan Y, Qi M H, et al. Broadband and fabrication-tolerant on-chip scalable mode-division multiplexing based on mode-evolution counter-tapered couplers. Opt Lett, 2015, 40: 1956–1959
49 Sun C L, Yu Y, Ye M Y, et al. An ultra-low crosstalk and broadband two-mode (de)multiplexer based on adiabatic couplers. Sci Rep, 2016, 6: 38494
50 Wang J, Deng S P, Wong C Y, et al. Monolithically integrated silicon hybrid demultiplexer with improved loss and crosstalk suppression. In: Proceedings of European Conference on Optical Communication, Gothenburg, 2017
51 Sun Y, Xiong Y, Ye W N. Experimental demonstration of a two-mode (de)multiplexer based on a taper-etched directional coupler. Opt Lett, 2016, 41: 3743–3746
52 Li C L, Dai D X. Low-loss and low-crosstalk multi-channel mode (de)multiplexer with ultrathin silicon waveguides. Opt Lett, 2017, 42: 2370–2373
53 Sun C L, Yu Y, Chen G Y, et al. Silicon mode multiplexer processing dual-path mode-division multiplexing signals. Opt Lett, 2016, 41: 5511–5514
54 Sun X, Liu H C, Yariv A. Adiabaticity criterion and the shortest adiabatic mode transformer in a coupled-waveguide

system. Opt Lett, 2009, 34: 280–282
55 Yariv A, Sun X K. Supermode Si/III-V hybrid lasers, optical amplifiers and modulators: a proposal and analysis. Opt Express, 2007, 15: 9147–9151
56 Driscoll J B, Grote R R, Souhan B, et al. Asymmetric Y-junctions in silicon waveguides for on-chip mode-division multiplexing. Opt Lett, 2013, 38: 1854–1856
57 Chen W W, Wang P J, Yang T J, et al. Silicon three-mode (de)multiplexer based on cascaded asymmetric Y-junctions. Opt Lett, 2016, 41: 2851–2854
58 Chen W W, Wang P J, Yang J Y. Optical mode interleaver based on the asymmetric multimode Y-junction. IEEE Photon Technol Lett, 2014, 26: 2043–2046
59 Chen W W, Wang P J, Yang J Y. Mode multi/demultiplexer based on cascaded asymmetric Y-junctions. Opt Express, 2013, 21: 25113–25119
60 Pan T H, Tseng S Y. Short and robust silicon mode (de)multiplexers using shortcuts to adiabaticity. Opt Express, 2015, 23: 10405–10412
61 Guo D F, Chu T. Silicon mode (de)multiplexers with parameters optimized using shortcuts to adiabaticity. Opt Express, 2017, 25: 9160–9170
62 Chung H C, Lee K S, Tseng S Y. Short and broadband silicon asymmetric Y-junction two-mode (de)multiplexer using fast quasiadiabatic dynamics. Opt Express, 2017, 25: 13626–13634
63 Chien K H, Yeih C S, Tseng S Y. Mode conversion/splitting in multimode waveguides based on invariant engineering. J Lightwave Technol, 2013, 31: 3387–3394
64 Martínez-Garaot S, Tseng S Y, Muga J G. Compact and high conversion efficiency mode-sorting asymmetric Y-junction using shortcuts to adiabaticity. Opt Lett, 2014, 39: 2306–2309
65 Tseng S Y, Wen R D, Chiu Y F, et al. Short and robust directional couplers designed by shortcuts to adiabaticity. Opt Express, 2014, 22: 18849–18859
66 Wang J, He S L, Dai D X. On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode- and polarization-division-multiplexing. Laser Photonic Rev, 2014, 8: 18–22
67 Wang J, Chen S T, Dai D X. Silicon hybrid demultiplexer with 64 channels for wavelength/mode-division multiplexed on-chip optical interconnects. Opt Lett, 2014, 39: 6993–6996
68 Dai D X, Li C L, Wang S P, et al. 10-channel mode (de)multiplexer with dual polarizations. Laser Photonic Rev, 2018, 12: 1700109
69 Dai D X, Wang J, Chen S T, et al. Monolithically integrated 64-channel silicon hybrid demultiplexer enabling simultaneous wavelength- and mode-division-multiplexing. Laser Photonic Rev, 2015, 9: 339–344
70 Chen K X, Wang S Y, Chen S T, et al. Experimental demonstration of simultaneous mode and polarization-division multiplexing based on silicon densely packed waveguide array. Opt Lett, 2015, 40: 4655–4658
71 Song W, Gatdula R, Abbaslou S, et al. High-density waveguide superlattices with low crosstalk. Nat Commun, 2015, 6: 7027
72 Yang N, Yang H S, Hu H R, et al. Theory of high-density low-cross-talk waveguide superlattices. Photon Res, 2016, 4: 233–239
73 Cerutti I, Andriolli N, Velha P. Engineering of closely packed silicon-on-isolator waveguide arrays for mode division multiplexing applications. J Opt Soc Am B, 2017, 34: 497–506
74 Tan K, Huang Y, Lo G Q, et al. Compact highly-efficient polarization splitter and rotator based on 90° bends. Opt Express, 2016, 24: 14506–14512
75 Dai D X, Bowers J E. Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler. Opt Express, 2011, 19: 18614–18620
76 Wu H, Tan Y, Dai D X. Ultra-broadband high-performance polarizing beam splitter on silicon. Opt Express, 2017, 25: 6069–6075
77 Zhang Y, He Y, Jiang X H, et al. Ultra-compact and highly efficient silicon polarization splitter and rotator. APL Photonics, 2016, 1: 091304
78 Xu H N, Shi Y C. Ultra-broadband 16-channel mode division (de)multiplexer utilizing densely packed bent waveguide arrays. Opt Lett, 2016, 41: 4815–4818
79 Xu H N, Shi Y C. Broadband nine-channel mode-division (de)multiplexer based on densely packed multimode waveguide arrays. J Lightwave Technol, 2017, 35: 4949–4953
80 Xu H N, Shi Y C. Ultra-broadband dual-mode 3 dB power splitter based on a Y-junction assisted with mode converters. Opt Lett, 2016, 41: 5047–5050
81 Luo Y C, Yu Y, Ye M Y, et al. Integrated dual-mode 3 dB power coupler based on tapered directional coupler. Sci Rep, 2016, 6: 23516
82 Atsumi Y, Kang J H, Hayashi Y, et al. Analysis of higher-order mode suppressed transmission in low-loss silicon multimode waveguides on silicon-on-insulator substrates. Jpn J Appl Phys, 2014, 53: 078002
83 Ahmmed K T, Chan H P, Li B. Broadband high-order mode pass filter based on mode conversion. Opt Lett, 2017,

42: 3686–3689
84 Guan X W, Ding Y H, Frandsen L H. Ultra-compact broadband higher order-mode pass filter fabricated in a silicon waveguide for multimode photonics. Opt Lett, 2015, 40: 3893–3896
85 Ríos C, Stegmaier M, Hosseini P, et al. Integrated all-photonic non-volatile multi-level memory. Nat Photon, 2015, 9: 725–732
86 Feldmann J, Stegmaier M, Gruhler N, et al. Calculating with light using a chip-scale all-optical abacus. Nat Commun, 2017, 8: 1256
87 Miller K J, Hallman K A, Haglund R F, et al. Silicon waveguide optical switch with embedded phase change material. Opt Express, 2017, 25: 26527–26536
88 Huang T Y, Pan Z P, Zhang M M, et al. Design of reconfigurable on-chip mode filters based on phase transition in vanadium dioxide. Appl Phys Express, 2016, 9: 112201
89 Xu Q F, Fattal D, Beausoleil R G. Silicon microring resonators with 1.5-μm radius. Opt Express, 2008, 16: 4309–4315
90 Gabrielli L H, Liu D, Johnson S G, et al. On-chip transformation optics for multimode waveguide bends. Nat Commun, 2012, 3: 1217
91 Dai D X. Multimode optical waveguide enabling microbends with low inter-mode crosstalk for mode-multiplexed optical interconnects. Opt Express, 2014, 22: 27524–27534
92 Sun C L, Yu Y, Chen G Y, et al. Ultra-compact bent multimode silicon waveguide with ultralow inter-mode crosstalk. Opt Lett, 2017, 42: 3004–3007
93 Callewaert F, Aydin K. Inverse-designed all-dielectric waveguide bend. In: Proceedings the 19th Annual Conference for Novel Optical Systems Design and Optimization, San Diego, 2016
94 Piggott A Y, Lu J, Lagoudakis K G, et al. Inverse design and demonstration of a compact and broadband on-chip wavelength demultiplexer. Nat Photon, 2015, 9: 374–377
95 Shen B, Wang P, Polson R C, et al. An integrated-nanophotonics polarization beamsplitter with 2.4×2.4 μm^2 footprint. Nat Photon, 2015, 9: 378–382
96 Mak J C C, Sideris C, Jeong J, et al. Binary particle swarm optimized 2×2 power splitters in a standard foundry silicon photonic platform. Opt Lett, 2016, 41: 3868–3871
97 Majumder A, Shen B, Polson R, et al. Ultra-compact polarization rotation in integrated silicon photonics using digital metamaterials. Opt Express, 2017, 25: 19721–19731
98 Xu K, Liu L, Wen X, et al. Integrated photonic power divider with arbitrary power ratios. Opt Lett, 2017, 42: 855–858
99 Piggott A Y, Petykiewicz J, Su L, et al. Fabrication-constrained nanophotonic inverse design. Sci Rep, 2017, 7: 1786
100 Liu V, Fan S H. Compact bends for multi-mode photonic crystal waveguides with high transmission and suppressed modal crosstalk. Opt Express, 2013, 21: 8069–8075
101 Chen H, Poon A W. Low-loss multimode-interference-based crossings for silicon wire waveguides. IEEE Photon Technol Lett, 2006, 18: 2260–2262
102 Bogaerts W, Dumon P, Thourhout D V, et al. Low-loss, low-cross-talk crossings for silicon-on-insulator nanophotonic waveguides. Opt Lett, 2007, 32: 2801–2803
103 Kim S H, Cong G W, Kawashima H, et al. Low-crosstalk waveguide crossing based on 1×1 MMI structure of silicon-wire waveguide. In: Proceedings of Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR), Kyoto, 2013
104 Zhang Y, Hosseini A, Xu X C, et al. Ultralow-loss silicon waveguide crossing using Bloch modes in index-engineered cascaded multimode-interference couplers. Opt Lett, 2013, 38: 3608–3611
105 Liu Y Y, Shainline J M, Zeng X G, et al. Ultra-low-loss CMOS-compatible waveguide crossing arrays based on multimode Bloch waves and imaginary coupling. Opt Lett, 2014, 39: 335–338
106 Xu H N, Shi Y C. Dual-mode waveguide crossing utilizing taper-assisted multimode-interference couplers. Opt Lett, 2016, 41: 5381–5384
107 Sun C L, Yu Y, Zhang X L. Ultra-compact waveguide crossing for a mode-division multiplexing optical network. Opt Lett, 2017, 42: 4913–4916
108 van Campenhout J, Green W M, Assefa S, et al. Low-power, 2×2 silicon electro-optic switch with 110-nm bandwidth for broadband reconfigurable optical networks. Opt Express, 2009, 17: 24020–24029
109 Dong P, Liao S R, Liang H, et al. Submilliwatt, ultrafast and broadband electro-optic silicon switches. Opt Express, 2010, 18: 25225–25231
110 Yang M, Green W M J, Assefa S, et al. Non-blocking 4×4 electro-optic silicon switch for on-chip photonic networks. Opt Express, 2011, 19: 47–54
111 Han S Y, Seok T J, Quack N, et al. Large-scale silicon photonic switches with movable directional couplers. Optica, 2015, 2: 370–375
112 Murray K, Lu Z Q, Jayatilleka H, et al. Dense dissimilar waveguide routing for highly efficient thermo-optic switches on silicon. Opt Express, 2015, 23: 19575–19585

113 Chen S T, Shi Y C, He S L, et al. Low-loss and broadband 2×2 silicon thermo-optic Mach-Zehnder switch with bent directional couplers. Opt Lett, 2016, 41: 836–839

114 Seok T J, Quack N, Han S, et al. Large-scale broadband digital silicon photonic switches with vertical adiabatic couplers. Optica, 2016, 3: 64–70

115 Wilkes C M, Qiang X, Wang J, et al. 60 dB high-extinction auto-configured Mach-Zehnder interferometer. Opt Lett, 2016, 41: 5318–5321

116 Nikolova D, Calhoun D M, Liu Y, et al. Modular architecture for fully non-blocking silicon photonic switch fabric. Microsyst Nanoeng, 2017, 3: 16071

117 Pérez D, Gasulla I, Crudgington L, et al. Multipurpose silicon photonics signal processor core. Nat Commun, 2017, 8: 636

118 Seok T J, Kopp V I, Neugroschl D, et al. High density optical packaging of high radix silicon photonic switches. In: Proceedings of Optical Fiber Communication Conference and Exhibition (OFC), Los Angeles, 2017

119 Sun C L, Yu Y, Chen G Y, et al. Integrated switchable mode exchange for reconfigurable mode-multiplexing optical networks. Opt Lett, 2016, 41: 3257–3260

120 Huang Q D, Jin W, Chiang K S. Broadband mode switch based on a three-dimensional waveguide Mach-Zehnder interferometer. Opt Lett, 2017, 42: 4877–4880

121 Ding Y H, Kamchevska V, Dalgaard K, et al. Reconfigurable SDM switching using novel silicon photonic integrated circuit. Sci Rep, 2016, 6: 39058

122 Wu X R, Xu K, Dai D X, et al. Mode division multiplexing switch for on-chip optical interconnects. In: Proceedings of OptoElectronics and Communications Conference (OECC), Niigata, 2016

123 Stern B, Zhu X L, Chen C P, et al. On-chip mode-division multiplexing switch. Optica, 2015, 2: 530–535

124 Zhang Y, Zhu Q M, He Y, et al. Silicon 1×2 mode- and polarization-selective switch. In: Proceedings of Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, 2017

125 Jia H, Zhou T, Zhang L, et al. Optical switch compatible with wavelength division multiplexing and mode division multiplexing for photonic networks-on-chip. Opt Express, 2017, 25: 20698–20707

126 Chan W Y, Chan H P. Reconfigurable two-mode mux/demux device. Opt Express, 2014, 22: 9282–9290

127 Sun C L, Yu Y, Chen G Y, et al. On-chip switch for reconfigurable mode-multiplexing optical network. Opt Express, 2016, 24: 21722–21728

128 Xiong Y L, Priti R B, Liboiron L O. High-speed two-mode switch for mode-division multiplexing optical networks. Optica, 2017, 4: 1098–1102

129 Chen S T, Shi Y C, He S L, et al. Compact eight-channel thermally reconfigurable optical add/drop multiplexers on silicon. IEEE Photon Technol Lett, 2016, 28: 1874–1877

130 Wang S P, Wu H, Tsang H K, et al. Monolithically integrated reconfigurable add-drop multiplexer for mode-division-multiplexing systems. Opt Lett, 2016, 41: 5298–5301

131 Wang S P, Feng X L, Gao S M, et al. On-chip reconfigurable optical add-drop multiplexer for hybrid wavelength/mode-division-multiplexing systems. Opt Lett, 2017, 42: 2802–2805

132 Xiao X, Xu H, Li X Y, et al. 60 Gbit/s silicon modulators with enhanced electro-optical efficiency. In: Proceedings of Optical Fiber Communication Conference and Exposition (OFC), Anaheim, 2013

133 Timurdogan E, Sorace-Agaskar C M, Sun J, et al. An ultralow power athermal silicon modulator. Nat Commun, 2014, 5: 4008

134 Xiong C, Gill D M, Proesel J E, et al. Monolithic 56 Gb/s silicon photonic pulse-amplitude modulation transmitter. Optica, 2016, 3: 1060–1065

135 Dubé-Demers R, LaRochelle S, Shi W. Ultrafast pulse-amplitude modulation with a femtojoule silicon photonic modulator. Optica, 2016, 3: 622–627

136 Vivien L, Polzer A, Marris-Morini D, et al. Zero-bias 40 Gbit/s germanium waveguide photodetector on silicon. Opt Express, 2012, 20: 1096–1101

137 DeRose C T, Trotter D C, Zortman W A, et al. Ultra compact 45 GHz CMOS compatible Germanium waveguide photodiode with low dark current. Opt Express, 2011, 19: 24897–24904

138 Chen G Y, Yu Y, Deng S P, et al. Bandwidth improvement for germanium photodetector using wire bonding technology. Opt Express, 2015, 23: 25700–25706

139 Chen G Y, Yu Y, Xiao X, et al. High speed and high power polarization insensitive germanium photodetector with lumped structure. Opt Express, 2016, 24: 10030–10039

140 Michel J, Liu J, Kimerling L C. High-performance Ge-on-Si photodetectors. Nat Photon, 2010, 4: 527–534

141 Logan D F, Velha P, Sorel M, et al. Defect-enhanced silicon-on-insulator waveguide resonant photodetector with high sensitivity at 1.55 μm. IEEE Photon Technol Lett, 2010, 22: 1530–1532

142 Preston K, Lee Y H D, Zhang M, et al. Waveguide-integrated telecom-wavelength photodiode in deposited silicon. Opt Lett, 2011, 36: 52–54

143 Mehta K K, Orcutt J S, Shainline J M, et al. Polycrystalline silicon ring resonator photodiodes in a bulk comple-

mentary metal-oxide-semiconductor process. Opt Lett, 2014, 39: 1061–1064
144 Alloatti L, Ram R J. Resonance-enhanced waveguide-coupled silicon-germanium detector. Appl Phys Lett, 2016, 108: 071105
145 Brouckaert J, Roelkens G, Van Thourhout D, et al. Thin-film III-V photodetectors integrated on silicon-on-insulator photonic ICs. J Lightwave Technol, 2007, 25: 1053–1060
146 Park H, Fang A W, Jones R, et al. A hybrid AlGaInAs-silicon evanescent waveguide photodetector. Opt Express, 2007, 15: 6044–6052
147 Ng D K T, Wang Q, Pu J, et al. Demonstration of heterogeneous III-V/Si integration with a compact optical vertical interconnect access. Opt Lett, 2013, 38: 5353–5356
148 Koppens F H L, Mueller T, Avouris P, et al. Photodetectors based on graphene, other two-dimensional materials and hybrid systems. Nat Nanotech, 2014, 9: 780–793
149 Bie Y Q, Grosso G, Heuck M, et al. A $MoTe_2$-based light-emitting diode and photodetector for silicon photonic integrated circuits. Nat Nanotech, 2017, 12: 1124–1129
150 Dong P, Xie C J, Buhl L L. Monolithic polarization diversity coherent receiver based on 120-degree optical hybrids on silicon. Opt Express, 2014, 22: 2119–2125
151 Doerr C R, Winzer P J, Chen Y K, et al. Monolithic polarization and phase diversity coherent receiver in silicon. J Lightwave Technol, 2010, 28: 520–525
152 Ding R, Liu Y, Li Q, et al. A compact low-power 320-Gb/s WDM transmitter based on silicon microrings. IEEE Photonic J, 2014, 6: 1–8
153 Gill D M, Proesel J E, Xiong C, et al. Demonstration of a high extinction ratio monolithic CMOS integrated nanophotonic transmitter and 16 Gb/s optical link. IEEE J Sel Top Quant Electron, 2015, 21: 212–222
154 Chen K X, Huang Q S, Zhang J H, et al. Wavelength-multiplexed duplex transceiver based on III-V/Si hybrid integration for off-chip and on-chip optical interconnects. IEEE Photonic J, 2016, 8: 1–10
155 Zhang C, Zhang S J, Peters J D, et al. 8×8×40 Gbps fully integrated silicon photonic network on chip. Optica, 2016, 3: 785–786
156 Chen G Y, Yu Y, Zhou D, et al. Three modes multiplexed photonic integrated circuit for large capacity optical interconnection. In: Proceedings of Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, 2017
157 Chen G Y, Yu Y, Ye M Y, et al. Switchable in-line monitor for multi-dimensional multiplexed photonic integrated circuit. Opt Express, 2016, 24: 14841–14850
158 Wu X R, Huang C R, Xu K, et al. 3×104 Gb/s single-λ interconnect of mode-division multiplexed network with a multicore fiber. J Lightwave Technol, 2018, 36: 318–324