Review article

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Multimode silicon photonics

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Abstract: Multimode silicon photonics is attracting more and more attention because the introduction of higher-order modes makes it possible to increase the channel number for data transmission in mode-division-multiplexed (MDM) systems as well as improve the flexibility of device designs. On the other hand, the design of multimode silicon photonic devices becomes very different compared with the traditional case with the fundamental mode only. Since not only the fundamental mode but also the higher-order modes are involved, one of the most important things for multimode silicon photonics is the realization of effective mode manipulation, which is not difficult, fortunately because the mode dispersion in multimode silicon optical waveguide is very strong. Great progresses have been achieved on multimode silicon photonics in the past years. In this paper, a review of the recent progresses of the representative multimode silicon photonic devices and circuits is given. The first part reviews multimode silicon photonics for MDM systems, including on-chip multichannel mode (de)multiplexers, multimode waveguide bends, multimode waveguide crossings, reconfigurable multimode silicon photonic integrated circuits, multimode chip-fiber couplers, etc. In the second part, we give a discussion about the higher-order mode-assisted silicon photonic devices, including on-chip polarization-handling devices with higher-order modes, add-drop optical filters based on multimode Bragg gratings, and some emerging applications.

Keywords: multimode; multiplexing; waveguide; silicon.

1 Introduction

In the past decade, silicon photonics has been developed very successfully and become very promising for various applications due to its unique advantages [1–7]. First, silicon has a very wide transparent window covering the wavelength range from near-infrared to mid-infrared light, which is important to achieve low-loss on-chip optical waveguides [8–12]. Second, there is an ultra-high index contrast between the silicon core and the silica (or air) cladding, which makes it possible to realize ultracompact photonic integrated devices and, thus, ultradense photonic integrated circuits (PICs). The footprint compactness is very helpful in reducing power consumption for active silicon photonic devices. Third, silicon photonics is compatible with the fabrication process of complementary metal-oxide-semiconductor (CMOS). As one of the most important advantages, the CMOS compatibility enables the reduction of the fabrication cost for silicon photonic devices. Currently, various silicon photonic devices and circuits have been demonstrated with high performances [13–20].

One might notice that most PICs are usually designed with the fundamental mode only, since higher-order modes are usually quite annoying due to the unacceptable crosstalk and loss caused by the multimode interference (MMI) [21, 22]. Therefore, optical waveguides are usually designed to be single mode according to the single-mode condition, so that higher-order modes are cut off. Currently, the situation is changing with the development of silicon photonics, which has some unique properties due to its ultra-high index contrast [23, 24]. From Figure 1A, which shows the dispersion curves for a typical silicon-on-insulator (SOI) strip nanowire with a 220-nm-thick top-silicon layer, it can be seen that SOI strip nanowires usually have ultrahigh birefringence and very strong mode dispersion. As a result, it is possible to realize mode-selective manipulation with low excess losses and low intermode crosstalk for all the guided modes in a multimode SOI waveguide even though these guided modes are overlapped in space, as shown in Figure 1B. This opens the door for utilizing higher-order modes in the design of silicon photonic devices by introducing multimode optical waveguides. The introduction of higher-order modes makes it possible to enable

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Figure 1: Mode properties of an SOI strip nanowire with $h_{\text{co}} = 220 \text{ nm}$.

(A) Calculated effective indices of the guided-modes. (B) Mode profiles for the fundamental and higher-order modes.

mode-division-multiplexing (MDM), which is a kind of space-division-multiplexed (SDM) for enhancing the link capacity of data transmissions with multiple mode-channels [24]. Another option for SDM is using dense optical waveguide arrays, as demonstrated in [25–27], which could be useful for data transmissions as well as other applications. In the past years, SDM optical communication systems have also been demonstrated with few-mode fibers and multicore fibers [28–33]. In addition to being useful for MDM systems, the introduction of higher-order modes also enhances the flexibility of device designs and helps to realize ultracompact photonic devices [24].

As a result, multimode silicon photonics has been attracting more and more attention in recent years [17–20]. For example, people have developed various multimode silicon photonics for MDM systems, including on-chip multichannel mode (de)multiplexers [34–89], multimode waveguide bends [90–104], multimode waveguide crossings [105–114], reconfigurable multimode silicon PICs [115–149], multimode chip-fiber couplers [29, 36, 150–163], etc. With these multimode silicon photonic devices, low-loss and low-crosstalk light manipulation with multiple mode-channels has been demonstrated for MDM systems. In addition, multimode optical waveguides with higher-order modes are also introduced for the realization of some special silicon photonic devices, which cannot be realized with the fundamental mode only. For example, high-performance on-chip polarization-handling devices with higher-order modes [164–189] and on-chip add-drop optical filters based on multimode Bragg gratings [190, 191] have been demonstrated. Some emerging applications with higher-order modes have also been reported recently [192–197].

In this paper, a review is given for recent progresses in representative multimode silicon photonic devices and circuits, including two parts. One is for multimode

silicon photonics for MDM systems, and the other is for higher-order mode-assisted silicon photonic devices. In Section 2, we give a review of multimode silicon photonics for MDM systems, including on-chip multichannel mode (de)multiplexers in Section 2.1, multimode waveguide bends in Section 2.2, multimode waveguide crossings in Section 2.3, reconfigurable multimode silicon PICs in Section 2.4, and multimode chip-fiber couplers in Section 2.5. In Section 3, we give a review of the higher-order mode-assisted silicon photonic devices, including on-chip polarization-handling devices with higher-order modes in Section 3.1, on-chip add-drop optical filters based on multimode Bragg gratings in Section 3.2, and some emerging applications in Section 3.3.

2 Silicon multimode photonics for MDM systems

In order to satisfy the enormous demand of ultra-high-link capacity in various scales of optical networks, advanced (de)multiplexing technologies have been developed successfully with great efforts, and huge-data transmissions have been achieved with many channels in parallel [9, 10]. As is well known, wavelength-division multiplexing (WDM) [11–14] and polarization-division multiplexing (PDM) [15] have been used very widely as mature technologies. Recently, MDM appears to provide a new approach for achieving more channels and enhancing the link capacity with a single wavelength carrier [60]. In MDM systems, signals are carried by multiple guided modes in a multimode bus waveguide. This involvement of the higher-order modes in MDM systems makes the situation very different and there are several major challenges for the development of MDM systems.

The first one is developing low-loss and low-crosstalk on-chip multichannel mode (de)multiplexers in order to realize efficient combination/separation of the signals carried by different mode-channels in MDM systems. Currently, various on-chip mode (de)multiplexers have been developed by using different silicon photonic structures [36–63], which is reviewed in detail in Section 2.1. The second one is achieving sharp multimode waveguide bends enabling low-loss and low-crosstalk transmissions with multiple mode-channels. There are several promising approaches that have been reported recently [90–104] and a discussion is given in Section 2.2. The third one is low-loss and low-crosstalk multimode waveguide crossings, which are usually indispensable for complicated PICs. Recent progresses on the multimode waveguide crossings on silicon are reviewed in Section 2.3. In order to enable intelligent and efficient optical networks, it is desired to develop reconfigurable multimode silicon photonics, which is discussed in Section 2.4. Finally, it is still a big challenge to build the connection between a few-mode fiber and a multimode silicon nanophotonic waveguide for MDM systems. The multimode fiber-chip couplers developed recently will be reviewed in Section 2.5.

2.1 On-chip multichannel mode (de)multiplexers

An on-chip multichannel mode (de)multiplexer is one of the most important elements in MDM systems. Many years ago, on-chip multichannel mode (de)multiplexers based on low- Δ optical waveguides were proposed with adiabatic Y-branches [17, 18, 34], which are very long to vary very gradually so that no power coupling happens between the guided-modes [17]. For the designed four-channel mode (de)multiplexer [18], the device length is about 50 mm, while the excess loss is about 0.1 dB and the intermode crosstalk is about -18 dB for the central wavelength of $1.5 \mu\text{m}$ in theory. For the fabricated four-channel mode (de)multiplexer demonstrated in [34], the device length is about 10 mm while the measured excess loss is about

1.5 dB and the intermode crosstalk is about -10.2 dB for a central wavelength of $1.55 \mu\text{m}$. The situation changed significantly when silicon photonics was introduced because silicon nanophotonic waveguides have very strong mode dispersion, which greatly for minimizing intermode coupling and improving mode selectivity. In the past years, various silicon-based on-chip (de)multiplexers have been demonstrated by utilizing e.g. multimode interferometers [36–39], asymmetric Y-junctions [41–47], adiabatic tapers [48–58], asymmetric directional couplers (ADCs) [59–66], grating-assistant couplers [67], etc. Some of them have high mode-channel number and high performances owing to the smart structural designs as well as advanced fabrication techniques. In principle, these devices can be divided into three categories.

The first type of mode (de)multiplexers is using the MMI in multimode sections. MMI happens when multiple guided modes in a multimode section are excited by the launched field at the input waveguide, and N-fold self-imaging can be achieved by choosing the length of the multimode section appropriately [35]. Figure 2 shows examples of the MMI-based mode (de)multiplexer [36–39]. For example, a four-channel mode (de)multiplexer for transverse electric (TE) mode polarization was proposed by using complicated MMI sections in cascaded, as proposed in [36]. This mode (de)multiplexer combines four key elements, i.e. mode separating/superposing sections, profile combining/dividing sections, image reversal sections, and phase shifting sections. For the designed four-channel mode (de)multiplexers, the excess loss is about 0.2 dB and the intermode crosstalk is about -20 dB for the central wavelength in theory. However, the device is pretty long even when used with high- Δ optical waveguides, and this design is inflexible to be extended. Recently, in [37], a two-channel mode (de)multiplexer on silicon was proposed by integrating an MMI-based mode converter-splitter (MCS), a butterfly-shape tapered phase shifter (PS), and 3-dB MMI coupler, as shown in Figure 2A. For the designed two-channel mode (de)multiplexer, the device length is less than $80 \mu\text{m}$, while the excess loss is less than 1 dB and the intermode crosstalk is less than -17 dB over

Figure 2: Examples of the MMI-based mode (de)multiplexer.

(A) A two-channel MMI-based mode (de)multiplexer consisting of an MCS, a butterfly-shape tapered PS, and a 3 dB MMI coupler [37].

(B) A two-channel mode (de)multiplexer based on a symmetric Y-junction and MMI waveguide [38]. A two-channel mode (de)multiplexer based on MMI couplers with a tilted joint [39].

the wavelength range from 1520 nm to 1580 nm. In order to simplify the design and improve the performance, a novel structure consisting of a symmetric Y-junction, tapered PSs, and a 2×2 MMI coupler was proposed [38], as shown in Figure 2B. The simulation results show that the designed device has excess losses of <0.3 dB and intermode crosstalk of <-22 dB in the broad band from 1500 nm to 1600 nm. In order to further increase the bandwidth, more recently, a subwavelength engineered MMI coupler was introduced to replace the conventional one and an ultra-broadband mode (de)multiplexer was designed in theory [40]. For the designed mode (de)multiplexer, the overall footprint is $36 \mu\text{m} \times 3.7 \mu\text{m}$, while the excess loss is <0.84 dB and the crosstalk is <-20 dB over an ultrabroad bandwidth of 300 nm (1.4–1.7 μm). In [39], another two-channel mode (de)multiplexer was proposed by using an angled MMI section with a tilted joint as the PS, as shown in Figure 2C. With the designed device with a length of 39.5 μm , the crosstalk is lower than -28 dB and the excess loss is <1.0 dB in the C-band. Unfortunately, these designed mode (de)multiplexers on silicon are still difficult to be extended for the case with more than two mode-channels and there have not been experimental results reported until now.

The second type of mode (de)multiplexers is based on the mode evolution in an adiabatic structure [17, 18], which is usually long but potentially have advantages of broad bandwidth. For example, in [40], a two-channel mode (de)multiplexer based on an asymmetric Y-junction on silicon was demonstrated with a large footprint of $>100 \mu\text{m}$ and intermode crosstalk of about -9 dB in the C band. This asymmetric Y-junction is long enough to be adiabatic, while the high crosstalk is mainly due to the nonperfect tiny gap in asymmetric Y-junction. Therefore, the fabrication should be very careful for asymmetric Y-junctions [41]. It is possible to achieve high performance (e.g. low loss and low crosstalk in a broad band) when the fabrication is improved. Furthermore, asymmetric Y-junctions can be easily cascaded in parallel [41] or in series [42, 43] to achieve more than two channels, as shown in

Figure 3A and B). In [43], the demonstrated three-channel mode multiplexer has excess losses of 3.3–5.7 dB and intermode crosstalk of <-9.7 dB in a bandwidth from 1537 nm to 1566 nm. Some other structures based on Y-junctions have also been proposed by introducing some special structures, such as MMIs [40], adiabatic tapers [44], and subwavelength structures [45], so that it is possible to realize compact footprints or relax the fabrication.

Adiabatic dual-core tapers in cascade have also been used for realizing multichannel mode multiplexers [46–56]. In this case, the gap between the dual cores can be chosen to be large enough. As a consequence, the fabrication becomes easier than that for Y-junctions. In [46], a mode (de)multiplexer was demonstrated by using tapered mode-evolution couplers consisting of dual cores with a 160-nm-wide gap. The realized three-channel mode (de)multiplexer has intermode crosstalk of about -13 dB (around 1550 nm) and excess losses of about 10 dB. Later, a multichannel mode (de)multiplexer with cascaded dual-core adiabatic tapers was demonstrated with ultrathin (~ 50 nm) silicon nanophotonic waveguides [49]. A three-channel mode (de)multiplexer was designed with a 150-nm-wide gap, and the fabricated device has intermode crosstalk of <-20 dB and an excess loss of <0.2 dB in a bandwidth of ~ 65 nm. Recently, the scheme of shortcuts to adiabaticity (STA) was proposed as a novel approach for the design of adiabatic tapers for on-chip mode (de)multiplexers [50–55]. In 2017, a four-channel mode (de)multiplexer with cascade STA tapers was designed and fabricated [55], as shown in Figure 4A. In this design, the bus waveguide has a uniform core width, while the width of the gap between the access and bus waveguides increases gradually with a minimum of 160 nm along the propagation direction. Any one of the STA tapers is as long as 100 μm to be adiabatic and the device works with excellent performance. For the realized four-channel mode (de)multiplexer, the excess loss for the conversion of TE_0 - TE_i - TE_0 ($i=0, 1, 2, 3$) is lower than 1.3 dB, while the intermode crosstalk is <-24 dB in the wavelength range from 1500 nm to 1600 nm. More recently, a

Figure 3: On-chip mode (de)multiplexers based on the mode evolution in an adiabatic waveguide structure. (A) An adiabatic Y-junction cascaded in parallel [43]. (B) An adiabatic Y-junction cascaded in series [45].

Figure 4: On-chip mode (de) multiplexers based on adiabatic waveguide structures.

(A) Schematic configuration of an STA taper for mode (de) multiplexers [57]. (B) Schematic configuration of a 10-channel mode (de) multiplexer with dual polarizations based on cascaded dual-core adiabatic tapers [58].

10-channel mode (de)multiplexer with dual polarizations was proposed and realized with cascaded dual-core adiabatic tapers for the first time [56], as shown in Figure 4B. The gap width is chosen as 150 nm regarding the requirement of the fabrication process. In this design, there are five stages of dual-core adiabatic tapers in cascade, and one can extract the desired highest-order modes of TE- and transverse magnetic (TM)-polarizations simultaneously at any stage. These two extracted mode-channels are then separated by using a polarization beam splitter (PBS). For this 10-channel mode (de)multiplexer, the measurement results show that all TM and TE mode-channels have low crosstalk ($-15 \sim -25$ dB) and low excess losses (0.2~1.8 dB) over a broad wavelength band of ~ 90 nm, which makes it WDM compatible and thus suitable for high capacity on-chip optical interconnects.

The third type of mode (de)multiplexers is based on cascaded ADCs consisting of two nonidentical waveguides in the coupling region [57–64], as shown in Figure 5. The scheme utilizes the mode-selective coupling of ADCs whose core widths are designed according to the phase matching condition [57, 58]. One should optimize the width of the i th straight section so that the fundamental mode of the narrow access waveguide and the i th higher-order mode in the bus waveguide have the same effective indices. In this way, one can achieve highly mode-selective coupling in an ADC. In comparison with the former two types of structures (i.e. MMI structures, adiabatic structures), the ADC-based structure has the advantages of compact footprints and easy design. In addition, it is flexible to be extended for multiple mode-channels [59]. Meanwhile, one should realize that the fabrication tolerance is not large because the evanescent

coupling is usually sensitive to the random variation of the waveguide core. Fortunately, the tapers in the cascaded ADCs greatly help remove the undesired higher-order modes, in which way the multichannel mode (de)multiplexer still has pretty low intermode crosstalk. For example, a low-loss (<1 dB) and low-crosstalk (<-23 dB) four-channel mode (de)multiplexer was proposed and demonstrated, as shown in Figure 5. More recently, an ADC consisting of a silicon hybrid plasmonic waveguide between two SOI waveguides was proposed to realize a very compact two-channel mode (de)multiplexer [62, 63]. For the designed device [63], the length of the coupling region in the ADC is $7.5 \mu\text{m}$, and the extinction ratio is >15 dB over the full C-band. The compactness of the device helps achieve an acceptably low excess loss of 0.32 dB at a central wavelength of 1550 nm even when there is some metal absorption.

Table 1 gives a summary for the reported on-chip mode (de)multiplexers. As demonstrated above, it is possible to realize high-performance multichannel mode (de)multiplexers with low losses and low crosstalk in a broad bandwidth. This makes it possible to further develop hybrid (de)multiplexers to enable MDM-WDM or MDM-PDM simultaneously [68–81]. For hybrid MDM-WDM (de)multiplexers, one can integrate mode (de)multiplexers with arrayed-waveguide gratings (AWGs) [1, 71] or microring resonators (MRRs) [73–78]. In [1], the realized hybrid MDM-WDM (de)multiplexer on silicon consists of a four-channel ADC-based mode (de)multiplexer and two bidirectional 17×17 AWG demultiplexers. The intermode crosstalk is about $-16 \sim -25$ dB in a broad wavelength band, while the crosstalk between the (non)adjacent wavelength-channels is ~ -14 dB. This has well proved that the mode (de)multiplexers can work well with WDM. Hybrid WDM-MDM (de)multiplexers have also been realized by integrating mode multiplexers and bidirectional MRRs [73–78]. In [73], a WDM-compatible MDM multiplexer was proposed and demonstrated, in which single-mode MRRs were coupled selectively to the different spatial modes in a multimode waveguide. The interchannel crosstalk is $-18 \sim -22$ dB and the excess losses is about 1.5 dB. Recently, a 32-channel hybrid MDM-WDM demultiplexer

Figure 5: A four-channel mode (de)multiplexer based on cascaded ADCs [60].

Table 1: Summary of the mode (de)multiplexers reported.

Ref.	Year	L (μm)	EL (dB)	CT (dB)	$\text{BW}_{\text{CT} < -15 \text{ dB}}$ (nm)	N_{ch}	Structure	E/T
[49]	2013	300	~ 0.5	~ -36	> 100	2	Adiabatic	E
[59]	2013	50	~ 0.3	-16	> 100	2	ADC	E
[61]	2013	~ 100	~ 0.5	-23	~ 70	4	ADC	E
[45]	2013	320	$3.3 \sim 5.7$	$-9.7 \sim -30$	~ 25	3	Y-branch	E
[48]	2015	520	~ 10	$-11 \sim -26$	~ 200	3	Adiabatic	E
[51]	2017	310	~ 0.2	$-18 \sim -33$	~ 80	3	Adiabatic	E
[46]	2017	200	< 1.9	< -19	80	2	Y-branch	E
[47]	2018	5	< 2.5	-19	> 60	3	Y-junction	E
[57]	2017	~ 450	1.3	-20	~ 100	4	Adiabatic	E
[80]	2014	~ 200	$0.2 \sim 3.5$	-20	~ 100	8	ADC	E
[58]	2017	~ 500	$0.2 \sim 1.8$	-15 to 25	~ 90	10	Adiabatic	E
[37]	2012	~ 80	1	-40	~ 50	2	MMI	T
[67]	2013	~ 500	$0.2 \sim 0.34$	-18	/	3	ADC-Grating	T
[65]	2018	7.5	0.32	-30	90	2	ADC	T

E, experiment; T, theory.

was realized by integrating a four-channel mode demultiplexer and two bidirectional MRR-based WDM filters with eight wavelength channels. The excess loss is $0.5 \sim 5$ dB, the intermode crosstalk is $-16.5 \sim -23.5$ dB, while the crosstalks between the adjacent and nonadjacent wavelength channels are about -25 dB and -35 dB, respectively [78].

2.2 Sharp multimode waveguide bends

It is well known that waveguide bends are usually inevitable for building PICs. For single-mode silicon nanophotonic waveguides, one can achieve extremely sharp bends ($\sim$ several microns) with a low loss due to the ultra-high-index contrast [86–89]. However, when multimode optical waveguides are bended sharply, there might be significant mode mismatch between a straight section and a bent section because the modal fields in the bend become distorted significantly [90]. As a consequence, the intramode mismatching and the intermode coupling occur when light propagates along a multimode straight waveguide connected to a multimode bent waveguide with a sharp bending radius R . This introduces some significant mode-mismatching loss as well as intermode crosstalk. Therefore, usually, the bending radius should be chosen as large as e.g. millimeters when using a regular arc-bend for a wide multimode waveguide (e.g. $w_{\text{co}} = 4 \mu\text{m}$ in [20]). In order to achieve sharp multimode bends, a kind of vertical multimode waveguide supporting multiple modes in the vertical direction was proposed to achieve a sharp bend (e.g. $R \sim 5 \mu\text{m}$), enabling low losses and low crosstalks [91]. However, this does not work for the case with a thin top-silicon layer, e.g. $h_{\text{co}} = 220$ nm, which has been used extensively.

Alternatively, a possible approach is using a special bent section whose *curvature* varies from zero to a given value gradually, in which way the guided modes in the bent section can be converted gradually with negligible mode distortion [92]. This idea was used for single-mode waveguide bends previously [88], and some impressive results were also reported for multimode waveguide bends recently. For example, in [93], a 90° bend for multimode waveguides with three quasi-TE modes by utilizing the design with Bezier curve was proposed, and in theory, the crosstalk is less than -23 dB over the wavelength range from 1520 nm to 1580 nm when $R = 20 \mu\text{m}$. In [94], a 90° bend for multimode waveguide was realized by using modified Euler curves, as shown in Figure 6. For the modified Euler curve, the curvature linearly increases from a small value to a large one [88, 89]. Figure 7A–D shows the

Figure 6: A 90° Euler-bend composed of a pair of 45° modified Euler-curves with a maximum curvature radius R_{max} at the starting point $(0, 0)$ and a minimum curvature radius R_{min} at the end point (x_E, y_E) [94].

Figure 7: Simulated light propagation in the designed Euler-bend with $R_{\text{eff}} = 45 \mu\text{m}$ (A–D) and a regular arc-bend with $R = 45 \mu\text{m}$ (E–H) when the TM_i mode of a straight waveguide is launched [94].

simulated light propagation in the designed Euler bend with an effective radius $R_{\text{eff}} = 45 \mu\text{m}$ when the TM_0 , TM_1 , TM_2 , and TM_3 modes of a straight waveguide are launched from the input port respectively. As shown in Figure 7A–D, no MMI is observed in the Euler bend. In contrast, serious MMI happens in the case with a regular arc-bend with a radius of $R = 45 \mu\text{m}$, as shown in Figure 7E–H. This indicates that more than one mode are excited in the regular 90° arc bend, and thus, significant undesired excess losses and crosstalks are introduced. As demonstrated in [94], the measurement results show that the fabricated Euler S-bend has low excess losses of $<0.5 \text{ dB}$ and low intermode crosstalk of $<-20 \text{ dB}$ over a broad band from

1520 nm to 1610 nm for all the four mode-channels of TM polarization. Furthermore, this design is flexible for more channel number. Recently, a low-loss and low-crosstalk sharp multimode waveguide bend with an effective radius of $40 \mu\text{m}$ was realized for supporting the low-loss and low-crosstalk transmission of 10 mode-channels in a $2.3\text{-}\mu\text{m}$ -wide bus waveguide [104].

An alternative approach is to introduce some special *mode converter* between the straight section and the bent section, so that their mode mismatch can be reduced and a regular arc bend with a constant bending radius R can be used. In this way, for a 90° multimode waveguide bend with mode converters at the two ends, the effective

Figure 8: On-chip multimode waveguide bends based on mode converter between the straight section and the bent section. (A) A two-mode waveguide bend combining a pair of mode converters (MCs) and a 90° normal bend [95, 96]. (B) A sharp multimode waveguide bending assisted with metamaterial-based mode converters [97]. (C) A two-mode waveguide bend combining Y-junction-based mode converters and two single-mode arc-bends with a 4π phase difference [98].

bending radius R' is given as $R' = R + L_{mc}$, where L_{mc} is the length of the mode converter. For example, in [95, 96], a mode converter was proposed for a sharp two-mode waveguide bend, as shown in Figure 8A. An optimized 5- μm -long mode converter was demonstrated for a multimode waveguide bend with $w_{co} = 1\text{ }\mu\text{m}$ to support the two lowest guided modes (i.e. the TE_0 and TE_1 modes). It was demonstrated experimentally that this design has a low intermode crosstalk of $< -22\text{ dB}$ in a bandwidth of 100 nm for the TE_0 and TE_1 modes when the bending radius is chosen as $R = 5\text{ }\mu\text{m}$ (i.e. $R' = 10\text{ }\mu\text{m}$). This performance is similar to that of a regular 90° arc bend with $R = 40\text{ }\mu\text{m}$ and $w_{co} = 1\text{ }\mu\text{m}$. One might notice that the design in [95] and [96] cannot be easily extended for the case with more than two modes. In [98], a sharp multimode bend with an effective radius $R' = 3\text{ }\mu\text{m}$ was realized for the two lowest guided modes by combining Y-junction-based mode converters and two single-mode arc bends with a 4π phase difference at 1550 nm. With this design, in theory, the excess loss is 0.8 dB and the intermode crosstalk is about -20 dB in the 30 nm bandwidth. Similarly to the design in [95] and [96], one should notice that this design also cannot be easily extended. More recently, in [97], another novel mode converter with a metamaterial-assistant polymethyl methacrylate (PMMA) upper-cladding was introduced and a sharp multimode waveguide bend was demonstrated with low losses ($< 1\text{ dB}$) and low crosstalks ($< -20\text{ dB}$) for four TM mode-channels over a 80 nm wavelength band, as shown in Figure 8B. In this design, the mode converter should be long enough to be adiabatic (e.g. $L_{tp} = 15.8\text{ }\mu\text{m}$ [97]), and thus, the effective radius for the demonstrated 90° arc-bend with $R = 30\text{ }\mu\text{m}$ is given as $R' = 45.8\text{ }\mu\text{m}$ (i.e. $R + L_{mc}$).

Another alternative approach for realizing the ultrasharp multimode waveguide bend is to directly modify the effective refractive index profile in the bent section, so that the mode mismatch can be reduced. In 2012, a sharp multimode waveguide bend was proposed and designed with the transformation optics theory [20]. In this design, the core height of the multimode waveguide in the bent section is decreased gently and gradually in the radial direction, in which way the mode mismatch between the straight and bent sections can be reduced. A three-mode waveguide bends with $R = 78.8\text{ }\mu\text{m}$ was demonstrated experimentally with an excess loss of -2.6 dB . One should notice that the grayscale-lithography process is needed for the fabrication. As it is well known, it is also possible to modify the effective index profile in the bent section by introducing some all-dielectric metamaterials with subwavelength structures (e.g. nanoholes as well as nanoslots [99, 100]). This approach was utilized for the design of single-mode waveguide bends previously [85] and has been extended for achieving sharp multimode waveguide bends [99, 100]. In [99], a pair of Y-junctions with the assistance of nanoholes were presented for realizing compact multimode bends, as shown in Figure 9A. It is possible to be used for more high-order modes by modifying the nanohole distribution. Similarly, a sharp waveguide bend consisting of many nanoholes was demonstrated in [100]. In this design, the waveguide-core region for bending was digitized into hundreds of pixels in nanoscale and these pixels are optimally determined to be filled by the core-material or not. Finally, the realized sharp waveguide bend has a radius as small as $R = 1\text{ }\mu\text{m}$ even when $w_{co} = 2\text{ }\mu\text{m}$. However, this works for the fundamental mode only, as demonstrated in [100].

Figure 9: On-chip multimode waveguide bends realized with modified effective refractive index profile in the bent section. (A) A two-mode waveguide bend consisting of a pair of equivalent Y-junctions designed with nanoholes [99]. (B) Configuration of a multimode waveguide bend with subwavelength structures [101].

More recently, another simple and efficient approach for multimode waveguide bends was proposed by introducing shallowly etched subwavelength-grating (SWG) structures in the bent section, as shown in Figure 9B [101]. As proposed previously, a SWG waveguide can support the Bloch-Floquet mode propagating without diffraction losses in theory [102, 103].

In this design, the introduced SWG structure spatially modifies the effective index profile in the bent section, so that the bent section has an equivalent refractive index profile matched very well with that of a straight multimode waveguide. In this way, the mode mismatching loss between the bent and straight sections can be minimized. The realized multimode waveguide bend has a low loss (0.5~0.8 dB) and low crosstalk (<-20 dB) for all three TE modes even when the bending radius is as small as $R=10\text{ }\mu\text{m}$, which is one of the best results reported until now. Table 2 shows a summary of the reported multimode waveguide bends with different structures. It can be seen that sharp multimode waveguide bends can be achieved to support low-loss and low-crosstalk multichannel light propagation.

2.3 Multimode waveguide crossing

As it is well known, waveguide crossings are also very important for a densely PICs like photonic networks-on-chip. Previously, various single-mode waveguide crossings have been demonstrated with low-loss and low-crosstalk transmissions for the fundamental mode [105–109]. For example, a single-mode waveguide crossing with low loss (~0.02 dB) and low crosstalk (~-40 dB) was realized by using MMI structures [108]. In this design, the MMI length is chosen optimally to achieve self-imaging for the fundamental mode so that the crossing influences the light propagation very slightly. However, the situation becomes very difficult when designing a multimode waveguide

crossing because higher-order modes behave very different from the fundamental mode and they usually have different self-imaging positions in the MMI section. This prevents achieving low-loss and low-crosstalk multimode waveguide crossings.

Recently, there have been several types of multimode waveguide crossings realized by introducing some special structural designs [110–114]. A two-mode waveguide crossing consisting of four tapers and two crossed MMI sections has been proposed and demonstrated [110], as shown in Figure 10A. The tapers were designed optimally, so that the launched TM_0 mode can excite to the TM_0 and TM_2 modes in the MMI section and the launched TM_1 mode can excite to the TM_1 and TM_3 modes in the MMI section. The width and length of the MMI section are further optimized to achieve self-images at the center of the crossing for the TM_0 and TM_1 modes. The fabricated waveguide crossing has an excess loss of <1.5 dB and crosstalk of <-18 dB over a broad bandwidth of >80 nm.

Another approach is to convert the higher-order modes to the fundamental mode, so that the regular single-mode waveguide crossings can be used. One should notice that $N \times N$ single-mode waveguide crossings are needed when there are N modes involved. For example, in [111], a two-mode waveguide crossing was realized by using Y-junction-based mode converters, as shown in Figure 10B. With the mode converter, both the fundamental modes and the first higher-order mode at the input port are converted to the combination of the fundamental modes in the two branch waveguides. In this way, four regular single-mode waveguide crossing are needed. On the other hand, more than two modes are not allowed for the design with the mode converter based on a Y-branch. In order to handle more than two modes, multichannel mode (de)multiplexers can be introduced. In [112], the three-channel mode (de)multiplexers based on an MMI section with nanoholes were introduced and a three-mode waveguide crossing was realized, as shown in Figure 10C.

Table 2: Reported multimode waveguide bends.

Ref.	Structures	M_{ch}	$R\text{ (}\mu\text{m)}$	EL (dB)		CT (dB)		BW (nm)	
				T	M	T	M	T	M
[20]	Gradational height	3	78.8	2.5	2.6	/	/	/	/
[93]	Bezier curves	3	20			-26	-23	60	60
[96]	Mode converter	2	5	0.12	0.2	-23	-22	100	100
[101]	Subwavelength	3	10	0.2~0.5	0.3~0.7	-30	-20	100	80
		4	20	0.2~0.5	0.4~0.8	-20	-15	100	90
[99]	Subwavelength	2	3.6	0.7	0.8	-25	-24	60	60
[98]	Y-branch	2	3	0.8	/	-20	/	30	/

T, theory; M, measurement.

Figure 10: On-chip multimode waveguide crossings.

(A) A two-mode waveguide crossing with two crossed MMI sections [110]. (B) A two-mode waveguide crossing with Y-junction based mode converters [111]. (C) A three-mode waveguide crossing with 1×3 mode (de)multiplexers and a 3×3 array of single-mode waveguide crossings [112].

Most recently, an ultracompact two-mode waveguide crossing based on MMI couplers with nanoholes was proposed and demonstrated experimentally [113]. For the fabricated waveguide crossing, the footprint is as compact as $4.8 \mu\text{m} \times 4.8 \mu\text{m}$, the excess loss is 0.6 dB, and the crosstalk is < -24 dB in the wavelength range from 1530 nm to 1590 nm for the TE₀ and TE₁ modes. Another multiport multimode waveguide crossing was proposed and demonstrated by using a metamaterial-based Maxwell's fisheye lens [114]. This lens was realized by introducing many silicon rods with varied diameters, as shown in Figure 11. With this lens, any one of the guided modes launched at the end of the input port can be focused and imaged to be the corresponding guided mode at the end of the output port. The experimental results show that the multiport multimode waveguide crossing works well with low losses (~ 0.3 dB) and low crosstalk (~ 20 dB).

2.4 Reconfigurable multimode silicon photonics

For photonic networks-on-chip, not only high capacity but also high reconfigurability are highly desired. Therefore, it becomes more and more important to develop reconfigurable silicon photonic devices [115–128]. As it is well known, there are two types of popular structures used for optical switches when operating with the fundamental mode [129–136]. One is using Mach-Zehnder interferometers (MZIs) for realizing broadband optical switches, and the other is using MRRs for realizing wavelength-selective optical switches. One might notice that the realization of reconfigurable silicon photonics with higher-order modes is more complicated than that with the fundamental mode only. Generally speaking, one needs to integrate mode-manipulation devices (e.g. mode (de)multiplexers/

Figure 11: A multiport multimode waveguide crossing using a metamaterial-based Maxwell's fisheye lens [114].

converters) with optical switches, and great progresses have been achieved in the recent years [118, 137–149].

For example, an on-chip switchable data exchange for two mode-channels was demonstrated by using a thermally-tunable MZI with multimode input/output waveguides [142], in which mode (de)multiplexers based on MRR-assisted ADCs are used. The MZI structure was assisted with a PS. 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. In [143], a nanosecond mode-selective optical switch was demonstrated for the TE₀ and TE₁ mode-channels by using an MZI, which consists of an input Y-junction, an output 2×2 MMI coupler, and a PN-junction phase-shifter at one of the MZI arms. In [115], a 2×2 multimode thermo-optic switch was realized by integrating two ADC-based mode demultiplexers, an array of 2×2 single-mode optical switches, and two ADC-based mode (de)multiplexers. This configuration was extended to realize an $N \times N$ multimode optical switch by integrating N pairs of mode (de)multiplexers with M mode-channels and an $MN \times MN$ optical switch array, as shown in Figure 12A

Figure 12: On-chip reconfigurable silicon photonic devices.

(A) An $N \times N$ multimode optical switch [115]. (B) A ROADM for hybrid WDM-MDM systems [145].

[115]. With this configuration, one can switch any mode-channel in any input multimode waveguide to any mode-channel in any output multimode waveguide nonblockedly. The optical switch is based on Benes network, so that less 2×2 switch units are needed than other networks [116, 117].

Currently, it is also becoming interesting to develop reconfigurable multimode silicon PICs for hybrid multiplexing systems with multiple modes/wavelengths/polarizations. For example, an on-chip multimode optical switch for hybrid WDM-MDM systems was demonstrated with two mode-channels and two wavelength-channels by cascading two thermal-tunable MRR-assisted ADCs [139]. The crosstalk is < -16.8 dB with a bit-rate error below 10^{-9} and the power penalty is < 1.4 dB for all channels with a bit rate of 10 Gb/s. The data routing in hybrid WDM-MDM systems can be also realized by combining optical switches and grating-assisted ADCs, as proposed in [142]. Recently an on-chip 1×2 mode-/polarization-selective switch for hybrid PDM-MDM systems was also proposed and fabricated with four modes and two polarizations [141]. Signals carried by the mode and polarization channels are input from the multimode bus waveguide and demultiplexed into eight channels by the PBS and the mode demultiplexer. Each channel is then routed by the corresponding MZI switch for the TE_0 or TM_0 mode. For this 1×2 mode-/polarization-selective switch, the insertion loss is < 8 dB and the intermode crosstalk is below -15 dB.

More recently, a silicon-based reconfigurable optical add-drop multiplexer (ROADM) for hybrid WDM-MDM systems was demonstrated by integrating a four-channel mode demultiplexer, four MRR-based wavelength-selective thermo-optic switches, and a four-channel mode multiplexer [145], as shown in Figure 12B. The signal is first demultiplexed into four groups by the four-channel mode demultiplexer (#1) and each group has N

wavelength channels ($\lambda_1, \dots, \lambda_n, \dots, \lambda_N$). These N wavelength-channels can be then dropped flexibly by the corresponding wavelength-selective optical switch. When the n th wavelength channel (λ_n) is dropped to drop port D_i , one can add local signals carried by wavelength λ_n from add port A_i simultaneously. This ROADM enables to add/drop any wavelength-channel selectively of any mode.

2.5 Multimode fiber-chip coupling

Even though single-mode fibers have been used very widely in long-haul optical networks since 1980s [150], currently, few-mode optical fibers are attracting more and more attention because of the ability to enhance the link capacity of a single fiber [29, 36, 151–155]. Therefore, it will be very helpful if one can connect a few-mode fiber with a multimode silicon photonic waveguide efficiently. However, it is still a big challenge because their mode mismatch is huge. Nevertheless, some efforts have been made to develop multimode fiber-chip couplers in both *vertical* and *edge* coupling ways.

For the way of *vertical coupling*, grating couplers are usually used as an excellent candidate. In the past years, some on-chip grating couplers have been demonstrated successfully for multimode fiber-chip coupling by using e.g. grating couplers integrated with beam splitters and phase-shifters [156], two-dimensional grating couplers [157, 158], and double-grating couplers combined with a curved Y-junction [158, 159]. For example, as demonstrated in [157], a complicated silicon PIC consisting of five two-dimensional grating couplers and four thermal-tunable phase-shifters was realized, as shown in Figure 13A. The silicon PIC can realize the mode-coupling from the fundamental modes in six optical waveguides to the six mode-channels in a few-mode fiber when the phase-shifters are tuning carefully.

Figure 13: Grating couplers for vertical multimode coupling.

(A) Two-dimensional grating couplers for multimode fiber-chip coupling [157]. (B) A double-grating coupler for multimode fiber-chip coupling [159].

The coupling loss is about 3 dB for these six mode-channels. In contrast, the double-grating coupler can work with a compact footprint and relatively high efficiency, as shown in Figure 13B [159]. The peak coupling efficiency is -3.68 dB and the 1-dB bandwidth is 35 nm. However, it is noteworthy that only the first-order mode LP_{11a} can be handled and cannot be extended for more modes.

For the way of *edge coupling*, there have been several structures reported [159–163]. Compared with the *vertical* coupling based on grating couplers, the edge coupling with mode-converters can overcome the disadvantages of polarization/wavelength sensitivity [159–163]. In [159], a double-tip inversed taper structure was demonstrated to realize the coupling between the LP_{11} mode in a few-mode fiber and the TE_1 mode in a multimode SOI waveguide, as shown in Figure 14A. For this coupler, the coupling loss for the first-order mode is about 5.5 dB in the wavelength range of 1515–1585 nm and the intermode cross-talk is about -15 dB. Unfortunately, this design cannot be applied to vertical higher-order modes (e.g. LP_{11b}) since the top-silicon thickness of SOI waveguides is usually 200–300 nm, which is single mode in the vertical direction. In [161], a special multimode converter was proposed and designed by using a silicon nanophotonic waveguide

with a single-tip inverse taper buried in a SiN strip waveguide, as shown in Figure 14B. With this mode converter, one can realize efficient mode conversion from six guided-modes (i.e. TE_{11} , TE_{21} , TE_{31} , TE_{41} , TM_{11} , and TM_{12}) of a multimode SOI nanowire waveguide to the six guided modes in the SiN strip waveguide which are compatible with the LP_{01} , LP_{11a} , and LP_{11b} modes in few-mode fibers. It is also possible to develop three-dimensional structures using waveguides with different heights for the conversion from the TE_{11} mode to the high-order modes (e.g., TE_{11} , TE_{21} , and TE_{12} modes), which match well with the LP_{01} , LP_{11a} , and LP_{11b} fiber-modes, respectively [162, 163]. This kind of mode converter usually has broad bandwidth while the fabrication becomes complicated with different waveguide-core heights.

3 Higher-order mode-assisted silicon photonics

As discussed above, higher-order modes in silicon nanophotonic waveguides have been used well for achieving more channels for high-capacity data transmissions. In recent years, higher-order modes have also been

Figure 14: Waveguide tapers for multimode fiber-chip coupling.

(A) Double-tip inversed taper [159]. (B) Inversed taper [161].

introduced to assist the realization of some special silicon photonic devices, which cannot be realized with the fundamental mode only. Examples are high-performance on-chip polarization-handling devices with higher-order modes and on-chip add-drop optical filters based on multimode Bragg gratings, and some emerging applications have been demonstrated recently, as reviewed below.

3.1 On-chip polarization-handling devices with higher-order modes

On-chip polarization-handling devices play important roles in various optical systems [198, 199], including PBSs and rotators [164–170]. As one of the most important elements for polarization handling, polarization splitter-rotators have attracted intensive attention and can be realized by utilizing the mode hybridization between the TM_0 fundamental mode and the TE_1 mode [172–186]. This idea for realizing polarization splitter-rotators was proposed in 2011 [172], as shown in Figure 15. Here, the TM_0 - TE_1 mode

Figure 15: A PSR with the TM_0 - TE_1 mode conversion in an adiabatic taper and the TE_1 - TE_0 mode conversion in an ADC [172].

conversion in an adiabatic taper and the TE_1 - TE_0 mode conversion in an ADC was introduced. It can be seen that the TE_1 mode is the key for the realization of the polarization rotation and splitting. The TM_0 mode launched at the input end of the adiabatic taper is converted into the TE_1 mode very efficiently when propagating along an adiabatic taper with specific core widths. Then, this TE_1 mode in the wide waveguide is coupled to the TE_0 mode of the adjacent narrow waveguide of the ADC. It can be seen that efficient polarization rotation from the TM_0 mode to the TE_0 mode is realized with the assistance of the TE_1 mode. It is also possible to introduce an MMI-based mode filter to improve the polarization extinction ratio, as demonstrated in [173]. For this polarization splitter and rotator (PSR), which is $\sim 70 \mu\text{m}$ long, the extinction ratio is $\sim 20 \text{ dB}$ over a broad band ranging from 1547 nm to 1597 nm. In particular, no special complicated fabrication processes are needed, and thus, one can realize PSR easily. In contrast, those conventional polarization rotators have special structural designs and usually need some complicated and critical fabrication processes [164–170]. Numerous similar designs with the assistance of high order modes have been proposed in the recent years for realizing PSRs [173–186].

The higher-order modes are also introduced to help the realization of compact PBSs on silicon. In [187], a short PBS was proposed by using an asymmetric three-waveguide coupling system (see Figure 16A), in which the TM_0 - TM_1 mode conversion was introduced. The three-waveguide coupling system consists of a narrow input waveguide, a narrow output waveguide, and a wide middle waveguide between them. The widths of the waveguides are designed so that the phase-matching condition is satisfied for the TM_0 mode in the narrow input/output waveguide and the TM_1 mode in the wide middle waveguide. In this way, the launched TM_0 mode in the narrow input waveguide

Figure 16: Proposed PBS assisted with higher-order modes.

(A) Schematic configuration of a PBS with the TM_0 - TM_1 mode conversion. Simulated light propagation in the designed PBS for TE (B) and TM (C) polarizations [187].

can be coupled completely to the TM_1 mode in the wide middle waveguide by choosing the optimal length of the coupling region (see Figure 16B). The TM_1 mode excited in the wide middle waveguide is then coupled to the TM_0 mode in the narrow output waveguide through the evanescent coupling between them. In contrast, there is a significant phase mismatch for TE polarization modes. As a result, the launched TE-polarized light finally outputs from the through port since there is little coupling in the coupling region due to the significant phase mismatch (see Figure 16C). The designed PBS is $\sim 25 \mu\text{m}$ long and has a good fabrication tolerance for the variation of the waveguide width (more than $\pm 20 \text{ nm}$) and a broad band ($\sim 50 \text{ nm}$) for an extinction ratio of $>15 \text{ dB}$. Such a three-waveguide coupling system with the TM_0 - TM_1 mode conversion was also extended to realize the PBS for the case with a relatively thick silicon core-layer (e.g. $h_{\text{co}} = 340 \text{ nm}$) [188]. Besides, this idea of utilizing the TM_0 - TM_1 coupling in an ADC was also used for the realization of on-chip polarizers [189]. As demonstrated in [189], the fabricated polarizer consisting of an ADC has a high extinction ratio of 15 dB in a broad band over 80 nm.

3.2 On-chip add-drop optical filters with higher-order modes

Higher-order modes are also introduced for realizing novel add-drop optical filters based on an F-P cavity [190] and Bragg grating [191, 200]. In [190], the proposed add-drop optical filter consists of a multimode F-P cavity coupled to single-mode bus waveguides, as shown in Figure 17A. In this device, there is partial coupling between the forward TE_0 mode in the single-mode bus waveguide and the forward TE_2 mode in the multimode F-P cavity waveguide when the waveguide widths are chosen optimally. For the F-P cavity, the grating

reflectors with the TE_0 - TE_2 mode conversion are introduced at both ends. With the grating reflector at the right side, the forward TE_2 mode in the cavity is converted to the backward TE_0 mode in the cavity. This backward TE_0 mode is not coupled out to the bus waveguide because of the huge phase mismatch and instead is coupled back to the TE_2 mode propagating forward with the grating reflector at the left. It can be seen that such a F-P cavity works very similarly to a four-port add-drop filter based on MRRs with the assistance of the multimode waveguide with higher-order modes.

Another novel add-drop optical filters based on a multimode Bragg grating was also proposed and realized [200], as shown in Figure 17B. This device consists of a two-channel mode multiplexer and a multimode Bragg grating. This multimode Bragg grating was designed to realize the mode conversion from the forward TE_0 mode to the backward TE_1 mode when the wavelength operates around the Bragg wavelength. It indicates that a wavelength-selective TE_0 - TE_1 mode conversion was generated and utilized. Then the taper-based mode (de)multiplexer introduced at the input side converts the backward TE_1 mode to the TE_0 mode in the narrow waveguide for the drop port. In this way, one can drop any wavelength in the specific wavelength-band around the Bragg wavelength. It has been shown that the excess loss at the drop port is about 0.8 dB and the extinction ratio is up to 24 dB at the through port. This design can be cascaded for the case with more wavelength-channels and might be useful for many applications. Multimode Bragg gratings could also be used as hybrid multimode resonators, as demonstrated in [201]. Here, a grating-assisted counterdirectional coupler is designed to allow phase-matching between the forward-propagating TE_0 mode and the backward propagating TE_1 mode around the targeted wavelength λ_0 . This design can be extended further for multichannel multiplexing by using cascaded resonators operating at different wavelengths.

Figure 17: On-chip add-drop optical filters with higher-order modes.

(A) An on-chip add-drop filter based on a multimode Fabry-Perot cavity [190]. (B) An on-chip add-drop filter based on a multimode Bragg grating [200].

3.3 Emerging applications with higher-order modes

Utilization of higher-order modes in multimode silicon nanophotonic waveguides have been recognized as a useful approach for many new applications of silicon photonics [192–197]. For example, it is possible to realize a thermal silicon photonic device by introducing multimode optical waveguide with higher-order modes. In [192], a temperature-insensitive MZI was proposed and demonstrated experimentally by introducing multimode MZI arms and mode (de)multiplexers. A pair of mode (de)multiplexers were introduced to convert the TM_0 mode in the single-mode arm-waveguide to the TM_1 mode in the multimode arm-waveguide. In particular, these two multimode MZI arms have identical widths, which was designed optimally so that the TM_0 mode and the TM_1 mode have the same temperature dependence. In this way, the MZI becomes athermal when light propagates in the MZI arms with the TM_0 and TM_1 modes, respectively. The demonstrated MZI achieves a temperature sensitivity less than 8 pm/°C in a wavelength range of 18 nm in the C-band.

It is also interesting to explore the utilization of higher-order modes for quantum photonics. In [193] and [194], multimode silicon photonics has been extended for realizing quantum PICs, where the guided-modes are introduced as a new degree of freedom. In [193], multimode silicon PICs have been developed for quantum information process. In particular, the transverse waveguide-mode degree of freedom was introduced to quantum PICs, and an on-chip coherent conversion of a photonic quantum state between path, polarization, and transverse waveguide-mode degrees of freedom was demonstrated [193]. In [194], quantum interference between the guided modes was demonstrated within a multimode optical waveguide using quantum circuit-building blocks. It shows that guided modes can be controlled very well and have the potential to enable practical and robust quantum information processing.

Recently, the utilization of higher-order modes has been introduced for on-chip nonlinear photonics [195, 196]. For example, an on-chip transverse-mode entangled photon source by using spontaneous four-wave mixing processes in a multimode waveguide was demonstrated [195]. In [196], a multimode optomechanical waveguide was used to create on-chip stimulated intermodal Brillouin scattering for the first time. In particular, on-chip mode (de)multiplexers were used to combine/separate two optical modes and avoid introducing the circulators and narrowband filters for separating pump and

signal waves. This new nonlinear coupling allows intermodal amplification and single-sideband energy transfer through highly engineerable control over Brillouin interactions. A net amplification of 2.3 dB and 50% energy transfer from one optical field to another were achieved.

A special suspended multimode silicon photonic waveguide can be even used for realizing low-loss on-chip light propagation for deep mid-infrared light when introducing the TE_1 mode, as proposed in [197]. For the suspended multimode silicon photonic waveguide, there is a SiO_2 pedestal underneath located in the middle of the silicon core. Since the electrical field intensity of the TE_1 mode is very weak at the center of the silicon core, the TE_1 mode has much lower light absorption loss of the SiO_2 insulator layer and the substrate leakage loss than the TE_0 mode. The simulation results show that the waveguide losses are respectively as low as 0.024 dB/cm and 0.53 dB/cm at wavelengths of 4.8 μm and 7.1 μm where the SiO_2 material absorption is 100 dB/cm and 1000 dB/cm, respectively. Such a low-loss silicon photonic waveguide is potentially useful for practical applications in deep mid-infrared.

These emerging applications with higher-order modes makes multimode silicon photonics more and more attractive. Higher-order modes provide a new option for the design of silicon photonic devices. It is possible to realize some special photonic devices when the higher-order modes are introduced.

4 Conclusions

In summary, this paper has given a review for the recent work on multimode silicon photonic integrated devices, including two parts. In the first part, we have reviewed the multimode silicon photonics for MDM systems, including on-chip multichannel mode (de)multiplexers, multimode waveguide bends, multimode waveguide crossings, reconfigurable multimode silicon PICs, as well as multimode chip-fiber couplers. It can be seen that these multimode silicon photonic devices have been developed successfully with high performances, e.g. low loss, low crosstalk, and compact footprints. For these devices, the highest channel number is 10. It might be necessary to further increase the mode-channel number and improve the performance, which is a big challenge in the design and fabrication. In the second part, we have given a review about the higher-order mode-assisted silicon photonic devices, including on-chip polarization-handling devices with higher-order modes, add-drop optical filters based

on multimode Bragg gratings, and some emerging applications with higher-order modes. It can be seen that the introduction of higher-order modes is necessary and very helpful.

Basically, it becomes not easy to handle when many higher-order modes are involved and one has to manipulate the modes carefully. Fortunately, silicon photonics provides an excellent platform for mode manipulation with higher-order modes because of ultrahigh mode dispersion, which can minimize the intermode crosstalk and also helps improve the mode selectivity. As discussed in this paper, currently, many multimode silicon photonic devices and circuits have been developed successfully. It will be very helpful for the applications of multimode silicon photonics if the performance of these devices can be improved further. In particular, more effort is needed to enhance the multimode fiber-chip coupling so that the multimode silicon photonics can help more the few-mode fiber optical communications. It is also interesting to further explore the utilization of multimode silicon photonics with higher-order modes in the field of e.g. quantum photonics, nonlinear photonics, etc. As a conclusion, the introduction of higher-order modes provides a new option for the design of silicon photonic devices, and more efforts should be made to develop multimode silicon photonics, which will potentially play more and more important roles for many applications in the future.

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