Frontiers of Information Technology & Electronic Engineering
www.jzus.zju.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Ten-channel mode-division-multiplexed silicon photonic integrated circuit with sharp bends*

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Received July 14, 2018; Revision accepted Sept. 24, 2018; Crosschecked April. 11, 2019

Abstract: A multimode silicon photonic integrated circuit (PIC) comprising a pair of on-chip mode (de)multiplexers with 10-mode channels and a multimode bus waveguide with sharp bends is demonstrated to enable multi-channel on-chip transmissions. The core width of the multimode bus waveguide is chosen such that it can support 10 guided modes, of which there are four transverse-magnetic polarization modes and six transverse-electric polarization modes. This multimode bus waveguide comprises sharp bends based on modified Euler curves. Experimental results demonstrate that the present silicon PIC enables the 10-channel on-chip transmission with a low inter-mode crosstalk of approximately −20 dB over a broad bandwidth of 1520–1610 nm even when the bending radius of the S-bend is as small as 40 μm. Compared with a silicon PIC using a conventional arc-bend with the same bending radius, our proposed PIC demonstrates a significant improvement.

Key words: Silicon; Multimode; Waveguide; Euler-bends
https://doi.org/10.1631/FITEE.1800386 **CLC number:** O439

1 Introduction

Recently, silicon photonic integrated circuits (PICs) for optical communication systems have attracted much attention (Dai and Bowers, 2014; Dai, 2017). To satisfy the increasing demands for capacity of optical interconnects and to increase the link of data transmission, advanced multiplexing technologies have been introduced and are very attractive in data transmission systems, e.g., wavelength-division multiplexing using several wavelength channels (Paniccia, 2011), space-division multiplexing using a number of cores or modes (Richardson et al., 2013), and polarization-division multiplexing using two orthogonal polarizations (Barwicz et al., 2007). Among them, mode-division multiplexing (MDM) using multiple modes in a multimode bus waveguide (Dai et al., 2013) has been increasingly gaining attention for academic research purposes, because it can strongly enhance the link capacity of optical interconnects. As is well known, waveguide bends are usually inevitable for building any PIC. However, for an MDM system with a multimode bus waveguide, there might be a significant mode mismatch between a multimode straight waveguide and a multimode bent waveguide when the bending radius is small. As a result, this introduces some inter-mode coupling,

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* Project supported by the National Science Fund for Distinguished Young Scholars (No. 61725503), the Zhejiang Provincial Natural Science Foundation, China (No. LZ18F050001), the National Natural Science Foundation of China (Nos. 61431166001 and 1171101320), and the National Major Research and Development Program, China (No. 2016YFB0402502)
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and thus causes not only some excess losses but also inter-mode crosstalk (Cherchi et al., 2013). To solve this problem, various approaches have been demonstrated with the realization of low-loss and low-crosstalk multiple-mode channel transmissions (Cherchi et al., 2013; Xu and Shi, 2018). For example, we previously proposed a type of vertical multimode silicon waveguide that supports high-order modes vertically and only the fundamental mode laterally. In this manner, ultra-sharp multimode waveguide bends are enabled (Dai, 2014). For the multimode waveguides supporting multiple guided modes in the lateral direction, Gabrielli et al. (2012) proposed a special waveguide design, and realized it by gradually varying the core height. With this design, a 4-μm-wide multimode waveguide bend with a bending radius of ~78 μm was demonstrated. However, the excess loss is ~2.5 dB in theory and ~2.6 dB experimentally, which are relatively high. Furthermore, the fabrication is not easy because a special grayscale lithography process is required. In Sun et al. (2016, 2017), a compact multimode waveguide bend with an effective radius of R'=10 μm was realized for the two guided modes by introducing 5-μm-long step-tapered mode converters at the input and output ends of a multimode arc-bend with a bending radius of R=5 μm. Unfortunately, it is still not easy to be extended for cases with more than two guided modes. Recently, another novel mode converter based on a subwavelength-structured polymethyl methacrylate (PMMA) upper cladding was introduced, and a compact multimode waveguide bend with an effective radius of R'=45.8 μm was enabled for four transverse-magnetic (TM) mode channels (Xu and Shi, 2018).

As suggested previously, a simple approach for achieving a sharp multimode waveguide bend is to use a special bent section with a curvature that is modified gradually (Jiang et al., 2018). In this manner, the guided modes in straight sections can be converted gradually to the guided modes in bent sections, making it possible to achieve low-loss and low-crosstalk transmissions with multiple-mode channels. This idea was proposed for the case with a single-mode waveguide bend to reduce the mode-mismatch loss at the straight-bent junction (Fujisawa et al., 2017). Fujisawa et al. (2017) introduced clothoid curves at the input and output of a 90° waveguide bend, so that the straight and bent waveguides are connected without increasing the footprint. Cherchi et al. (2013) experimentally demonstrated 4-μm-thick multimodal silicon-on-insulator (SOI) waveguide bends using the Euler spiral design. With this design, sharp waveguide bends with radii below 10 μm and losses below 0.02 dB/90° were realized for the fundamental mode. More recently, Jiang et al. (2018) demonstrated a 90° multimode waveguide bend based on the modified Euler curves with four mode channels having TM polarization for the first time. In this study, a sharp multimode waveguide bend based on a modified Euler curve is demonstrated for the multimode bus waveguide supporting 10-mode-channel on-chip transmissions. A multimode PIC is demonstrated by integrating a pair of 10-channel on-chip mode (de)multiplexers and a multimode bus waveguide with sharp bends for the first time. The 10-channel on-chip mode (de)multiplexers used here are based on cascaded dual-core adiabatic tapers, as demonstrated in Dai et al. (2018). The 10 guided modes supported in the multimode bus waveguide are made up of four TM-polarization modes and six transverse-electric (TE) polarization modes. It has been demonstrated experimentally that the inter-mode crosstalk of the transmission in the present silicon PIC is less than −20 dB over a broad bandwidth of 1520–1610 nm even when the bending radius of the S-bend is as small as 40 μm. In contrast, the inter-mode crosstalk in a silicon PIC using a conventional arc-bend with the same bending radius is as high as −3 dB. The present design provides a good option for on-chip multimode data transmissions.

2 Configuration and design

Fig. 1a shows the configuration of the present multimode silicon PICs comprising a pair of 10-channel on-chip mode (de)multiplexers and a multimode bus waveguide with a sharp S-bend. Here, the S-bend comprises two sharp bends based on a modified Euler curve. The width of the multimode bus waveguide is chosen as 2.3 μm to support 10 mode channels. A pair of 10-channel on-chip mode (de)-multiplexers is based on cascaded dual-core adiabatic tapers proposed in our previous study (Dai et al., 2018). Here, the 10-channel mode (de)-

multiplexer works with five cascaded dual-core adiabatic tapers, which are designed optimally for the TM_0, TM_1, TM_2, TM_3, TE_0, TE_1, TE_2, TE_3, TE_4, and TE_5 mode channels. Fig. 1b shows the dual-core adiabatic tapers for simultaneously extracting one TM-polarization mode channel and one TE-polarization mode channel. An integrated polarization beam splitter (PBS) is then introduced to separate these two mode channels extracted. For the PBSs used here, the design based on cascaded bent direction couplers (DCs) are used to achieve near-perfect performances in an ultra-wide wavelength band (Wu et al., 2017), as shown in Fig. 1c.

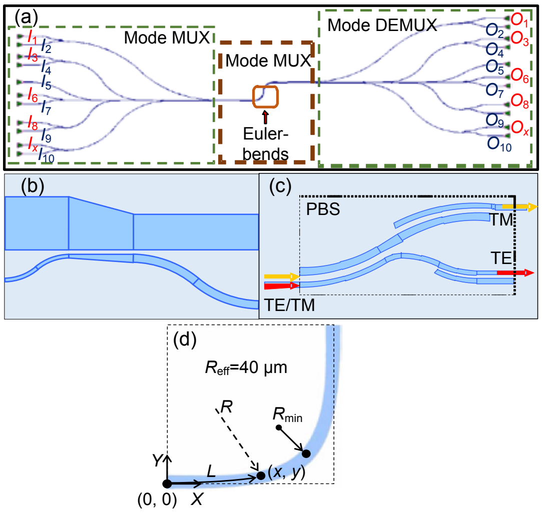

Fig. 1 Proposed multimode silicon photonic integrated circuit comprising a multimode bus waveguide with sharp bends and two 10-channel on-chip mode (de)-multiplexers: (a) schematic configuration; (b) an dual-core adiabatic taper; (c) a polarization beam splitter based on cascaded bent direction couplers working in an ultra-wide wavelength band; (d) a 90° Euler-bend with an effective curvature radius R_{eff} and a minimal curvature radius R_{min}

Ports marked in red font denote output ports for transverse-magnetic polarization mode channels. Ports marked in blue font denote output ports for transverse-electric polarization mode channels. MUX: multiplexer; DEMUX: demultiplexer; PBS: polarization beam splitter; TM: transverse-magnetic; TE: transverse-electric. References to color refer to the online version of this figure

At the input side, these 10 mode channels are combined to propagate along the multimode bus waveguide using the mode multiplexer when launched from the corresponding input ports (I_1–I_{10}) (Fig. 1a). After propagating along the multimode bus waveguide, these 10 channels are separated and output from the corresponding output ports (O_1–O_{10}) by the mode demultiplexer. The S-bend inserted in the multimode bus waveguide consists of two sharp bends based on a modified Euler curve (Fig. 1d). To reduce excess losses and inter-mode crosstalk, the maximum radius R_{max} should be large enough to avoid any significant mode mismatch at the junction between the multimode straight and the multimode bent waveguide, while radius R_{min} is required to be large enough to make the waveguide bent adiabatically. Point position (x, y) in the modified Euler curve is given as follows (Fujisawa et al., 2017):

$$\begin{cases} x = A\int_0^{L/A} \sin\left(\dfrac{\theta^2}{2} + \dfrac{A\theta}{R_{max}}\right)\mathrm{d}\theta, & (1) \\ y = A\int_0^{L/A} \cos\left(\dfrac{\theta^2}{2} + \dfrac{A\theta}{R_{max}}\right)\mathrm{d}\theta, & (2) \end{cases}$$

where L is the curve length between start point (0, 0) and point (x, y), $A=[L_{max}/(1/R_{min}-1/R_{max})]^{1/2}$ is a constant, with L_{max} the total curve length. For example, here we choose R_{min}=28.3 μm and A=25 for a multimode bus waveguide whose core width w_{bus}=2.3 μm. In this case, the effective bending radius for the designed Euler-bend is R_{eff}=40 μm. Commercial software (Lumerical FDTD) was used to simulate the light propagation in the designed multimode waveguide bend. Figs. 2a–2j show the simulation results for the light propagation along the multimode waveguide bend when the TE_0, TE_1, TE_2, TE_3, TE_4, TE_5, TM_0, TM_1, TM_2, and TM_3 modes in the straight multimode waveguide are launched from the straight-bent junction at the input end, respectively. Here, the operation wavelength is 1550 nm.

It can be seen that the launched mode is converted gradually along the designed Euler-bend and there is no notable crosstalk observed. This indicates that the Euler-bend is bent adiabatically and that the inter-mode crosstalk is very low. For comparison, we also simulate the light propagation in the conventional arc-bend with a bending radius of R=40 μm. In this case, some obvious mode interference was observed. This indicates that more than two guided modes are excited when light enters the arc-bend section (Fig. 3). This introduces some fatal inter-mode crosstalk and prevents multimode bus

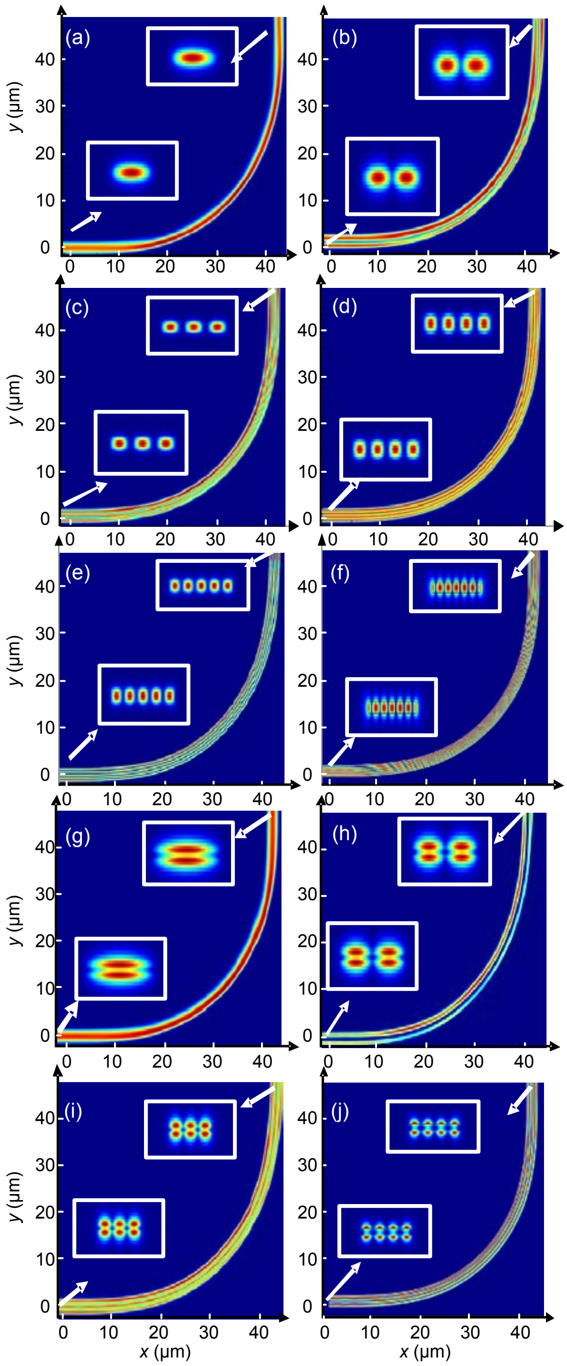

Fig. 2 Simulated light propagation in the designed 90° Euler-bend with R_{eff}=40 μm, when launching the TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) modes from the input end
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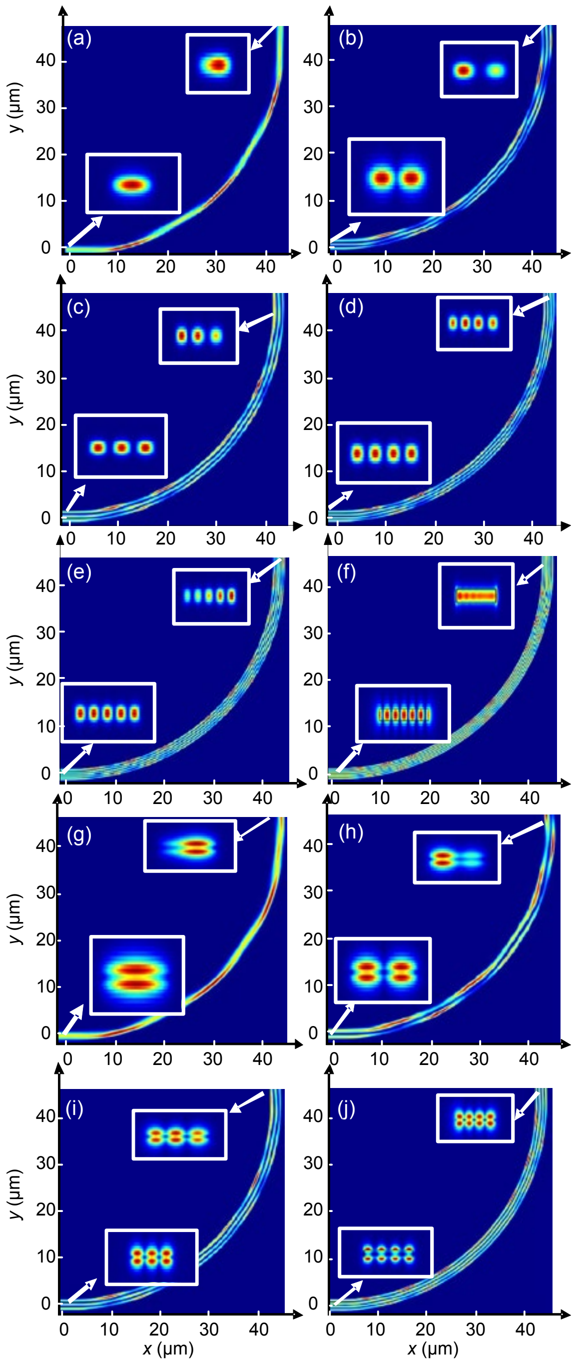

Fig. 3 Simulated light propagation in the arc-bend with *R*=40 μm, when launching the TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) modes from the input end
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waveguide with bends from achieving a low-bit-error-rate data transmission.

Figs. 4a–4j show the simulation results for the wavelength dependence of the transmissions at the output end of the modified Euler curves with R_{eff}=40 μm when one launches light from one of the input ends corresponding to the TE_0, TE_1, TE_2, TE_3, TE_4, TE_5, TM_0, TM_1, TM_2, and TM_3 modes, respectively. One can observe that the crosstalk is less than −20 dB, while the excess loss is less than 0.5 dB over a broad band ranging from 1.5 μm to 1.6 μm, very similar to the results for the silicon PIC comprising a straight multimode waveguide. Here, the cross-polarization crosstalk is low and negligible.

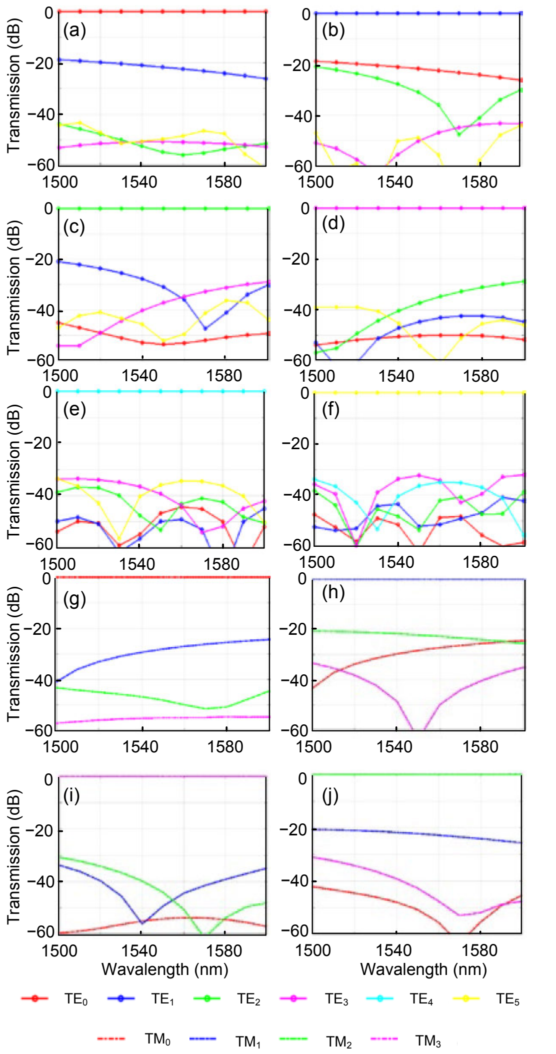

Fig. 4 Simulated results for the wavelength dependence of transmissions at the output end of the modified 90° Euler-bends with R_{eff}=40 μm when light is launched from the input end corresponding to the TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) modes

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3 Fabrication and measurement

The designed silicon PIC was fabricated on a SOI wafer, which has a 220-nm-thick silicon core-layer on a 2-μm-thick buried SiO_2 layer. First, an E-beam lithography process was used to pattern the waveguide structures and grate couplers. Then an inductively coupled plasmon etching process was performed to etch the top silicon layer down to the etching depth. Finally, a 2-μm-thick SiO_2 upper cladding was formed by the plasma enhanced chemical vapor deposition process. Fig. 5a shows the microscope picture of the fabricated silicon PIC combining two 10-channel mode (de)multiplexers and a multimode bus waveguide with an S-bend. The S-bend comprises two 90° Euler-bends with R_{eff}= 40 μm (Fig. 5b).

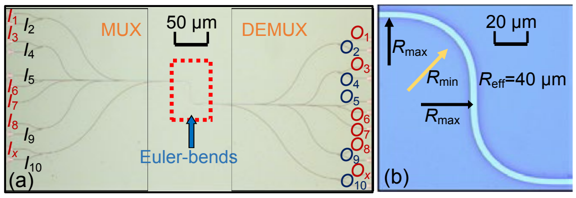

Fig. 5 Microscope images: (a) the fabricated silicon photonic integrated circuit, which comprises a pair of 10-channel mode multiplexer and mode (de)multiplexer connected with an S-bend based on two 90° Euler-bends with a 10-channel mode multiplexer of R_{eff}=40 μm with two 40-μm sharp bends; (b) the S-bend with two 90° Euler-bends

Ports marked in red font denote output ports for transverse-magnetic polarization mode channels. Ports marked in blue font denote output ports for transverse-electric polarization mode channels. MUX: multiplexer; DEMUX: de-multiplexer; PIC: photonic integrated circuit. References to color refer to the online version of this figure

For the measurement of the fabricated devices, we used a system comprising a broad band amplified spontaneous emission light source (with a range of 1510–1610 nm) and an optical spectrum analyzer. The grating couplers used had a fiber-chip coupling efficiency of approximately 30%. Figs. 6a–6j show the measured transmissions at the output ends (O1–O10) when the mode channels of TE0, TE1, TE2, TE3, TE4, TE5, TM0, TM1, TM2, and TM3 are launched respectively from the corresponding input end. The silicon PIC comprising two 10-channel mode (de)multiplexers and a straight multimode bus waveguide without any bend was also fabricated to be a reference. The measurement results for the transmissions at the output ends are shown in Fig. 7. In the experiment, the 10 mode channels were not launched

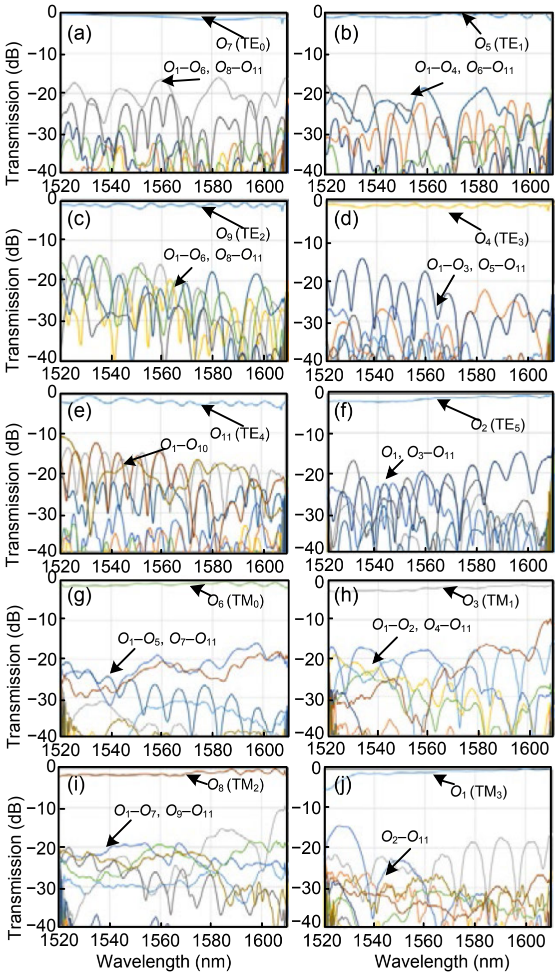

Fig. 6 Measured spectral responses at the output ports (O_1–O_{11}) when launching the TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) modes from the input end and going through the multimode bus waveguide comprising an S-bend consisting of two 90° Euler-bends with R_{eff}=40 μm

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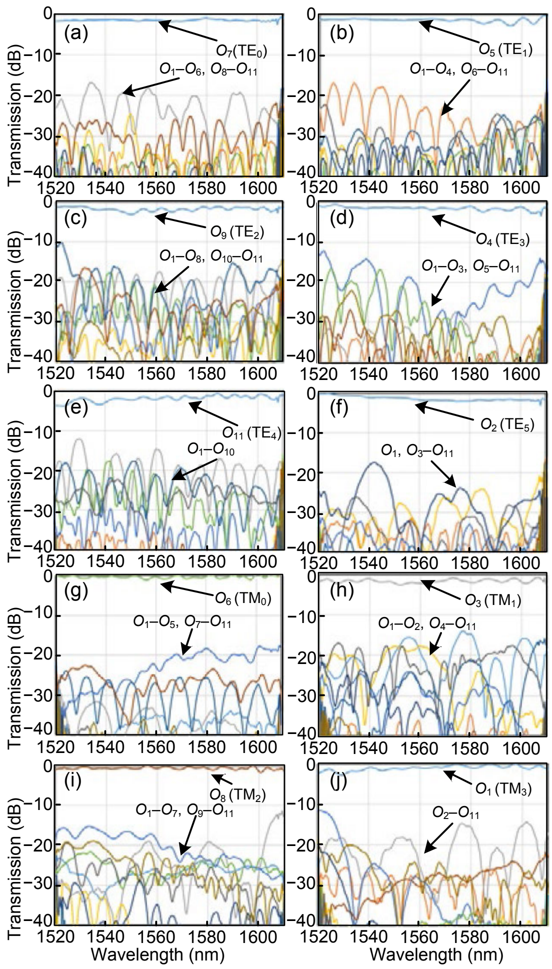

Fig. 7 Measured spectral responses at the output ends (O_1–O_{11}) when launching the TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) modes from the input end to a pair of 10-channel mode (de)multiplexers and a "straight" multimode bus waveguide without any bend

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simultaneously because the 10-channel fiber arrays were not available in the laboratory. Fortunately, it is still reasonable to estimate the inter-mode crosstalk according to the measured transmissions at all output ends when light is launched from any one of the input ends. From Fig. 7, it can be observed that the total excess losses are 0.2–2.0 dB and the inter-mode crosstalk is −20–−15 dB in the 1520–1610-nm-wavelength band even when using a "straight" multimode bus waveguide. This is due to the undesired mode coupling in the mode (de)multiplexers. In contrast, when introducing the S-bend based on the 90° Euler-bends with R_{eff}=40 μm as designed, the total excess losses and the inter-mode crosstalk (Fig. 7) are similar to the one using a "straight" multimode bus waveguide over a wavelength band of >80 nm (1520–1600 nm). This comparison shows that the S-bend based on the 90° Euler-bends with R_{eff}=40 μm does not introduce significant excess losses and an inter-mode crosstalk.

We also fabricated a silicon PIC comprising two mode (de)multiplexers with 10 mode channels, and a multimode bus waveguide with an S-bend based on regular arc-bends with R=40 μm. The measurement results for the transmissions at the output ends are shown in Fig. 8. The regular arc-bends with R=40 μm in the multimode bus waveguide introduce very strong inter-mode coupling. These measurement results demonstrate that the total excess losses are extremely high, that the inter-mode crosstalk is in the higher part of the 1520–1610-nm wavelength range, and that the device cannot even work.

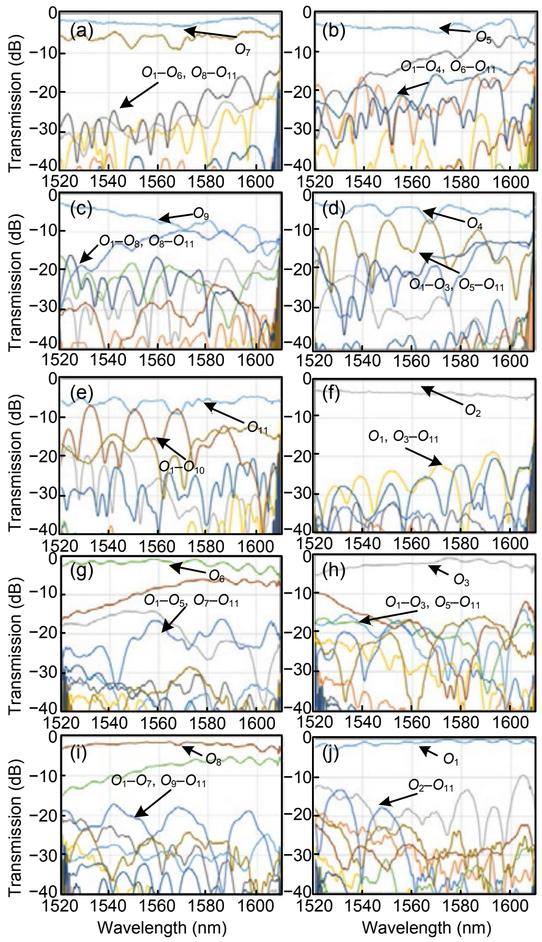

Fig. 8 Measured spectral responses at the output ends (O_1–O_{10}) when the mode channel of TE_0 (a), TE_1 (b), TE_2 (c), TE_3 (d), TE_4 (e), TE_5 (f), TM_0 (g), TM_1 (h), TM_2 (i), and TM_3 (j) is launched from the corresponding input end of the silicon photonic integrated circuit comprising two 10-channel mode (de)multiplexers and a multimode bus waveguide with an S-bend based on regular arc-bends with R=40 μm

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Finally, we measured the data transmissions with the fabricated silicon PIC using the experimental setup shown in Fig. 9. The operation wavelength-channel is 1550.12 nm and the bit rate is 26 Gb/s. As there is no 10-channel fiber array available in our laboratory, we did not realize data transmission with 10 mode channels. Instead, the mode channels of the silicon PIC were characterized one by one. The distributed feedback (DFB) laser was used as the light source and the wavelength was tuned to be 1550.12 nm (Fig. 9). The signal light was modulated by a Mach-Zehnder modulator (MZM) with the non-return-zero format generated by a bit-error-rate tester (BERT, Anritsu® MP1800A). The optical data went through an erbium-doped fiber amplifier (EDFA) as well as a polarization controller (PC) and then got coupled into the silicon PIC from the i^{th} input port I_i using a grating coupler (GC). Then the data were coupled out from the silicon PIC through GC at the i^{th} output port O_i, and finally received by an optical receiver composed with an EDFA and a photodetector (PD, u^{2}t XPDV2140R). A variable optical attenuator (VOA) was introduced before the receiver so that the optical power could be adjusted. The detected on-off-keying signals after the receiver were then recorded with a real-time oscilloscope (Agilent 86100A) for the eye-diagram test. The bit-error-ratio was analyzed with the bit error rate tester (BERT, MP 1800A).

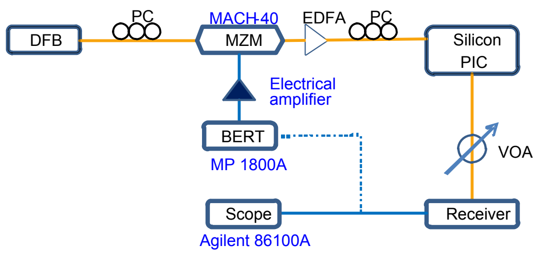

Fig. 9 Experimental setup for the test of data transmission

DFB: distributed feedback; PIC: photonic integrated circuit; PC: polarization controller; MZM: Mach-Zehnder modulator; VOA: variable optical attenuator; EDFA: erbium-doped fiber amplifier; BERT: bit-error-rate tester

Fig. 10 shows the measured eye diagrams for the data transmission with all 10 mode channels. One can observe that the eye diagrams for these 10 mode channels are clear and wide open. These eye diagrams are similar to those for data transmission in the silicon PIC with a straight multimode bus waveguide on the same chip. We also undertook BER measurement for data transmission for all 10 mode channels (Fig. 11). It can be observed that low-BER data transmissions can be achieved with the present silicon PIC.

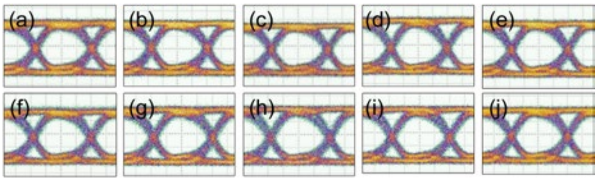

Fig. 10 Measured eye diagrams for data transmissions in the silicon PIC, which comprises a 10×1 mode multiplexer, a multimode bus waveguide with an S-bend based on modified Euler-bends, and a 1×10 mode demultiplexer: (a) TE_0-mode channel; (b) TE_1-mode channel; (c) TE_2-mode channel; (d) TE_3-mode channel; (e) TE_4-mode channel; (f) TE_5-mode channel; (g) TM_0-mode channel; (h) TM_1-mode channel; (i) TM_2-mode channel; (j) TM_3-mode channel

The bit rate is 26 Gb/s for a single mode channel

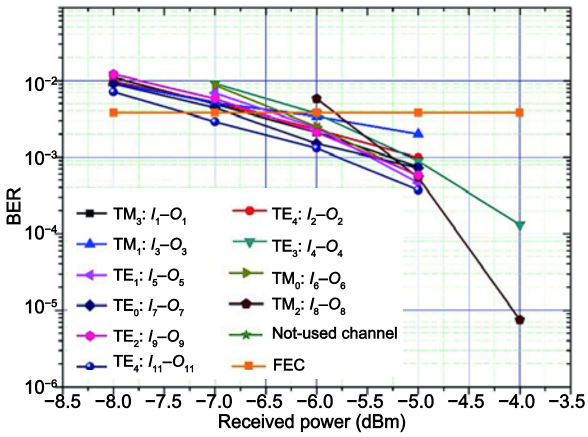

Fig. 11 Measured results of the bit error rate (BER) for data transmissions of all the 10 mode channels for the 1550.12-nm wavelength

FEC: forward error correction

4 Conclusions

We have proposed and demonstrated multimode silicon PICs enabling on-chip transmissions with 10 mode channels by monolithically integrating two 10-channel mode (de)multi-plexers and a multimode bus waveguide with a sharp S-bend based on modified Euler-bends. In the present case, we chose a multimode bus waveguide with a core width of 2.3 μm so that it supports 10 guided modes: four TM-polarization and six TE-polarization modes. The modified Euler-bends inserted in the multimode bus waveguide were designed optimally to have a small effective bending radius of $R_{\rm eff}$=40 μm. Our theoretical simulation demonstrated that the designed Euler-bend works well with low excess losses and a low inter-mode crosstalk for all mode channels. The measurement results demonstrated that the fabricated silicon PIC comprising an S-bend based on two 90° Euler-bends with $R_{\rm eff}$=40 μm has low losses (0.9–1.9 dB) and a low inter-mode crosstalk (about less than −20 dB) in a bandwidth of >80 nm (1520–1600 nm). This is similar to the measurement results for the silicon PIC with a straight multimode bus waveguide. It indicated that the S-bend based on the 90° Euler-bends with $R_{\rm eff}$=40 μm does not introduce notable excess losses or inter-mode crosstalk. In contrast, for the silicon PIC comprising an S-bend based on regular arc-bends, the excess losses were as high as 5 dB and the inter-mode crosstalk was as high as −2 dB in the wavelength range of 1520–1610 nm. This leads us to the conclusion that the modified Euler-bend is helpful for the realization of high-performance multimode silicon PICs with compact footprints.

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