On-chip data exchange for mode division multiplexed signals

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Abstract: Data exchange is an important function for flexible optical network, and it has been extensively investigated for the time and wavelength domains. The mode division multiplexing (MDM) has been proposed to further increase the transmission capacity by carrying information on different modes with only single wavelength carrier. We propose and experimentally demonstrate a novel on-chip data exchange circuit for the MDM signals by utilizing two micro-ring resonator (MRR) based mode converters. For demonstration, single and four wavelengths non-return-to-zero on-off-keying (NRZ-OOK) signals at 10 Gb/s carried on different modes are successfully processed, with open and clear eye diagrams. Measured bit error ratio (BER) results show reasonable power penalties. The proposed circuit can be potentially used in advanced and flexible MDM optical networks.

OCIS codes: (060.4230) Multiplexing; (130.3120) Integrated optics devices; (250.5300) Photonic integrated circuits.

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1. Introduction

The silicon photonic is commonly regarded as a promising solution for next generation optical network due to its low cost, high refractive index contrast, and compatibility with matured Complementary Metal-Oxide-Semiconductor (CMOS) technologies [1]. To meet the growing demand of the chip-level transmission capacity, various multiplexing technologies are exclusively utilized. The wavelength division multiplexing (WDM) as the most mature multiplexing technology, which is widely used to increase the transmission capacity in the optic fiber networks, however meets its bottleneck for the on-chip applications due to multiple laser sources on silicon platform are hard to realize and difficult to manage [2]. Alternatively, silicon based mode division multiplexing (MDM) technology attracts more and more attentions by taking advantages of increasing the transmission capacity efficiently with only one wavelength carrier [2–17]. Furthermore, various reported MDM schemes are compatible with the existing WDM and polarization division multiplexing (PDM) technologies [3, 7 ,9, 11, 14, 17]. By combining MDM with other multiplexing technologies, the capacity of the on-chip communication network is promising to be further increased.

Most on-chip MDM researches are concentrated on the design and optimization of the basic mode conversion (MC) [2, 4, 5, 8, 9, 12, 13, 16], which performs the conversion from one mode to another while preserving data information, as shown in Fig. 1(a). In recent years, more and more flexible and advanced multifunctional technologies in MDM networks had been proposed. Reference [14] proposed and demonstrated an integrated multimode switch which can simultaneously process on different wavelengths and modes. In our previous work [15], a silicon based MDM circuit which can simultaneously achieve the demodulation of WDM differential-phase-shift-keying (DPSK) signals had been demonstrated. The data exchange is an important function for flexible and advanced optical network, and extensive investigation had been given to time and wavelength division multiplexed systems. However, data exchange for MDM system has not been investigated, while it is highly desirable to increase robustness and throughput of the chip-level network utilizing mode multiplexing.

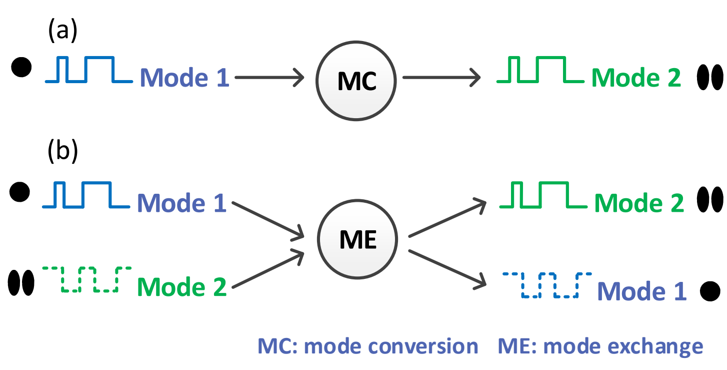

Fig. 1. (a) Conventional mode conversion; (b) proposed mode exchange.

#255368 Received 10 Dec 2015; revised 30 Dec 2015; accepted 3 Jan 2016; published 7 Jan 2016

In this paper, we propose and demonstrate a novel on-chip data/mode exchange scheme, which can perform the exchange function for data carried on different modes, as shown in Fig. 1(b). Similar to the existing wavelength exchange scheme [18] for WDM networks, proposed mode processing can be regarded as an improved function of conventional MC, using high performance mode converter. The proposed circuit is based on the silicon-on-insulator (SOI) platform by utilizing a structure combing two micro-ring resonator (MRR) based mode converters. The first MRR serves as a TE_1-TE_0 mode converter while the second one serves as a TE_0-TE_1 mode converter, achieving exchange of input data carried on different modes. For demonstration, single and four wavelengths non-return-to-zero on-off-keying (NRZ-OOK) signals at 10 Gb/s are successfully processed. Measured results show open and clear eye diagrams, and the bit error rate (BER) measurements indicate reasonable power penalties. The proposed circuit can be potentially used as routing component in advanced MDM optical networks.

2. Schematics

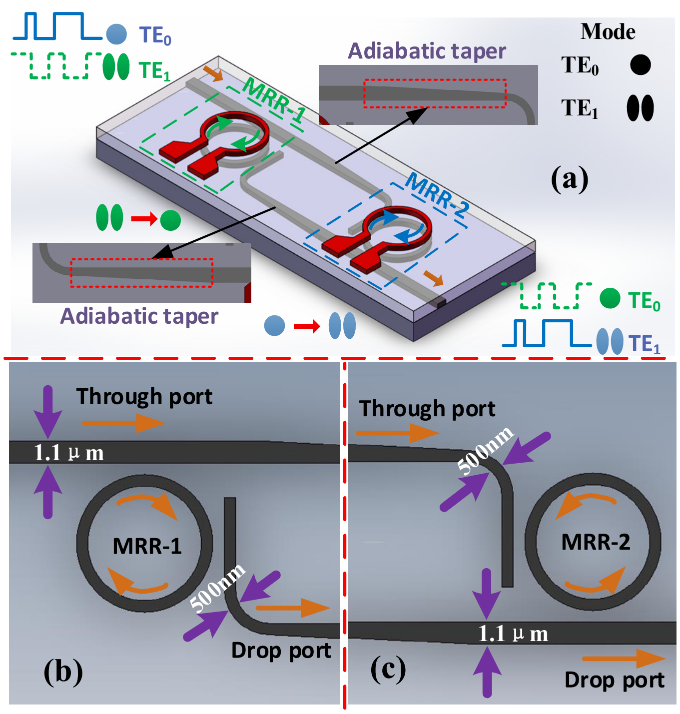

Fig. 2. (a) Schematics of the proposed circuit and structures of (b) MRR-1; (c) MRR-2.

Schematic diagram of the proposed circuit is presented in Fig. 2(a). MDM signals containing TE_0 and TE_1 modes transmit into the first MRR (MRR-1), which performs the TE_1–TE_0 mode conversion. The structure of MRR-1 is shown in Fig. 2(b). Drop port and ring bend waveguides of MRR-1 are set to be single-mode, while width of the through port waveguide is specifically designed to satisfy the phase matching condition in the coupling region between fundamental mode of ring bend waveguide and TE_1 mode of through port waveguide. TE_1 mode signal will be converted into TE_0 mode at the drop port while TE_0 mode signal keeps unchanged by passing through MRR-1 at the through port. On the other hand, the second MRR (MRR-2) serves as a TE_0-TE_1 mode converter. The structure of MRR-2 is symmetric with MRR-1, which is shown in Fig. 2(c). Through port and ring bend waveguides of MRR-2 are set to be single-mode, while width of the drop port waveguide is specifically designed to satisfy the phase matching condition in the coupling region between fundamental mode of ring bend waveguide and TE_1 mode of drop port waveguide. The

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original TE_0 mode signal will be coupled in MRR-2 and converted into TE_1 mode at the drop port, while the converted TE_0 mode signal from MRR-1 keeps unchanged by passing through MRR-2. The two converted modes are combined, and mode exchanged signals can be obtained at the output port. Two tapers are utilized to connect the waveguides with different widths, as the insets in Fig. 2(a) shown. Length of the tapers is designed to be sufficient long to achieve adiabatic TE_0 mode signal transmission. This specific design ensures only desired mode can be coupled into the MRR to perform the mode conversion. Compared with other mode converters, MRR based scheme shows a relatively compact and reconfigurable structure [3, 9, 14, 15]. Furthermore, additional WDM filtering functionality can be simultaneously realized, which is an important function for current WDM networks. The resonant wavelengths of the two MRRs can be tuned for alignment by the thermal-optic effect.

Principle and details of the MRR based mode converter and multiplexer/de-multiplexer can be found in [15]. In order to obtain the transfer functions of MRR-1 and MRR-2, the coupling strengths for TE_0-TE_0 and TE_0-TE_1 waveguide coupling are caculated. Taking MRR-2 as representative, for TE_0-TE_0 waveguide coupling, the coupling strength refers to ratio of the power from TE_0 mode at ring bend waveguide to the power of TE_0 mode at fundamental waveguide at through port of MRR-2, while coupling strength for TE_0-TE_1 waveguide coupling is defined as ratio of the power from TE_1 mode at drop output to the power of TE_0 mode at ring bent waveguide of MRR-2. The caculation is accomplished using the commercial software of Lumerical FDTD solutions, where the Finite Difference Time Domain method is utilized. The calculated results show coupling strengths of 0.08262 and 0.04374 for TE_0-TE_0 and TE_0-TE_1 waveguide coupling, respectively. By using the calculated values, the transfer functions of the MRR-1 and MRR-2 can be further simulated. The details of the simulation method can be found in Reference [19].

Simulated transfer functions within the C-band are presented in Fig. 3. The curves represent the drop output port of the specific MRR when only one specific mode is launched at the through input port (for instance, black curve represents the drop output port of MRR-1 when only TE_1 mode is launched at its through input port). To be noted, the red curve presents the crosstalk output from MRR-1 with only TE_0 mode launched. Simulation results indicate insertion loss is ~0.07 dB and crosstalk is as low as ~-36 dB at the resonant wavelengths.

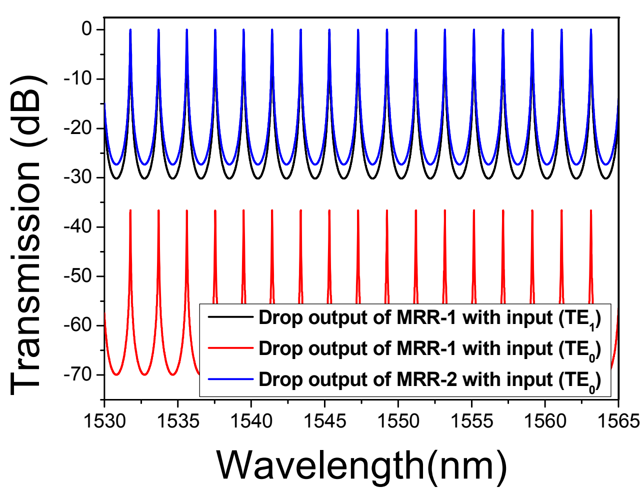

Fig. 3. Simulated transmission spectra for the MRR mode converter within C-band.

3. Fabrication

The proposed circuit is designed and fabricated based on the SOI wafer with top silicon layer of 220 nm and SiO_2 layer of 2 µm. The 248 nm deep ultraviolet lithography and inductively coupled plasma (ICP) etching are used to form the waveguide structure. Etching depth of the ridge waveguide is 130 nm. The widths of single-mode waveguide are chosen as 500 nm, while the multimode waveguide is designed as 1.1 µm to satisfy the phase matching condition of TE_0-TE_1 mode conversion. The length of the adiabatic tapers is set as 150 µm. The radius and gap of the MRRs are chosen to be 50 µm and 300 nm, respectively. An integrated TiN heater is fabricated on top of each micro-ring to tune the resonant wavelength for alignment. Thickness and width of the heaters are 200 nm and 5 µm, respectively. In order to experimentally evaluate performance of the proposed circuit, extra mode multiplexer and de-multiplexer are designed to perform the multiplexing and de-multiplexing for input and output signals, respectively. One of the rings is a pure single-mode ring, followed by an adiabatic taper for adaptation to a multimode waveguide, and another MRR mode multiplexer performs the TE_0-TE_1 conversion. For simplification, the single-mode ring is actually can be replaced by an adiabatic taper to couple the TE_0 mode to the multimode bus waveguide. However, the ring structure brings more flexible functionalities. More than 20 dB extinction ratio (ER) is achieved for both MRRs. Insertion loss is measured to be 2.5 and 4.5 dB for TE_0-TE_0 and TE_0-TE_1 mode conversions, respectively. The mode crosstalk is measured to be −32 and −26 dB for above mentioned conversions. The grating couplers (GCs) are used to couple light into and out of the chip, forming by an array of ridges with width of 310 nm, etching depth of 70 nm and period of 620 nm. Measured coupling loss is ~4.5 dB and 1 dB bandwidth is ~20 nm for single GC. The microscope image of the fabricated device is illustrated in Fig. 4. The circuit was fabricated at the Institute of Microelectronics (IME) in Singapore.

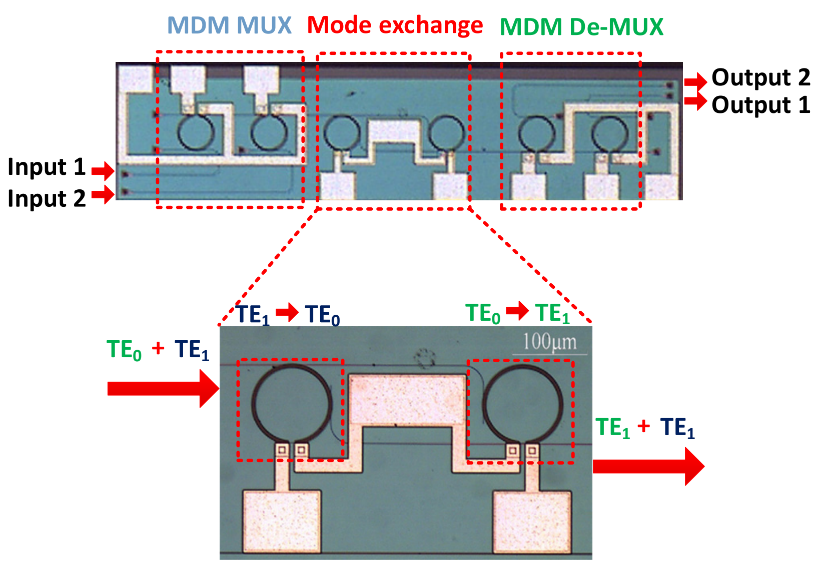

Fig. 4. Microscope image of the fabricated device. Inset: image of the proposed mode exchange part.

4. Measurement

In order to chracterize the performance of the fabricated circuit, transmission spectra within the C-band at two output ports are measured, for signals injection on each of the two input ports, respectively. The results are illustrated in Fig. 5. The total insertion loss is ~11.5 dB, which is mainly from the mode multiplexer and de-multiplexer (~7 dB). The extinction ratio

#255368 Received 10 Dec 2015; revised 30 Dec 2015; accepted 3 Jan 2016; published 7 Jan 2016

(ER) of more than 20 dB can be found within the C-band. For performance reference purpose, the device comprising only MDM multiplexer and de-multiplexer with same parameters is fabricated on the same chip. Insertion loss for TE_0-TE_0 and TE_0-TE_1 mode conversions are measured to be 2.5 and 4.5 dB, and the mode crosstalk is measured to be lower than −20 dB for both conversions.

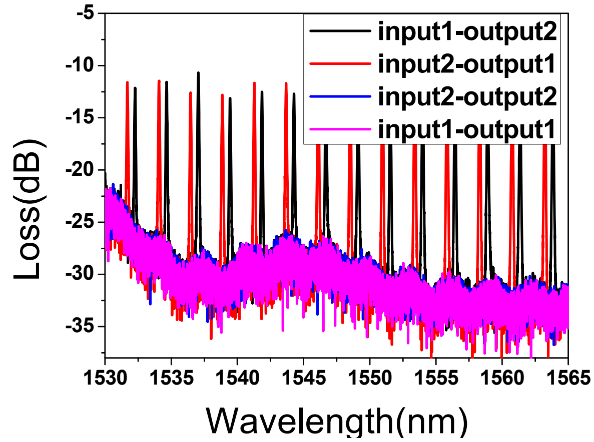

Fig. 5. Measured optical spectra of the proposed circuit.

The NRZ-OOK signal at 10 Gb/s is used to further test the fabricated circuit. The experimental setup is illustrated in Fig. 6. Four-channel continuous wave laser lights (1546, 1548.5, 1551 and 1553.5 nm) are separately modulated in NRZ-OOK format via the Mach-Zehnder modulators (MZMs), and combined by the array waveguide grating (AWG). The pseudorandom bit sequence length is 2^{31}-1. The de-correlation of four patterns was performed through splitter and delays in RF domain. The Erbium Doped Fibre Amplifier (EDFA) and attenuator (ATT) are utilized to optimize the output power for a fair comparison, and the band pass filter is used to filter out wavelength of interest for measurement. To be noted, in order to characterize the performance of the fabricated circuit conveniently, individual data input has been utilized in the measurement. Simultaneous data exchange experiment could be further demonstrated. In that case, two different data patterns should be used on different modes and fiber array should be used for simultaneous coupling both at the input and output.

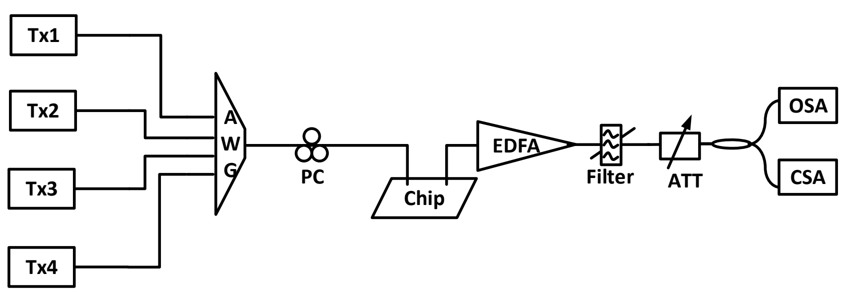

Fig. 6. The experimental setup. (PC: Polarization Controller, OSA: Optical Spectrum Analyzer, CSA: Communication Signal Analyzer).

The eye diagrams of the signals from both output1 and output2 are measured, using input1 and input2, respectively. Figure 7(a) shows the measured eye diagrams of the input and output signals of single wavelength (1548.5 nm) case. Clear and open eyes can be obtained at one output port while signal from the other output port can be barely detected, indicating a good performance of the mode exchange circuit. To be noted, the proposed circuit is capable of handling WDM signals due to the multiple resonant wavelengths of the MRRs, and thus the mode exchange for WDM signals can be expected. Figure 7(b) shows the measured eye diagrams of the WDM signals at exchanged output, indicating good performance for WDM processing.

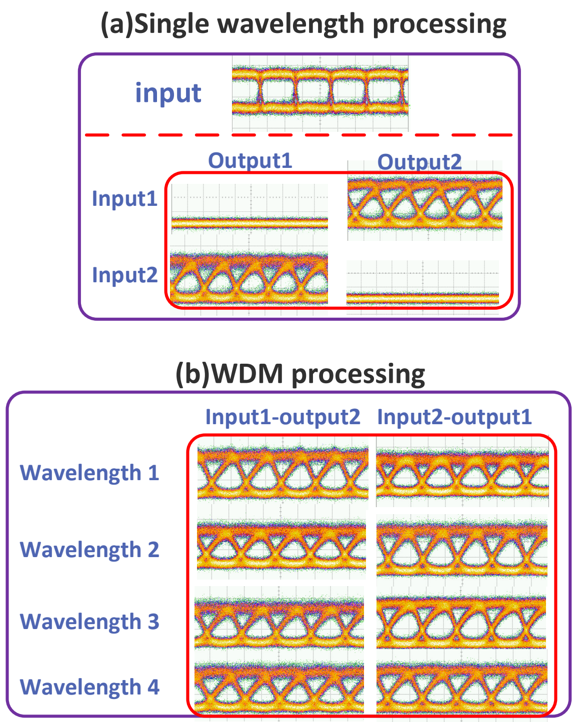

Fig. 7. The measured eye diagrams for (a) single wavelength processing and (b) WDM processing.

The BER measurements are further performed to qualitatively evaluate the performance, with results being plotted in Fig. 8. The worst power penalties within 4 wavelengths are measured to be 1.72 dB for input1-output2, and 1.55 dB for input2-output1, corresponding to the conversions of TE_0-to-TE_1 and TE_1-to-TE_0 data exchange, respectively. The dispersion of the measured penalties is quite small. The variation is less than 1 dB. For reference purpose, BER measurements of the reference device comprising only MDM multiplexer and de-multiplexer are also measured to be 0.69 and 1.04 dB, respectively. Considering the power penalty introduced by the multiplexer and de-multiplexer, the excess penalties due to the data exchange are smaller than 1.72 dB for input1-output2 and 1.55 dB for input2-output1.

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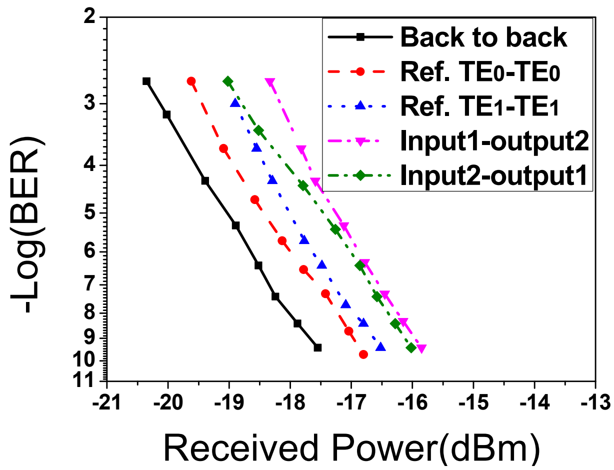

Fig. 8. The BER measurement results.

5. Conclusion

In summary, we have proposed and experimentally demonstrated a novel on-chip data exchange circuit based on the MDM signals by utilizing a structure combing two MRR based mode converters. The data carried on different modes will be exchanged through this circuit. For demonstration, 4 × 10 Gb/s NRZ-OOK signals are successfully processed. Measured results show open and clear eye diagrams, and the BER measurements indicate reasonable power penalties. The proposed circuit can be potentially used as routing component in advanced MDM optical networks.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 61475050 and 61275072); the New Century Excellent Talent Project in Ministry of Education of China (NCET-13-0240); the Fundamental Research Funds for the Central Universities (HUST2015TS079). The authors would like to thank Dawei Yu for helpful discussions.