High speed and small footprint silicon micro-ring modulator assembly for space-division-multiplexed 100-Gbps optical interconnection

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Abstract: We designed and fabricated a 4-channel silicon micro-ring modulator (MRM) assembly chip with arrayed grating couplers for space-division-multiplexed optical interconnection. Only 4 channels out of 7 have been utilized with the consideration of popular multi-source-agreements (MSA) compatibility with respect to a 7-core multi-core-fiber (MCF). Experimental modulations at 10, 15, 20 and 25 Gbps have been carried out for all the four channels with clearly opened eye-diagrams which indicates a single-fiber aggregate capacity of 100 Gbps with only one laser input for SDM optical interconnection. The silicon MRM assembly demonstrated in this work is advantageous for practical applications due to its simplified modulation solution (NRZ-OOK) with high capacity (100-Gbps), small footprint (0.45 mm²) and long reach (1 km).

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1. Introduction

The explosively increasing amount of data generated by applications like 4G/5G, cloud computing, artificial intelligence (AI), internet-of-things and so on, has been boosting the demand of optical interconnection bandwidth within or between data centers and high performance computers [1, 2]. In recent years, space-division multiplexing (SDM) has been attracting a lot of interest as the most competitive solution for overcoming the optical communication capacity crunch of single-mode fiber (SMF) [3]. There are two alternative approaches for SDM: few-mode fiber (FMF) based mode-division-multiplexing (MDM) and multi-core fiber (MCF) based fiber-core-multiplexing [4, 5]. Due to the very different structure compared with the conventional standard SMF, MCF is quite difficult for optical transmission application since all the devices must be compatible with MCF. On the other hand, since most of the transmitter and receiver devices can be customer designed and fabricated on chip, photonic integrated SDM is thus quite promising for optical interconnection to achieve large-capacity single-fiber data communication.

Currently, the single-fiber optical interconnection capacity has been boosted to terabit-per-second based on wavelength-division-multiplexing (WDM) by optical comb source [6]. However, the on-chip optical comb is very stringent for generation and usually a large amount of power will be needed for the Kerr nonlinear process [7]. On the other hand, most of the current popular multi-source-agreements (MSA), such as parallel-single-mode-4 (PSM4), Quad Small Form-factor Pluggable (QSFP), and so on [8], are based on single wavelength modulation with multiple parallel fiber channels to realized SDM in order to maintain the overall cost, packaging complexity, reliability, as well as the yield. Only several or tens of parallel channels are needed for practical application. Therefore, the MCF based SDM solution, which has single-fiber for hosting multiple channels, would have great potential for practical optical interconnection applications with significantly increased optical interconnection density, single fiber capacity and reduced packaging complexity (with only single fiber for coupling). There have been several demonstrations of MCF SDM using silicon photonic integrated circuits (PIC). For example, T. Pinguet et. al. from Luxtera have presented the general principle of 8-core fiber silicon chip optical interconnection as early as 2012 [9]. Corning inc. has applied the patent of using silicon grating coupler assembly for optical interconnect PIC at 2014 [10]. X. Wu et. al. from the Chinese University of Hong Kong have demonstrated the use of MDM with MCF based SDM for realizing the single-fiber
312-Gbps optical interconnection at 2017, only that just 3 cores have been utilized without parallel operation [11]. Recently, plasmonic modulator array has been experimentally demonstrated for MCF based SDM with a capacity of 4X20-Gbps, which is very close to the milestone of single fiber 100-Gbps optical interconnection [12]. Particularly, P. Hayn et. al. from Interuniversity Microelectronics Centre (IMEC) Belgium have demonstrated an MCF optical link based on GeSi electro-absorption modulator and photodetector (EAM-PD) arrays with 896-Gbps single fiber aggregate capacity, only that the working window of EAM is at around 1610 nm [13, 14].

The objective of this study is to explore the potential and prove the feasibility of silicon PIC for MCF based SDM in single-fiber optical interconnection. We designed and fabricated the micro-ring modulator (MRM) modulator assembly chip with arrayed grating couplers for chip-to-MCF coupling. The single input has been split into four branches for modulation and thus a single-fiber-input and single-fiber-output SDM optical interconnection system has been built. Experimental modulations at 10, 15, 20 and 25 Gbps have been carried out for all the four channels with clearly opened eye-diagrams which indicates a single-fiber aggregate capacity of 100 Gbps with only one laser input for SDM optical interconnection. The overall footprint of the 4-channel MRM assembly chip is only 0.45 mm².

2. Silicon MRM assembly chip design and measurement

The silicon MRM assembly chip in this work has three main functions. The first function is to split the optical input into four parallel branches so that only one laser is needed in this system in order to reduce the cost and the footprint. The single input is also of great importance for realizing the single-fiber-input and single-fiber-output SDM optical interconnection, and thus improved packaging simplicity and yield can be expected during practical application. The second function of the silicon MRM assembly chip is the parallel modulation by four MRMs. The very small footprint of MRM makes the Tx chip very compact and thus reduced cost can be expected. Meanwhile, the WDM compatibility, high speed modulation and low power consumption of MRM will make the SDM transmitter even more competitive. The third function of the silicon MRM assembly chip is the paralleled multi-channel coupling between the chip and MCF by using arrayed grating couplers for SDM.

The layout of the silicon MRM assembly chip is shown in Fig. 1(a) with the schematic picture showing the chip-to-MCF coupling. Shown in Fig. 1(b) is the microscope image of the fabricated silicon MRM assembly chip. The overall footprint of the chip as presented by Fig. 1(b) is $1.10 \times 0.41 = 0.45$ mm².

The chip was fabricated over standard silicon-on-insulator (SOI) process by multi-project-wafer (MPW) fabrication run at Institute of Microelectronics (IME), Singapore. The SOI chip has 220-nm top silicon, 2-micron buried oxide and oxide cladding. On the chip, three two-stage cascaded 1X2 multi-mode-interferometer (MMI) couplers are used for the 1-to-4 splitting and thus four parallel optical channels can be built. Four identical MRMs are aligned in parallel in the four optical branches for modulation. The MRM fabrication is based on the standard process of IME with a ring diameter of 40 μm. At the output, four grating couplers...
are hexagonally placed. The grating couplers are designed with focused structure so that the footprint can be kept small enough to realize arrayed alignment for the matched coupling between the grating couplers and the MCF cores. The hexagonal 7-core fiber is currently the most popular MCF. In this study, the grating couplers are hexagonally aligned with a pitch of 42 μm for matching the MCF which has a core diameter of 24 μm, and a core-to-core pitch distance of 42 μm. The MCF can support single mode transmission for all the seven cores with very low crosstalk of less than −100 dB (10km @1550nm). The attenuation and chromatic dispersion at 1550 nm are respectively about 0.24 dB/km and 17.7 ps/nm/km.

The MCF can then be placed above the grating coupler array for receiving the output signal. In this case, four cores are used in the experiment. Although the MCF is experimentally available to us but the manual alignment based on our facility is too much difficult during experiment. This coupling difficulty can be overcome by various methods including automatic alignment assisted by computers and up to 37-core fiber-to-chip coupling has been successfully demonstrated [15, 16]. Therefore, a bridge fiber with only one center core (single core with exactly the same profile compared with all the cores of the MCF) is going to be used for testing instead of the MCF. Since the core of the bridge fiber has the same profile like the cores of the MCF for this study, we believe the single-core fiber measurement is also reliable for proving the SDM optical interconnection feasibility of the silicon MRM assembly.

![Fig. 2. Transmission spectra of the four MR M channels on the same silicon PIC. The right picture is the zoom-in spectra showing the resonances of the MRMs at around 1559.5 nm.](image1)

![Fig. 3. Transmission spectra of the MRMs under different bias voltages.](image2)

The transmission of the silicon MRM assembly is measured by using an amplified spontaneous emission (ASE) source and an optical spectral analyzer (OSA) with 0.02-nm wavelength resolution. Shown in Fig. 2 are the transmission spectra of the four MRM channels on the same silicon PIC. The right picture in Fig. 2 shows the zoom-in spectra for the resonances of the MRMs at around 1559.5 nm. One can observe the resonant wavelengths of 1559.30, 1559.51, 1559.48 and 1559.12 nm for the four channels respectively. Although the MRMs are on the same chip with very close location, but the resonant wavelengths are still not identical with 0.39-nm float range which is within the standard fluctuation of silicon fabrication capability and thermal variation. Since single laser is used in our SDM solution and thus the resonances for the four MRMs should be adjusted to be identical so that optimized modulation can be achieved for all channels at the same laser wavelength. Thermal
tuning is a very standard method for adjusting the resonant wavelength of a MRM with tuning range up to tens of nanometers [17, 18]. We did not experimentally use the thermal tuning to compensate the resonance deviation, although we have designed the thermal tuning circuits on the MRM. During the experiment, we simply use different laser wavelength (tunable laser) for the different MRM modulation to test the performance. The laser wavelengths we used in the study are 1559.54, 1559.78, 1559.89 and 1559.27 nm.

Table 1. The measured optical transmission performance for the four MRM channels.

| Channel | FSR (nm) | Q factor | ER (dB) | Resonant wavelength (nm) | Wavelength tuning rate (pm/V) |
|---------|----------|----------|---------|--------------------------|-----------------------------|
| Channel-1 | 5        | 10396    | 18      | 1559.30                   | 9.2                         |
| Channel-2 | 5        | 10756    | 16      | 1559.51                   | 7.5                         |
| Channel-3 | 5        | 10398    | 16      | 1559.48                   | 8.3                         |
| Channel-4 | 5        | 10394    | 13      | 1559.12                   | 10.0                        |

The electrical tuning of the MRM transmission has been measured by using reverse-biased DC voltage and the transmission spectra are shown in Fig. 3 for all the four MRM channels. The DC voltage sweeps from 0 to −10 V with a step of 2 V. Significant resonant wavelength shifting can be observed. Therefore, one can obtain the averaged electrical wavelength tuning rate (resonant wavelength shift versus voltage) of about 8.3~10 pm/V. Several key parameters including free spectral range (FSR), quality factor (Q factor), extinction ratio (ER) and resonant wavelength have also been measured together with the electrical wavelength tuning rate as shown in Table 1, with 5-nm FSR, about 10,000 Q factor, 13~16 dB ER. The total insertion loss is 22 dB for all the channels includes the grating coupling loss of about 6 dB for each, the cascaded two 3-dB MMI coupler loss, as well as the MRM transmission loss.

Fig. 4. The eye-diagrams at 10, 15, 20, and 25 Gbps after 1-km bridge fiber transmission.
3. High speed modulation for the Silicon MRM assembly

The high speed modulation performance of the four MRMs has been further tested by using 1-km single-core bridge fiber which has a chromatic dispersion of 17.7 ps/nm/km. The optical source is an off-chip fiber laser with narrow linewidth of only about 1 KHz. The high speed none-return-to-zero on-off-keying (NRZ-OOK) signals are generated by using an arbitrary waveform generator (AWG) with 25 GHz bandwidth. The NRZ-OOK signals are biased onto the MRMs through a Bias-Tee (26.5-GHz bandwidth) and a broadband RF probe (40-GHz bandwidth). The optical signals are detected by a PD with 40-GHz bandwidth after an erbium doped fiber amplifier (EDFA) for booting the optical signal. The output electrical signals are then captured by a sampling scope with 50-GHz bandwidth for eye-diagram measurement and a real time digital sampling oscilloscope (DSO) with 59-GHz bandwidth for offline bit-error-rate (BER) measurement.

The high speed modulation tests were firstly carried out at 10, 15, 20, and 25 Gbps, and the eye-diagrams are shown in Fig. 4 at a received power of 2 dBm. Clearly opened eye-diagrams have been obtained with 4.13, 4.09, 3.60 and 2.91-dB averaged SNR respectively at 10, 15, 20, and 25 Gbps as listed in Table. 2. The MRM modulation is known to be very unstable. The SNR float for the four MRM channels are respective 0.96, 1.09, 0.82 and 1.20 dB for 10, 15, 20, and 25 Gbps. The averaged SNR float is about 1.02 dB for the four modulation rates.

Table 2. The SNR measurement for the four MRM channels at 10, 15, 20, and 25 Gbps.

|            | 10 Gbps | 15 Gbps | 20 Gbps | 25 Gbps |
|------------|---------|---------|---------|---------|
| Channel-1  | 4.75 dB | 3.69 dB | 3.51 dB | 2.97 dB |
| Channel-2  | 3.98 dB | 3.81 dB | 3.20 dB | 2.13 dB |
| Channel-3  | 3.98 dB | 4.78 dB | 4.02 dB | 3.33 dB |
| Channel-4  | 3.79 dB | 4.06 dB | 3.65 dB | 3.20 dB |
| Average    | 4.13 dB | 4.09 dB | 3.60 dB | 2.91 dB |

Fig. 5. The BER at 15, 20, and 25 Gbps after 1-km bridge fiber transmission.
Shown in Fig. 5 are the BER curves for the four MRM channels at modulation speed of 15, 20, and 25 Gbps. The BER rises at higher modulation speed. Error free operation can be achieved for all the four MRM channels with respect to hard decision forward error correction (HD-FEC) threshold of BER = 3.8E-3. The receiver sensitivities are listed in Table. 3 for all the MRM channels. The averaged sensitivities are respectively −2.5, −0.8 and 1.2 dBm for 15, 20 and 25 Gbps. The stability is worse at higher speed with up to 4.5 dB sensitivity float at 25 Gbps. The error free operation at 25 Gbps for the four MRM channels indicate an aggregated signaling capacity of 100 Gbps.

| Channel | 15 Gbps | 20 Gbps | 25 Gbps |
|---------|---------|---------|---------|
| Channel-1 | −2.5 dBm | −1.0 dBm | −1.0 dBm |
| Channel-2 | −2.3 dBm | 1.2 dBm  | 2.7 dBm  |
| Channel-3 | −3.8 dBm | −3.1 dBm | −0.4 dBm |
| Channel-4 | −1.5 dBm | −0.2 dBm | 3.5 dBm  |
| Average   | −2.5 dBm | −0.8 dBm | 1.2 dBm  |

The high speed modulation at 30 Gbps have also been carried out and the eye-diagrams are shown in Fig. 6. Only Channel-3 can achieve open eye operation with an SNR of 3.38 dB. The BER for Channel-3 is measured to be less than 1E-3 at received power of 2 dBm. As for Channel-1, Channel-2 and Channel-4, the eye-diagrams are almost closed and error free operation cannot be achieved for FEC threshold of 3.8E-3. The reason includes the unstable operation of MRM (different experiment condition due to the different coupling, probing and laser control) and also the limited bandwidth of MRM which is about 17 GHz (3-dB bandwidth) based on our measurement for Channel-3 (modulation variation is more obvious at higher speed). However, the successful 30-Gbps modulation with error free also indicates the possibility of aggregated capacity of 120 Gbps signaling with thermal control and chip-level packaging for stabilized operation.
The hexagonally distributed 7-core MCF is very popular with less fabrication complexity and has been demonstrated for a lot of optical transmission and interconnection applications. We have only used four cores out of seven in this work with the consideration of popular MSA compatibility, but the other cores can also be utilized. The seven-channel MRM assembly with grating couple array compatible with the 7-core MCF has also been designed and fabricated based on the same process. Shown in Fig. 7 are the schematic layout and microscope image of the silicon PIC which has a footprint of only $0.94 \times 0.61 = 0.57$ mm$^2$. With the full use of the seven cores, a single-fiber capacity scale up to 210 Gbps can be expected with the consideration of 30-Gbps modulation capability for the MRM.

![Fig. 7. Layout (a) and microscope image (b) of the 7 channel MRM assembly chip.](image)

Shown in Table. 4 is the benchmark for the photonic integrated SDM demonstrations with active modulators. The demonstrated silicon MRM assembly chip can support 4-channel and 1-km parallel optical interconnection with aggregated capacity of 100 Gbps. The footprint is only 0.45 mm$^2$ corresponds to a signaling efficiency (capacity/footprint) of 222 Gbps/mm$^2$. A commercial coarse wavelength division multiplexing (CWDM) chip from MACOM based on silicon Mach-Zehnder modulator (MZM) is also shown in Table. 4 for comparison, indicating a signaling efficiency of only 4.24 Gbps/mm$^2$ [18]. The silicon MRM assembly demonstrated in this work is advantageous for practical applications due to its reduced laser cost (single laser input), simplified modulation solution (NRZ-OOK) with high capacity (100-Gbps), small footprint (0.45 mm$^2$) and long reach (1 km).

| Modulator Modulator | Modulation format | Parallel channels | Capacity Gbps | Footprint | Signaling efficiency | Reach | Working wavelength | Ref. |
|---------------------|-------------------|-------------------|--------------|------------|----------------------|-------|-------------------|------|
| Silicon MRM         | NRZ               | 4                 | 4*25 = 100   | 0.45 mm$^2$| 222 Gbps/mm$^2$     | 1 km  | C band            | This work |
| Plasmonic MZM       | NRZ               | 4                 | 4*20 = 80    | N.A.       | N.A.                 | N.A.  | 1550 nm C band    | PTL2017 [12] |
| Silicon MRM         | DMT               | 3                 | 3*104 = 312  | N.A.       | 2 m                  | 1550 nm C band | JLT2017 [11] |
| GeSi EAM            | NRZ               | 16                | 16*56 = 896  | 1.5 mm$^2$ | 597 Gbps/mm$^2$     | 1 m   | 1610 nm L band    | OFC2017 [13] |
| Silicon MZM (Commercial) | NRZ               | 4 (CWDM)         | 4*28 = 112   | 26.4 mm$^2$| 4.24 Gbps/mm$^2$    | 2 km  | 1310 nm O band    | MACOM @2016 [19] |

The SDM chip has quite large loss which includes the coupling loss at the two grating couplers (~18 dB in total), the splitting loss of the two cascaded MMI coupler (~6 dB) and the insertion loss of the MRM (~1dB). The total chip access loss (fiber-to-fiber) is about 25 dB. With better optimization during fabrication, one can significantly reduce the grating coupler loss to less than 3 dB and a total loss reduced to 13 dB can be expected. Therefore, 12-dBm...
output power of the laser will be needed with the consideration of −1 dBm sensitivity of Channel-1 at 25Gbps as shown in Table. 3.

4. Conclusion

In summary, we demonstrated a silicon MRM assembly chip with arrayed grating couplers for SDM optical interconnection. The parallel SDM optical interconnection based on the single laser input can significantly reduce the needed laser number and thus reduce the overall cost of the system. Modulations up to 25-Gbps have been demonstrated for all the four channels, indicating a single-fiber aggregate capacity of 100-Gbps. The silicon MRM assembly chip demonstrated in this work is advantageous for practical applications due to its simplified modulation solution (NRZ-OOK) with high capacity (100-Gbps), small footprint (0.45 mm²) and long reach (1 km).

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