A 400 Gb/s O-band WDM (8×50 Gb/s) Silicon Photonic Ring Modulator-based Transceiver

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Abstract: We present a 400 (8×50) Gb/s-capable RM-based Si-photonic WDM O-band TxRx with 1.17nm channel spacing for high-speed optical interconnects and demonstrate successful 50Gb/s-NRZ TxRx operation achieving a ~4.5dB Tx extinction ratio under 2.15Vpp drive.

1. Introduction

The exponential increase in intra-Datacenter traffic generated by the 4G/5G, Internet of Things and Cloud Computing applications is currently pushing for high-speed and energy-efficient optical interconnects [1]. This has shaped the next-generation transport interface rates to be aligned with the 400 Gb/s Ethernet (GbE) that projected to extend to 800 GbE and 1.6 TbE [2] in the following years. To cope with these requirements, photonic Transceiver (TxRx) industry intends to scale its aggregate interface line-rates from the current 100 GbE wavelength (λ) division multiplexing (WDM) modules, initially to 200 GbE and 400 GbE capacities by increasing the # of lanes in WDM or SDM Tx setups and/or by increasing the single-lane bitrate [3].

In this race, Silicon-photonic (Si-pho) TxRxs appear as a key technology that has already mastered the 100 GbE commercial TxRx segment and is gradually penetrating also the 400 Gb/s capacity area, with successful C-band configurations reporting on 8×56 Gb/s PAM4 [4], 16×25 Gb/s NRZ [5] and 4×100 Gb/s DMT [6] TxRx schemes. Si-based TxRxs with 4×50 Gb/s PAM4 [7] and 8×50 Gb/s NRZ [8] capabilities have also been shown in O-band that forms currently the dominant spectral region in intra-DC interconnects. However, all these Si-based 400 Gb/s-capable multi-lane TxRx modules rely on Mach-Zehnder Modulators (MZM), that have increased energy and footprint requirements due to their relatively large device length, with the highest number of wavelengths in the only available WDM Tx layout [6] being not higher than 4. On the other hand, Si ring modulators (RMs) are well-known for their small footprint and lower energy consumption compared to their MZM counterparts but have managed so far to yield 400 Gb/s-capable WDM TxRxs only via increasing the number of lanes and with rather low-speed components at 25 Gb/s [9]. Despite impressive single-channel RM-based Si Tx demonstrations with high line-rates of ≥56 Gb/s NRZ, providing up to 112 Gbaud [10] and 128 Gbaud [11] via PAM4 in C- and O-band, respectively, 400 Gb/s WDM capacities offered by high-speed Si-RM arrays with ≥40 Gb/s line-rates has been only recently shown to reach 160 (4×40) Gb/s [12] exploiting a co-integrated 4-element WDM RM array with a 4-channel Si-MUX on the same Si chip.

In this paper, we present, to the best of our knowledge, the first 8-channel WDM 400 (8×50) Gb/s-capable O-band Si-pho RM-based TxRx retaining the energy and footprint benefits of RM- versus the MZM-based solutions and allowing for single-fiber connector and transmission schemes compared to the SDM solutions. We demonstrate 8×50 Gb/s NRZ Tx operation achieving ~4.5 dB extinction ratio (ER) under 2.15 Vpp drive featuring a WDM channel spacing of 1.17 nm and also Rx operation with externally-modulated 50 Gb/s NRZ signals. The energy efficiency (EE) of the TxRx was estimated at 1.04 pJ/bit/ch on average. To the best of our knowledge, this is the first Si-pho RM-based WDM TxRx with 400 Gb/s-NRZ capabilities among C- and O-band Si WDM TxRxs presented so far, that relies on high-speed (50 Gb/s) components rather than on increasing the number of lanes, enabling also the energy- and footprint-related advantages of RM over MZM Si structures to penetrate the 400 Gb/s TxRx technology area.

2. Device fabrication and layout

The 8-channel WDM TxRx was fabricated via a custom MPW run within IMEC's ISSIP50G CMOS Si-photonics platform. A photo of the TxRx chip (7400×3700 μm^2) can be seen in Fig. 1. The TxRx employed TE-polarization grating couplers (GC) for optical I/O with a λ peak at 1315 nm, comprising the following designated I/O ports, namely *Tx#1-8* in and *Tx out*. The Tx comprises 8 carrier-depletion RMs designed with a resonance free-spectral range (FSR) of 9 nm, respectively. The RMs exhibit a capacitance of ~30 fF, a Q factor of ~5500 and an E-O bandwidth (BW) of 33 GHz @ 0 V. Each RM can be thermally tuned via a dedicated tungsten heater controlled by respective DC pads. 3 dB MMI couplers are incorporated in the Tx optical circuitry after the RM of each respective channel leading to the waveguides connected with the *Tx#1-8 mon* output GCs for intermediate monitoring purposes. The modulated signals originating from all 8 RMs are multiplexed into a common output via a 2nd-order microring resonator (MRR) 8×1

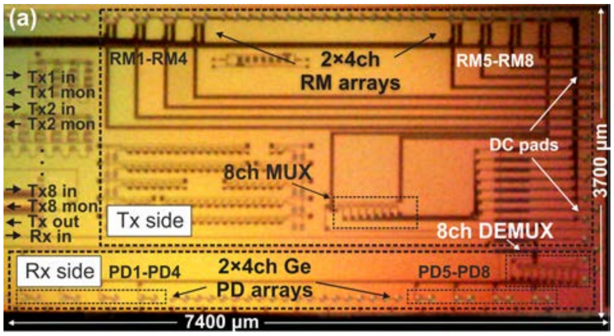

Fig. 1 (a) Microscope photo of the O-band WDM Si-photonic optical TxRx employing RMs & SiGe PDs.

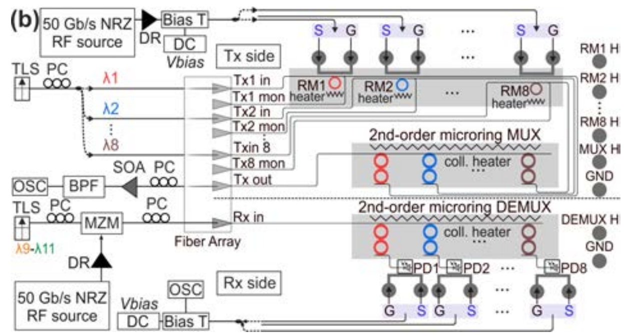

Fig. 2 Schematic of the WDM TxRx and the experimental setup used for the 8×50 Gb/s NRZ evaluation.

multiplexer (MUX) designed with 1.13 nm channel spacing and an FSR of 9 nm. The MUX channels can also be thermally tuned simultaneously by a collective tungsten heater. The Rx is accessed through the respective *Rx in* input port and comprises a 2[nd]-order MRR 8×1 demultiplexer (DEMUX) identical to the MUX that splits the input WDM signal in 8 waveguides leading to the 8 SiGe PDs. The PDs have a BW of 50 GHz, a responsivity of 0.95 A/W at 1315.1 nm for a -1 V reverse bias, while the PD dark current was 10.69 nA±0.68 at -1 V reverse bias.

3. Experimental results

Fig. 2 shows the schematic layout of the 8-ch TxRx and the experimental setup used for the 50 Gb/s evaluation. The Tx was probed with a fiber array while a GS RF probe was used for RMs #1 sequentially. A tunable laser source (TLS) was used to generate each one of the CW signals at λ1=1308.4 nm, λ2=1309.65 nm, λ3=1310.79 nm λ4=1312.18 nm, λ5=1313.24 nm, λ6=1314.73 nm, λ7=1315.55 nm and λ8=1316.56 nm, that were sequentially launched at *Tx1-Tx8 in*, respectively. An RF source was used to generate a 50 Gb/s NRZ PRBS7 signal that was amplified by a driver (DR) and applied to the RMs along with a reverse-bias voltage. The output signals at *Tx out* was amplified by a semiconductor optical amplifier (SOA) and filtered out of the amplified spontaneous emission (ASE) noise of the SOA by a 0.5 nm tunable bandpass filter (BPF) before being monitored at the oscilloscope (OSC). The Rx was also probed through the FA while an RF GS probe was used to access PDs #1-8 sequentially. A TLS was used to generate each one of the CW signals at λ9=1311.5 nm, λ10=1314.9 nm and λ11=1318.7 nm that were modulated by an external Mach Zehnder Modulator (MZM) driven by a 50 Gb/s PRBS7 NRZ source and were sequentially launched at the *Rx in* port. The PDs were reverse-biased and their electrical output signal was monitored by the OSC.

Fig. 3(a) depicts the Tx output spectra. The MUX exhibited a channel spacing of 1.17 nm, a 3 dB-BW of 0.73 nm, an FSR of 9.36 nm and insertion losses between 0.9-2.7 dB, respectively. Fig. 3(b) depicts RM1 spectra for different reverse bias voltages revealing a modulation efficiency of 29 pm/V at 0 V to -2 V, which was also verified for the rest of the RMs. Fig. 3(c) depicts the overlapping spectra of RM#i and the MUX channel #i for each channel #i of the 8 Tx channels, respectively, without enforcing any thermal tuning at either the RMs or MUX. The FSR of the MUX

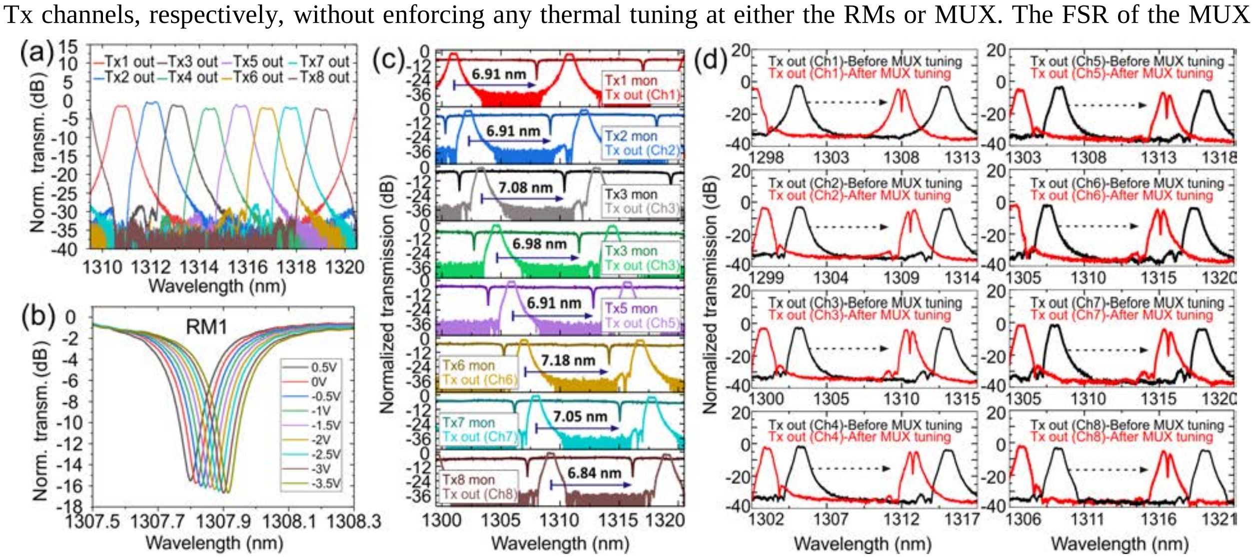

Fig. 3 (a) Tx output spectra, (b) RM1 transmission spectra for different reverse bias voltages, (c) overlapping output spectra of RMs #1-8 and MUX ch. #1-8, (d) Tx output spectra before and after tuning the MUX to the RM resonances.

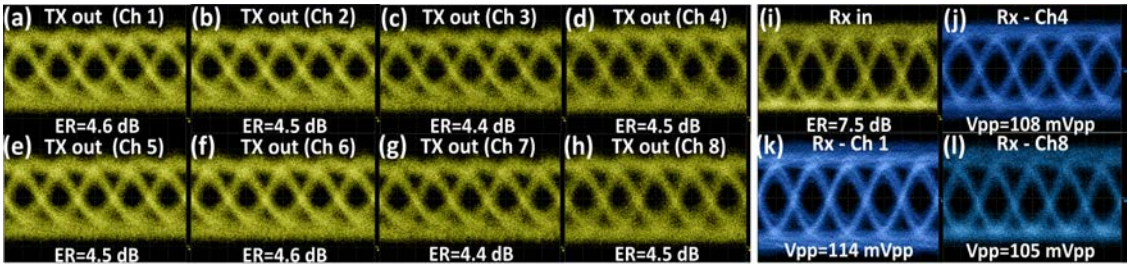

Fig. 4 Eye diagrams at 50 Gb/s NRZ operation: (a)-(h) Tx modulated signals (4 mV-10 ps/div). (i) externally-modulated Rx input signal (4 mV-10 ps/div) and (j)-(l) Rx electrical signals by PDs 1, 4 and 8 (10 mV-10 ps/div).

channels and the RMs #1-8 resonances was measured to be 9.78 nm and 9 nm on average. The spectral distance of the MUX passbands from their respective channel RM resonances without enforcing thermal tuning was found between 6.84-7.18 nm indicating a required average MUX tuning of 6.98 nm to tune the MUX to the RM resonances. The RM resonances near 1315 nm were selected for the operation so as to reside close to the GC's λ peak. Fig. 3(d) shows the Tx output spectra of all 8 Tx channels before and after tuning the MUX to the RM resonances for Tx operation.

The Tx was evaluated in an 8×50 Gb/s NRZ modulation scheme. Figs. 4(a)-4(h) show the eye diagrams of the 50 Gb/s NRZ Tx signals at Tx out obtained for each one of the Tx channels separately, exhibiting ERs in the range of 4.4 to -4.6 dB, respectively. The 8 RMs were driven with ~2.15 Vpp with a reverse bias of ~1.1 V, respectively. The optical power of the 8 CWs before *Tx#1-8 in* was 10 dBm, while the average power of the 8 data signals at *Tx out* was measured to be between -14.5 dBm and -9.5 dBm, respectively. The break-down of the optical losses is as following: GCs: ~7-8 dB, MMIs after RMs: ~3.3 dB, MUX ~0.9-2.7 dB (depending on the channel), RM transmission penalty: ~3-4 dB (depending on the Tx channel and operating wavelength). The average optical power of the signals at λ1-λ8 after the BPF was in the range of 3.5 dBm to 8.5 dBm, respectively. The SOA was driven at 175 mA. The MUX heater consumed 400 mW in total while no power was applied to the RM heaters during the evaluation. The total Tx EE at 50 Gb/s NRZ was estimated at 1.04 pJ/bit/ch, i.e. 40 fJ/bit/RM and 1 pJ/bit/MUX channel. The Rx was also evaluated with externally-modulated 50 Gb/s optical signals imprinted at λ9-λ11 that were sequentially launched at *Rx in* with an optical power of 6 dBm. The signals reached the respective PDs #1-8 through the DEMUX and the electrical output of the PDs was monitored in the OSC. Fig. 4(i) depicts the eye diagram of the external 50 Gb/s PRBS7 NRZ signal while Figs. 4(k)-(j) show the electrical eye diagrams received by PDs #1, 4 and 8, respectively. A reverse bias of -2.5 V was applied to the PDs. The electrical eye diagrams exhibited a Vpp value in the range of 105 mVpp to 114 mVpp and a signal-to-noise ratio (SNR) of ~4.7. No DEMUX heating was enforced during the Rx evaluation.

4. Conclusion

We presented a 400 (8×50) Gb/S-capable Si-photonic WDM O-band TxRx with a channel spacing of 1.17 nm comprising high-speed RMs in the Tx and SiGe in the Rx for high-speed optical interconnects. We demonstrated successful 8×50 Gb/s NRZ operation with Tx ER values of ~4.5 dB and also Rx operation with externally-modulated 50 Gb/s NRZ signals. This work comprises the first 400 Gb/s-NRZ-capable TxRx that relies on high-speed components among all reported C- and O-band operating WDM Si-photonic TxRxs presented so far, introducing the low energy and low footprint credentials of Si-RM platform in the 400 Gb/s WDM transmitter technology.

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