A 160 Gb/s (4x40) WDM O-BAND Tx SUBASSEMBLY USING A 4-CH ARRAY OF SILICON RINGS CO-PACKAGED WITH A SiGe BiCMOS IC DRIVER

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Abstract

We demonstrate a 4-channel O-band transmitter comprising a Silicon Photonics RM array co-packaged with a SiGe BiCMOS integrated driver chip. 4×40 Gb/s data modulation with an average ER of 3.39 dB is reported, with the transmitter module exhibiting a high energy efficiency of 2.52 pJ/bit.

1 Introduction

The explosive growth of data center (DC) traffic [1] , fuelled by Cloud and AI computing, is stretching the limits of currently deployed optical transceiver technologies, calling for advances in operational speed, aggregate bandwidth and energy efficiency. In this context, the transition from current 100 (4×25) Gb/s Ethernet (GbE) implementations, towards 200 GbE and even 400 GbE interfaces, enforces multi-channel transmitter configurations exploiting either space division multiplexing (SDM) or wavelength division multiplexing (WDM), in conjunction with line-rates up-to or even higher than 50 Gb/s. Silicon photonics transmitters (Tx) arise as a key enabling technology, already employed in 100 GbE commercial modules, with recent demonstrations [2]-[5] extending the Silicon Photonic credentials towards higher bandwidth multilane setups, achieving 4x40 G [2] and even 8x40 G [3] in C-band configurations.

The dominance, however, of the O-band spectral window in the high-speed DC interconnect segment, has shifted research efforts towards O-band Txs [6]-[11], with ,higher than 25 Gb/s, demonstrations focusing either on single-lane transmitter layouts [6]-[9] or on multi-channel setups [10]. All of them have been, however, implemented as standalone photonic chips, without being yet incorporated into photonic/electronic co-packaged subassemblies. More specifically, travelling wave Mach Zehnder modulator (MZM) arrays have been recently shown to perform at up to 400G aggregate date rates [10] when operating as standalone Si-Pho chips, requiring additional effort towards bringing them into a Tx subassembly that can reliably ensure the in-package high-frequency electronics for successfully driving the MZM optics. On the other hand, Si-based ring modulator (RM) counterparts are well-known to offer significant footprint and energy consumption benefits compared to MZM-based arrangements [6]- [9], but these have been only recently validated in O-band Tx subassemblies employing just a single channel layout at >=50 Gb/s operation [8],[12]. O-band Si-based RM multi-channel Tx setups have been just recently demonstrated by us to offer 4×40 Gb/s performance [13], without having been, however, yet incorporated and validated into a fully-fledged electronic/photonic sub-assembly package.

In this paper, we extend our previous work on RM-based WDM optical transmitters [13] and demonstrate a fully co-packaged 4×40 Gb/s O-band Tx subassembly that comprises a SiPho WDM RM array and a 4-channel electronic driver circuit co-assembled onto a polymer high-speed RF electronic board. The silicon WDM modulator array comprises 4 high-speed carrier depletion RMs, with a channel spacing of 2 nm, interconnected through a 4-channel Si-based ring-based multiplexer (MUX). The 4-channel electronic circuit has been fabricated in a 55 nm SiGe platform and employs 4 fully-differential drivers, ensuring high-bandwidth and low power operation through a lumped driving scheme that exploits the short driver-to-RM distance. A 4×40 Gb/s data modulation experiment for all four transmitter channels is presented, revealing open eye-diagrams, with extinction ratio (ER) values ranging between 3 dB and 3.75 dB. The 4-element driver array delivers an average Vpp of 2 V to each RM, consuming only 244 mW that translates to an energy efficiency of 1.525 pJ/bit increasing to 2.51 pJ/bit, when considering also the consumption of the RM thermal tuning mechanism.

2. Device fabrication and description

A microscope photo of the 4-channel, RM-based, WDM O-band transmitter module is illustrated in Fig. 1(a). The transmitter comprises a Silicon Photonic chip, fabricated in imec's ISIPP50G platform, incorporating a 4-channel RM array [13], wire bonded to an electronic 4-channel ultra-low power fully differential driver [14], fabricated in 55 nm SiGe BiCMOS technology [14],[15]. Both chips were mounted on a high frequency polymer board, facilitating the necessary electronic components required for the operation of the driver circuitry (e.g. de-coupling capacitors, wire-bonding pads, power supply I/O pins) and the routing of the driver's input signals, through 50GHz electrical traces. The deployed printed circuit boards were specifically developed as basis for an electro-optical circuit board (EOCB), providing a very low topography surface, to eventually enable the fabrication of polymer optical waveguides with submicrometer precision on the top side of the boards. Moreover, the copper traces provide nearly vertical sidewalls and well controlled gap width, yielding low impedance variations and allowing features size down to 40µm. The high-speed routing credentials of the polymer RF traces, have already been validated in previous demonstrations, achieving seamless electrical transmission of 112 Gb/s PAM-4 signals through 4cm long lines [16]. Finally, the electronic and photonic chips were placed in close proximity, in order to minimize the wire bonding induced inductance, while a specially designed layout, allowed connectivity to the driver inputs through the use of solderless, RF connectors (Ardent TR70).

A close-up view of the assembled Silicon and Electronic ICs is illustrated in Fig. 1(b). The fabricated Si chip exhibited a footprint of 2.7×5.2 mm, while the driver chip occupied 1.0×2.4 mm. Access to the integrated modulator array is achieved via TE-polarization grating couplers (GC) at the west side of the chip, designated as Tx in 1-4 and Tx out, and referring to the 4 transmitter inputs and the combined transmitter output, respectively. The RM array comprises 4 high-speed O-band carrier-depletion RMs with 7.5 µm, 7.502 µm, 7.504 µm and 7.506 µm radius, respectively. The RMs Q factor was measured to be ~5000, close to the design specifications, while the simulated group index was 4.03 corresponding to an FSR of 9.0 nm. Finally, the normalized E-O S21 response of a single RM, fabricated with the same specification in the same run, revealed an average f_{3dB} of approximately 33.8 GHz. Each RM can be thermally tuned by a dedicated heating element accessed by respective electrical DC pads at the east side of the chip. The resulting modulated signals from all four RMs are multiplexed in a 4-channel MUX unit, based on 2nd-order micro-ring resonators, and are accessible through the common Tx output. A collective heater implemented at the sides of the double-ring-based structures, allows thermal tuning of the 4-channel MUX. The 4-channel electronic driver employs a lumped driving scheme, by leveraging the short electrical connections (wire-bonds) between the driver and RM pads, in order to avoid the use of termination resistors resulting in increased energy efficiency, while eliminating the respective resistor heat dissipation. An unbalanced output stage is also exploited, in order to allow DC-coupling to the modulator without the use of an external bias-tee, significantly reducing the real-estate and cost of the resulting Tx assemblies.

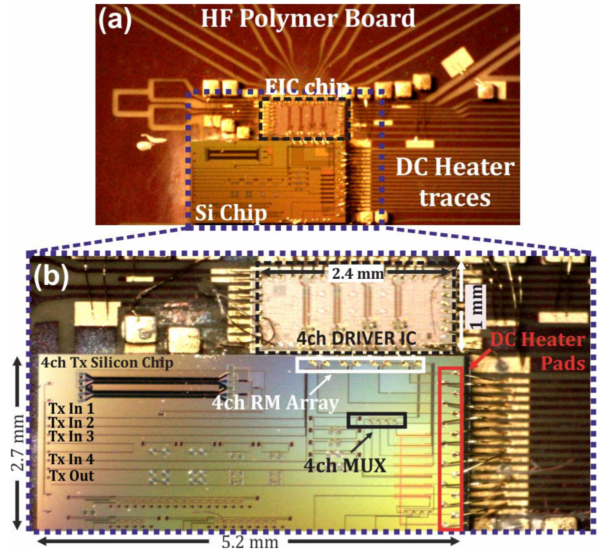

Fig. 1: (a) Polymer Board (b) Si and EIC chip highlight

3 Experimental setup & results

The experimental setup employed for the characterization and the 4×40 Gb/s data modulation experiment of the Tx sub-assembly, is depicted in Fig. 2. A bit pattern generator was used to generate a differential signal of an NRZ pseudo-random binary sequence (PRBS^7-1) at 40 Gb/s, with a peak amplitude of 180 mV, that was applied to the driver's input through TR70 pluggable RF connectors. The electronic driver circuitry was powered by four voltage supplies. i.e V_{pre}, V_{dd}, V_{bias1} and V_{bias2}, with the first associated with the pre-driver operation, the second corresponding to the main supply voltage and the last two employed for setting the bias point of the RMs. The operational settings of the integrated drivers were fine tuned for each RM, in order to provide the best perfomance in terms of modulation depth and optical eye diagram opening. A tunable laser source (TLS) was used to

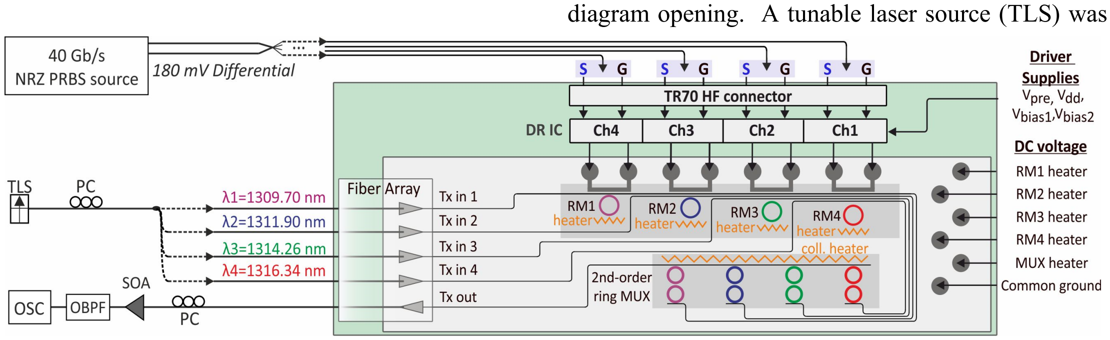

Fig. 2: Schematic of the 4-channel WDM Tx and experimental setup used for the 4×40 Gb/s modulation experiment.

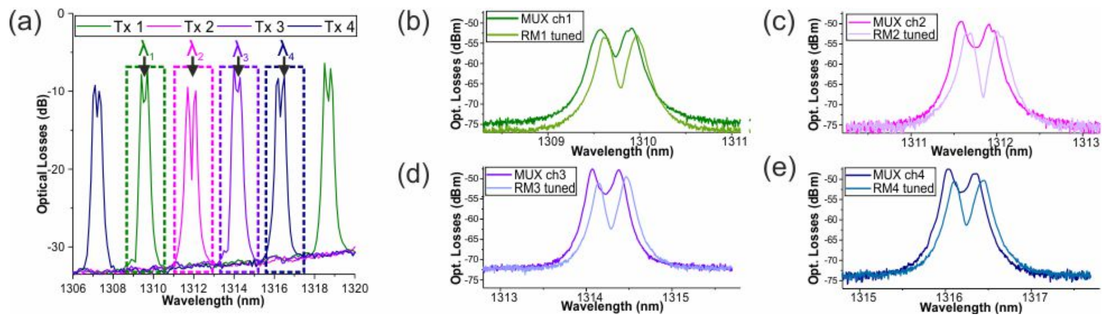

Fig. 3: (a) Optical Spectra of the 4-channel MUX (b)-(e) Tx out channel#1-4 output spectra before and after tuning RM#1-4 resonance to the nearest respective MUX channel#1-4, for each of the four Tx channels.

sequentially generate one of the 4 CW signals, at λ_1=1309.70 nm, λ_2=1311.90 nm, λ_3=1314.26 nm and λ_4=1316.34 nm, according to the RM operating points. The CW signals were injected through a fiber array at the input GCs, corresponding to Tx In1-4, respectively. A polarization controller was used to match the incoming light's polarization to the grating couplers. The resulting modulated signal was coupled out of the chip through an output grating coupler (Tx out) and after amplification in a semiconductor optical amplifier (SOA), it was injected in an optical bandpass filter (OBPF) with 0.5 nm 3 dB-bandwidth, to filter out the SOA amplified spontaneous emission (ASE). Finally, the signal was evaluated in a sampling oscilloscope (OSC).

Figure 3 illustrates the spectral transfer function of the 4-channel MUX obtained by sequentially sweeping each Tx input port with a TLS and measuring the optical power at the common Tx Out port. The MUX featured a free spectral range (FSR) of 9.02±0.2 nm, and a channel spacing of 2±0.2 nm, while the insertion loss was 8-10 dB, due to a design error, deviating from the expected specifications of 2-3 dB. The wavelength annotations (λ1-λ4) in Fig. 3 (a) indicate the MUX channels that were used for the 4×40 Gb/s data transmission, while Fig. 3(b)-3(e) depict the output spectra of the respective MUX channels before and after tuning the respective RM resonances inside the MUX transfer function.

The performance of the 4-channel transmitter was assessed via a 4×40 Gb/s NRZ OOK data modulation experiment. Figures 4 (a)-(d) illustrate the optical eye diagrams, obtained at the common output port of the MUX, with each RM sequentially operated at the appropriate wavelength and

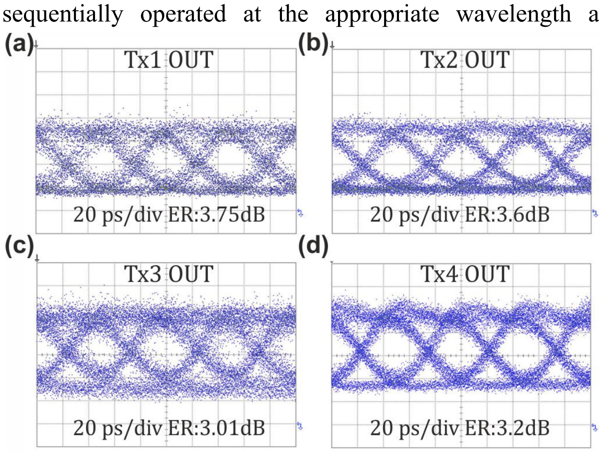

Fig. 4: (a)-(d) Eye diagrams for the Tx 4×40 Gb/s operation.

required tuning power, revealing ER values of 3.75 dB, 3.6 dB, 3.01 dB and 3.2 dB, respectively. The RMs were driven with approximately 2Vpp, provided by the integrated driver array with each driver input fed by a 180-mVpp differential signal, and the RMs DC reverse biased at -0.39 V, -0.41 V, -0.42 V, -0.38 V, respectively. The optical power of the CW signal injected at all four wavelengths of the transmitter (λ1-λ4), was 10 dBm, while the average optical power of the resulting modulated signals emerging at the common output port, were -17.7 dBm, -18 dBm, -19.1 dBm and -19 dBm, respectively. Breaking down the optical losses, the GCs imposed ~9 dB, the MUX ~10-12 dB, while the RM insertion losses ranged from 6-9 dB, depending on the Tx channel and operating wavelength. Subsequent fabrication runs, can decrease the total optical power requirement, by targeting 2-3dB MUX loss, 4dB GC loss and 4dB RM loss, resulting in an optimized optical loss of 15 dB, enabling amplifier-less operation. The SOA was electrically driven at 276 mA, providing an average gain of 20±2dB, depending on the operating wavelength of each Tx channel. In order to tune the RM resonances, to the respective MUX channel, the electrical powers applied to the integrated heater of RM1-RM4 were 39.3 mW, 47.58 mW, 33.63 mW and 38.75 mW, respectively. The power consumption of the driver array was 244 mW, corresponding to a low energy efficiency of 1.525 pJ/bit, and concluding to a total Tx power efficiency of 2.52 pJ/bit, taking into account the RM heater consumption.

4 Conclusion

We demonstrated an O-band 4-chanel silicon photonic WDM optical transmitter, comprising a 4-element RM array co-packaged with fully differential SiGe electronic drivers. Demonstration of 4×40 Gb/s data modulation, revealed an average optical ER of 3.39 dB, while the drivers operated with an input voltage as low as 180 mVpp, provided via a dedicated high-speed polymer PCB. The co-packaged module achieved an energy efficiency of 2.52 pJ/bit, while the high-speed credentials of the photonic and electronic devices hint at even higher data rate operation in follow-up experiments.

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