Fully integrated silicon photonic high-speed transmitter with Ring-Assisted Mach-Zehnder modulator

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Abstract: We report a fully integrated transmitter which includes a DFB laser and a push-pull drive ring-assisted Mach-Zehnder modulator. We demonstrate 224Gb/s PAM-4 transmission with 1.8Vppd differential driving swing and transmitter penalty (TDECQ) of 1.25dB.

1. Introduction

With the unprecedented growth in high-performance and data intensive computing demands, particularly from workloads like artificial intelligence and machine learning, the necessity for optical interconnects in data centers and high-performance computing systems has intensified. Silicon photonics technology provides high-bandwidth, energy-efficient, and highly scalable optical interconnect solutions for both intra- and inter- data center communications [1]. Moreover, it can be seamlessly co-packaged with compute electronics to establish an optical I/O superior to traditional all-electrical I/O for high-performance computing applications [2,3]. High bandwidth ring modulators are compact and with resonant nature, making them inherently suitable for bandwidth density scaling applications [4,5]. Incorporating ring modulators inside a balanced Mach-Zehnder interferometer (MZI) to form a ring-assisted Mach-Zehnder modulator (RAMZM) brings together the benefits of ring modulators and Mach-Zehnder modulators (MZM), including compact footprint, push-pull driving on lumped electrodes, chirp-free operation, and excellent linearity [6,7]. The push-pull driving configuration enables each individual ring to operate with a V_{pp} (peak-to-peak voltage) of $<1V_{pp}$, greatly expanding the design space for electronic IC (EIC) using leading edge CMOS processes. The on-chip laser source, enabled by die to wafer bonding of III-V material onto silicon, mitigates optical coupling losses between the light source and the photonic integrated circuits (PICs). In this work, we experimentally demonstrate this fully integrated transmitter capable of realizing chirp-free and highly linear 224Gb/s PAM-4 data transmission with $1.8V_{ppd}$ (0.9Vpp on each ring modulator) push-pull driving swing.

2. Transmitter PIC design and characterization

The schematic of the RAMZM transmitter is shown in Fig. 1 (a). It has a hybrid silicon/III-V DFB laser emitting at approximately 1310nm, delivering an output power exceeding 13dBm. This power is equally distributed between two waveguides using a 2x2 multimode interferometer (MMI). The microring modulators (MRMs) on the two MZI arms are designed nominally to be identical with a radius of 10μm. Following the MRMs, phase tuners are utilized for the MZI quadrature bias adjustment. Inside the MZI, inline monitor photodetectors (MPDs) are used to align the MRM resonance with the laser. At the MZI's output, another set of MPDs is implemented for monitoring MZI quadrature bias. The total MZI arm length is around 800um, including MRMs, phase tuners and MPDs. An additional input optical coupler is utilized for DC characterization. All devices on the transmitter are fabricated with Intel's 300mm silicon photonics process. Fig. 1 (b) shows a microscope image of the fabricated transmitter chip.

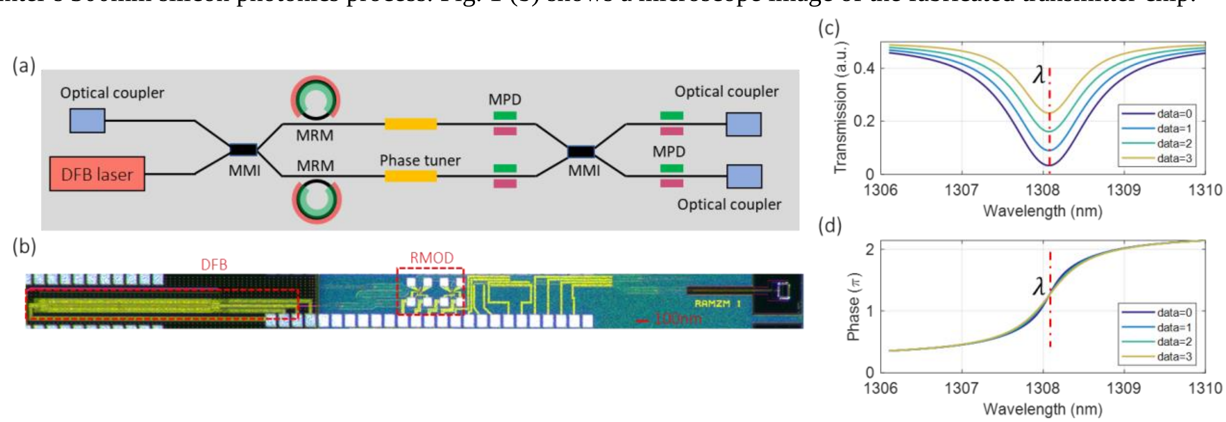

Fig. 1 (a) Schematic and (b) microscope image of the RAMZM transmitter PIC. (c) and (d) are simulated transmission and phase response of the RAMZM in the push-pull operation.

The operation principle of this RAMZM is to use the two MRMs as phase modulators inside an MZI. The two MRMs are strongly over-coupled and operate precisely on-resonance. The MZI arms are biased at the quadrature point, and the two MRMs are driven in a push-pull manner. In this configuration, we can achieve chirp-free modulation and simultaneously mitigate the nonlinearity from the MRM. In contrast, the ring assisted MZM using two MRMs as amplitude modulator does not eliminate the nonlinearity from the MRMs, consequently leading to unequal PAM4 eye levels [7]. Fig. 1 (c) and (d) show the simulated power transmission and phase response of the RAMZM. When applying push-pull driving signals, the intensity changes exhibit uniform spacing, and the phase at operation wavelength remains at zero under different applied voltages. Therefore, the device can achieve ultra-linear and zero-chirp modulation.

For DC characterization of the RAMZM, both MRMs were biased at -3V, and aligned with the DFB laser wavelength at 1311.1nm. Phase tuners were used to set the MZI quadrature bias point. Then the DC transmission spectra of the RAMZM were measured by sweeping an external tunable laser. The measured spectra are shown in Fig. 2(a). For each individual MRM, the extinction ratio (ER) is measured to be 7.5dB, and the loaded Q factor is around 2200. The total insertion loss (IL) of the RAMZM is 10.5dB with 7.5dB attributing to the MRMs and 3dB to the MZI's quadrature operation. RAMZM IL can be reduced by decreasing the MRM ER at cost of reduced Q factor leading to lower modulation efficiency. Fig. 2(b) illustrates the extracted optical power at resonant wavelength (operating wavelength) versus applied push-pull voltages. It shows that with a 1.8V_{ppd} driving swing, the DC modulation efficiency is 5dB. Fig. 2(c) shows the measured electro-optic (EO) S_{21} response for the MRM with the same design, detuned by -75pm and -125pm from the resonant wavelength. The 3-dB bandwidth is measured to be 58.5GHz. When operating the MRM on resonance, the bandwidth will be slightly less than this.

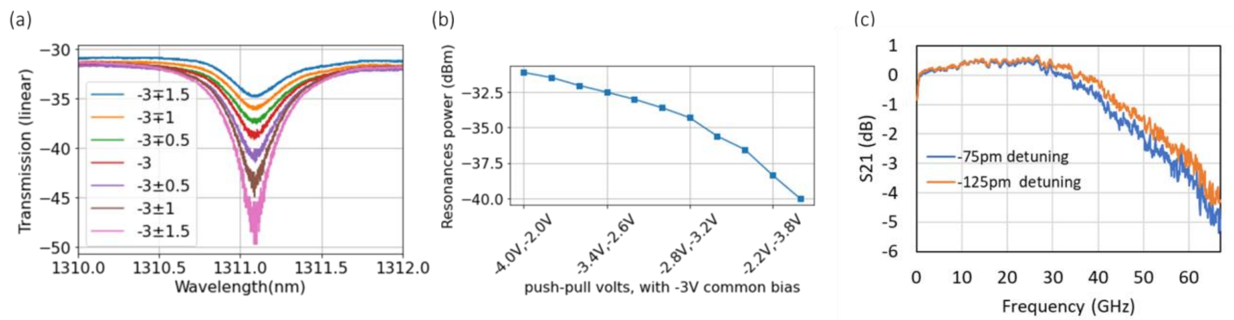

Fig. 2 (a) Measured transmission spectra when applying different reverse bias voltages on the two MRMs. (b) The extracted DC modulation efficiency at the resonant wavelength when applying different push-pull voltages on the two MRMs. (c) Measured EO S21 responses of the MRM detuned by 75pm and 125pm from the resonant wavelength, respectively.

3. Experimental setup and results

We then characterize the PAM-4 data transmission performance of this transmitter using the setup depicted in Fig. 3 (a). DFB laser is biased at 80mA delivering 10dBm optical power in each of the ring bus waveguides. Throughout the experiment, both MRMs were biased at -3V common bias. Differential electrical driving signals were generated by a 128GS/s arbitrary waveform generator (AWG). The electrical signals were then amplified by two individual RF amplifiers before being applied to the MRMs via a GSSG RF probe. The frequency response of the AWG front-end, the RF amplifiers, the bias tees, and RF cables were de-embedded using the signal de-emphasis function of the AWG. This operation flattened the response of the RF driver link up to 50 GHz. The modulated signal was then amplified by a praseodymium-doped fiber amplifier (PDFA) and was subsequently detected by the optical sampling head of a digital communication analyzer (DCA) with 65 GHz optical bandwidth.

Fig. 3(b) illustrates a 224Gb/s PAM-4 eye diagram obtained with a 1.8V_{ppd} driving swing (0.9V_{pp} on each MRM). The outer ER is 3.3dB and the TDECQ penalty at 2e-2 target SER is measured to be 1.25dB with implementing 53-tap feed forward equalizer (FFE) at the receiver. RAMZM operating under different swing voltages were characterized at 224Gb/s PAM-4 modulation, as shown in Fig. 3 (c). The outer ER ranges from 2dB to 6dB, corresponding to swing voltages of 1Vppd to 3.2V_{ppd}. Across all driving voltages, the TDECQ consistently remained below 1.7dB. Moreover, the measured transmitter linearity RLM (defines how equally the 4 levels are distributed) consistently exceeded 0.95, and the inter-eye skew was measured to be 0fs. In contrast, for a single ring modulator, the RLM is usually less than 0.9, and an obvious eye skew can be observed [5,8]. Fig. 3 (c) shows the 224Gb/s PAM4 modulation with 1.8V_{ppd}, the TDECQ as a function of received optical power (power before PDFA)

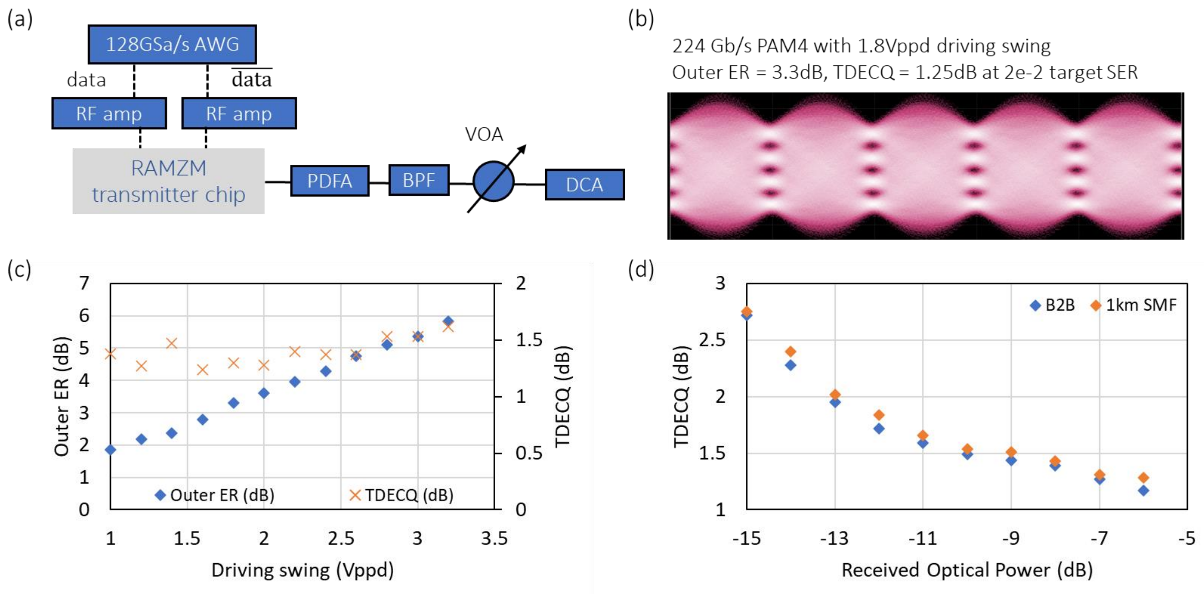

Fig. 3 (a) Experimental setup of the PAM-4 transmission measurements. (b) Eye diagrams after B2B transmission, at 224Gb/s with 1.8vppd driving swing. (c) Measured Outer ER versus driving V_{ppd} and corresponding TDECQ. (d) TDECQ at different received optical power after B2B and transmission over a 1km SM fiber. RAMZM operating at 224Gb/s with 1.8Vppd driving swing.

after back-to-back (B2B) and 1-km Standard Single-Mode Fiber (SSMF) transmission. It is worth to note that no significant TDECQ degradation was observed for the 1-km fiber transmission compared to the B2B case. No optical transmitter pre-equalization was applied for these measurements. We expect further improvements in these results with the use of smaller MRMs with higher bandwidth and lower MRM loss.

4. Conclusion

We have demonstrated a high-speed silicon photonic transmitter consisting of an ultra-linear and efficient ring-assisted Mach-Zehnder modulator and a fully integrated DFB laser, operating at data rates of up to 224 Gb/s using a $1.8V_{ppd}$ push-pull drive swing without optical transmitter pre-equalization. The TDECQ for 224Gb/s PAM4 modulation was measured to be 1.25dB. Negligible TDECQ degradation was observed after 1-km transmission over a SSMF.

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References

[1] S. Amiralizadeh et al., "System Optimization of High-efficiency 400 Gb/s PAM4 Silicon Photonics Transmitter for Data Center Applications," OFC (2021).
[2] S. Fathololoumi, et al., "1.6 Tbps silicon photonics integrated circuit and 800 Gbps photonic engine for switch co-packaging demonstration." J. Light. Tech. 39.4, 1155-1161 (2020).
[3] M. Wade, et al., "An error-free 1 Tbps WDM optical I/O chiplet and multi-wavelength multi-port laser." OFC (2021).
[4] Z. Xuan et al., "A 256 Gbps Heterogeneously Integrated Silicon Photonic Microring-based DWDM Receiver Suitable for In-Package Optical I/O," VLSI (2023).
[5] X. Wu et al., "A Single-Chip High-Speed Silicon Photonic Transmitter with Integrated Laser and Micro-Ring Modulator," SiPhotonics (2023).
[6] J. Cardenas, et al., "Linearized silicon modulator based on a ring assisted Mach Zehnder inteferometer," Opt. Express 21, 22549-22557 (2013)
[7] R. Li, et al., "High-speed low-chirp PAM-4 transmission based on push-pull silicon photonic microring modulators," Opt. Express 25, 13222-13229 (2017)
[8] J. Sun, et al., "A 128 Gb/s PAM4 Silicon Microring Modulator With Integrated Thermo-Optic Resonance Tuning," J. Light. Tech., 37.1, 110-115 (2019).