Compact and Thermally-Robust Offset-QAM Optical Transmitters using RAMZI Modulators

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***Abstract*—Energy- and area-efficient coherent optical transmitters are essential for achieving higher data rates in future co-packaged optics (CPO) systems. In this paper, we address this by proposing an offset-QAM transmitter with high optical power tolerance using MRMs in ring-assisted MZI (RAMZI) structures.**

I. Introduction

As AI/ML accelerators, GPUs and network switches begin to demand tens of Tb/s of off-package I/O bandwidths, the adoption of co-packaged optics (CPO) is imminent [1]. Wavelength- and polarization-division multiplexing (WDM/PDM) have been proposed for CPO to increase data rates per fiber. However, these techniques can only provide limited scalabilities due to practical limitations (e.g., limited available laser lines for WDM). Therefore, achieving energy-efficient higher data rates will require more advanced and coherent modulations. While coherent optics have been used widely for long haul (+10km) applications using Mach Zehnder Interferometer (MZI)-based transmitters, the large footprint of these devices (multi-mm^2) makes them impractical for meeting the necessary shoreline and aerial bandwidth densities for CPO. Microring modulators (MRMs) have shown a great promise for CPO due to their small footprint, and have been adopted mainly to perform pulse-amplitude modulation. Building MRM-based coherent transmitters can be an ultimate solution for future CPO platforms, however it is challenging due to the coupled nature of MRMs' phase and amplitude outputs. One proposed solution is to use the MRM as a single-ring BPSK modulator (SRBM) by biasing the resonance and laser to induce a π phase shift while keeping amplitude constant [2]. However, the limited wavelength shift of the PN junctions gives these SRBM approaches an inherently high insertion loss ($IL > 10\ dB$). More importantly, MRMs have limited capability to handle large optical powers inside the cavity due to nonlinear effects such as free carrier absorption (FCA) and thermal sensitivity [3]. This has resulted in distorted constellations for SRBMs [2]. To address these challenges, we propose a novel offset-QAM-4 transmitter architecture using Ring-Assisted MZI (RAMZI) [4] structures. We use RAMZIs to generate phase-constant amplitude modulators which are the building blocks of our offset-QAM transmitter. This approach can be easily extended to higher-order QAM modulations (like QAM-16) as well.

II. Proposed Photonic Circuit

The proposed RAMZI photonic circuit consists of two MRMs on either arm of an MZI (Fig. 1a). Each MRM's resonance wavelength can be thermally tuned to ensure that their resonances lie on opposite sides of the laser wavelength, and differential (i.e., push-pull) driving voltages are applied to simultaneously modulate the MRMs' resonances in opposite directions towards or away from the laser wavelength (Fig. 1b). This gives each MRM an identical amplitude change with opposite phase shift, which modulates the RAMZI's output amplitude while holding output phase constant. A bias thermal phase shifter is included in one arm of the RAMZI. This

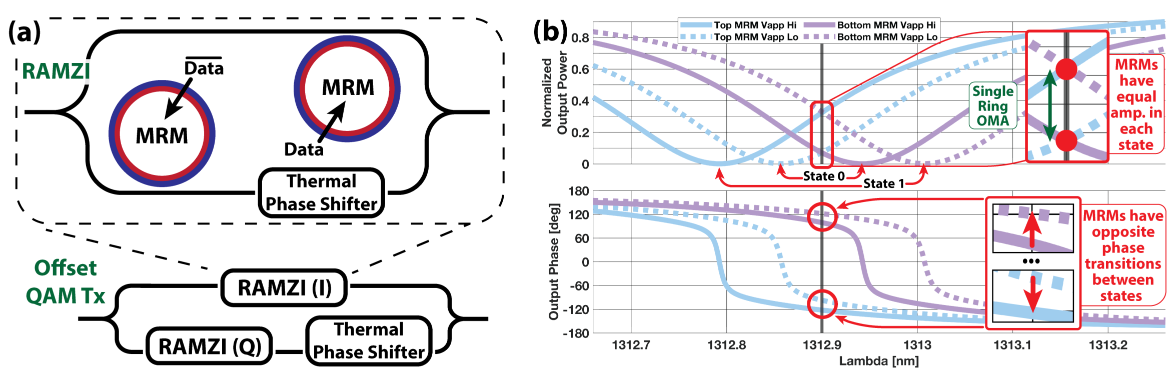

Fig. 1. (a) Proposed RAMZI and Offset-QAM-4 Transmitter, (b) Amplitude and phase of thermally tuned top and bottom MRMs at high/low driving voltages.

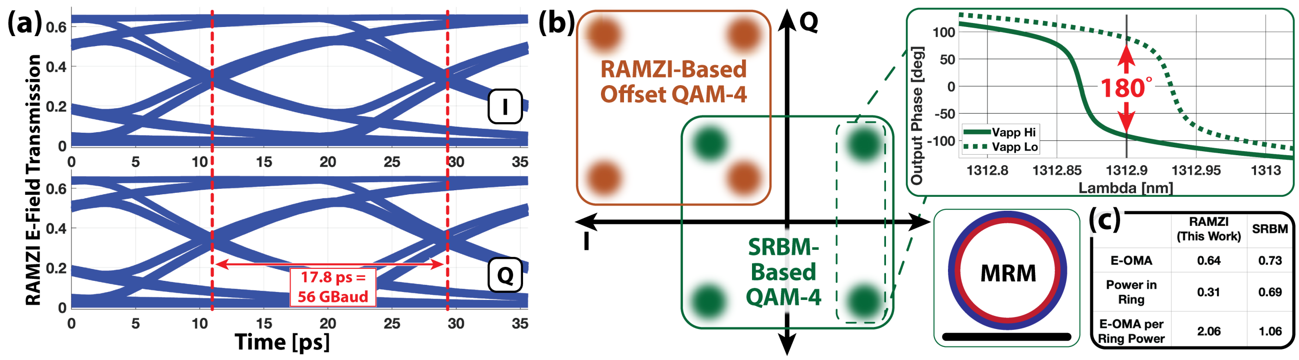

Fig. 2. (a) Eye Diagram of RAMZI electrical field transmission at 56 GBd (both I and Q components of a RAMZI-based offset-QAM-4 transmitter shown). (b) Constellations of RAMZI-based offset-QAM-4 transmitter and a SRBM-based QAM-4 transmitter (SRBM circuit and operation principle is shown). (c) Comparision of electrical-field OMA (OMA_E), power in each ring, and ratio of OMA_E to power in each ring for a single-channel RAMZI vs SRBM (all values normalized to input electrical field/power).

can be tuned so that the individual MRM outputs interfere constructively in the high transmission state and destructively in the low transmission state. Thus, in addition to offering phase-constant operation, the RAMZI offers an amplitude contrast superior to that of a single MRM by taking advantage of both amplitude and phase modulation in the MRM. Two RAMZIs with separate data inputs can be combined with a $\frac{\pi}{2}$ phase shift to make an offset-QAM-4 transmitter (Fig. 1a).

III. Simulation Methodology

We simulate the proposed photonic circuit performance using MRM models with a radius of $7.5\ um$ and models of other photonic devices (e.g. thermal phase shifter, 1x2 MMI splitter, etc.) from the Global Foundries 45SPCLO process in Cadence. We sweep the MRM thermal tuning levels in the O-band ($\sim 1310\ nm$) to find the optimal bias point at applied voltages of $0V$ and $-4V$ to the PN junction (typical overall driving voltage swing for MRMs). The MRM operates in the critically-coupled regime with a Q of ~ 3500 to support high-speed baud-rates of $50+\ GBd$. We tune the RAMZI's arm phase shifter to maximize output optical modulation amplitude in the electrical field domain (OMA_E), and measure the phase error (phase variations between the two states). In order to evaluate the relative effectiveness of this design, we additionally optimize and simulate the performance of an SRBM. For this circuit, we verify that the output phase contrast is $180°$ and measure the OMA_E by adding the amplitudes in both states to account for the $180°$ phase shift. We normalize all OMA_E values to be relative to the input electrical field strength.

IV. Results & Discussion

Our simulations show that after the arm phase shifter is properly tuned, the RAMZI can achieve an OMA_E of 0.64 with a negligible phase error of $1.9°$. The I/Q eye-diagrams are shown for an example baud-rate of $56\ GBd$ shown in Fig. 2a. Meanwhile, the SRBM can achieve an OMA_E of 0.73 (Fig. 2b). While the OMA_E is almost identical between both methods, in the RAMZI, only 0.31 of input optical power resides in each MRM, whereas in the SRBM, 0.69 of the input optical power resides in the MRM. This means that for a given maximum optical power limit inside each MRM, the proposed approach can generate $\sim 2\times$ greater OMA_E. Consequently, our RAMZI-based offset-QAM-4 transmitter can achieve $\sim \sqrt{2}\times$ larger signal photocurrent at the receiver over a QAM modulator built from SRBMs [2].

To account for I-Q combining losses inherent to optical QAM transmitters, we divide OMA_E values for both systems by $\sqrt{2}$. This results in an OMA_E of 0.45 for the RAMZI-based offset-QAM-4 transmitter by and an OMA_E of 0.52 for an SRBM-based QAM-4 transmitter.

Area- and energy-efficient coherent silicon photonic transmitters can revolutionize the future of CPO to the meet the ever-growing I/O bandwidth demands of GPUs, AI/ML accelerators, and network switches. In this work we present for the first time the use of a RAMZI to realize a compact, WDM-compatible, and efficient MRM-based coherent modulator. We show how the RAMZI can be the building block of an offset-QAM-4 modulator, which can be easily extended to higher-order QAM modulations (like QAM-16) as well. We show that it achieves a similar effective electrical field contrast to the previously-proposed SRBM-based QAM transmitter, while providing a larger tolerance to laser power.

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