Data Rate Enhancement of Dual Silicon Ring Resonator Carrier-Injection Modulators by PAM-4 Encoding

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Abstract:
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Introduction

In order to realize the 400GBE communication standard, silicon photonics technology has emerged as a primary candidate. Modulators based on Mach-Zehnder interferometers (MZI) and Ring Resonators (Si-RRM) have demonstrated speeds of 10 Gb/s and up to 25 Gb/s per channel. An advantage of Si-RRMs is their small footprint, lower optical loss and lower drive voltages compared to MZI modulators, making them ideal candidates for Dense Wavelength Division Multiplexing (D-WDM). These advantages come at the expense of lower tolerance to fabrication variations, requiring active thermal control to maintain resonance at a desired wavelength. Si-RRMs have also been demonstrated using both carrier depletion and injection, each with their respective application-dependent advantages. Depletion mode Si-RRMs demonstrate higher insertion loss and weaker electro-optic interaction. Carrier injection rings, on the other hand, can achieve higher extinction ratio (ER) while maintaining a small diameter. Recently, Si-RRMs using carrier injection driven by a CMOS chip with pre-emphasis and active thermal tuning at 10 Gb/s was demonstrated successfully, intended for an 80 GHz channel spacing.

The optical modulation bandwidth of a single channel can be extended by using sophisticated data encoding schemes such as Quadrature Amplitude Modulation or Phase Amplitude Modulation, among others. Doing so increases the effective data rate of the link by factors of two and while easing various design parameters for the CMOS circuitry used to drive such devices. At lower data rates, static components can be used for signal amplification rather than the current mode logic circuits which consume significant amount of power. Furthermore, equalization and pre-emphasis modulation voltage are implemented more easily and consume less power.

Studies in the past have demonstrated PAM data encoding using carrier depletion mode Si-RRMs and carrier injection mode Si-RRMs using only a single Si-RMM. The work presented here attempts to double the bandwidth of a carrier-injection Si-RRM link by implementing PAM-4, using two ring resonators coupled to the same bus waveguide and tuned to near resonance of each other. This approach offers unique flexibility for a system application where redundant rings can be reconfigured to various channel wavelengths to enhance their data rate. Thermal tuning of these rings also allows for greater tolerance to fabrication and temperature variation for an on-board application.

The Si-RRM device used for the work presented here have demonstrated an open eye diagram at 10 Gb/s data previously and employ a silicon resistor heater for resonance tuning. For this experiment, the rings are thermally tuned to the same resonance wavelength and modulated at different extinction levels with two, uncorrelated, NRZ encoded PRBS data sources, thereby achieving four levels of modulation. Initial results are shown for 1 GBd/s modulation (2 Gb/s) using a pre-emphasis driving scheme as a proof-of-concept. A discussion of the results follows with steps to be taken for further increase of the modulation speeds and data rates.

Theoretical Approach

To achieve open eye diagrams for PAM-4, the overall ER of a single NRZ eye diagram must be divided into three equal segments. In order to achieve a symmetric eye diagram, the modulation of each ring resonator must be accurately controlled with as sharp as a resonance as possible. Therefore, ring resonators with slightly large cavity Q (＞5,000) are desirable for this experiment. Thermal effects, however, complicate the optical response of a ring resonator. Thermally tuning
a Si-RMM to a desire wavelength causes a red shift in the spectrum but also degrades the cavity Q factor. This results in degradation of the output eye diagram in both ER, increased noise and a reduction of overall eye magnitude. Furthermore, RF modulation in forward bias for carrier injection causes an increased average temperature, further degrading the eye. This effect is compounded by the presence of pre-emphasis often required for carrier injection modulation of Si-RRMs. Therefore, the DC resonance tuning and modulation data rate play a key factor in the eye diagram quality in both noise and ER that can be achieved. In the ideal approach to achieve a PAM-4 with two Si-RRMs, one ring is tuned to a wavelength 50 pm longer w.r.t. to the other ring. To ameliorate the complications seen from thermal effects for eye diagram noise, we choose to tune the operation wavelength 60-100 pm at longer wavelength w.r.t to the resonance of the initial ring. This wavelength is chosen since the electro-optic modulation effect causes a blue shift in the resonance of the ring. Once the rings are accurately tuned and wavelength is set, the most and least significant bit of PAM-4 encoding is realized from each of the PRBS data sources by modulating the two rings at different depths. An ideal spectra is shown in Fig. 1 with the on and off state of each ring resonator, with a vertical marker showing a sample value of operation wavelength.

The non-linear output of the rings with respect to modulation voltage is another factor which plays an important role in the quality and symmetry of the resulting PAM-4 eye. Therefore, active thermal and wavelength control must be maintained to achieve a symmetric, low-noise eye diagram.

**Experimental**

The devices used for this experiment were fabricated in the CEA-Leti process comprising of a 250 nm silicon layer on a 2000 nm buried oxide layer. The test structure comprises of a single bus waveguide, 325 nm wide, to which two ring resonators are coupled with a gap of 300 nm, with a drop port waveguide spaced 350 nm away. Integrated silicon resistive heaters enable resonance tuning of the resonators. The rings were designed with the same radius, however, due to fabrication variation, the resonances were not precisely aligned. Using grating couplers, the output spectrum of the structure was obtained and plotted in Fig 2. The resonance of the rings were tuned as mentioned previously and confirmed by monitoring the output power at the desired wavelength. The electrical driving voltage, with pre-emphasis, was generated by combining the DATA and /DATA output of a PRBS source with a pre-calibrated delay component tuned to 300 ps for a 1 Gbd/s data rate. Each output of the two PRBS sources can be configured with a peak to peak voltage (V_{pp}) and given a DC bias (V_{dc}) to create the pre-emphasis. These values were individually controlled for optimization of the resulting output eye. Initially, each ring was modulated individually to optimize the pre-emphasis voltage parameters to achieve different ER for each ring. The values for each of the outputs for the rings are shown in Tab. 1. With these settings, ring 1 and ring 2 achieved an ER of -4 dB and -7 dB, respectively. Then the rings were simultaneously modulated to achieve a PAM-4 output eye diagram, plotted in Fig 3. This eye diagram is for one pattern length of a 2^7 PRBS data pattern.

**Discussion**

The devices used in this experiment were intended to have the same cavity Q and ER, presenting unique challenges when doing PAM-4 modulation using two rings. Accurate control of ER for each modulator is a complex relationship of the pre-emphasis voltage levels and difficult to optimize for arbitrary levels of extinction. Therefore, with modulators using carrier injection, two rings with different ER and nearly the same Q
would be more ideal for this experiment. This would then enable the rings to be modulated at the same voltage levels, keeping thermal effects comparable to each other, which plays an important role in the final output eye diagram quality. Alternatively, a single carrier injection Si-RMM can be designed with two electrodes covering different lengths of the ring circumference. This would also allow a PAM-4 data encoding scheme with a single device. Though the Si-RRMs used in this experiment individually show modulation bandwidth up to 10 Gb/s, extending PAM-4 beyond 1 Gb/s presented challenges in obtaining a clean optical eye. This is attributed to thermal effects that dominate at higher data rates and the higher pre-emphasis drive voltages needed to obtain a clean output eye diagram at speeds beyond the ones used here.

Conclusions
This work demonstrated PAM-4 data encoding with carrier injection modulation with two rings as a demonstration of the approach. This approach offers a solution that extends the bandwidth of a single channel modulator and reduces power consumption and complex CMOS drive circuit design needed at higher data rates. And by using a dual-ring approach, D-WDM systems that have a greater number of Si-RMMs than the channel count can offer flexibility with the redundant rings to enhance the data rate for the desired channel. Certain challenges, unique to carrier-injection modulators, may be overcome by careful optical design of the two rings. This would ameliorate thermal degradation effects on the optical eye diagram and enable PAM-4 modulation at higher data rates.

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References