

# Differential Optical Ring Modulator: Breaking the Bandwidth/Quality-factor Trade-off

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**Abstract** We present a differential ring modulator that breaks the optical bandwidth/quality factor trade-off known to limit the speed of high-Q ring modulators. This structure maintains a constant energy in the ring to avoid pattern-dependent power droop.

## Introduction

Improving bandwidth-density product in fully integrated silicon photonic systems necessitates a corresponding enhancement in modulator performance. Ring resonator modulators are promising candidates to realize compact, high-speed and low-power silicon photonic transceivers<sup>1</sup>. Intensity modulation is commonly achieved by index modulation or coupling modulation. It is desirable to have high-Q rings as, for a given extinction ratio, higher Q results in better energy efficiency. However, there is a trade-off between Q of the ring resonator modulator and its optical bandwidth. As previously shown<sup>2</sup>, the time domain dynamic transmission of the ring,  $T(t)$  can be written as

$$T(t) = \sigma(t) + \frac{\kappa(t)}{\kappa(t - \tau)} a(t) \exp[-i\phi(t)] \times [\sigma(t - \tau)T(t - \tau) - 1] \quad (1)$$

where,  $\sigma$  and  $\kappa$  are transmission and coupling coefficients,  $a$  is the attenuation,  $\phi$  is the phase shift inside the ring and  $\tau$  is the resonator round trip.

Fig. 1 shows numerical solution of equation (1) using an iterative approach. The Q-bandwidth trade-off in an index-modulated ring is shown in Fig. 1 (b) and (c), which results in the low-pass response for the index-modulated ring of Fig. 2 (a). Conversely, a high-pass response can be obtained using the coupling modulated ring of

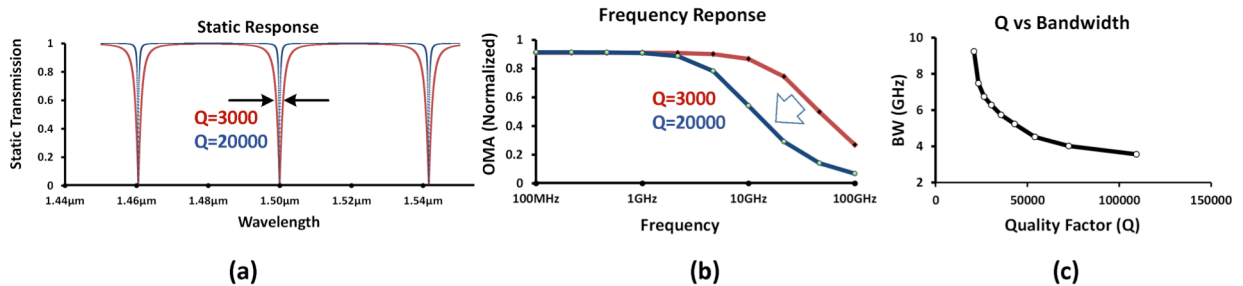
Fig. 2 (b), with a sufficiently fast variable coupler<sup>3</sup>. In this case, long sequence of 1's causes energy droop in the ring and signal degradation (Fig. 2 (b)). We propose a differential ring modulator that overcomes the Q-bandwidth trade-off in ring modulators (Fig. 2 (c)). This structure does not exhibit droop in energy stored in the ring.

## Proposed Modulator Structure

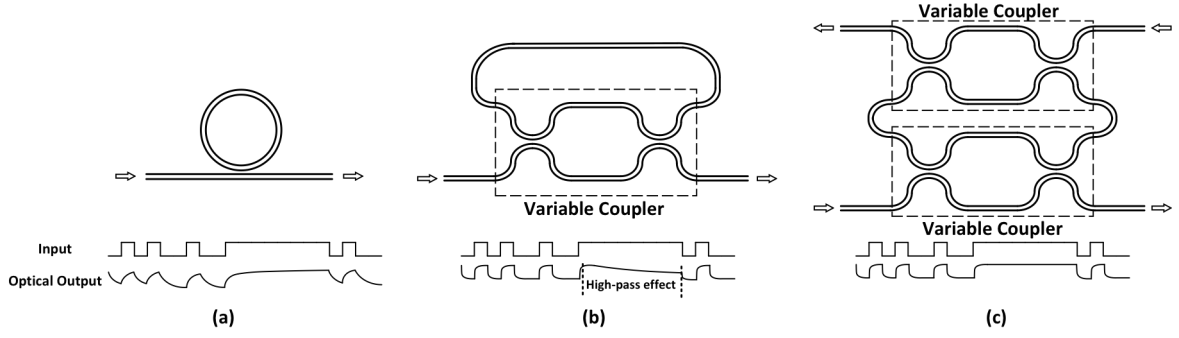
The block diagram of the proposed structure (shown in Fig. 3) consists of two variable couplers, each of which consists of two differential phase shifters and two 3dB couplers. A Y-junction with a controllable thermal phase shifter is used to split the input beam into two beams with the same phase ( $A_1$  and  $A_2$ ). The variable couplers operate out of phase and when coupling of one increases the other decreases.

The proposed DRM achieves considerably lower  $V_\pi$  compared to a regular MZI modulator. Considering the electric field at various locations in the DRM, it can be shown that at resonance the static transmission is

$$\left| \frac{B_1}{A_1} \right|^2 = \left( a - \left| \cos \frac{\Delta\phi}{2} \right| \right)^2 / \left( 1 - a \left| \cos \frac{\Delta\phi}{2} \right| \right)^2 = \left( a - \left| \cos \frac{V}{2V_\pi} \pi \right| \right)^2 / \left( 1 - a \left| \cos \frac{V}{2V_\pi} \pi \right| \right)^2 \quad (2)$$



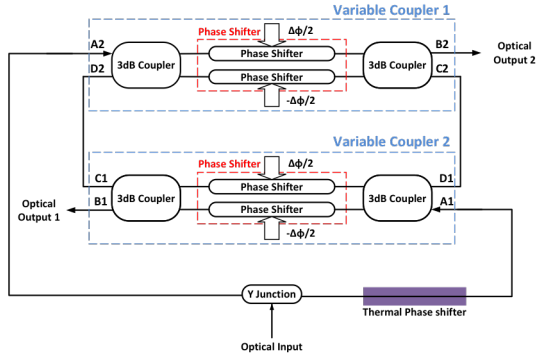
**Fig. 1:** Index-modulated ring's (a) static transmission (b) optical frequency response (c) simulated Q vs -3dB bandwidth



**Fig. 2:** (a) Index-modulated ring (b) Coupling-modulated ring (c) Proposed differential ring modulator

Where  $a$  is the loss factor and  $V_\pi$  is the voltage required to achieve a differential phase shift of  $\pi$  in phase shifters. Critical coupling (where maximum extinction ratio is achieved) happens when

$$|C_1|^2 = |C_2|^2 = \sin \frac{\Delta\phi}{2} \left( 1 + \frac{a^2}{4} \cos^2 \frac{\Delta\phi}{2} \right) / \left( 1 - \frac{a^2}{4} \cos^2 \frac{\Delta\phi}{2} \right) \quad (4)$$

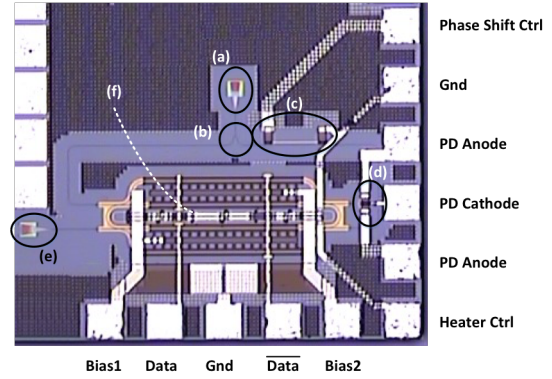


**Fig. 3:** Block diagram of the differential ring modulator

$$V \equiv V_{\pi, DRM} = \frac{2V_\pi}{\pi} \times \cos^{-1}(a) \quad (3)$$

therefore, for a  $Q$  of 32,000,  $V_{\pi, DRM}$  is 8 times smaller than  $V_\pi$ .

The DRM structure maintains the energy stored in the ring constant in all conditions. This can be demonstrated by calculating the amplitude of  $C_1$  and  $C_2$  (shown in Fig. 3) when data switches from 1 to 0 (Equation 4).

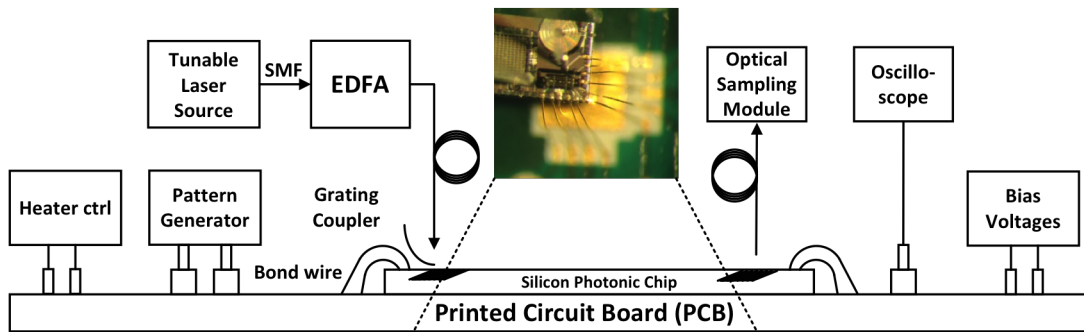


**Fig. 4:** Die micrograph of the fabricated prototype and measurement setup. (a) Optical input grating coupler (b) Y-junction (c) heater for phase shift controller (d) photodiode connected to one output for testing purposes (e) Optical output grating coupler

Intuitively, by modulating the couplers differentially, the overall coupling to the ring remains constant. Thus, the variation of energy stored in the ring is minimized.

### Measurements

A prototype chip has been fabricated in OpSIS



**Fig. 5:** Measurement setup

IME platform<sup>4</sup> and occupies less than 0.35mm<sup>2</sup> (Fig. 4). Grating couplers are used for optical input and output. A heater is placed at in the center of the ring for uniform distribution of temperature. A second heater is placed at one of the Y-junction's branches to calibrate phase mismatch between the two inputs of the ring. The second output of the ring is connected to an on-chip photodiode for testing.

The chip was wire-bonded to a custom designed PCB that carries high-speed and DC signals. A tunable laser source followed by an EDFA was used as the input and the output was monitored by optical sampling scope. The high-speed differential data signals were driven by a PRBS 31 sequence using a pattern generator. The voltage swing for each single-ended signal was 1.75V p-p. Fig. 6 shows measured eye diagrams at the output for 5Gb/s and 10Gb/s data streams. The extinction ratio of the output optical data is measured to be 6.2dB. Some of the noise seen at the output is associated with the EDFA noise and limited sensitivity of the optical sampling scope.

Fig. 7 (a) shows measured static transmission of the ring near one operational wavelength bias points. From this measurement,

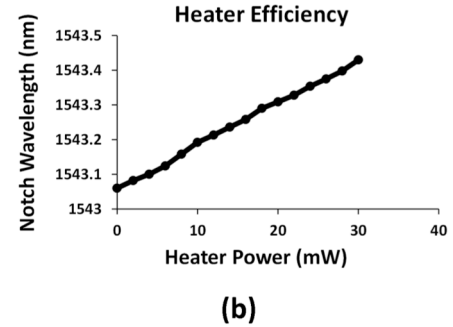
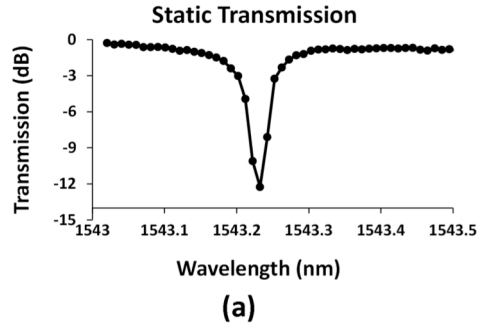


Fig. 7: (a) Measured steady-state transmission of the ring near a notch (b) tunability of the ring

varying the input voltage of the heater, and was measured to be 12.3pm/mW.

## Conclusions

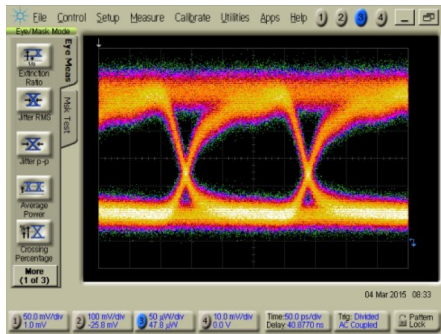
A differential ring modulator structure is presented that breaks the optical bandwidth/quality factor trade-off known to limit the speed of high-Q ring modulators. This structure maintains the total energy stored in the ring constant, hence, unlike coupling modulation schemes, the ring does not suffer from power droop when long sequences of 1's or 0's are transmitted. A prototype has been fabricated and 10Gb/s operation of the ring is demonstrated.

## Acknowledgements

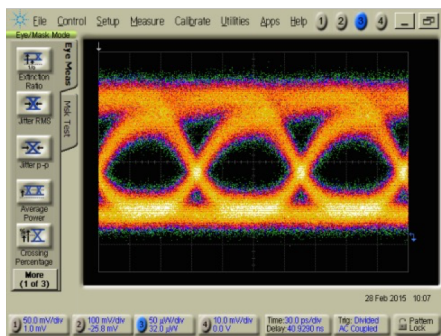
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(a)



(b)

Fig. 6: Output eye diagram of the differential ring modulator opening at (a) 5Gb/s (b) 10Gb/s

the Q of the ring is derived to be roughly 32,000. The tunability of the ring was measured by