A Microring-based Time-Division Demultiplexer with Differential Signaling

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***Abstract*—We propose a new electronic-photonic integrated circuit for time-division demultiplexing based on time-interleaved sampling by microring couplers. The quasi-differential circuit design overcomes the issue of input signal feedthrough due to the extinction ratio limitation of microrings.**

I. Introduction

As optical interconnected computing systems continue to scale in size, complexity, and performance, the increasing demands for link bandwidth and system reconfigurability motivate us to explore time division multiplexing (TDM) techniques [1]. A microring-based TDM multiplexer has been demonstrated in [2], which uses an optical pulse and microring couplers to sample a series of electrical inputs. On the receiver side, we are interested in investigating similar microring-based sampling circuits for TDM demultiplexing. Microring devices are attractive for electronic-photonic integrated circuits (EPIC) because of their good wavelength selectivity, compact size, and low RF power requirement for modulator drivers [3].

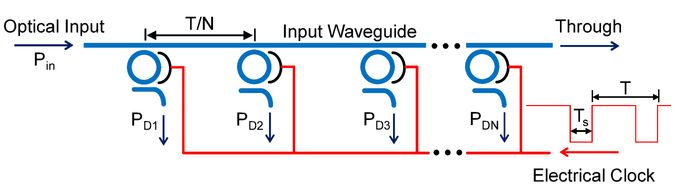

Fig. 1. Concept of an N-tap time-interleaved TDM demultiplexer.

Sampling by a microring coupler was proposed in [4], which showed good theoretical performance using high-order coupled-ring coupler with extinction ratio over 50 dB. In a recent paper [5], we proposed the concept of a micoring-based TDM demultiplexer (DEMUX), as shown in Fig. 1, using the time-interleaving circuit technique. The input optical signal propagates along the input waveguide, which functions as an optical delay line, and is sampled by a series of microring couplers in sequence, which are modulated by an electrical clock. The optical delay per tap determines the sampling rate, which can potentially reach hundreds of GHz. In this paper, we further explore its design and implementation as a silicon photonic EPIC.

II. Sampling by Microring Coupler

In the proposed TDM DEMUX circuit, a microring coupler is used as an optical sampler, and sampling is carried out by tuning its resonance using the modulator sections embedded within the microring. The on- and off-resonance transfer functions of the microring couplers determine its sampling characteristics. Using silicon photonics, the electro-optic modulator is typically implemented as PN junctions, which severely limit the *loaded* Q of the microring coupler due to their high optical loss. The extinction ratio (ER) of the sampler therefore is typically limited given the available driving voltage swing by CMOS electronics. The problem is further complicated by the time-interleaving circuit architecture because both the drop and through ports transfer functions are involved now [5].

To achieve a relatively high Q and hence larger ER for the microring coupler, we make the following design choices on the device level: First, a small coupling coefficient is used for the microring coupler. Second, the microring is designed to have relatively large size (diameter $\geq 10\mu$m). Third, the PN junction doping profile in the modulator section is optimized to lower the optical loss while maintaining the modulation efficiency. Lastly, higher order coupled ring structures can be employed to sharpen the resonance edge. The last method has to be used moderately however, considering microring's susceptibility to process variations due to its resonant nature. In this work, we adopt a double-ring coupler structure in the design.

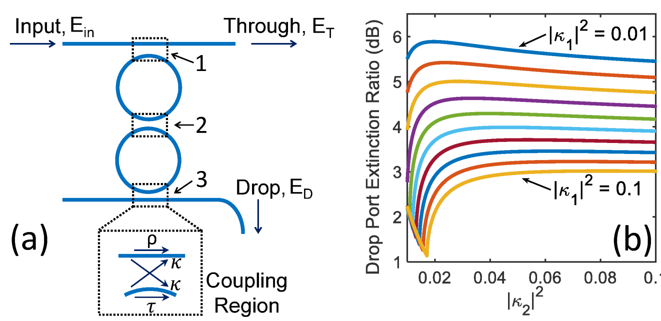

Fig. 2. (a) Structure and signals in a double-ring coupler; Outside the coupling regions, the rib waveguides in both rings are loaded with PN junctions for EO modulation (not shown). (b) Extinction ratio as a function of the coupling coefficients. The sweep increment for $|\kappa_1|^2$ is 0.01.

For a double-ring coupler, the transfer functions of electric field at the drop and through ports are:

$$\frac{E_D}{E_{in}} = \frac{\kappa_1\kappa_2\kappa_3 p^2}{1 - \tau_2 p^2(\tau_1 + \tau_3) + \tau_1\tau_3 p^4} \quad (1)$$

$$\frac{E_T}{E_{in}} = \frac{\rho_1 {\kappa_1}^2 p^2(\tau_2 - \tau_3 p^2)}{1 - \tau_2 p^2(\tau_1 + \tau_3) + \tau_1\tau_3 p^4} \quad (2)$$

$$p = \exp(-\alpha L/2)\exp(j\beta L/2) \quad (3)$$

where κ_{1-3}, ρ_{1-3}, and τ_{1-3} are S-parameters of the three

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coupling regions as shown in the Fig. 2-a inset. Note $\rho_2 = \tau_2$. α and β are the attenuation coefficient and propagation constant of the modulator section waveguides outside the coupling regions, which has a length of L for each ring. The power transfer functions at the drop and through ports, therefore, are $H_D = |E_D/E_{in}|^2$ and $H_T = |E_T/E_{in}|^2$, respectively. The drop port ER can be expressed as H_{D1}/H_{D0}, where H_{D0} is the off-resonance transfer function when the coupler passes the input optical signal, and H_{D1} is the on-resonance one when the coupler samples the signal. Note that time delays are not explicitly shown here for clarity.

For a symmetric double-ring coupler with 10-μm diameter rings and 60-μm long modulator sections (see next section for design details), the drop port ER is calculated as shown in Fig. 2-b. Smaller ring-waveguide coupling $|\kappa_1|^2$ improves ER, while ring-to-ring coupling $|\kappa_2|^2$ has minimal impact.

III. Circuit Design

The small ER of the microring coupler poses a challenge for the sampling application. The input optical signal would be partially coupled to the drop port even in the off-resonance state, when it is not supposed to be sampled. This input signal feedthrough outside the sampling window causes the degradation of the signal-to-noise ratio in the time-interleaved circuit, since the following detector (photodetector and comparator) potentially operates within a larger detection time window and hence the feedthrough becomes interference.

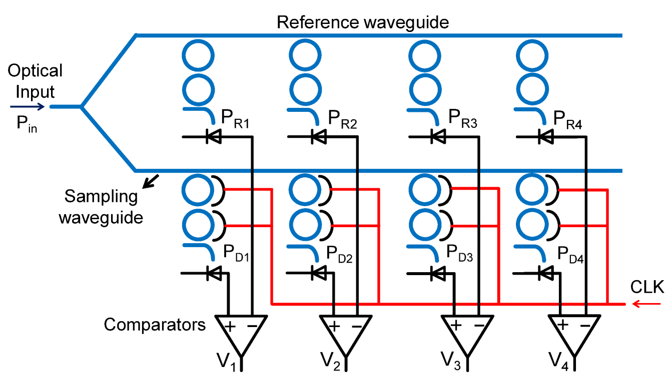

Fig. 3. The proposed quasi-differential TDM DEMUX circuit design. The photodetectors and comparators use ideal models.

To address this problem, we propose to cancel the input signal feedthrough by employing a differential signaling scheme. Fig. 3 shows a *quasi-differential* circuit implementation. The input optical signal is first divided into two waveguides by a splitter. The couplers on the reference waveguide are not driven by the clock, and biased at on-resonance. The dropped signal from each reference tap P_{Ri} are used to cancel the feedthough at the comparator.

To demonstrate the circuit operation, a 4-tap prototype circuit is designed and implemented using a standard SOI silicon photonics technology. The input signal optical wavelength is at 1550 nm. The single-mode rib waveguides are 450 nm × 220 nm, and the slab is 60 nm thick. All microrings have a radius of 10 μm based on FDTD simulation. Each optical delay line section is 766-μm long for 10-ps delay, corresponding to a sampling rate of 100 GHz. The two modulator sections in each ring are both 30 μm long rib waveguides embedded with PN junctions. The depletion mode modulators operate are biased at 0 V and driven by a negative pulse sampling clock, i.e., 0 V for off-resonance (sampling OFF) and -3 V for on-resonance (sampling ON). The modulation efficiency is Vpi*L=0.86 cm*V. The loaded Q for the coupler is 6480 at on-resonance and 6030 at off-resonance. Most of the optical loss comes from the modulator sections (α=90 dB/cm).

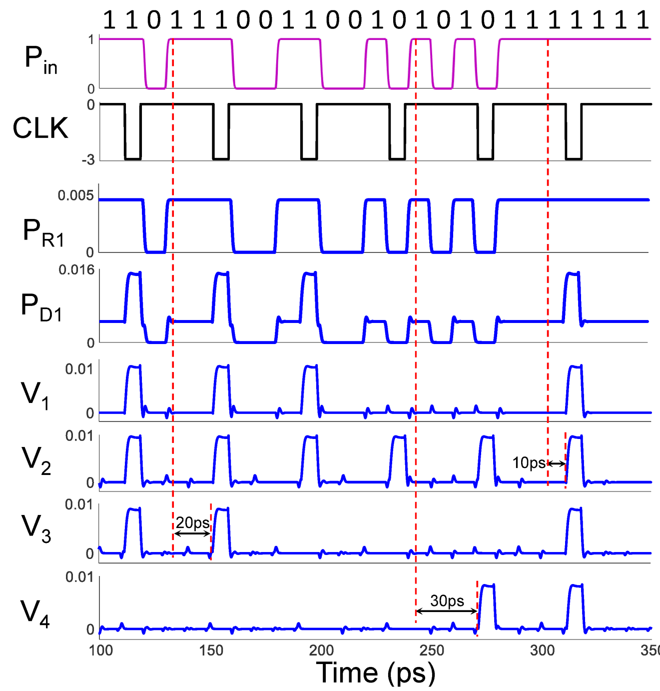

Fig. 4. Simulation results from the prototype circuit.

The time domain simulation results are shown in Fig. 4. A 100-Gbps PRBS signal is used as the input, and the bits are marked. We can see the input is clearly demultiplexed into 4 time-interleaved outputs. The sampling window corresponds to the negative pulse of the clock. The clock period is 40 ps, and each tap generates a 25-Gbps output. Note that the glitches are caused by the coupling from the ring back into the input waveguide after sampling.

IV. Conclusion

We propose a new EPIC based on double-ring couplers to demultiplex high-speed optical signals. Quasi-differential signaling is employed to eliminate input feedthough due to small ER. A 4-tap 100-Gbps prototype circuit is designed in a standard SOI silicon photonic technology and demonstrated with time-domain simulation results.

References

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