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Nonreciprocal Transmission of 10 Gbps OOK Data through an All-Silicon Passive Optical Diode

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Abstract

An optical diode transmits forward 10Gbps data with less than 0.5dB power penalty, while suppressing and distorting backward data with a 11dB nominal power penalty. The nonreciprocal transmission is also demonstrated with a silicon modulator.

Keywords

optical nonreciprocity; micro-resonator

I. INTRODUCTION

Silicon photonics provides a cost and energy efficient platform for future chip-level optical information processing and computer interconnects. However, its full potential has been limited by the lack of on-chip optical nonreciprocity (ONR), which is indispensable for implementation of isolators and other components. Most previous demonstrations of ONR require external physical assistance, such as magnetic fields [1–3], radio-frequency modulation [4], or optical pumping [5]. Moreover, many of them require materials or processes that are incompatible with CMOS technology.

We have recently demonstrated an all-silicon optical diode based solely on optical nonlinearity in micro-resonators [6]. It consists of two 5 μ m-radius silicon rings (Fig. 1a), a notch filter (NF) at critical coupling regime, and a resonance-matched add-drop filter (ADF) with asymmetric coupling gaps ($G_2 > G_3$). Resonance matching is achieved through thermal tuning provided by a titanium micro-heater near NF. At low optical power, the forward and backward transmission spectra are identical. At ~10 dBm input power (~2 dBm at the diode), strong ONR is observed when optical nonlinearity takes effect, with ~35 dB nonreciprocal transmission ratio (NTR) between forward (red) and backward (blue) operations at ~1546.75 nm (Fig. 1b). Unlike other nonlinearity based devices, our diode works across a broad power range (>18 dB NTR for power range from 85 to 2,100 μ W at the diode [6]).

However, resonance enhancement has a fundamental limitation: reduced operation bandwidth. Practical devices require the capability of processing high-modulation-rate data, 10~40 Gbps, which have a bandwidth similar to, or larger than the diode (fig. 1c). Circumventing such a limitation is one of the crucial issues in silicon photonics. Here we show that our optical diode can accommodate 10 Gbps data streams, despite its limited bandwidth. The diode transmits a bit sequence with minimal distortion in forward direction, while suppressing and distorting the signal in backward direction.

II. EXPERIMENTS

In the experiment, we used a lithium niobate intensity modulator to perform NRZ OOK coding. Light is coupled in and out of the chip through surface grating couplers, with 8 dB loss per coupling. A post-EDFA was used to compensate the chip insertion loss of 32 dB. To reduce ASE, a 0.4nm-FWHM band-pass filter was inserted afterwards.

With a 9.953 Gbps OOK bit sequence input ($2^{31}-1$ PRBS), eye diagrams of both forward and backward operations are taken and shown in Fig. 1c. The forward eye is large and clean, while the backward eye is small and scrambled. Compared to the broadband high transmission in forward direction in Fig. 1b, the backward attenuation, which is responsible for the strong ONR, is highly non-uniform across the input signal wavelength range. Fig. 2a shows the optical spectrum of the 10Gbps signal through the diode in both directions, as well as the back-to-back (B2B) result. The red curve (forward) is similar in shape to the black one (B2B), consistent with the diode forward transmission spectrum feature. The blue curve (backward) shows a strong dip around the center, which is the signature of the backward operation of the diode. Compared to Fig. 1b, the NTR for the 10Gbps data is reduced from ~35 dB to ~23 dB at the center wavelength, or to ~13 dB in terms of integrated power, since the input signal has a bandwidth comparable to the resonance width. Nevertheless, a strong diode effect still retains for the 10 Gbps data stream.

Besides the backward power suppression, strong dispersion, scrambling the backward eye (Fig. 1c), also contributes to the nonreciprocal data transmission. In the backward direction, the resonant dip from the NF operating in the critical coupling regime functions as an edge detector. Fig. 2b shows two time-averaged waveforms that pass the diode in different directions, which are both normalized, and aligned in time to stress the backward waveform reshaping. At each transition from logic '0' to '1' or from '1' to '0', a narrow peak appears on the backward transmitted waveform. The backward diode thus performs differential or difference operation to the input data, whose function is similar to that of a DPSK decoder. In other words, the backward transmitted waveform carries completely different information from the input, even though it can in principle be interpreted. This edge detection or difference operation effect does not impact diode forward operation, for which the nonlinearity shifts the resonance away.

To further evaluate the robustness of the signal passing the optical diode, bit-error-rate (BER) was measured. In Fig. 2c, the forward (red) BER curve shows a small power penalty of less than 0.5 dB. BER was also measured for the differentiated data transmitted in

backward direction, where a power penalty of 7~11 dB to the forward BER curve is observed.

Our optical diode effect is achieved primarily through the strong thermo-optic nonlinearity in silicon [6], which reacts to optical powers averaged over a few μs , far longer than the ~ 0.1 ns pulse duration. This facilitates the nonreciprocal transmission of 10 Gbps data streams, since the long integration time desensitizes the device nonlinear operation to fluctuations associated with rapidly varying data patterns.

III. INTEGRATION WITH AN ON-CHIP MODULATOR

Integration of an optical diode with an on-chip modulator may advance the approach for chip-level optical information processing and communication. As a first step, we replaced the bulk modulator with a silicon photonic modulator based on the carrier depletion effect [7]. The modulator was fabricated on an 8" SOI wafer in a commercial CMOS foundry using 130 nm technology (Fig. 3a). The modulator chip was mounted on a separate precision stage, and a post-EDFA was used to compensate the chip insertion loss of ~ 22 dB. Two representative eye diagrams of both operations are shown in Fig. 3b, clearly showing the diode effect.

IV. CONCLUSION

We demonstrate nonreciprocal transmission of 10 Gbps OOK data through an all-silicon optical diode. Eye diagrams and BER results show that in the forward direction, the diode can transmit modulated light with minimal distortion; in the backward direction, both power reduction and device dispersion help block the data transmission, with a nominal power penalty of ~ 11 dB observed.

REFERENCES

1. Espinola RL. Magneto-optical nonreciprocal phase shift in garnet/silicon-on-insulator waveguides. *Opt. Lett.* 2004; 29:941–943. [PubMed: 15143634]
2. Tien M. Silicon ring isolators with bonded nonreciprocal magneto-optic garnets. *Opt. Express.* 2011; 19:11740–11745. [PubMed: 21716405]
3. Bi L. On-chip optical isolation in monolithically integrated non-reciprocal optical resonators. *Nat. Photonics.* 2011; 5:758–762.
4. Yu Z, Fan S. Complete optical isolation created by indirect interband photonic transitions. *Nat. Photonics.* 2009; 3:91.
5. Kang MS. Reconfigurable light-driven opto-acoustic isolators in photonic crystal fibre. *Nat. Photonics.* 2011; 5:549.
6. Fan L. An All-Silicon Passive Optical Diode. *Science.* 2012; 335:447–450. [PubMed: 22194410]
7. Spector SJ. CMOS-compatible dual-output silicon modulator for analog signal processing. *Opt. Express.* 2008; 16:11027. [PubMed: 18648416]

Fig. 1.

(a) Schematic of the optical diode. Silicon waveguides and rings have a cross section of 500 nm by 250 nm. $G_1=380$ nm, $G_2=550$ nm and $G_3=500$ nm. (b) The diode transmission spectrum taken at 10 dBm, with a sweeping continuous-wave laser source. (c) Two representative 10 Gbps OOK eye diagrams of the diode in both forward and backward directions, taken with the same experimental setting.

Fig. 2.

(a) The optical spectrum of the 10Gbps NRZ OOK PRBS through the diode. (b) The time-averaged waveforms that pass through the diode in both forward (red) and backward (blue) directions. (c) The bit-error-rate (BER) characterization of the optical diode.

Fig. 3.

(a) An optical image of the silicon intensity modulator from a CMOS foundry. (b) Two representative 10Gbps OOK eye diagrams of the diode in both operations, taken with the same experimental setting.