One-way transmission of 10 Gbps data through a silicon optical diode based on nonreciprocal resonance reshaping

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Abstract: The reduced optical bandwidth associated with resonance enhancement poses a significant challenge for resonators to process wide-bandwidth optical data. We report one-way transmission of 10 giga-bit-per-second optical data through a silicon optical diode based on both the resonance-enhanced optical nonlinear effects and resonance reshaping. The diode is operated with a forward-only or backward-only input. In the backward direction, the diode corrupts the data through the strong dispersion and attenuation associated with the resonance of a microring. In the forward direction, the data pass through the diode with negligible distortions because the resonance is red-shifted from the carrier wavelength. In this experimental context the finite bandwidth associated with the optical resonance may be considered beneficial, since the phase response makes an additional contribution to transmission nonreciprocity beyond what is seen with unmodulated light.

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1. Introduction

Optical nonlinearity is a key enabler for on-chip optical information processing [1]. It is generally weak and usually demands high optical power or long light-matter interaction lengths to take effect [2–4]. Resonance enhancement [5, 6] can reduce such requirements and enable functionalities previously not available, such as on-chip optical nonreciprocity, or an optical diode [7–9]. The optical diode consists of two resonance-matched 5μm-radius Si rings [Fig. 1(a)]. Without any external assistance, strong nonreciprocity occurs as a result of direction dependent resonance shift induced by a forward-only or backward-only input.

However, the resonance enhancement also introduces a fundamental limit: the reduced bandwidth within which the enhancement occurs. The data rate limitations and waveform distortions due to the finite bandwidth of resonant devices are well known, for example, in research on slow light devices [10–12]. In this paper we investigate these important effects in the operation of the optical diode. In our experiments, the bandwidth of the resonant transmission dip responsible for suppression of backward data [Fig. 1(b)] is much narrower than that of a 10 Gbps pseudorandom binary sequence typically used to emulate a telecommunication channel. Quantitatively, the diode's bandwidth specified at nonreciprocal transmission ratios (NTRs) of >20 dB and >10 dB are only 15 pm (1.9 GHz) and 50 pm (6.25 GHz), respectively. Here we show that the diode can accommodate 10 Gbps data and achieve one-way transmission of information. In the forward direction, the finite bandwidth of the resonances has minimal effect: under nonlinear operation the resonance is pushed away from the carrier wavelength and 10 Gbps data is transmitted with minimal reshaping. In the backward direction, nonreciprocal intensity transmission is preserved, but as expected, the degree of nonreciprocity is reduced due to the finite bandwidth. However, in the backward direction we can also take advantage of the resonant spectral phase variation to distort and scramble the transmitted data. In this context the finite bandwidth associated with resonators may be considered beneficial, in the sense that the phase response contributes an additional manifestation of transmission nonreciprocity beyond what is seen with unmodulated light.
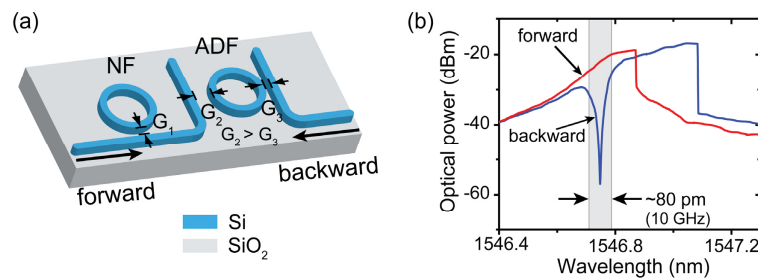

Fig. 1. (a) Schematic of the silicon optical diode. NF: notch filter; ADF: add-drop filter. (b) Nonreciprocal transmission spectra measured at a ~2 dBm power at the diode.

2. Experimental results

The optical diode in Fig. 1(a) consists of two resonance-matched 5μm-radius silicon rings, one an add-drop filter (ADF) with asymmetric coupling gaps ($G_2 > G_3$, where $G_2 = 550$ nm and $G_3 = 380$ nm) and one a notch filter (NF) at the critical coupling regime ($G_1 = 500$ nm). The waveguides' dimensions are 500 nm by 250 nm. The diode operates at the quasi-transverse-magnetic polarization. The resonance matching is achieved through thermally tuning the refractive index of the NF by a titanium micro-heater. With a continuous-wave (CW) laser input of 2 dBm power, we observed a nonreciprocal transmission ratio (NTR) of ~32 dB at $\lambda_C \approx 1546.75$ nm [Fig. 1(b)].
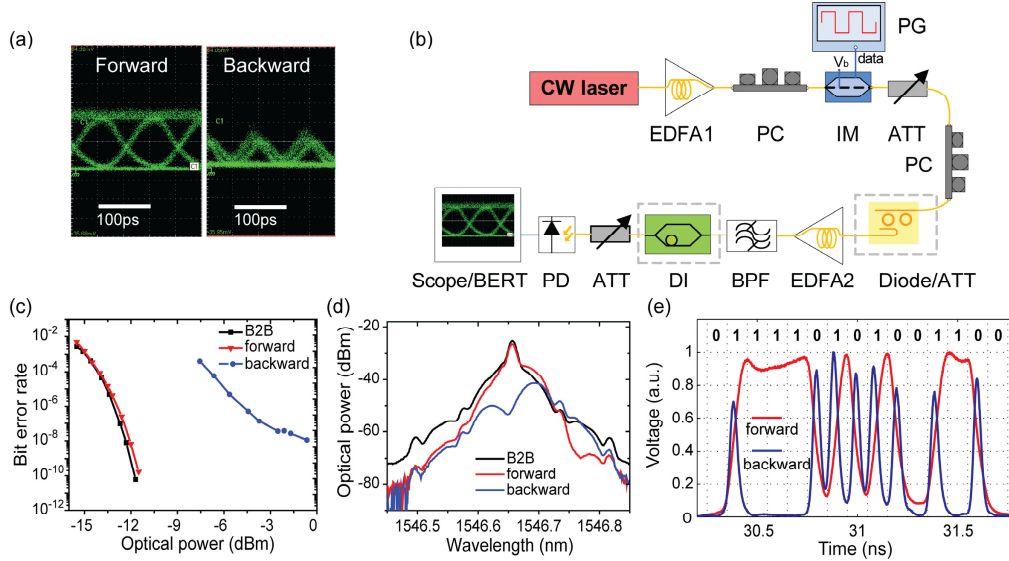
2.1. Nonreciprocal transmission of 10 Gbps OOK data

Fig. 2. (a) The eye diagrams of 10 Gbps OOK PRBS that pass through the optical diode and are amplified by an erbium-doped fiber amplifier (EDFA). (b) The setup for OOK/DPSK transmission experiment. CW: continuous-wave; PC: polarization controller; IM: intensity modulator; PG: pattern generator; ATT: optical tunable attenuator; BPF: band-pass filter; PD: photodetector; DI: delayed-bit interferometer based DPSK decoder; BERT: bit-error-rate tester. DI is not used in the OOK experiments. The DPSK are decoded at the destructive interference port of the DI. In the B2B measurement, the diode is replaced with an ATT set at 32 dB. (c) The bit-error-rate (BER) measurement. (d) The optical spectra of the 10 Gbps NRZ OOK PRBS (2^{31}-1) is taken right after the diode chip. The suppression of the backward eyes in (a) is less than the attenuation shown in (d), due to a higher gain for the backward data at EDFA2. (e) A 10 Gbps OOK sequence of '0111 1010 1001 1000' pass through the diode in both directions. They are normalized in peak intensity to stress the differential effect by the backward diode.

The optical diode enables nonreciprocal transmission of a 10 Gbps pseudorandom binary sequence (PRBS) using non-return-to-zero (NRZ) on-off keying (OOK) [see Fig. 2(a)] [13]. The experimental setup is depicted in Fig. 2(b). The OOK (2^{31}-1 PRBS) were encoded using a lithium niobate Mach-Zehnder interferometer (MZI) intensity modulator. Light was coupled in and out of the diode chip through surface grating couplers, with a coupling loss of ~8 dB per facet at ~1550 nm. A post-chip erbium-doped fiber-amplifier (EDFA) was used to boost the output, and a band-pass filter with a 0.4 nm FWHM was inserted afterwards to suppress most of the out-of-band amplified spontaneous emission (ASE). As shown in Fig. 2(a), the OOK data with an average power of ~2 dBm pass through the diode with minor distortions in the forward direction. The measured eye diagrams are clear and open [Fig. 2(a), left] with a negligible power penalty (less than 0.5 dB) with regards to the baseline case in the back-to-

back (or B2B) measurement [Fig. 2(c)]. In contrast, the backward transmitted data are suppressed and distorted [Fig. 2(a), right]. In the experiment, the drive current setting of EDFA2 was kept the same for both forward and backward operations of the diode. Because the optical amplifier EDFA2 was partially saturated by the relatively strong output from the diode under forward operation, the diode output under backward operation experienced a higher gain. As a result, only a 2 × difference in peak amplitude is observed in Fig. 2(a), which is not as large as the power penalty in Fig. 2(c). In the B2B measurement, we replaced the diode with an optical attenuator set at 32 dB [Fig. 2(b)], which was the same as the chip's insertion loss under forward operation at 1546.75 nm measured with a CW input.

First, there remains a significant contrast between forward and backward transmissions. Figure 2(d) shows the optical spectra of the 10 Gbps OOK PRBS taken right after the diode chip, where the backward transmission dip at λ_C results in a NTR of ~23 dB at the carrier wavelength λ_0 that matches with λ_C. The NTR reduces to ~13 dB if one integrates optical power throughout the spectra, which results from the power spread over the modulation bandwidth. In addition to the power attenuation, the optical diode reshapes the backward data through the strong dispersion, which is provided by the transmission dip associated with the NF resonance λ_C. Under the backward operation, the critically coupled NF retains a fast-varying phase spectrum around its resonance λ_C. When λ_0 is on resonance, the light circulating in the NF couples back to the bus waveguide and destructively interferes with the through portion of the input light [14]. During an input transition from '0' to '1', the output increases immediately first and then quickly drops close to zero after light builds up in the NF. From '1' to '0', the output overshoots prior to reaching '0' since the power stored in the NF will continue coupling out for certain duration before dieing out. Figure 2(e) shows a 10 Gbps OOK sequence of '0111 1010 1001 1000' passing through the diode in both directions. The forward transmitted waveform closely resembles the input, whereas the backward waveform peaks only at times corresponding to the transitions in the input or forward data. Thus, the backward diode, or mainly the critically coupled NF, performs edge detection on the rapidly-varying pattern and outputs a differentiated bit sequence which has a completely different appearance from the input.

This differential operation itself may effectively enable one-way data transmission if the carried information cannot be recovered. Here, because of the relatively low modulation rate at 10 Gbps, peaks in the backward waveform are still distinct from each other and the information can be recovered by determining the position of each peak. Nevertheless, the recovery requires high amplification due to the power suppression by the backward diode. Measured backward BER shows a power penalty of 7-11 dB with regards to the forward BER as well as an error floor [Fig. 2(c)]. With an increased data rate or with a longer response time of the NF (e.g. a higher Q factor), the peak widths in the backward waveform will become longer than the bit duration, and intersymbol interference will result in readout errors [15].

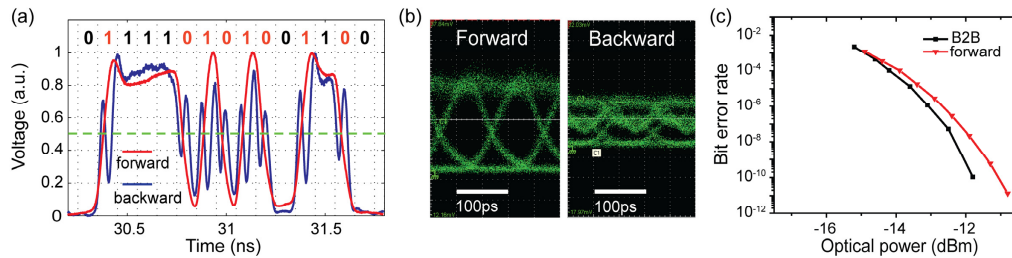*2.2. One-way transmission of 10 Gbps OOK data with a carrier wavelength detuned from λ_C*

Fig. 3. With the carrier wavelength λ_0 detuned from the NF resonance λ_C by −30 pm, (a) the same 10 Gbps OOK sequence of '0111 1010 1001 1000' as in Fig. 2(e) pass through the diode. The bits prone to erroneous readout are shown in red. (b) The eye diagrams of the 10 Gbps OOK PRBS that pass through the diode. (c) The BER measurement.

Even at 10 Gbps, complete corruption of backward data was observed when the carrier wavelength λ_0 was detuned from the NF resonance λ_C. Since matching λ_0 with λ_C results in a differentiated sequence, a slight detuning from λ_C can lead to a hybrid that is between the differential sequence and the original one. Here reducing λ_0 by ~30 pm leads to a corrupted waveform with drastic oscillations at all bit transitions [Fig. 3(a)]. The magnitudes and settling times of the oscillations are data dependent [16], and there exists no single threshold for distinguishing '1's from '0's [Fig. 3(a)]. This is confirmed by both the closed backward eye diagram [Fig. 3(b), right] and a BER of ~50% for any power level at the photodetector. The forward eye diagram and BER indicate that wavelength detuning does not significantly affect the forward transmission [Figs. 3(b) and 3(c)].

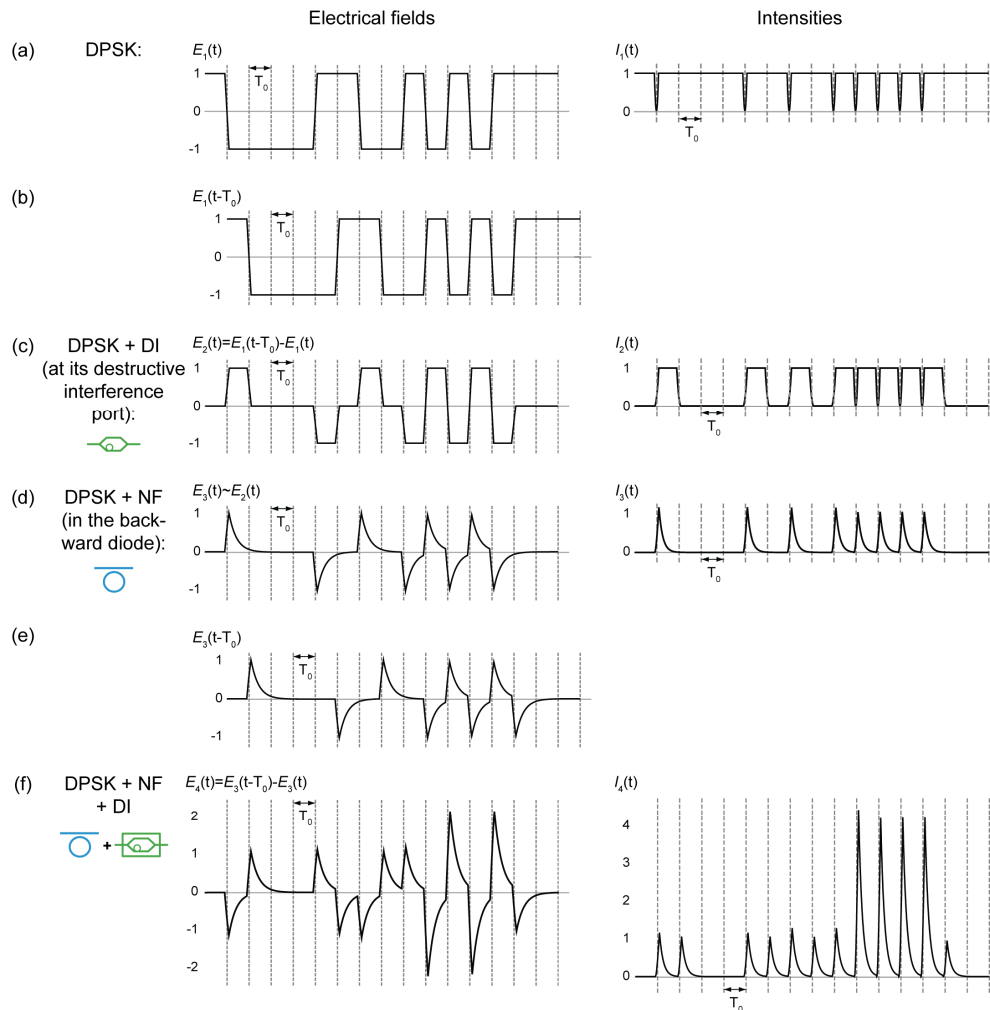### 2.3. One-way transmission of 10 Gbps DPSK data

Fig. 4. Schematics for encoding and decoding a 10 Gbps NRZ DPSK sequence, and that for propagating the sequence through the optical diode. (a) Encode a DPSK sequence of '0$\pi\pi\pi$ π00π π0π0 π000' using an intensity modulator. (b) Delay the sequence in (a) by one bit. (c) Decode the sequence in (a) at the destructive interference port of a delay-bit interferometer (DI) based DPSK decoder. (d) Pass the DPSK sequence in (a) through the critically coupled, linear NF in the backward diode, which acts as an edge detector. (e) Delay the sequence in (d) by one bit. (f) Pass the DPSK sequence in (a) through both the NF and DI sequentially.

The diode can directly block the transmission of backward information using NRZ differential-phase-shifting keying (DPSK). In the experiment, we encoded NRZ DPSK sequences using a MZI intensity modulator, which was biased at its transmission null and driven by a RF signal with an amplitude of V_π and with a zero offset voltage [17]. The RF driving signal is a differentially-phase-encoded version of the intended information, for example, here, '0100 0101 0111 1100'. Figure 4(a) shows a schematic of the generated DPSK sequence of '$0\pi\pi\pi$ $\pi00\pi$ $\pi0\pi0$ $\pi000$'. Its electric field $E_1(t)$ contains levels of −1 and 1, and its intensity $I_1(t)$ is constant at a high level of 1 except notches at times corresponding to the phase transitions. In the schematics a rise time of 20 ps in the modulator is assumed, which accouts for the intensity notches in $I_1(t)$. The DPSK data were experimentally decoded at the destructive interference port of a delayed-bit interferometer (DI) based DPSK decoder, which differentiates its input. At the destructive interference port, the electric field of the decoded DPSK is given by $E_2(t) = E_1(t\text{-}T_0) - E_1(t)$ with levels of ± 1 and 0 [Figs. 4(b) and 4(c)], and its intensity $I_2(t)$ shows high levels of 1s at times corresponding to the phase transitions in the input $E_1(t)$. $I_2(t)$ correctly presents the intended information of '0100 0101 0111 1100'.

Figure 5(a) shows the eye diagrams of a 10 Gbps NRZ DPSK PRBS that pass through both the diode and the DPSK decoder sequentially. First, the forward eyes show only minor distortions, with a power penalty of less than 0.5 dB with respect to the B2B case [Fig. 5(b)]. In addition to the power suppression, the backward eyes display a new feature of three voltage levels, as shown clearly in the inset which was taken with a higher amplified power at the detector. In Fig. 5(c) of the optical spectra, a resonance dip on the blue trace for the backward transmission results in a NTR of ~20 dB at the carrier wavelength. The NTR reduces to only ~7 dB in terms of integrated power, since power is spread more across the modulation bandwidth in DPSK [17]. Nevertheless, the creation of the extra voltage level precludes the setup of a single threshold voltage to distinguish '1's from '0's in the backward data. Thus, the distortion of the backward data induced by the strong dispersion effectively enhances the NTR for purposes of data detection.
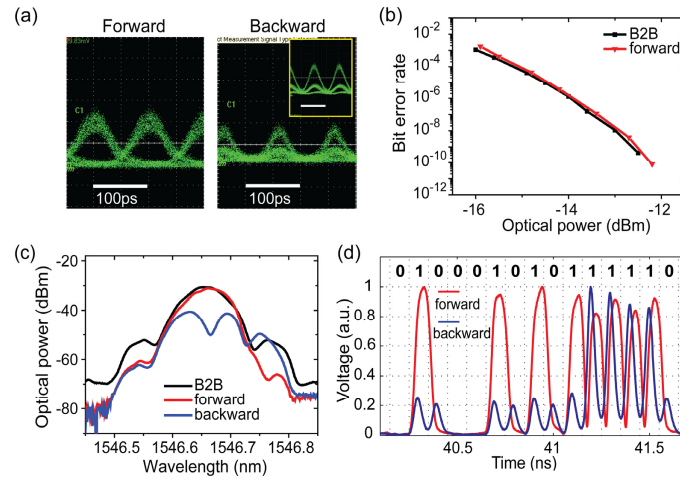

Fig. 5. (a) The eye diagrams of a 10 Gbps DPSK PRBS that pass through both the diode and DI. (b) The BER measurement. (c) The optical spectra of the 10 Gbps DPSK PRBS are taken right after the diode. (d) A 10 Gbps DPSK sequence pass through both the diode and DI.

The formation of the extra voltage level in the backward eyes can be explained based on the schematics in Fig. 4. First, as in the OOK experiment, the critically coupled, linear NF in the backward diode is responsible for the distortion of the backward data. It functions as an edge detector or a differentiator, similar to the destructive interference port of a DI [18]. This is manifested by the simulation in Fig. 4(d), where the information decoded at the through

port of the NF is the same as that by the DI decoder in Fig. 4(c). In the diode experiment, since the DPSK data passed through both the backward diode and the DI sequentially, they were differentiated twice. In the corresponding simulation in Fig. 4(f), the sequence obtained via passing the DPSK through both the NF and DI is expressed as $E_4(t) = E_3(t\text{-}T_0) - E_3(t)$ [see Fig. 4(e)], which contains levels of $0, \pm 1$, and ± 2. Its intensity $I_4(t)$ thus shows levels of 0, 1, and 4, the same as that in the backward eyes in Fig. 5(a). To experimentally confirm this, the same DPSK sequence of '$0\pi\pi\pi$ $\pi00\pi$ $\pi0\pi0$ $\pi000$' was passed through the diode and decoded by the DI [Fig. 5(d)]. The red (forward) and blue (backward) traces in Fig. 5(d) closely resemble I_2 and I_4 in Fig. 4, respectively, and the amplitude ratio of peaks in the blue trace is exactly 4:1.

For RZ DPSK, in which each bit is represented by a distinct positive or negative pulse, the backward diode (or NF) can produce peaks at both the rising and falling edges of each bit and consequently the backward transmitted data will be scrambled more significantly than that in the NRZ DPSK case.

3. Discussion

In both OOK and DPSK experiments, both nonreciprocal transmission and nonreciprocal dispersion contribute to the one-way data transmission. The resonant dip affecting backward operation not only suppresses transmission of power, but also introduces strong dispersive reshaping. These effects do not affect the forward operation of the diode, for which the optical nonlinear effects shift the NF resonance away. The primary nonlinear effect that determines the functionality of the optical diode is the thermo-optic effect (TOE) [8], which reacts to optical power averaged over a few µs, far longer than the ~0.1 ns bit duration. Consequently, the resonance shift of the NF is independent of the subnanosecond-scale input power variations in the PRBS. Under the forward operation, the transmission spectrum is relatively flat over the 10 Gbps bandwidth [Fig. 1(b)], and the data pass through the optical diode with low power penalties in all cases [Figs. 2(c), 3(c), and 5(b)].

The wide power dynamic range of the diode, i.e., the NTR does not degrade appreciably with a moderately reduced input power [7, 8], is another enabler for the one-way data transmission. When light is modulated at 10 Gbps or higher rates, less optical power couples into the rings due to the spread power spectrum. Nevertheless, the wide dynamic range helps maintain the strong effect of the direction dependent resonance shift that is responsible for corrupting backward data, allowing one-way data transmission.

4. Conclusion

The reduced optical bandwidth associated with resonance enhancement is well known to limit data rates in optical signal processing. We have investigated bandwidth effects in the nonreciprocal transmission of data through an optical diode that exploits nonlinearities in an asymmetrically coupled microring resonator arrangement. The optical diode is operated with a forward-only or backward-only input. In the backward direction strong spectral phase variation and resonant attenuation cause waveform corruption. The forward transmitted data nonlinearly shifts the resonance away from the carrier wavelength; therefore, it sees an approximately flat spectrum and is not reshaped. Hence the dispersion associated with strongly resonant structures, often a limit in signal processing, is beneficial in our experimental context to facilitate nonreciprocal data transmission.