Giant Enhancement in Signal Contrast Using Integrated All-Optical Nonlinear Thresholder

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Abstract: We experimentally demonstrate, for the first time, an all-optical nonlinear thresholder on a silicon photonic integrated circuit. This thresholder enhances signal amplitude contrast 40-fold and improves receiver sensitivity by 10 dB.

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1. Introduction

Thresholders are the heart of analog-to-digital converters, comparators and operational amplifiers. Thresholders based on simple, effective and integrable all-optical components can work well beyond the limit of electronic counterparts, particularly in terms of the operation speed. Therefore, all-optical thresholders have found their unique and indispensable role in a variety of applications which need fast signal processing [1–3]. In these applications, the all-optical thresholder eliminates the incomplete suppression of the zero-level signal and noise, thus essentially boosting the signal to noise ratio (SNR) of optical signals.

Substantial efforts have been taken to develop high performance all-optical thresholders by exploring different nonlinear effects and materials. However, most of these all-optical thresholders are constructed with bulky and discrete photonic devices, therefore lacking the abilities of massive integration. The rapid development of silicon on insulator (SOI) platform offers the possibility to integrate all-optical thresholders on an ultracompact silicon chip, with favorable reduction of size, weight and power consumption (SWaP). The high refractive index and nonlinearity coefficient of silicon enable an efficient nonlinear interaction of the lightwave within a short waveguide [4]. Moreover, the nonlinearity of silicon can be further enhanced by resonators, e.g. microring resonators, which increases the effective interaction length and instantaneous optical powers through coherent power build-up. All-optical thresholders based on silicon microring resonators with different structures have previously been proposed. But these devices were previously only analyzed numerically and demonstrated with simulation results [5, 6].

In this paper, for the first time, to the best of our knowledge, we experimentally demonstrate an integrated all-optical thresholder based on microring-enhanced nonlinearity in a Mach-Zehnder interferometer (MZI) fabricated on SOI. Our device is capable of discriminating two signals with very close power levels. Using this thresholder, we can achieve a giant signal contrast enhancement of an optical signal by a factor of ~ 40.

2. Principle and Chip Design

The idea of the proposed optical thresholder is to exploit an intensity-dependent phase shift to achieve a thresholding transfer function. In silicon waveguides, the third order optical nonlinearity (i.e. the Kerr effect and plasma dispersion (carrier) effect) can induce a phase shift in the signal of interest. A MZI is used to convert the phase change into intensity change. With a sufficiently large phase shift, the signal from the two arms of the MZI can interfere destructively, leading to self-switching. To achieve significant self-switching effect under low optical power, we design an all-optical thresholder based on MRR-enhanced MZI. As shown in Fig. 1(a), the MRR is loaded on the arm of an MZI. This can considerably reduce the device footprint and power needed to achieve self-switching by increasing the effective interaction length and instantaneous optical power through coherent power buildup.

To maximize the thresholding effect, it is critical to switch off the undesirable lower power signal by achieving a destructive interference. A perfect destructive interference requires the signals in the two MZI arms to have balanced amplitudes and an exact π phase difference. Therefore, we designed a mach-zehnder coupler (MZC) coupled to the MRR-loaded MZI through a wideband 3-dB coupler. The bias of the MZC can be adjusted to balance the power into the two arms of MZI. Meanwhile, the MZI bias can be independently tuned to provide an exact π phase shift to the signals on the two MZI arms.

Our all-optical thresholder sample has a silicon thickness of 220 nm and a width of 500 nm with fully etched waveguide, a 3 μm oxide passivation layer, a Ti/W heating filament layer, and an Al routing layer. The MRR on the MZI's arm has a relatively small radius of 5 μm and high coupling coefficient (gap = 100 nm), yielding a Q-factor $\sim$ 10,000. The lower Q-factor effectively reduces the photon lifetime in the cavity and minimizes the two-photon absorption (TPA) and free carrier absorption (FCA) effects in the resonator. A microheater on the MRR provides flexible resonance control over a full free spectral range. Thus, the input signal with different wavelengths can be easily accommodated. The two microheaters are also deposited on the arms of MZC and MZI respectively. These tunable elements can efficiently change the biases of the device and enables us to locate the sweet spot of thresholding for the signals with different wavelengths and initial signal contrast.

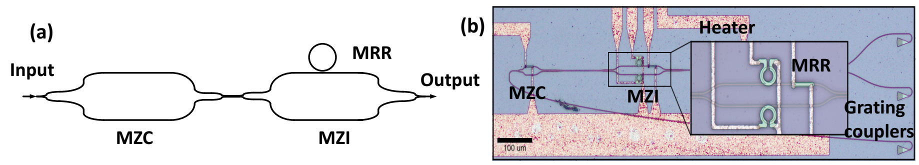

Fig. 1. (a) Schematic illustration of the proposed all-optical thresholder (b) Micrograph of the fabricated device. The resonance wavelength of the MRR on the lower arm of MZI is tuned away from the operating wavelength and therefore plays no role in the device's operation.

3. Experimental Setup and Results

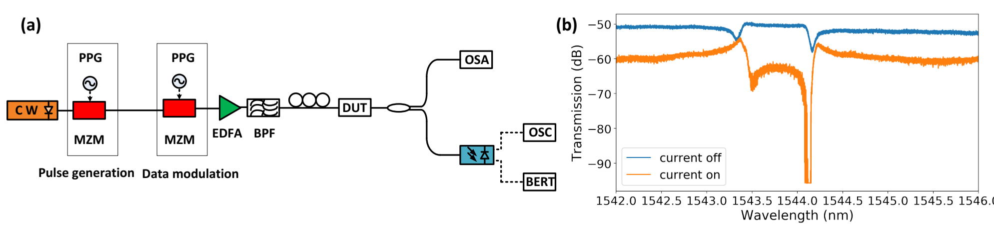

Fig. 2. (a) Experimental setup (b) transmission spectra of the proposed thresholder.

The experimental setup is shown in Fig 2(a). The testing signal is generated by modulating the output from a distributed feedback laser (DFB) with two cascaded Mach-Zehnder modulators (MZMs). The first MZM is driven by an electrical pulses from a pulse pattern generator (PPG). A pulsed optical signal with $\sim$ 80 ps pulsewidth and equalized peak power is generated. The second MZI is driven by patterned data. This yields a pulsed signal with a two different power levels, and the contrast between two power levels can be flexibly adjusted by tuning the bias of the second MZM. The optical signal is amplified to 20 dBm by an erbium doped fiber amplifier (EDFA) to trigger the nonlinearity in the silicon waveguide and compensate the fiber-to-chip coupling loss. The optical signal is coupled to the device through focusing sub-wavelength grating couplers with a coupling loss $\sim$ 8 dB. The input and output signals to the thresholder are tapped out. The eye diagrams obtained by photodetectors and monitored using a sampling oscilloscope (OSC). The signal optical spectra are monitored using an optical spectral analyzer (OSA). The microheaters are independent driven by computer-controlled current sources to optimize the parameters to attain a high signal contrast ratio.

The highly sensitive thresholding effect can predicted by the Fano resonance effect, which results from interference between a resonance pathway (MRR) and a coherent background pathway (MZI) [7]. This effect can be confirmed by the asymmetric line shapes of the resonance as shown by the transmission spectra in Fig 2(b). Two typical line shapes are shown in Fig. 2(b). When the biases are off (blue curve), the transmission spectrum reveals a close-to-Lorentzian line shape with an on-off ratio of $\sim$ 7.5 dB. The slightly asymmetric resonance shape may come from the residual path unbalance between two MZI arms. When the biases are on (orange curve), their currents are adjusted such that

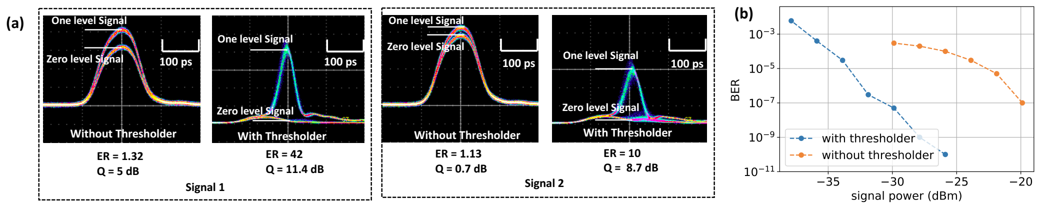

Fig. 3. (a) Eye diagrams (b) BER test of signals with and without the proposed all-optical thresholder

the optical power is completely shut off at one wavelength (see the dip of the resonance). In this case, the transmission spectrum reveals an asymmetric line shape with an on-off ratio of more than 45 dB.

Fig. 3(a) shows the performance of the all-optical thresholder using input optical signals with two different extinction ratios. Both input signals have extinction ratios closed to 1, resulting in a significantly degraded Q-factor, even though the received average power (0 dBm) is much higher than the sensitivity of our photodetector. After being processed by the thresholder, the lower power pulses in both signals are suppressed to a zero amplitude due to the perfect destructive interference. As a result, the signals after thresholding have a significant extinction ratio enhancement ($\sim$ 40 times for signal 1, and 7.5 times for signal 2). The extinction ratio enhancement leads to Q factor improvement of 6.4 dB for signal 1 and 8 dB for signal 2. Our thresholder works well under low extinction ratios of close to 1, indicating that the thresholder has a steep "thresholding slope". Fig. 3(b) shows the results of bit error rate (BER) measurement of signal 1 using a BER tester (BERT). Assisted with the all-optical thresholder, the signal can achieve an error-free detection (BER = 10^{-9}) at the signal power of -27.5 dBm due to its opened eye. Without processed by the thresholder, it is difficult for the BERT to idenity a threshold value. Therefore, at the same detection power (-27.5 dBm), the signal has a bit error rate more than 10^{-4}. At the BER of 10^{-7}, the receiver sensitivity with our thresholder is improved by 10 dB, compared to the original signal.

4. Conclusion

In conclusion, we have experimentally demonstrated, for the first time, an all-optical programmable nonlinear thresholder on a silicon integrated circuit. This thresholder employs the self-switch effect in microring-enhanced Mach-Zehnder interferometer and achieves a 40 $\times$ enhancement in signal amplitude contrast. The giant enhancement is realized by perfect destructive interference of the lower power pulses, which relies on highly flexible and precise bias control of the proposed devices. This programmability also opens up the possiblities of realizing different desirable transfer functions for a variety of applications.

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