Abstract—We experimentally demonstrate an all-optical programmable thresholder on a silicon photonic circuit. By exploiting the nonlinearities in a resonator-enhanced Mach-Zehnder interferometer (MZI), the proposed optical thresholder can discriminate two optical signals with very similar amplitudes. We experimentally achieve a signal contrast enhancement of 40, which leads to a bit error rate (BER) improvement by 5 orders of magnitude and a receiver sensitivity improvement of 11 dB. We present the thresholding function of our device and validate the function with experimental data. Furthermore, we investigate potential device speed improvement by reducing the carrier lifetime.

Index Terms—Optical thresholder, nonlinear silicon photonics.
contributing to the phase shift [15], [16]. All these techniques are compatible with our proposed thresholder.

II. DEVICE PRINCIPLE, DESIGN AND CHARACTERIZATION

The idea of the proposed optical thresholder is to exploit the optical-power-dependent phase shift induced by the nonlinearity in silicon waveguide. An MZI is used to convert the phase change into an intensity change with a large extinction ratio. With a sufficiently large phase difference due to the power-dependent nonlinearity, the interference between the signals from the two arms of the MZI can switch from constructive to destructive, leading to self-switching. To achieve a significant self-switching under low optical powers, we load an MRR in one arm of the MZI, resulting in an all-optical thresholder based on an MRR-enhanced MZI (Fig. 1(a)). This enhancement considerably reduces the required optical power supply 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 low power signal through destructive interference. Perfect destructive interference requires the signals traveling in the two MZI arms to have equal amplitudes and an exact \( \pi \) phase difference. Therefore, we designed a MZC preceding the MRR-loaded MZI through a wideband 3 dB coupler. The bias of the MZC (through the heater on one of its arms) can be adjusted to balance the amplitudes at the two arms of the MZI, while the MZI bias can be independently tuned to introduce a \( \pi \) phase difference. The bias on the MRR also needs to be carefully adjusted to ensure that the thresholder is working around the resonance wavelength to achieve the highest sensitivity.

Our all-optical thresholder consists of fully-etched, 500 nm-wide waveguides (Fig. 1(b)) on a passive-SOI platform with silicon thickness of 220 nm, a 3 \( \mu \)m oxide passivation layer, a Ti/W heating filament layer, and an Al routing layer. The MRR on the MZI’s arm has a radius of 5 \( \mu \)m and high coupling coefficient (\( \text{gap} = 100 \text{ nm} \)), yielding a Q-factor \( \sim 25000 \). The resonance of the MRR on the lower arm of MZI is tuned away from the operating wavelength and is not used in our experiment. A microheater on the MRR provides flexible resonance control over a full free spectral range (FSR). Thus, input signals of different wavelengths can be easily accommodated. Two microheaters are deposited on the arms of MZC and MZI. These tunable elements can control the interference condition of the device and enable us to locate the sweet spot of thresholding for the signals.

Two typical transmission spectra under different microheater DC current biases are shown in Fig. 1(c). When the biases are off (blue curve), the resonance features on the transmission spectrum resemble a Lorentzian-like shape with an on-off ratio of \( \sim 7.5 \) dB. However, there is a slight asymmetry in the shape due to the residual path unbalance between the two MZI arms. When the bias currents are on and adjusted (orange curve), the optical power at resonance is \( \sim 90 \) dBm denoting an off condition. The on-off ratio in this case is found to be more than \( 45 \) dB. This result indicates that, loading an MRR on the MZI can significantly improve the on-off ratio of the device transfer function. This highly sensitive transfer function can be explained by the Fano resonance effect, which results from the interference between a resonance pathway (MRR) and a coherent background pathway (MZI) [17], [18].

III. SIGNAL CONTRAST ENHANCEMENT EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 2. The signal is generated by modulating a distributed feedback (DFB) laser output using two cascaded MZMs. The first MZM is driven by electrical pulses from a pulse pattern generator (PPG) (Anritsu MP1763b). A pulsed optical signal with \( \sim 80\text{ps} \) pulselength and equalized peak power is generated. The second MZM is driven by probed programed data at a rate of \( 400 \text{Mb/s} \). This yields a \( 400 \text{Mb/s} \) return-to-zero (RZ) signal with two different power levels, and the contrast between two power levels can be dynamically adjusted by tuning the bias of the second MZM. The data speed is limited by the decay time of the TPA-induced carriers. 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 for the fiber-to-chip coupling loss. The optical signal is coupled to the device by free-space coupling through a sub-wavelength grating coupler with \( \sim 8 \) dB coupling loss. The eye diagrams of the input and output signals are obtained by photodetectors and monitored using a sampling oscilloscope (OSC) (Tektronix DSA8300). The signal optical spectrum is monitored using an optical spectral analyzer (OSA) (APEX AP2440A). The microheaters are independently driven by computer-controlled current sources to optimize the parameters necessary to attain a high signal contrast ratio.
Fig. 3(a) shows the device performance using two sets of signals with different input signal contrast ratios. Both sets of signals have contrast ratios close to 1, resulting in significantly degraded signal quality (Q-factor) even though the received average powers (0 dBm) are much higher than the receiver sensitivity. After being processed by the thresholder, the lower power pulses in both signals are fully suppressed. As a result, the signals after thresholding have a significant signal contrast enhancement (~40 times for signal 1, and 7.5 times for signal 2), which leads to a Q-factor improvement of 6.4 dB for signal 1 and 8 dB for signal 2. The result confirms that our thresholder works well under signal contrast close to 1.

Fig. 3(b) shows the results of BER measurement of signal 2 using a BER tester (BERT). Assisted with the all-optical thresholder, the communication link can achieve an error-free detection (BER = 10^{-9}) at a received signal power of -27.5 dBm due to the contrast enhancement leading to an opened eye. Without the thresholder, at the same received power (-27.5 dBm), the link has a BER higher than 10^{-4}. The presence of this thresholder can also effectively improve the receiver sensitivity by 11 dB at a BER of 10^{-7} (see Fig. 3b).

IV. THRESHOLDING TRANSFER FUNCTION

To correctly model the thresholding behavior of our device, nonlinearities in the silicon waveguide including the Kerr effect, TPA, TPA induced free-carrier absorption (FCA) and FCD are taken into consideration. Thermal-optic effect is excluded due to its long response time compared to the signal speed. In our simulation model, the MZC and MZI are treated as linear waveguides due to their short lengths. Nonlinear coupled-mode theory is used to study the change in the signal complex amplitude and carrier density in the MRR [19]. The evolution of the normalized complex amplitude $a$, and the normalized carrier density $n$ is governed by

$$\frac{\partial a}{\partial t} = i(\delta \omega - n_{Kerr}|a|^2 + \sigma_{fca|a|} a) - (1 + \alpha_{tpa}|a|^2 + \gamma_{fca}\alpha_{tpa} a) + \sqrt{\gamma_p P_{in}(t)}(1a)$$

$$\frac{\partial n}{\partial t} = |a|^2 - n/\tau, \quad (1b)$$

where $\delta \omega$ is the frequency detuning between the light source and the MRR resonance; $t$ is the time variable normalized with $\Gamma_0^{-1} = 2Q_L/\omega_0$, $Q_L$ is the total quality factor; $P_{in}$ is the power input, and $(n_{Kerr}, \alpha_{tpa}, \sigma_{fca}, \gamma_p) \propto (n_2\omega_0, \beta_2, \sigma_{e,h}, \omega_0, \sigma_{fca}, \Gamma_e/\Gamma_0^3)$, are the Kerr, TPA, FCD, FCA, and quality factor coefficients, respectively. These equations were simplified from Ref. [19], and renormalized so that the two-photon absorption term only appears in Eq. (1a) [12].

The input signals are Gaussian pulses with widths of 100 ps. Their wavelength is located at 150 GHz away from the MRR resonance, and the MRR Q factor is 25000. These conditions are consistent with those in the experimental measurement. The power splitting ratio on MZC and the phase bias on MZI are optimized such that the slope of the transfer function is maximized. The transfer function in Fig. 3(a) shows that, through our thresholder, a signal contrast of 1 dB (the signal contrast is numerically equal to the extinction ratio (ER) of 1.25) between the two input signals is enhanced to 17.4 dB (ER = 54.9) in the output signals, resulting a 44× signal contrast enhancement. Fig. 4(b.iii) shows the nonlinearity-induced intensity dependent phase change in the MRR, which renders an amplitude shift in the MZI output. Along with this phase change, we can optimize the biases applied to the MZC and MZI to maximize the ratio of the peak powers between two output signals. This can be accomplished when the phase difference of the 1-level signal and 0-level signal is approximately $\pi$, and a destructive interference occurs on the 0-level signal while a constructive interference occurs on the 1-level signal. In the simulation, we also verify that FCD significantly dominates over the Kerr effect and governs the nonlinear phase shift. Such a verification is conducted by observing the difference in signal phase when the Kerr effect is included and excluded, and we find that the phase difference is insignificant (the results are not shown in this paper) in these two cases. The input and output pulsewidths of the two signals are plotted in Fig. 4(b.i) and (b.ii). The simulated contrast enhancement and the pulse waveform match well with the experimental data.

V. DEVICE SPEED DISCUSSION

Although FCD plays a dominant role in discriminating the signals, its long lifetime hinders fast nonlinear signal processing (>10 GHz) in silicon. Therefore, the processing
speed of the current device is limited to 400 Mbit/s. A widely applied technique to overcome the speed limitation is by active carrier removal, i.e., reverse-biasing a p-i-n junction transversal to the silicon waveguide to reduce the lifetime of free carriers. The carrier lifetime can be effectively reduced by increasing the reverse-biasing voltage [20].

Here, we study the device speed with active carrier removal and characterize the device speed under different carrier lifetime $\tau$ using our simulation model described in Eq. [1]. In device speed characterization, the input signal is an impulse with a pulsewidth $<1$ ps. The device speed is defined as $1/T$, where $T$ is the time that takes to reduce the free carrier number by 99% compared to the peak carrier number. It is worth noting that the definition of $T$ here takes the cavity effect of MRR into consideration, and thus is not equivalent to the carrier lifetime. Fig. 5 shows the device speed as a function of the carrier lifetime. As expected, reducing the carrier lifetime can increase the device speed. With reduced lifetime, the similar thresholding function can still be achieved at the cost of requiring a higher signal power. Our current device operates at a speed of 400 Mbit/s and is marked in Fig. 5. The inset of Fig. 5 is a zoom-in view when the carrier lifetime is smaller than 40 ps. As shown in the inset, our thresholder has the potential of working beyond 10 GHz when the carrier lifetime is reduced to $\sim 18$ ps [20].

The processing speed limitation imposed by carrier effects can be further relaxed by designing MRR with a lower Q factor. Other alternative approaches include the use of a silicon-organic hybrid waveguide and other TPA-free nonlinear materials [15], [16]. All these methods are compatible with the design of our proposed thresholder.

VI. CONCLUSION

We have proposed and experimentally demonstrated an all-optical programmable nonlinear thresholder based on resonator-enhanced nonlinearity in a Mach-Zehnder interferometer. This device can discriminate signals with extremely close power levels due to its sharp thresholding transfer function, as predicted by a theoretical model based on nonlinear coupled theory. We experimentally demonstrated that this thresholder enables an enhancement of 40 times in signal amplitude contrast, and consequently, an improvement of 11 dB in the receiver sensitivity. The proposed thresholder, developed on a CMOS-compatible silicon-on-insulator (SOI) platform, can find uses in a number of high-performance optical signal processing applications and can be monolithically integrated with other on-chip functionalities.

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