Enhanced fast light and low-distortion slow light in microring-resonator assisted Mach-Zehnder Sagnac loop on a silicon-on-insulator platform

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Abstract **— An optical resonance analogous to electromagnetically induced transparency (EIT) is realized by using a silicon microring resonator assisted Mach-Zehnder Sagnac loop. Enhanced fast light and low-distortion slow light are experimentally achieved with the fabricated device.**

Keywords **— electromagnetically-induced-transparency (EIT), microring resonator (MRR), Sagnac loop, fast and slow lights.**

I. Introduction

Optical resonances analogous to electromagnetically induced transparency (EIT) have found wide applications in recent years, including optical signal buffering, biochemical sensing, and quantum signal processing [1].

Control of light velocity has attracted much attention due to its capability in optical signal buffering and storing, such as in all optical packet switched networks [2], true time delay for synthetic aperture radars [3] and optical interconnections in computer systems [4]. Silicon-on-insulator (SOI) structure is recognized as an ideal platform for on-chip integration due to its high refractive-index contrast between the silicon core and silica cladding, which allows strong optical confinement and enables ultra-compact photonic devices. In a previous study, 25-ps pulse delay and 6-ps pulse advancement were obtained in a silicon microring resonator (MRR) with mutually-coupled modes [5]. In this paper, for the first time to the best of our knowledge, we propose and demonstrate a microring-resonator assisted Mach-Zehnder Sagnac loop (MRR-MZ-SL) on a silicon-on-insulator (SOI) platform. By introducing counter-propagation mode coupling induced by a Mach-Zehnder Sagnac loop, optical resonance analogous to EIT effect can be achieved with a single MRR, which eliminates the stringent requirement of precise control of respective resonances in conventional coupled-resonator systems [6]. Experimental results show enhanced fast lights of 125 ps and 130 ps at resonance notches, respectively, as well as low-distortion slow light of 33 ps at the central transparency window for 2-Gb/s return-to-zero (RZ) pulses. Owing to the reflection of the Sagnac loop, light passes the MRR twice and possesses doubled group delay. Furthermore, relatively large bandwidth of the transparency window also minimizes the distortion for the delayed signal.

II. Device Structure and Operation Principle

The schematic diagram of the proposed MRR-MZ-SL is shown in Fig. 1. The system input is divided into two parts with different paths at Coupler I, one part goes through the upper arm of the Mach-Zehnder interferometer (MZI) with a side-coupled MRR, while the other goes through the lower arm without the MRR. After converging at Coupler II and going through the Sagnac loop, each part is further divided into two parts with opposite traveling directions. As a result, there exist four degenerate modes in this configuration: one passes the MRR twice counter-directionally, one travels along the waveguide without passing the MRR, and the other two pass the MRR only once, with circulating clockwise (CW) and circulating counterclockwise (CCW), respectively.

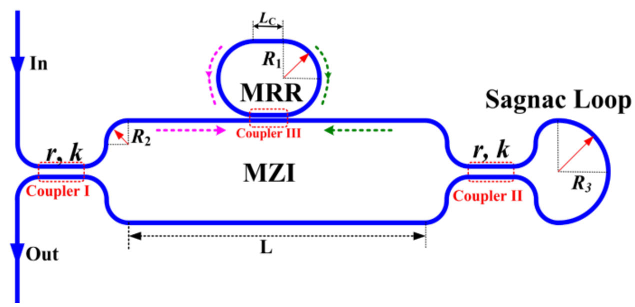

Fig. 1. Schematic diagram of the proposed MRR-MZ-SL.

Based on the scattering matrix method [7], the transfer function of the proposed configuration can be written as follows:

$$T = aa_1a_2e^{i(\phi+\phi_1+\phi_2)}[-2\kappa^2r^2t^2+(r^2-\kappa^2)^2t-2r^2\kappa^2] = Ae^{i\Psi} \quad (1)$$

$$t = \frac{r'-a'\exp(i\phi')}{1-r'a'\exp(i\phi')}, \quad (2)$$

where $r_1 = r_2 = r$ and $\kappa_1 = \kappa_2 = \kappa$ are the transmission and cross-coupling coefficients of Coupler I and Coupler II depicted in Fig. 1; $\Phi_{1,2} = kL_{1,2}$, with k representing the propagation constant, are the phase shifts associated with the two arms of the Mach-Zehnder Sagnac loop with lengths of $L_1 = 2\pi R_2+L$ and $L_2 = 2\pi R_2+L$, respectively; $a_{1,2} = exp(-\alpha L_{1,2}/2)$, with α denoting the loss factor, are the transmission factors associated with the waveguides with lengths of $L_{1,2,}$ respectively; $\Phi=kL_s$ and $a= exp(-\alpha L_s/2)$ are the phase shift and the transmission factor of the Sagnac loop with length of $L_s = 2\pi R_2+\pi R_3$; t is the transfer function of the single MRR. The three terms in the transfer function correspond to the three kinds of coherent resonance paths. The lights travel through these paths and interfere at Coupler I, and finally compose the system output with an EIT-like transmission spectrum.

We define the phase response of the proposed device as $\Psi = \arg(T)$, and the dispersion-induced group delay (GD) as $\tau_g = -d\Psi(\omega)/d\omega$. Pulse delay/advancement can be obtained when τ_g is positive/negative, respectively. The magnitude of the GD reaches peak at the resonance wavelengths. Fig. 2 shows the normalized transmission intensity and GD responses for various κ. If $\kappa^2 = 0.5$, i.e., Coupler I and Coupler II are 3-dB couplers, maximum transmission intensity outside the EIT-like resonances can be achieved. The group delay is negative to generate fast light at the resonance notches on both sides, while it is positive in the central transparency window to produce slow light.

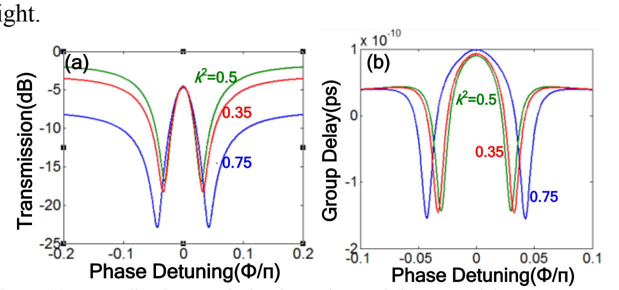

Fig. 2. (a) Normalized transmission intensity, and (b) group delay responses of the proposed configuration with various cross-coupling coefficient κ.

III. Experimental Setup and Results

Figure 3(a) shows the micrograph of the fabricated device. The above designed configuration is fabricated on an 8-inch SOI wafer with a 220-nm-thick top silicon layer and a 2-μm-thick buried dioxide layer. The radius of the microring is ~10 μm. The gap size in the three coupling regions is ~180 nm. The cross section of the waveguides is 450×220 nm^2 with an effective area of 0.1 μm^2 for the transverse-electric (TE) mode. Thermal-optic microheaters are fabricated along the two arms of the MZI to tune the phase shift of each arm, thus a symmetric EIT-like spectrum can be obtained.

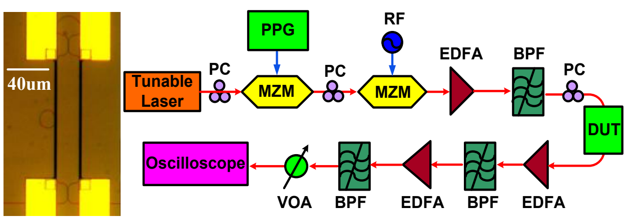

Fig.3. (a) Micrograph of the fabricated device. (b)Experimental setup for the demonstration of fast light and slow lights with the proposed MRR-MZ-SL.

We perform an experiment to investigate the fast/slow-light performance of the fabricated device. The experimental setup is depicted in Fig. 3(b). A 2-Gb/s return-to-zero (RZ) pulse train with a duty cycle of 50% is generated using two cascaded Mach-Zehnder modulators (MZMs). The first MZM is driven by a pseudo-random signal sequence (PRBS) signal, while the second MZM is used as a pulse carver driven by a radio frequency (RF) signal with the same frequency. The output of the second MZM is amplified by an erbium-doped fiber amplifier (EDFA) followed by a tunable band-pass filter (BPF) to suppress the amplified spontaneous emission (ASE) noise. A polarization controller (PC) is inserted before the device to make sure that the input signal is transverse electrical (TE) polarized. Two cascaded EDFAs are employed to compensate the vertical coupling loss and a variable optical attenuator (VOA) is employed to adjust the power of the output signal. The waveforms are recorded by an oscilloscope.

The blue solid curve in Fig. 4(a) shows the measured transmission spectrum. The on-chip insertion loss is ~12.5 dB. The measured curve is fitted by the red dashed curve obtained from Eq. (1) with fitting parameters of $n_g = 4.33353$, $r = 0.51863$ and $r' = 0.9110$. As shown in Fig. 4(a), points A, B, C, and D correspond to four wavelengths around the split resonances. Firstly, we set the signal wavelength off-resonance at point A and take corresponding pulse waveform as a reference [Fig. 4(b), black curve]. When the wavelength is tuned to the split resonance at point B, the pulse is advanced by ~130 ps [Fig. 4(b), green curve]. If the signal wavelength sits between split resonances at point C, it is observed that the pulse is delayed by ~33 ps [Fig. 4(b), red curve]. Finally, when the wavelength is tuned to another split resonance at point D, ~125-ps pulse advancement can also be obtained [Fig. 4(b), blue curve]. It is noted that the experimentally observed pulse advancements and delay are a combined result of various frequency components within the signal bandwidth, thus they are smaller than the simulated resonance GD. The signal distortion of the slow light is minimized owing to the broadened bandwidth in the central transparency window.

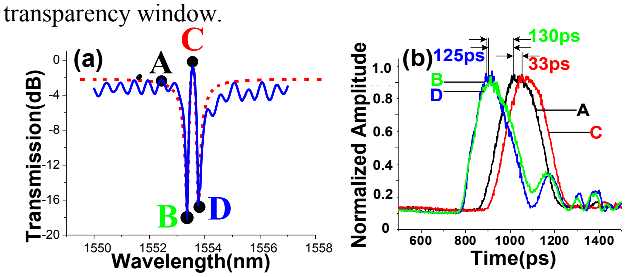

Fig. 4. (a) Measured and fitted transmission spectra at a split resonance. (b) Experimentally measured temporal waveforms of 2-Gb/s RZ pulse when the wavelength of the CW light is set differently as in (a).

IV. Conclusion

We propose and demonstrate a MRR-MZ-SL on a SOI platform with an EIT-like transmission spectrum. Enhanced fast lights of 130 ps as well as low-distortion slow light of 33 ps for 2-Gb/s RZ pulses are experimentally achieved with the fabricated device.

V. Acknowledgement

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