Continuous Slow and Fast Light Generation Using a Silicon-on-Insulator Microring Resonator Incorporating a Multimode Interference Coupler

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***Abstract*—Continuously tunable slow and fast light generation using a silicon-on-insulator microring resonator (MRR) incorporating a multimode interference (MMI) coupler is proposed and experimentally demonstrated. The MMI coupler is optimized for the transverse-magnetic mode. By changing the input polarization state, the self-coupling coefficient and the loss factor of the MRR are changed. The depth and the bandwidth of the MRR are tunable by tuning the self-coupling coefficient and the loss factor; thus, a tunable phase shift can be achieved at the resonance wavelength, which leads to the generation of a tunable slow and fast light. The proposed scheme is experimentally evaluated. A tunable slow light with a maximum time delay of 35 ps and a slow-to-fast light with a continuously tunable range of 102 ps are achieved for a 13.5-GHz Gaussian optical pulse by using a double-MMI coupler MRR and a single-MMI coupler MRR, respectively.**

***Index Terms*—Silicon-on-insulator (SOI) microring resonator (MRR), silicon photonics, slow and fast light.**

I. Introduction

CONTROLLING the speed of light is an interesting topic which has attracted great interest in the recent years. Slow light (time delay) and fast light (time advance) can find applications in optical communications, radar and signal processing [1]. Different schemes have been proposed to generate slow light and fast light such as electromagnetically induced transparency [2], coherent population oscillation [3], and stimulated Brillouin scattering (SBS) [4]. Slow light and fast light can also be generated based on optical dispersive devices such as a tilted fiber Bragg grating and a chirped fiber Bragg grating [5], [6].

Recently, photonic integrated circuits implemented based on silicon have attracted great interest due to the advantages such as compact size, low loss and high stability. The fabrication process is compatible with the mature electronic integrated circuit technology, thus making the fabrication greatly simplified with significantly reduced cost. Slow and fast light generation has been demonstrated based on silicon photonics microring resonators (MRRs) [7]–[17]. The structures include cascaded MRRs [7], zigzag chain of MRRs [8], vertically cascaded MRRs [9], and multi-state microrings [10]. A tunable slow and fast light can also be generated using an MRR by controlling the mutual mode coupling inside the MRR cavity [11], [12]. In [13], a p-i-n diode is incorporated into an MRR to change the free carrier injection and change the absorption loss of the cavity and consequently achieve electro-optically tunable slow and fast light. In [14], metallic micro-heaters are utilized for the modulation of the bus waveguide-to-cavity coupling, thus the linewidth of the resonance is changed which leads to the change of the group velocity. In [15], the gain in an MRR is changed by optically pumping the ring cavity that is erbium-ytterbium co-doped [15], or by electrically pumping the ring cavity that incorporates an optical semiconductor amplifier [16], consequently the linewidth of the resonance is changed and the group delay is changed correspondingly. In [17], the group delay is tuned by applying a voltage to a p-i-p microheater integrated directly inside a MRR. The main drawback in the schemes in [13]–[17] is that an additional procedure is needed in the fabrication process, making the fabrication more complicated. In addition, the use of the tuning schemes in [13]–[17] would increase the circuit footprint. Furthermore, the operating wavelength should be shifted which is not desirable for most of the applications [17]. A solution to the problem is to use all optical tuning. Recently, on-chip generation of a slow and fast light based on SBS in a long chalcogenide rib waveguide has been reported [18]. A large time delay (20 ns) and time advance (−10 ps) was achieved. However, the bandwidth was very small (in the order of tens of MHz). In addition, the optical carrier should be tuned at two different wavelengths corresponding to the Stokes and anti-Stokes wavelengths to generate the slow and fast light.

In this paper, we propose a technique to generate all-optically tunable slow and fast light based on a silicon-on-insulator (SOI) MRR incorporating multi-mode interference (MMI) couplers. The tuning is achieved by controlling the polarization of the input light wave. The key features of an SOI MRR is that the self-coupling coefficient and the loss factor are polarization dependent which are used to tune the time delay or time advance. In the MRR, the MMI couplers are optimized for the TM (transverse-magnetic) mode. The self-coupling coefficient of the MRR is reduced if the input polarization state is tuned away from the direction that is aligned with the TM mode. Moreover, the loss factor of the MRR is intrinsically polarization dependent. By changing the self-coupling

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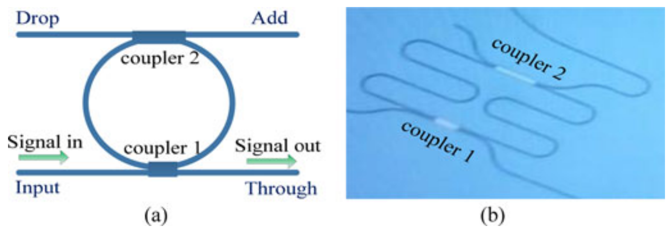

Fig. 1. (a) The schematic diagram of a double-MMI coupler MRR. (b) The picture of the fabricated double-MMI coupler MRR.

coefficient and the loss factor, the characteristics of the resonance notch, including its depth and width, are changed, which leads to the change of the phase (φ) inside the resonance. The group delay ($d\varphi/d\omega$) is correspondingly changed inside the resonance. In addition to the possibility of designing an MMI coupler to be optimized for the TM mode to achieve polarization-dependent time delay or advance tuning, another reason of using an MMI-coupler MRR in this proposal is that it has a larger resonance bandwidth compared with a directional coupler MRR [19].

The use of an MMI-coupler MRR for the generation of slow and fast light is studied. We first theoretically study the impact of changing the input polarization state on the self-coupling coefficient and the loss factor, and the corresponding time delay or advance. A double-MMI coupler MRR and a single-MMI coupler MRR are then fabricated and their use for slow and fast light generation is experimentally evaluated. A slow light with a tunable time delay of 35 ps and a slow-to-fast light with a tunable time delay of 102 ps are demonstrated experimentally for the double-MMI coupler MRR and the single-MMI coupler MRR, respectively.

II. Principle

In this section, the effect of changing the input light polarization on the group delay response of the two types of MRRs is studied.

A. Double-MMI Coupler MRR

The schematic diagram of a double-MMI coupler MRR is shown in Fig. 1(a) and a picture of a fabricated double-MMI coupler MRR is shown in Fig. 1(b). The transmission power spectra at the through port of the MRR is expressed as [20]

$$|T|^2 = \alpha_{\mathrm{MMI1}}^2 \left[\frac{t_1^2 - 2\alpha t_1 t_2 \cos\theta + \alpha^2 t_2^2}{1 - 2\alpha t_1 t_2 \cos\theta + \alpha^2 t_1^2 t_2^2}\right] \tag{1}$$

where t_1 and t_2 are the self-coupling coefficients of the through port coupler (coupler 1) and the drop port coupler (coupler 2), respectively, L is the length of the ring cavity, $\theta = 2\pi n_{\mathrm{eff}} L/\lambda$ is the total round trip phase accumulation, $\alpha = \alpha_{\mathrm{MMI1}} \cdot \alpha_{\mathrm{MMI2}} \cdot \alpha_{\mathrm{ring}}$ is the combined loss factor including the ring propagation loss factor (α_{ring}) and the two coupler loss factors ($\alpha_{\mathrm{MMI1}}, \alpha_{\mathrm{MMI2}}$), n_{eff} is the waveguide effective index, and λ is the wavelength in vacuum.

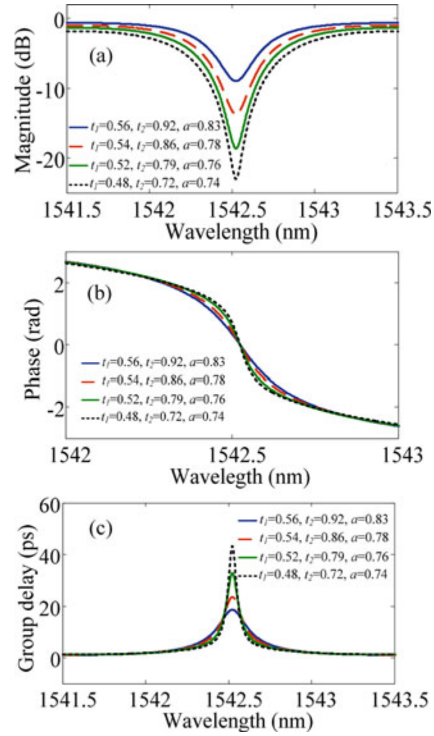

Fig. 2. The simulation results for a double-MMI coupler MRR (a) The magnitude (b) phase, and (c) group delay responses when the polarization state of the input light is changed from a TM to a TE mode.

An MRR has multiple resonances. If a light wave is located in the bandwidth of a resonance, a time delay ($d\varphi/d\omega > 0$) or time advance ($d\varphi/d\omega < 0$) would be produced depending on the slope of the phase response. The group delay can be expressed as

$$\tau = \frac{d\phi}{d\omega}. \tag{2}$$

By designing the MMI coupler to be optimized for the TM mode coupling, the self-coupling coefficient would be strongly polarization dependent and would decrease by changing the polarization state from a TM to a TE mode. In our designed double-MMI coupler MRR, coupler 1 has a 50:50 splitting ratio while coupler 2 has an 85:15 splitting ratio. The MMI couplers are optimized for the TM mode coupling. By changing the polarization state from a TM to TE mode, the self-coupling coefficients are changed significantly, and the loss factor α is also changed. At the designed central wavelength of the MMI coupler (1550 nm), the coupling coefficients and the loss factor are expected to decrease when the input polarization is rotated from TM to TE. Based on our calculation, at an operating wavelength of 1542.5 nm, t_1, t_2 and α are also decreased by changing the polarization state from a TM to TE mode. Fig. 2 shows the transmission, phase, and group delay spectra of an MRR with the ring cavity having a length of 350 μm, when the input polarization is changed from a TM to TE mode. In this case, self-coupling coefficient t_1 is decreased from 0.56 to 0.48, t_2 is decreased from 0.92 to 0.72, and the loss factor α is decreased from 0.83 to 0.74. As can be seen from Fig. 2(a), the depth and the

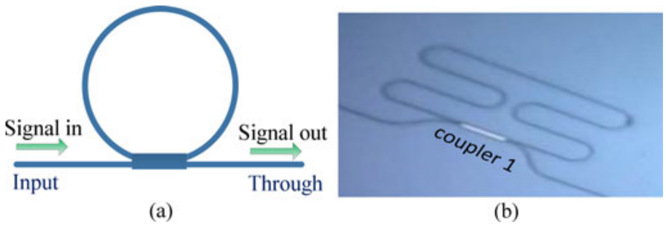

Fig. 3. (a) The schematic diagram of a single-MMI coupler MRR. (b) The picture of the fabricated double-MMI coupler MRR.

bandwidth of the resonance are changed, which lead to the change in the slope of the phase response, as shown in Fig. 2(b), and correspondingly the group delay is changed, as shown in Fig. 2(c). It should be noted that the coupling regime for all cases here is the over-coupled regime. Therefore, the phase slope ($d\varphi/d\omega$) is positive. Thus, only a tunable slow light is generated with the tuning done by tuning the polarization state of the input light in a double-MMI coupler MRR.

B. Single-MMI Coupler MRR

The schematic diagram of a single-MMI coupler MRR is shown in Fig. 3(a) and a picture of a fabricated single-MMI coupler MRR is shown in Fig. 3(b). The transmission spectrum of a single-MMI coupler MRR depends on the self-coupling coefficient (t) of the MMI coupler and also on the loss factor ($\alpha = \alpha_{\text{ring}} \cdot \alpha_{\text{MMI}}$) which is the combination of the MMI coupler loss factor (α_{MMI}) and the ring propagation loss factor (α_{ring}). The transmission power spectra of the MRR can be expressed as [20]

$$|T|^2 = \alpha_{\text{MMI}}^2 \left[\frac{t^2 - 2\alpha t \cos\theta + \alpha^2}{1 - 2\alpha t \cos\theta + \alpha^2 t^2} \right]. \qquad (3)$$

In our designed single-MMI coupler MRR, the MMI coupler has an 85:15 splitting ratio for the TM mode and is optimized for the TM mode coupling. Therefore, it is strongly polarization dependent and would decrease by changing the polarization state from a TM to TE mode. At the designed central wavelength of the MMI coupler (1550 nm), t and α are expected to decrease when the input polarization is rotated from TM to TE. However, in a small selected wavelength range away from the central wavelength, t can be decreased while α is increased which is the case at our selected operating wavelength of 1558.06 nm. Fig. 4 shows the transmission, phase, and group delay spectra of an MRR with the ring cavity having a length of 340 μm, when the input polarization is changed from a TM to TE mode. In this case, the self-coupling t is decreased from 0.87 to 0.63, and the loss factor α is increased from 0.71 to 0.82. As can be seen from Fig. 4(a) the depth and bandwidth of the resonance are changed, which leads to the change in the slop of the phase response, as shown in Fig. 4(b), and correspondingly the group delay is changed, as shown in Fig. 4(c). As can be seen in Fig. 4(b), by changing the input polarization from a TM to TE mode, not only the phase is changed but also its slope sign is changed. When $t > \alpha$, $d\varphi/d\omega$ is negative thus the group delay is negative and fast light can be achieved, and when $t < \alpha$, $d\varphi/d\omega$ is positive thus the group delay is positive and slow light can be achieved. It should be noted that the coupling in this MRR can be in the under-coupled, critically-coupled, and over-couple regimes. Therefore by changing the input light polarization state, continuous slow and fast light can be achieved in a single-MMI coupler MRR.

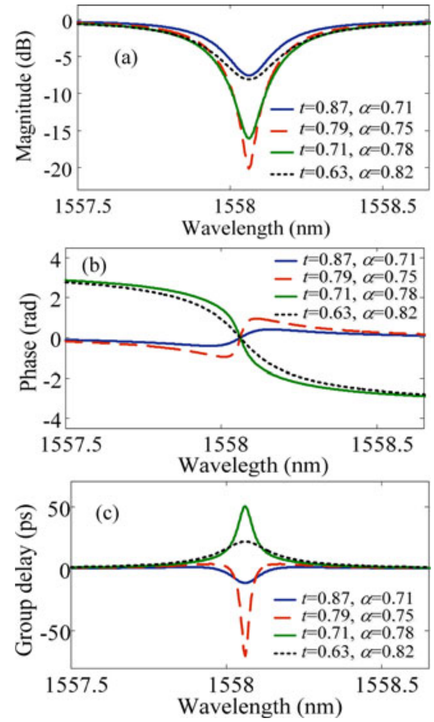

Fig. 4. The simulation results. (a) The magnitude, (b) phase, and (c) group delay responses of a single-MMI coupler MRR.

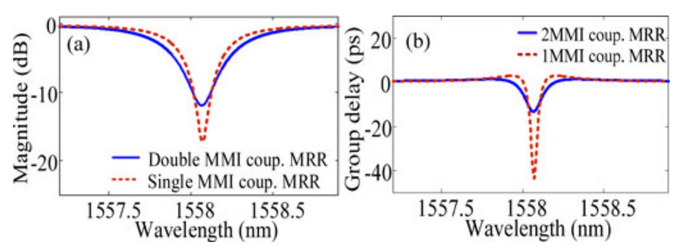

Fig. 5. The simulation results. (a) The normalized magnitude and (b) group delay responses of a double-MMI coupler MRR (solid line) and a single MMI coupler MRR (dashed line).

It should be noted that there are two differences between the single-MMI coupler MRR and the double-MMI coupler MRR. The first difference is that only a tunable slow light can be achieved in the double-MMI coupler MRR by changing the input polarization state while a tunable slow and fast light can be achieved by using a single-MMI coupler MRR since its coupling regime changes by changing the input polarization. The other difference is that their resonance bandwidths are different. Fig. 5 shows the simulation of the magnitude response, and group delay of the two types of MRRs. The loss factors are assumed to be

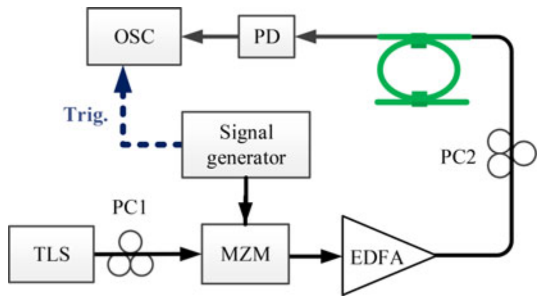

Fig. 6. Experimental setup. TLS: tunable laser source, MZM: Mach–Zehnder modulator, EDFA: erbium-doped fiber amplifier, Pol: polarizer, PC: polarization controller, PD: photodetector, OSC: oscilloscope.

the same in both MRRs and the two MMI couplers optimized for TM mode coupling are assumed to be identical in both MRRs. As can be seen the resonance bandwidth of the single-MMI coupler MRR is 50% narrower than that of the double-MMI coupler. Therefore, the amount of the distortion for a delayed signal with a fixed bandwidth in the double-MMI coupler MRR is less, and a double-MMI coupler MRR is more suitable for achieve a time delay for an optical signal with a wider bandwidth. However, as can be seen in Fig. 5(b) the amount of the time advance achieved by the double-MMI coupler MRR is less than that achieved by a single-MMI coupler MRR.

III. Experiment

An experiment based on the setup shown in Fig. 6 is performed. A continuous-wave light from a tunable laser source (TLS) is sent to a Mach-Zehnder modulator (MZM) via a polarization controller (PC1). At the MZM, the light is modulated by a Gaussian pulse. The Gaussian pulse has a temporal width of 50 ps (13.5 GHz) which is generated by a signal generator. The modulated signal is amplified by an erbium-doped fiber amplifier (EDFA), and its polarization state is tuned by using a second polarization controller (PC2, JDS Uniphase PR2000). PC2 is electrically controlled with a higher precision. The light is coupled into and out of the MRR by two tapered fibers. The output light from the MRR is detected at a 53 GHz photodetector (PD) and the waveform is observed by a sampling oscilloscope (OSC, Agilent 86100C). In order to measure the time delay or advance, a reference waveform that is not time delayed or advanced is used as a comparison. In the experiment, the reference waveform is the output pulse when the wavelength of the TLS is placed out of the resonance spectrum, thus the signal would not experience a time delay or advance caused by the resonance.

A. Double-MMI Coupler MRR

The generation of a time delayed pulse using a double-MMI coupler MRR is first experimented. The double-MMI coupler MRR is fabricated on an SOI wafer with a 260 nm thick silicon layer on a 2-μm thick BOX layer. Ring and the bus waveguides are patterned on the wafer by e-beam lithography. The cross section of the ring and the bus waveguides is 450 nm (width) × 260 nm (height). The cavity length is 350 μm. The

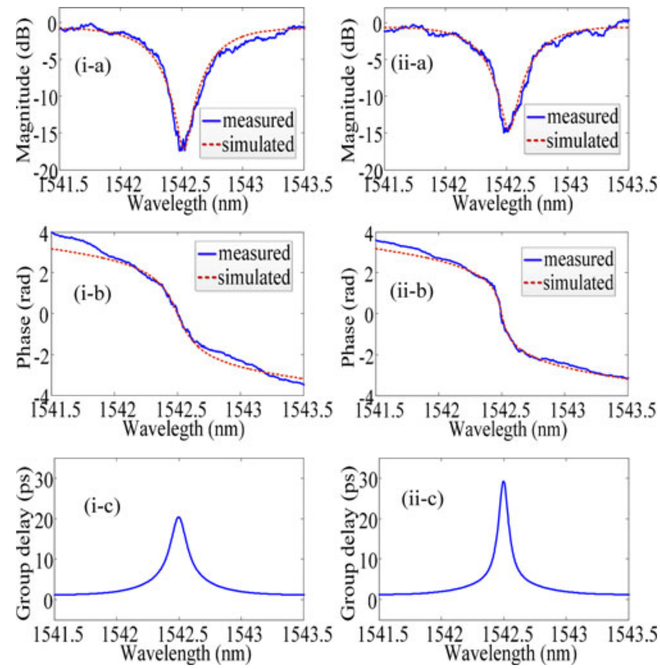

Fig. 7. (a) The measured (solid lines) and simulated (dashed lines) (a) magnitude and (b) phase responses of the fabricated double-MMI coupler MRR at two different polarization states of (i) and (ii). (c) The simulated group delay responses at the two polarization sates.

upper cladding of the MRR is a layer of SU8 polymer. The through port and drop port MMI couplers have a length and width of 3 μm × 8.5 μm and 2 μm × 15 μm, respectively. The edge to edge separation of the input/output waveguides in the two MMI couplers is 550 nm. The picture of the fabricated double-MMI coupled MRR is shown in Fig. 1(b). Based on our measurements at the wavelength of 1542.5 nm, t_1, t_2 and α are decreased by changing the input pulse from a TM to TE mode. Fig. 7(i-a) shows the measured transmission spectrum of the fabricated MRR (solid line) around a resonance centered at 1542.5 nm. The measured phase response of the MRR around the resonance is shown in Fig. 7(i-b). The simulated magnitude and phase responses are also shown as dashed lines for comparison. The parameters of the MRR used in the simulations are $t_1 = 0.53, t_2 = 0.85$ and $\alpha = 0.81$. Fig. 7(ii-a) and (ii-b) shows the measured (solid line) and simulated (dashed line) magnitude and phase responses of the same ring resonator but for an input light at a different input polarization state. The parameters for the MMI coupler used in the simulations are changed to $t_1 = 0.51$ $t_2 = 0.77$ and $\alpha = 0.78$.

It should be noted that the measured phase responses are achieved by using a vertical network analyzer (VNA). In fact, the VNA measures the phase of the device under test which includes a fiber, a waveguide, a ring and a PC. However, the simulated phase response is, in fact, the phase response of a single ring. Therefore, the amount of the phase jump at the resonance wavelength should be considered for the comparison. Fig. 7(c) shows the simulated group delays for these two different input polarization states. It can be seen that by changing the polarization state, the resonance shape is changed, the

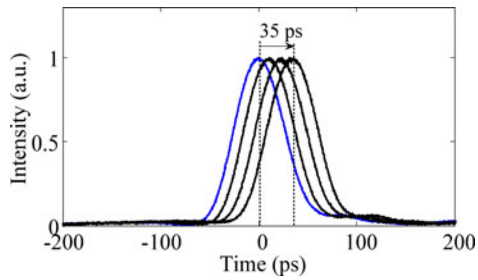

Fig. 8. The time delayed (slow light) Gaussian pulses by tuning the input light polarization state in the double-MMI coupler MRR.

phase shift at the resonance wavelength is changed and correspondingly different groups delays at the resonance wavelength are achieved which can be used to demonstrate a tunable slow light. By incorporating the fabricated MRR in the experimental setup in Fig. 6, and applying a 13.5 GHz Gaussian pulse that is modulated on a light at 1542.5 nm to the MRR, a time delayed Gaussian pulse is generated with the amount of time delay depending on the input polarization. As shown in Fig. 8, for three different polarization states, three different time delays are obtained. A maximum time delay of 35 ps is achieved with no visible distortions to the time-delayed pulse.

B. Single-MMI Coupler MRR

Then, the generation of a time delayed and advanced pulse using a single-MMI coupler MRR is experimented. Again, a single-MMI coupler MRR is fabricated on an SOI wafer with a 260 nm thick silicon layer on a 2 μm thick BOX layer. The length and width of the MMI coupler is 2 $\mu\text{m} \times 15\ \mu\text{m}$, and the cavity length is 340 μm. The picture of the fabricated single-MMI coupled MRR is shown in Fig. 3(b). Based on our measurements at the wavelength around 1558.06 nm, t is decreased and α is increased by changing the input pulse from a TM to TE mode. Fig. 9(i)-(a) shows the measured transmission spectrum of the fabricated MRR (solid line). The measured phase response of the MRR around the resonance is shown in Fig. 9(i)-(b). The simulated magnitude and phase responses are also shown as dashed lines for comparison. The parameters of the MMI coupler used in the simulations are $t = 0.79$ and $\alpha = 0.745$. Fig. 9(ii)-(a) and (ii)-(b) shows the measured (solid line) and simulated (dashed line) magnitude and phase responses of the same ring resonator but for an input light at a different input polarization state. The parameters for the MMI coupler used in the simulations are changed to $t = 0.68$ and $\alpha = 0.8$. Fig. 7(c) shows the simulated group delays for these two different input polarization states. As can be seen by changing the input light polarization state, the resonance shape is changed and correspondingly the phase shift is changed. Note that in Fig. 9(b), not only the phase shift is changed but also the slope sign $(d\varphi/d\omega)$ is changed from negative to positive. Therefore, the group delay is changed from negative to positive and a tunable slow-to-fast light is generated. By using this MRR in the experimental setup in Fig. 6, with a 13.5 GHz Gaussian pulse modulated on an optical carrier at 1558.06 nm, and changing the polarization

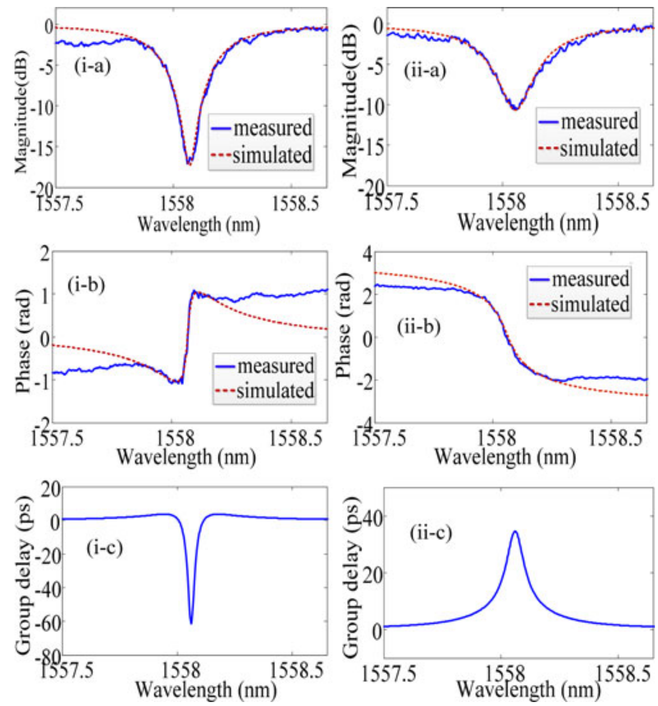

Fig. 9. The measured (solid lines) and simulated (dashed lines) results. (a) The magnitude, and (b) phase responses of the fabricated single-MMI coupler MRR at two different polarization states of (i) and (ii). (c) The simulated group delay responses at the two polarization sates.

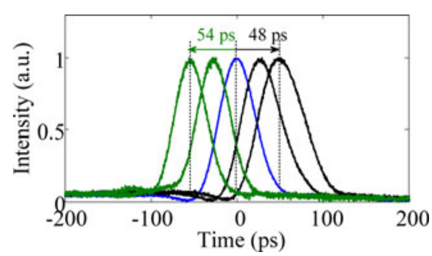

Fig. 10. The time delayed (slow light) and advanced (fast light) Gaussian pulses by tuning the input light polarization state in a single-MMI coupler MRR.

state continuously, a tunable slow-to-fast light is generated. The delayed and advanced Gaussian pulses for five different polarization states are shown in Fig. 10. As can be seen a fast light with a maximum time advance of 54 ps is changed to a slow light with a maximum time delay of 48 ps. Therefore, a 102 ps tunable slow-to-fast light is achieved. As discussed in Section II, the amount of distortion in this MRR is more than the double-MMI coupler MRR which is noticeable by comparing Figs. 8 and 10.

IV. Conclusion

An approach to generating a tunable slow and fast light using an MRR incorporating polarization-dependent MMI couplers were proposed and demonstrated experimentally. The tuning was achieved by tuning the input light polarization state since the MMI couplers were designed to be optimized for the TM mode. The group delays applied to the TE and TM modes are different. If a pulse has a polarization state just in between, the corresponding group delay is a vector sum of the two delay terms. In fact, the tuning was achieved by changing the ratio of the two pure eigenmodes in the light. Two MRRs with one having double MMI couplers and the other having a single MMI coupler were fabricated and the use of the MRRs to generate a slow light and a slow-to-fast light was studied. By changing the input light polarization state from a TM to TE mode, a tunable slow light with a time delay of 35 ps was achieved experimentally using the double-MMI coupler MRR, and a 102 ps tunable slow-to-fast light was achieved using the single-MMI coupler MRR. Since the bandwidth of a single-MMI coupler MRR is intrinsically narrower than that of a double-MMI coupler MRR, there was a greater distortion in the time delayed pulses by the single-MMI coupler MRR.

References

[1] J. Capmany, I. Gasulla, and S. Sales, "Microwave photonics: Harnessing slow light," *Nature Photon.*, vol. 5, no. 12, pp. 731–732, Dec. 2011.

[2] L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, "Light speed reduction to 17 metres per second in an ultracold atomic gas," *Nature*, vol. 397, no. 6720, pp. 594–598, Feb. 1999.

[3] W. Xue, S. Sales, J. Capmany, and J. Mørk, "Wideband 360° microwave photonic phase shifter based on slow light in semiconductor optical amplifiers," *Opt. Exp.*, vol. 18, no. 6, pp. 6156–6163, Mar. 2010.

[4] L. Xing, L. Zhan, S. Luo, and Y. Xia, "High-power low-noise fiber Brillouin amplifier for tunable slow-light delay buffer," *IEEE J. Quantum Electron.*, vol. 44, no. 12, pp. 1133–1138, Dec. 2008.

[5] H. Shahoei and J. P. Yao, "Continuously tunable slow and fast light by using an optically pumped tilted fiber Bragg grating written in an erbium/ytterbium co-doped fiber," *IEEE Photon. Technol. Lett.*, vol. 24, no. 10, pp. 818–820, May 2012.

[6] H. Shahoei, M. Li, and J. P. Yao, "Continuously tunable time delay using an optically pumped linearly chirped fiber Bragg grating," *J. Lightw. Technol.*, vol. 29, no. 10, pp. 1465–1472, May 2011.

[7] F. Morichetti, A. Melloni, A. Breda, A. Canciamilla, C. Ferrari, and M. Martinelli, "A reconfigurable architecture for continuously variable optical slow-wave delay-lines," *Opt. Exp.*, vol. 15, no. 25, pp. 17 273–17 282, Dec. 2007.

[8] P. Chamorro-Posada and F. J. Fraile-Pelaez, "Fast and slow light in zigzag microring resonator chains," *Opt. Lett.*, vol. 34, no. 5, pp. 626–628, Mar. 2009.

[9] C. Ciminelli, C. E. Campanella, F. Dell'Olio, and M. N. Armenise, "Fast light generation through velocity manipulation in two vertically-stacked ring resoator," *Opt. Exp.*, vol. 18, no. 3, pp. 2973–2986, Feb. 2010.

[10] N. Pornsuwancharoen, N. Sangwara, and P. P. Yupapin, "Generalized fast and slow lights using multi-state microring resonators for optical wireless links," *Optik*, vol. 121, no. 19, pp. 1721–1724, Oct. 2010.

[11] T. Wang, F. Liu, T. Ye, Z. Zhang, J. Wang, Y. Tian, M. Qiu, and Y. Su, "Continuously-tunable slow and fast light using silicon microring add-drop filter with mutual mode coupling," in *Proc. Opt. Fiber Commun. Conf.*, San Diego, CA, USA, Mar. 2009, Paper OWC4.

[12] Q. Li, Z. Zhang, J. Wang, M. Qiu, and Y. Su, "Fast light in silicon ring resonator with resonance-splitting," *Opt. Exp.*, vol. 17, no. 2, pp. 933–940, Jan. 2009.

[13] X. Luo, H. Chen, and A. W. Poon, "Electro-optical tunable time delay and advance in silicon microring resonators," *Opt. Lett.*, vol. 35, no. 17, pp. 2940–2942, Sep. 2010.

[14] H. Atabaki, B. Momeni, A. A. Eftekhar, E. S. Hosseini, S. Yegnanarayanan, and A. Adibi, "Tuning of resonance-spacing in a traveling-wave resonator device," *Opt. Exp.*, vol. 18, no. 9, pp. 9447–9455, Apr. 2010.

[15] Y. H. Wang, C. S. Ma, X. Yan, and D. M. Zhang, "Analysis for amplifying characteristics of Er3+−Yb3+-co-doped microring resonators," *Opt. Laser Technol.*, vol. 42, no. 2, pp. 336–340, Mar. 2010.

[16] D. G. Rabus, Z. Bian, and A. Shakouri, "Ring resonator lasers using passive waveguides and integrated semiconductor optical amplifiers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 13, no. 5, pp. 1249–1256, Sep. 2007.

[17] J. Xie, L. Zhou, Z. Zou, J. Wang, X. Li, and J. Chen, "Continously tunable reflective-type optical delay lines using microring resonators," *Opt. Exp.*, vol. 22, no. 1, pp. 817–823, Jan. 2014.

[18] R. Pant, A. Byrnes, C. G. Poulton, E. Li, D. Y. Choi, S. J. Madden, B. Luther-Davies, and B. J. Eggleton, "On-chip slow and fast light using stimulated Brillouin scattering," in *Proc. Bragg Gratings, Photosensitovity, Polling Glass Waveguides Conf.*, Colorado Springs, CO, USA, Jun. 2012, Paper ITu3C.

[19] D. X. Xu, A. Densmore, P. Waldron, J. Lapointe, E. Post, A. Delâge, S. Janz, P. Cheben, J. H. Schmid, and B. Lamontagne, "High bandwidth SOI photonic wire ring resonators using MMI couplers," *Opt. Exp.*, vol. 15, no. 16, pp. 3149–3155, Mar. 2007.

[20] A. Yariv, "Universal relations for coupling of optical power between microresonators and dielectric waveguides," *Electron. Lett.*, vol. 36, no. 4, pp. 321–322, Feb. 2000.

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