Enhanced fast light in microfiber ring resonator with a Sagnac loop reflector

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Abstract: We fabricate a microfiber knot-type ring resonator with a Sagnac loop reflector, and control the light velocity using the device. In this structure, light is reflected by the Sagnac loop and passes through the ring resonator twice. Thus, it possesses doubled transmission and group delay comparing with the microfiber ring resonator without the Sagnac loop. We experimentally demonstrate pulse advancement in an under-coupled microfiber knot-type ring resonator with a Sagnac loop reflector. In the experiment, a maximum of ~25 ps pulse advancement was achieved for a 5-Gb/s RZ signal.

OCIS codes: (060.2310) Fiber optics; (230.5750) Resonators; (060.2280) Fiber design and fabrication.

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#127555 - $15.00 USD Received 26 Apr 2010; revised 23 May 2010; accepted 26 May 2010; published 15 Jul 2010

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1. Introduction

In recent years, controlling the velocity of light has been of great interest for its potential applications, such as tunable optical delay lines, optical buffers, true time delay for synthetic aperture radars, cryptography, and imaging in the quantum information field [1,2]. Fast light is interesting since the superluminal signal velocity can be achieved without violating Einstein causality [3]. In the previous works, fast light has been demonstrated based on optical fibers using stimulated Brillouin scattering (SBS) [4], metamaterial with negative refractive index [5], and coupled resonators with structural dispersion [6]. These demonstrations are based on optical materials with very large anomalous dispersion. Therefore, group index n_g is less than one and may even become negative, resulting in fast group velocity of light [7]. In practical systems, fast light is limited by several factors. Advancement of ultra-short pulses is hard to achieve due to narrow spectral region with linear dispersion of the transmission media [8]. Pulse distortion is also likely to occur from signal attenuation or gain saturation in the fast light system based on sharp absorption or gain resonance as well as high order dispersion [9].

On the other side, optical microfibers drawn from standard single mode fibers (SMFs) are attractive in terms of low cost, easier coupling to SMFs, and significantly lower loss than most lithographically fabricated waveguides. The typical transmission loss of a microfiber with micrometer-scaled diameter is lower than 0.1dB/mm at 1550-nm wavelength [10]. In addition, the microfiber-based loop-type or knot-type ring resonators possess good optical resonances [11,12] and offer the possibility to realize cost-effective optical interconnection systems. To date, fast light behavior in the microfiber-based resonator systems has not been investigated though slow and fast light based on asymmetric parallel coupled structures consisting of silica and silicon nanowires were analyzed [13]. In this paper, we experimentally demonstrate, for the first time to the best of our knowledge, the pulse advancement using a microfiber knot-type ring resonator. A Sagnac loop [14] is used to eliminate the coupling issue of the microfiber device with SMF when combined with a circulator. Meanwhile, group delay is enhanced as the light travels the microfiber ring resonator twice owing to the Sagnac loop reflector.

2. Operational principle

The schematic of the microfiber ring resonator connected to a Sagnac loop is shown in Fig. 1. The incident wave Si coupled from the SMF passes through the microfiber ring resonator, and splits into two parts at the coupling region of the Sagnac loop. The two parts of the light propagate along the loop counter-directionally. With a proper coupling length, the Sagnac loop can reflect most of the light coupled into the loop [14]. The reflected light then passes through the same ring resonator for the second time. Let Sr be the light reflected back to the SMF, and κ_1 and κ_2 be the coupling coefficients of the microfiber ring resonator and the Sagnac loop, respectively, the transmission function of the system is given by [15]:

$$T(\lambda)=\frac{S_r}{S_i}=4\kappa_2(1\text{-}\kappa_2)\mathrm{e}^{-\alpha L_2}\left(\frac{\sqrt{1-\kappa_1}-e^{-(\alpha+j\beta)L_1}}{1-\sqrt{1-\kappa_1}\,e^{-(\alpha+j\beta)L_1}}\right)^2 \quad (1)$$

where α is the attenuation coefficient, $\beta = kn_{eff}$ is the propagation constant, $k = 2\pi/\lambda$ is the vacuum wavenumber, n_{eff} is the effective refractive index of the microfiber, L_1 is the perimeter of the ring resonator, and L_2 is the length of the Sagnac loop.

#127555 - $15.00 USD Received 26 Apr 2010; revised 23 May 2010; accepted 26 May 2010; published 15 Jul 2010

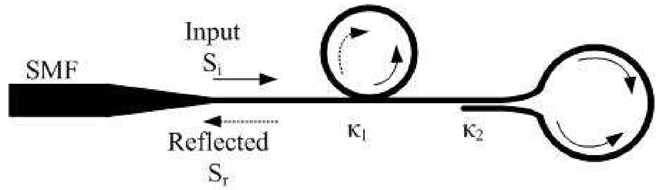

Fig. 1. Schematic of the microfiber knot ring resonator with a Sagnac loop reflector. Incident wave S_i travels twice in the ring by the reflection of the Sagnac loop.

The effective phase shift Φ can be defined as Φ(ω) = arg(T), and the dispersion-induced group delay τ_g can be defined as τ_g = -dΦ(ω)/dω. It implies that pulse delay/advancement can be achieved through the microfiber resonator system if τ_g is positive/negative, respectively. As the light can travel twice of the ring resonator with the help of the Sagnac loop reflector, the dispersion induced group delay is expected to be doubled.

Figure 2(a) shows the group delay at resonant wavelength varies with coupling coefficient of the ring resonator κ_1. It shows that maximal positive/negative group delay can achieve ~2 ns when the value of κ_1 is around the critical coupling condition, where the loss in microfiber ring is equal to the coupling energy. With the increasing of the optical loss α, the value of κ_1 is required to increase to obtain maximal positive/negative group delay. As shown in Fig. 2, κ_1 increases from 0.1 to 0.83 as α changes from 0.1 dB/mm to 1.7 dB/mm. In addition, around the critical coupling condition, the sign of group delay changes from negative to positive once κ_1 crosses the point. To study the group delay around resonances, we plot the group delay as a function of wavelength with α = 1.7 dB/mm. As shown in Fig. 2(b), positive group delays are achieved when $\kappa_1 > 0.83$ (over-coupling condition) and maximal delay decreases as κ_1 becomes larger. When $\kappa_1 < 0.83$ (under-coupling condition), negative group delays take place and the maximal advancement increases with the increasing of κ_1.

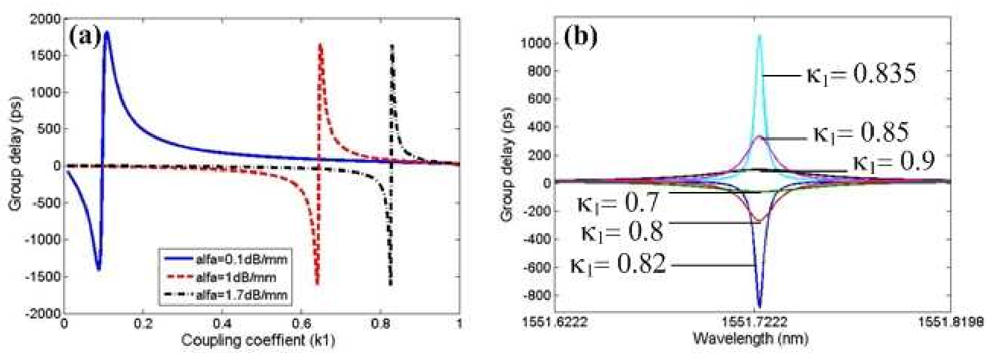

Fig. 2. Group delay at resonant wavelength versus coupling coefficient k_1 with different transmission loss α (a) and group delay with respect to wavelength around resonances with different k_1 (b).

3. Device fabrication and characterization

Figure 3 displays optical microscope images of the fabricated microfiber knot resonator and a zoom-in section of the microfiber. With the conventional flame-heated taper drawing technique [9], we firstly obtain a microfiber with a diameter of a few micrometers from a standard SMF, and tie it into a knot by micromanipulation with the help of microscope and probe [10]. The freestanding end of the microfiber is then bent to form a Sagnac loop by electrostatic and Van der Waals attraction. In Fig. 3(a), the SMF with diameter of 125 µm is placed in parallel with the microfiber device for comparison. The diameters of the knot ring and the microfiber are measured with the microscope system to be ~4.2 µm (Fig. 3(a)) and ~700 µm (Fig. 3(b)), respectively.

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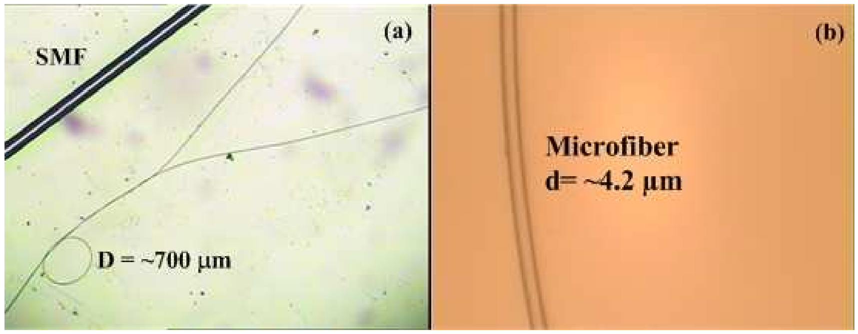

Fig. 3. Microscope image of the fabricated microfiber ring resonator connected to a Sagnac loop (a) using the drawn microfiber with diameter of ~4.2 μm (b).

Since the end of the fabricated device is standard SMF, it can be directly connected to optical fiber systems with its transmission property be measured by an optical spectra analyzer (OSA). After tuning the extinction ratio of the resonance by carefully adjusting the coupling region of the ring resonator, we obtain the spectral transmission curve shown in Fig. 4(a). The insertion loss is ~15 dB, resulting from the coupling loss of the Sagnac loop as well as the bending and propagation loss of the microfiber. Despite the large loss, the inter-twisted overlap at the knot area is long enough for producing effective coupling and offering high robustness to environmental perturbations comparing with the planar lithography circuits, which require precisely control of the coupling region. In addition, fiber-to-waveguide coupling loss is unavoidable for the planar lithographic circuit, while the microfiber circuit is directly drawn from standard single mode fiber without coupling problem and the cost is very low. The free space range (FSR) is ~0.8 nm. Based on Eq. (1), we fit the transmission spectrum of two resonances around 1552 nm, as shown in the dash circle in Fig. 4(b)). The obtained coupling coefficient κ_1 and optical loss α are ~0.56 and ~1.7 dB/mm, respectively. According to the black curve with triangle symbols in Fig. 2, the group delay induced by this microfiber resonator is estimated to be ~-25 ps.

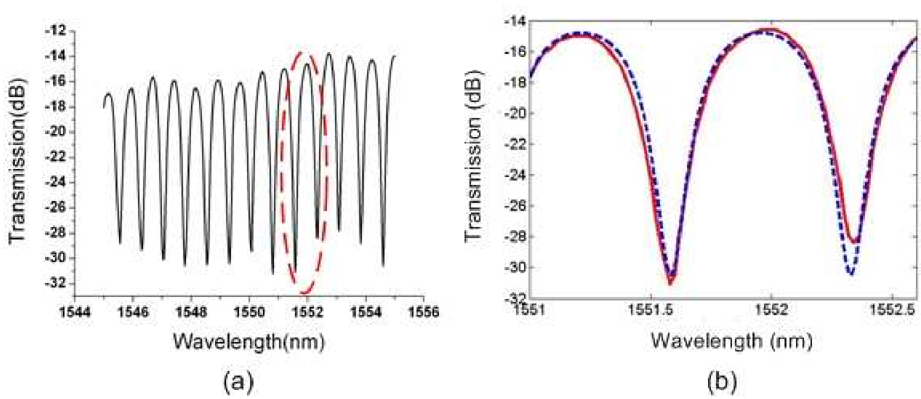

Fig. 4. Transmission spectrum of the microfiber resonator device (a) and zoom-in spectrum of two resonances (b). In (b), the solid curve represents the measured transmission spectrum and the dashed curve is the fitted one based on the transmission function.

4. Experimental results and discussion

To verify the negative group delay obtained from theoretical calculation, we investigate the propagation of 5-Gb/s return-to-zero (RZ) pulses in the microfiber ring resonator with a Sagnac loop reflector. We choose 5 Gb/s as the signal data rate to make sure pulse advancement can be clearly observed without being much affected by the signal distortion

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resulting from the filtering effect and third order dispersion [16,17]. The schematic diagram of the experimental setup is depicted in Fig. 5. Two cascaded Mach-Zehnder modulators (MZMs) are used to generate the RZ signal with a duty circle of 50%, which is taken as the input to port 1 of a circulator after an Erbium-doped fiber amplifier (EDFA) and amplified spontaneous emission (ASE) noise filtering. Before the signal is fed into the microfiber ring resonator from port 2 of the circulator, a polarization controller (PC) is inserted as the Sagnac loop is polarization dependent. The reflected signal from the Sagnac loop passes the ring resonator again and exits at port 3 of the circulator. After being amplified by two EDFAs, the signals are recorded by an oscilloscope and a power meter.

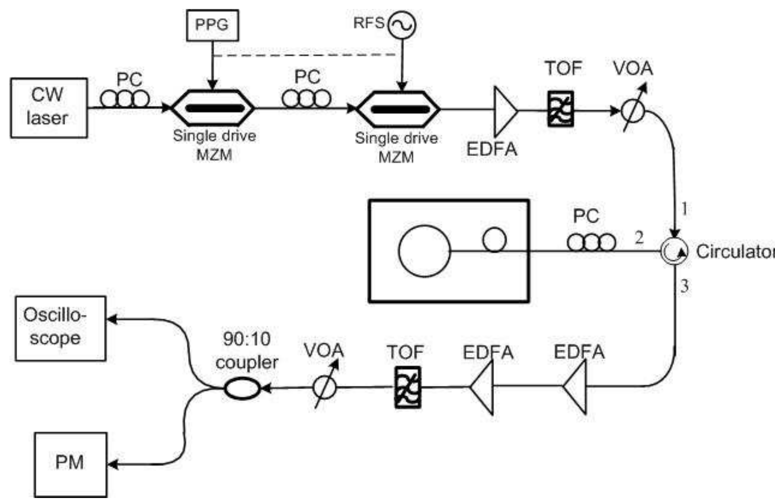

Fig. 5. Experimental setup for fast light using microfiber ring resonator with a Sagnac loop reflector. CW: Continuous wave; PC: Polarization controller; MZM: Mach-Zehnder modulator; PPG: Pulse pattern generator; RFS: Radio frequency synthesizer; EDFA: Erbium-doped fiber amplifier; TOF: Tunable optical filter; VOA: Variable optical attenuator; PM: Power meter.

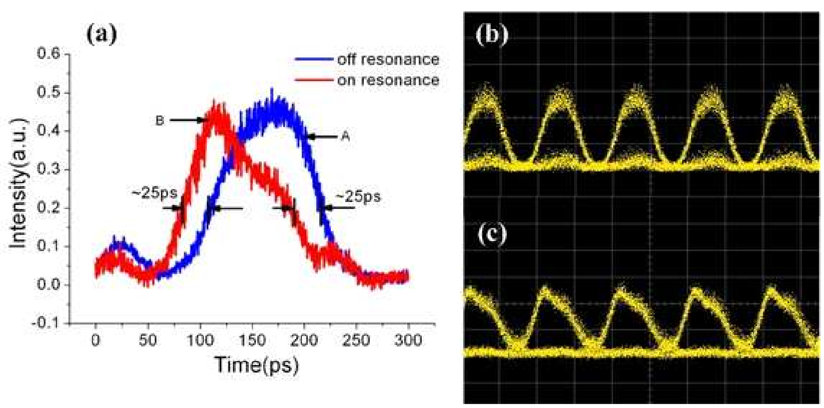

Fig. 6. (a) Normalized traces of the 5-Gb/s RZ signals. Eye diagrams of the signals off (b) and on (c) resonance.

In order to measure the pulse delay and advancement, we tune the signal wavelength around the resonances. Firstly we set the signal wavelength off resonance (1551.26nm) and take the corresponding pulse waveform (curve A), as shown in Fig. 6(a). Then we tune it to the resonance wavelength (1551.66nm) and obtain curve B in Fig. 6(a). Comparing the full width at half maximum (FWHM) of the two waveforms, we observe that the pulse is advanced by ~25 ps. Therefore, the corresponding advancement-bandwidth product of 0.0625, which is calculated by multiplying the signal bandwidth (5GHz) and the pulse advancement

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(25 ps), is comparable with that of 0.065 previously demonstrated in a silicon ring resonator [18]. Figure 6(b) and 6(c) display the eye diagrams of the signals off and on resonance, respectively.

To further explore the influence of signal distortion, we simulate the pulse advancement with different date rates through the microfiber resonator system. It can be seen from Fig. 7(a) that pulse advancement of ~25ps is achieved for 5-Gb/s signal, which is in accordance with the experimental result. When the signal data rate decreases to 2 Gb/s, pulse distortion reduces significantly, as shown in Fig. 7(b). However, one can see from Fig. 7(c) that severe pulse distortion occurs when the data rate increases to 10 Gb/s and the pulse advancement cannot be accurately evaluated. In addition, pulse delay takes place if the coupling coefficient κ_1 increases to 0.92, which is larger than the critical coupling point, as shown in Fig. 7(d).

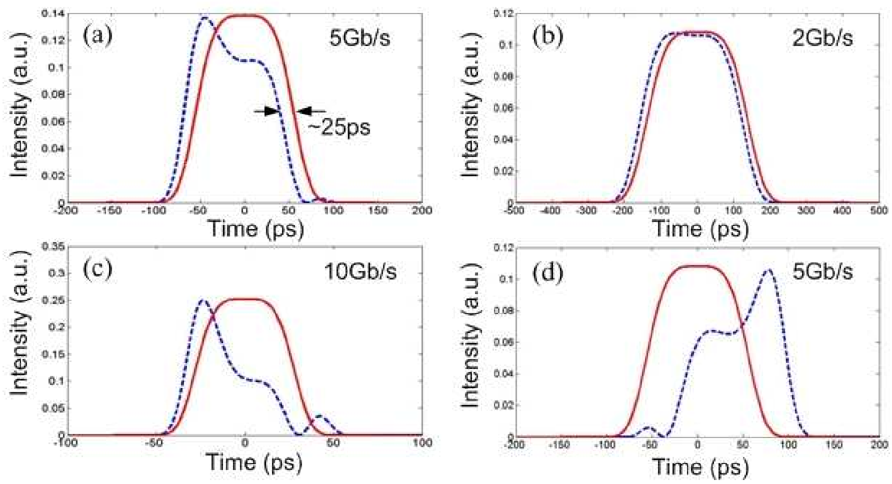

Fig. 7. Simulated pulse advancement in the microfiber device with (a) 5Gb/s, (b) 2Gb/s, and (c) 10Gb/s RZ signals, respectively. Pulse delay of 5-Gb/s RZ signal (d) is also obtained when the microfiber resonator is over-coupled.

5. Conclusion

In this paper, we experimentally demonstrate fast light in microfiber knot-type ring resonator with a Sagnac loop reflector. As the loss in the ring resonator is larger than the coupling energy, fast light can be realized in the under-coupled microfiber ring resonator. With the help of the Sagnac loop, light can travel twice in the same microfiber ring resonator, leading to double group delay. In the experiment, an advancement of ~25 ps is obtained with 5-Gb/s RZ signal pulses. Pulse delay is also achievable if the microfiber ring resonator operates at the over-coupling condition by increasing the coupling efficient of the ring resonator.

Acknowledgement:

This work was supported by the NSFC (60777040), and 863 High-tech program (2009AA01Z257).