Continuously Tunable Slow and Fast Light by Using an Optically Pumped Tilted Fiber Bragg Grating Written in an Erbium/Ytterbium Co-Doped Fiber

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***Abstract*— Continuously tunable slow and fast light is achieved by using a tilted fiber Bragg grating (TFBG) written in an erbium/ytterbium co-doped fiber. By pumping the TFBG, the magnitude and group delay responses of the cladding mode resonances are changed, which can be used to achieve a tunable time delay or time advance. The proposed method is demonstrated by an experiment in which a tunable time delay from –38 to 18 ps corresponding to a fast to a slow light is achieved for a 13.5-GHz Gaussian pulse.**

***Index Terms*— Fast light, microwave photonics, slow light, tilted fiber Bragg grating, tunable time delay.**

I. Introduction

In the recent years, controlling the speed of light has become an interesting topic which can find numerous applications such as in optical communications, optical signal processing and microwave photonics [1]. Various techniques have been proposed to generate slow light (time delay) and fast light (time advance) such as electromagnetically induced transparency (EIT) [2], coherent population oscillation (CPO) [3]–[5], and stimulated Brillouin scattering (SBS) [6], [7]. Among these methods, slow and fast light generation based on the SBS has attracted much attention since a large and continuously tunable time delay can be generated by using a low-power pump. However, the small intrinsic bandwidth of the SBS limits its applications. Although some methods have been proposed to improve the bandwidth [8], [9], the systems become complicated.

Fiber Bragg gratings (FBGs) have been used to produce tunable slow and fast light [10], [11]. In [10], a tunable time delay is achieved in an apodized FBG by introducing a high power signal (~2 kw). Since the power of the signal is very large, the practical applications of this method are limited. In [11], by optically pumping a uniform FBG, the time delay close to the band edge varies rapidly which is used to introduce a time delay of 0.9 ns to a signal with a bandwidth of 200 MHz. The main limitation of this method is again the small bandwidth, which is not suitable for applications where a large bandwidth is required. Tunable time delays based on mechanical or thermal tuning have also been achieved by using a linearly chirped fiber Bragg grating (LCFBG) [12]-[14]. In these methods, the tunable range can be large, but the tuning speed is low and the system has poor stability, especially for mechanical tuning. Recently, we proposed a method to tune a LCFBG by optical pumping. The LCFBG was written in an erbium/ytterbium (Er/Yb) co-doped fiber [15], by optically pumping the LCFBG, the group delay response is changed which leads to the change of the time delay. A continuously tunable time delay of 200 ps for a 7.8-GHz Gaussian pulse was experimentally achieved. This method can be used to achieve a tunable time delay, but not a time advance. A slow and fast light can be generated using a tilted fiber Bragg grating (TFBG), in which the group delay response was tuned by controlling the refractive index of the medium surrounding the TFBG or via thermal tuning [16]. Again, the tuning speed is low and the tuning resolution is poor.

In this letter, we propose a novel and simple method to achieve a continuously tunable slow and fast light by optically pumping a TFBG written in an Er/Yb co-doped fiber. By changing the pump power, the magnitude and group delay responses of the TFBG are continuously changed which can be used for the continuously tuning of the slow and fast light. The key significance of this technique is that a continuous control of the speed of light from slow to fast light or from fast to slow light can be realized all optically, which can find applications for advanced signal processing. In addition, the tuning mechanism is simpler and more accurate in comparison with the previously reported methods.

The operation of the proposed method is described and is verified by an experiment. A TFBG is fabricated. The use of the TFBG to achieve a continuously tunable slow and fast light is experimentally demonstrated. Continuous tuning of a 13.5-GHz Gaussian pulse with a tunable time delay from -38 ps to 18 ps is achieved. The experimental results are also compared with the results based on a simulation. A good agreement is achieved.

II. Principle

In a regular FBG, the variation of the refractive index is along the length of the fiber. In a TFBG, however, the variation of the refractive index has an angle to the optical axis.

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The tilt angle has an effect on the spectral response. The transmission spectrum of a TFBG consists of two different resonances resulted from two different couplings. The first one is the coupling between the forward and backward core modes and the other is the coupling between the contra-propagating core mode and the cladding modes. The resonance wavelength corresponding to the self-coupling of the core mode and the resonance wavelengths corresponding to contra-propagating cladding modes are given by

$$\lambda_{Bragg} = \frac{2n_{eff,\ core}\Lambda_g}{\cos\theta}, \quad (1)$$

$$\lambda_{coupling} = \left(n_{eff,\ cladding} + n_{eff,\ core}\right)\frac{\Lambda_g}{\cos\theta} \quad (2)$$

respectively, where θ is the tilt angle of the TFBG, Λ_g is the nominal grating period, $n_{eff,\ core}$ and $n_{eff,\ cladding}$ are the effective refractive indices of the core mode and a particular cladding mode, respectively. The group velocity of a light pulse can be defined as

$$v_g = c/n_g, \quad (3)$$

where c is the speed of light in vacuum, and n_g is the group index given by

$$n_g = n + \omega\frac{dn}{d\omega}, \quad (4)$$

where n is the frequency-dependent refractive index, and $dn/d\omega$ is the first derivative of n with respect to the frequency ω. Since $dn/d\omega$ can be either positive or negative, the group index can be either larger or smaller than the refractive index n and a time delay (slow light) or time advance (fast light) can be achieved. Thus, by tuning $dn/d\omega$, the slow and fast light can be tuned.

The tuning can be achieved by optically pumping the TFBG. Thanks to the high absorption of an Er/Yb co-doped fiber, the refractive index of the fiber is changed [17]. In [15], we have shown that by pumping an FBG written in an Er/Yb co-doped fiber, the refractive index along the FBG changes correspondingly to the pumping profile,

$$\Delta n(z) \propto \frac{dp(z)}{dz}, \quad (5)$$

where z is the position along the fiber, $\Delta n(z)$ is the index change along the fiber and $p(z)$ is the pumping power distribution along the fiber. Thus, by pumping the grating with a 980-nm laser diode (LD) with a tunable pump power, the refractive index along the grating is changed which leads to the shift of the resonance wavelengths and the change of the coupling coefficients [18]. Consequently, the frequency dependency of the refractive index $dn/d\omega$ is changed, which results in the tuning of the slow and fast light.

Fig. 1(a) shows the magnitude and group delay responses of one of the cladding-mode resonances of a TFBG at 1540.32 nm, which is measured using an optical vector analyzer (LUNA TECHNOLOGIES, Optical vector analyzer CT_e). By pumping the TFBG with a 980-nm LD, the resonance wavelength is shifted to a longer wavelength and the group delay response is also shifted correspondingly. As can be seen from Fig. 1(b), at 1540.36 nm a tunable time from a time advance of about -38 ps to a time delay of about 18 ps is achieved when the pumping power to the TFBG is tuned from 0 mW to 150 mW. The full-width at half-maximum (FWHM) bandwidth of the resonance shown in Fig. 1(a) is about 22 GHz. Thus, the time-bandwidth product is 1.23.

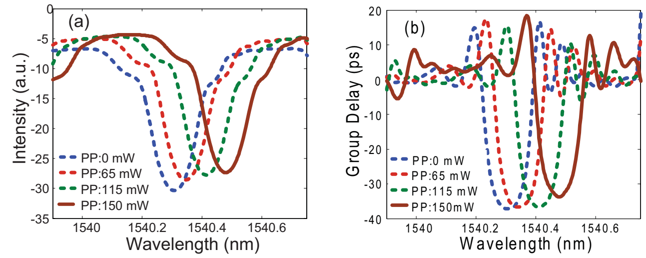

Fig. 1. (a) Magnitude response and (b) group delay response of one channel of a TFBG with a tilt angle of 10°. PP: pumping power.

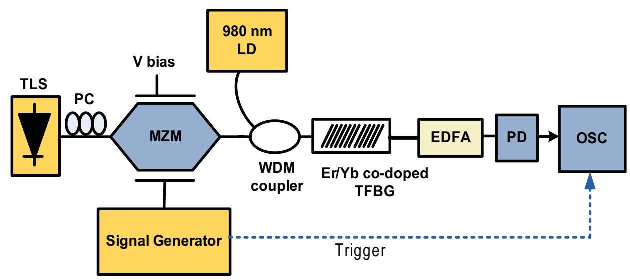

Fig. 2. Experimental setup. TLS: tunable laser source. LD: laser diode. MZM: Mach–Zehnder modulator. PC: polarization controller. WDM: 980/1550-nm wavelength-division multiplexer. PD: photodetector. OSC: oscilloscope. EDFA: erbium-doped fiber amplifier.

III. Experiment

The proposed technique for achieving tunable time delay and time advance is experimentally studied. The experimental setup is shown in Fig. 2. A light wave from a tunable laser source (TLS) is sent to a 20-GHz Mach-Zehnder modulator (MZM). A Gaussian pulse with a FWHM bandwidth of 13.5 GHz generated by a signal generator [Agilent N4901B Serial Bit Error Rate Tester (BERT)] is applied to the MZM via the RF port to modulate the light wave. The modulated light wave is sent to a TFBG with a tilt angle of 10° through a wavelength division multiplexing (WDM) coupler. The TFBG is fabricated by using an excimer laser with a uniform phase mask. The tilt angle is introduced by a focal lens. The fiber used to fabricate the TFBG is a photosensitive Er/Yb co-doped fiber (EY 305, Coractive) which is hydrogen loaded for two weeks to further increase the photosensitivity. The TFBG is pumped by a 980-nm LD; by increasing the injection current to the pump LD, the pump power is increased. A time-delayed or advanced light signal transmitted through the TFBG is sent to an erbium-doped fiber amplifier (EDFA) to compensate for the loss caused by the resonance notch and is detected by a 53-GHz photodetector, and the electrical waveform is observed by a sampling oscilloscope (Agilent 86100C). In order to have a reference to measure the time delay or advance of the detected signal, the wavelength of the TLS is first tuned to

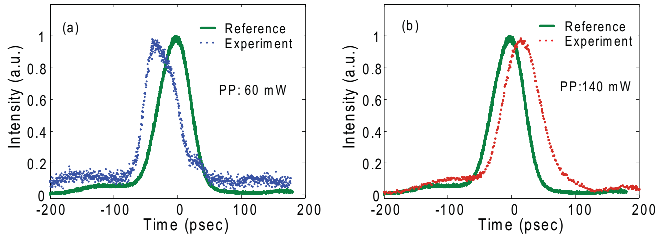

Fig. 3. Detected signals at different pump power levels. (a) 60 mW. (b) 140 mW. PP: pumping power.

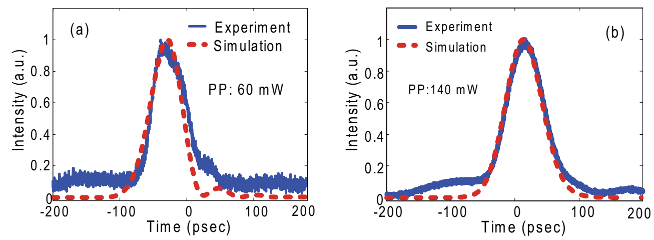

Fig. 4. Simulated (dashed) and experimentally generated (solid) signals with a pumping power of (a) 60 mW and (b) 140 mW. PP: pumping power.

be out of the resonance spectrum, thus the light signal would not experience a time delay or advance caused by the mode resonance. Then, the wavelength of the light wave is tuned to 1540.36 nm to be inside one of the cladding mode resonances (as shown in Fig. 1, one cladding mode resonance is located at the wavelength of 1540.32 nm). As can be seen in Fig. 3, by pumping the TFBG with a power of 60 mW, a time advance of -38 ps is achieved, and when the pumping power is tuned to 140 mW, a time delay of 18 ps is achieved. By continuously tuning the pump power tuned from 60 mW to 140 mW, a continuous tuning from a fast to slow light with a tunable range of 56 ps is achieved. Since the bandwidth of the input pulse is 13.5 GHz, the tunable time-bandwidth product in this experiment is 0.75.

To evaluate the performance of the proposed technique, a simulation is performed, in which the time delay and advance for the TFBG with a pumping power at 60 mW and 140 mW are calculated. The simulated (dashed) results are shown in Fig. 4. The experimental results are also shown for comparison. As can be seen, a good agreement is reached between the simulated and experimentally generated waveforms. A slight mismatch between the simulated and the experimentally generated waveforms is observed, which is caused by the non-ideal Gaussian pulse generated by the BERT.

IV. Conclusion

A novel and simple method to achieve continuously tunable slow and fast light was proposed and experimentally demonstrated. This method is based on the optically pumping of a TFBG written in an Er/Yb co-doped fiber. The magnitude and group delay responses of the mode resonances of the TFBG were tuned by tuning the pumping power to the TFBG, which led to the tuning of the group delay response of the TFBG, thus the time delay or advance. A continuous tuning from a fast light (-38 ps) to a slow light (18 ps) was demonstrated experimentally for a 13.5-GHz Gaussian pulse by pumping the TFBG with a pumping power tuned from 60 mW to 140 mW. The proposed technique can find applications in tunable photonic microwave filtering, photonically assisted arbitrary waveform generation, and true time delay beamforming.

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