Tunable microwave photonic phase shifter based on slow and fast light effects in a tilted fiber Bragg grating

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Abstract: A continuously tunable microwave phase shifter based on slow and fast light effects in a tilted fiber Bragg grating (TFBG) written in an erbium/ytterbium (Er/Yb) co-doped fiber is proposed and experimentally demonstrated. By optically pumping the TFBG, the magnitude and phase responses of the cladding mode resonances are changed, which is used to introduce a tunable phase shift to the optical carrier of a single-sideband modulated signal. The beating between the phase-shifted optical carrier and the sideband will generate a microwave signal with the phase shift from the optical carrier directly translated to the generated microwave signal. A tunable phase shifter with a tunable phase shift of 280° at a microwave frequency tunable from 24 to 36 GHz is experimentally demonstrated.

OCIS codes: (350.4010) Microwaves; (060.5625) Radio frequency photonics; (050.5080) Phase shift.

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1. Introduction

Controlling the speed of light has been a topic of interest in the past several years, and can find numerous applications such as microwave filtering, true-time delay beam forming and arbitrary waveform generation [1]. In particular, a microwave phase shifter implemented based on photonics can generate a tunable phase shift at a high frequency with large tunable range, which is particularly useful for applications such as phased-array antennas [1–3], and microwave filters [1,4]. So far, several photonic schemes have been reported for the purpose of implementing microwave phase shifters [4–9]. For instance, a phase shift of 114° at 3 GHz was obtained by using a distributed-feedback (DFB) laser through optical wavelength conversion [5]. In [6], a phase shifter with 18-GHz bandwidth and 360° tuning range was demonstrated based on stimulated Brillouin scattering (SBS) in an optical fiber in which the phase tuning was achieved by changing the optical carrier wavelength. Also, phase shifts can also be achieved based on slow- and fast-light effects induced by coherent population oscillations (CPOs) in semiconductor optical amplifiers (SOAs) [7–10]. A 200° phase shifter at a microwave frequency of 1 GHz was realized in a 2.5-mm quantum-well SOA [7]. By cascading two SOAs with two electroabsorber sections, a phase shift of 110° at 4 GHz was achieved [8]. In [9], a continuously tunable phase shift of 240° at 19 GHz was demonstrated by cascading three SOAs. However, the use of multiple SOAs makes the structure more complicated especially when a larger range of phase shift with a wider bandwidth is needed. Recently, Capmany and his group have demonstrated a 360° phase shift at 20 GHz by using a single SOA [10]. The phase shift was achieved by tuning the carrier wavelength and the optical input power injected to the SOA. Although a full phase shift of 360° was achieved in [10], the phase shift tuning was realized by changing the carrier wavelength, and as a result the phase shift is not constant for different microwave frequencies or at least by changing the microwave frequency the injection current to the SOA should be changed accordingly to achieve a constant phase shift.

In this paper, we propose and demonstrate a novel and simple microwave phase shifter based on slow- and fast-light effects in a tilted fiber Bragg grating (TFBG) written in an Erbium-Ytterbium (Er/Yb) co-doped fiber. In the proposed system, the microwave signal to be phase shifted is modulated on an optical carrier at an optical single-sideband (OSSB) modulator. A phase shift is introduced to the optical carrier of the OSSB-modulated signal by placing the optical carrier within the bandwidth of one of TFBG cladding-mode resonances. This phase shift is tunable by optically pumping the TFBG by a 980-nm laser diode (LD). The beating between the phase-shifted optical carrier and the sideband will generate a microwave signal with the phase shift from the optical carrier directly translated to the generated microwave signal. A continually tunable phase shift of 280° at a microwave frequency from 24 to 36 GHz is experimentally demonstrated.

2. 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. 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 the contra-propagating cladding modes are given by

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

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

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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. Although it is possible to obtain multi-cladding resonances by cascading a strong FBG and long period gratings (LPGs) [11], using a single TFBG can be simpler and more effective. Based on Kramers-Kronig relations, a change in the amplitude results in a change in the phase (φ), and consequently a change in the group delay ($\frac{d\varphi}{d\omega}$). Thus, within the bandwidth of each cladding-mode resonance, a tunable phase shift and consequently a tunable time delay can be achieved by slightly tuning the wavelength. To achieve a tunable phase shift, the TFBG is written in an Er/Yb co-doped fiber and is optically pumped. Thanks to the high absorption of an Er/Yb co-doped fiber, the refractive index of the fiber is changed [12], [13],

$$\Delta n(z) \propto \frac{dp(z)}{dz}, \qquad (3)$$

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 TFBG with a 980-nm LD having a tunable pumping power, the refractive index along the TFBG is changed which leads to the shift of the resonance wavelengths and thus the change of the phase shifts at each cladding-mode resonance.

Figure 1 shows the transmission spectrum of a TFBG with a tilt angle of 6° and a Bragg wavelength of 1560 nm. A theoretical study of the coupling between the core mode and the

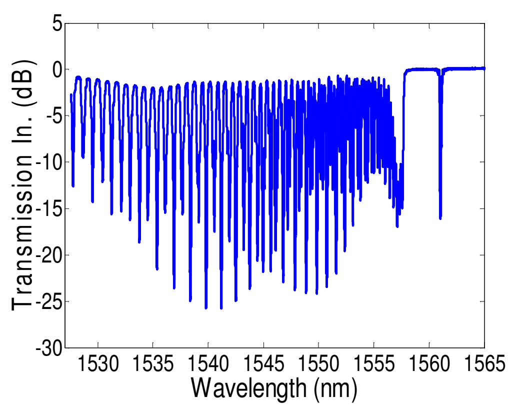

Fig. 1. (a) The transmission spectrum of a TFBG with a tilt angle of 6°, and a Bragg wavelength of 1560 nm.

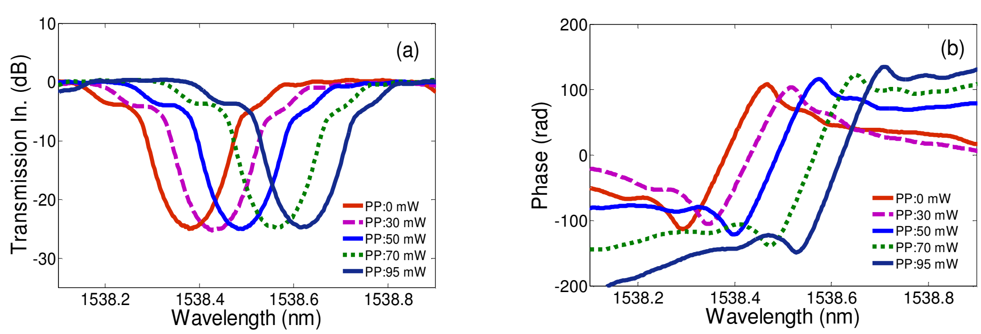

Fig. 2. (a) The magnitude response, and (b) the phase response of one cladding-mode resonance channel of the TFBG. PP: pumping power.

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cladding modes can be found in [14]. Figures 2(a) and 2(b) show the magnitude and phase responses of one of the cladding-mode resonances of a TFBG at 1538.38 nm, which is measured using an optical vector analyzer (LUNA Optical vector analyzer CT_e). As can be seen, by pumping the TFBG, the resonance wavelength is shifted to a longer wavelength and the phase response is also shifted accordingly. This tunable phase shift can be used to introduce a tunable phase shift to the optical carrier of an OSSB-modulated signal to obtain a phase-shifted microwave signal.

Figure 3 shows the schematic block diagram of the proposed phase shifter. First, a microwave signal to be phase shifted is modulated on an optical carrier at an OSSB modulator, the OSSB-modulated signal is then sent to a TFBG with the optical carrier located at one cladding-mode resonance of the spectral response to introduce a phase shift to the optical carrier. The phase-shifted optical carrier and the single sideband are applied to a photodetector (PD). The beating between the phase-shifted optical carrier and the sideband will generate a microwave signal with the phase shift from the optical carrier directly transferred to the generated microwave signal.

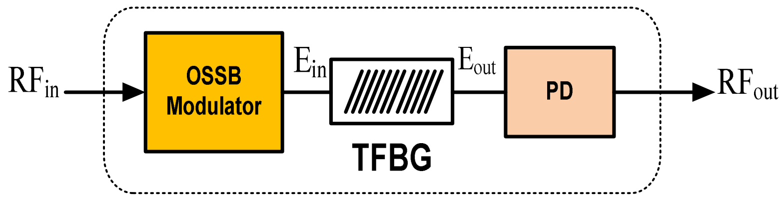

Fig. 3. Schematic block diagram of the proposed phase shifter. OSSB: optical signal-sideband, PD: photodetector.

Mathematically, under small-signal modulation condition, the optical field at the output of the OSSB modulator, when it is driven by a microwave tone $\exp(2\pi f_{RF} t)$, is given by

$$E_{in}(t) = A_0 \exp(j\,2\pi v_0 t) + A_1 \exp\left[j\,2\pi(v_0 + f_{RF})t\right], \tag{4}$$

where A_0 and v_0 are the amplitude and frequency of the optical carrier, and A_1 and $v_0 + f_{RF}$ are the amplitude and frequency of the first-order sideband, respectively. If the optical carrier is tuned to be located at one of the cladding-mode resonance of the TFBG, the optical carrier is modified by $A\exp(j\varphi)$, where A is the amplitude modification factor and φ is the optical phase shift introduced by the TFBG; thus the optical filed at the output of the TFBG is given by

$$E_{out}(t) = A_0 A \exp(j\varphi)\exp(j2\pi v_0 t) + A_1 \exp\left[j2\pi(v_0 + f_{RF})t\right]. \tag{5}$$

Note that the sideband is tuned away of the cladding-mode resonance; thus the amplitude and phase of the sideband are not affected.

By detecting the optical signal at the PD, a phase-shifted microwave signal is obtained, which is given by

$$I(t) = R\left|E_{out}\right|^2 = RAA_0\cos(2\pi f_{RF} t + \varphi) \tag{6}$$

where R is the responsivity of the PD. As can be seen from Eq. (6), the phase shift to the optical carrier is directly translated to the microwave signal. The amount of φ is optically tunable by pumping the TFBG which causes a continuous shift of the resonance spectrum and consequently the phase shift, as can be seen from Figs. 2(a) and 2(b). Based on this scheme, the microwave phase shift is independent of the microwave frequency f_{RF}, and thus the bandwidth of the phase shifter can be very broad, which is just limited by the resonance spacing in the TFBG spectrum, and the bandwidths of the MZM and the PD.

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3. Experiment

The proposed optically tunable phase shifter is experimentally studied. The experimental setup is shown in Fig. 4. A light wave from a tunable laser source (TLS) is sent to a 40-GHz Mach-Zehnder modulator (MZM). The wavelength of the light wave is selected to be in the bandwidth of one of the TFBG cladding-mode resonances. A microwave tone generated by a signal generator (Agilent E8254A) is applied to the MZM via the RF port to modulate the light wave. The MZM is biased at the quadrature point. Then, an optical double-sideband (ODSB) with carrier signal is obtained at the output of the MZM. To suppress one of the two sidebands, a wave shaper (Finisar WaveShaper 4000S), serving an optical notch filter to suppress one sideband, is connected to the output of the MZM, and an OSSB modulated signal is thus obtained. The OSSB-modulated optical signal is sent to a TFBG 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 LCFBG 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. The optical signal at the output of 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 PD, with the electrical waveform observed by a sampling oscilloscope (Agilent 86100C). Assuming that the bandwidths of the MZM and the PD are sufficiently large, the bandwidth of the phase shifter is limited by the resonance bandwidth and resonance spacing of the TFBG. For the experiment, a TFBG with a tilt angle of 6° and a Bragg wavelength of 1560 nm is used. The wavelength of the optical carrier is selected to be in the bandwidth of the resonance shown in Fig. 2. The bandwidth of this resonance is 24 GHz and the resonance spacing is 60 GHz. As can be seen in Fig. 2(b), the phase shift is from about −140° to 140° by tuning the pumping power from 30 to 95 mW. This TFBG resonance with these properties has the potential to be a phase shifter with a continuously tunable range of 280° and a bandwidth of 24-60 GHz. The experiment is done for the frequencies from 24 to 36 GHz because of the limited bandwidths of the MZM and the PD.

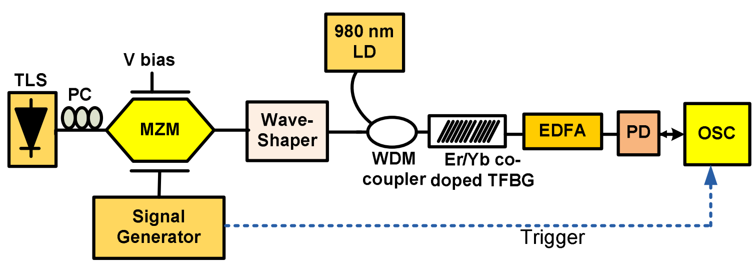

Fig. 4. Experimental setup. TLS: tunable laser source, PC: polarization controller, MZM: Mach–Zehnder modulator, LD: laser diode, WDM: 980/1550 nm wavelength division multiplexer, EDFA: erbium-doped fiber amplifier, PD: photo-detector, OSC: oscilloscope.

Figures 5(a) and 5(b) show the phase-shifted microwave signals at 28 and 34 GHz. The phase-shifted microwave signal obtained at a pumping power of 60 mW is chosen as a reference, and by tuning the pump power from 30 to 95 mW, a tunable phase shift from + 140° to −140° is achieved. As expected, the phase shift is independent of the microwave frequency. Figure 6 shows the phase shift of the recovered microwave signal at different frequencies. As can be seen a tunable phase shift from −140° to 140° is achieved by tuning the pumping power from 30 to 95 mW for a microwave frequency tunable from 24 to 36 GHz. The pumping powers corresponding to the different phase shifts in Fig. 6 are 30, 40, 50, 60, 70, 80, and 95 mW from top to bottom.

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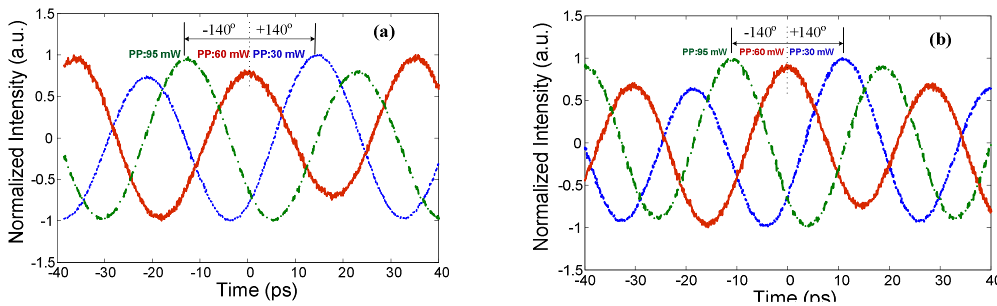

Fig. 5. The detected signals at pump power levels of 30, 60 and 95 mW for the RF frequency of 28 GHz, and (b) 34 GHz. PP: pumping power.

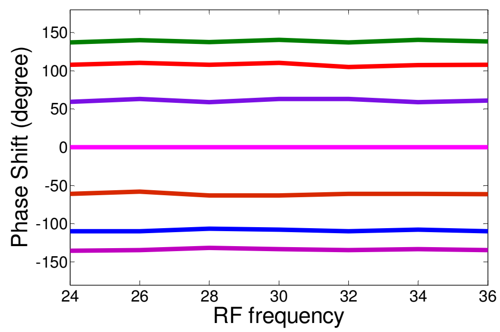

Fig. 6. Measured phase shifts at different pumping power levels. The phase shifts are independent of the microwave frequency.

4. Conclusion

A novel and simple approach to implementing a photonic phase shifter based on a TFBG written in an Er/Yb co-doped fiber with continuously tunable phase shift was proposed and demonstrated. This method is based on the optically pumping of a TFBG written in an Er/Yb co-doped fiber. The magnitude and phase responses of the cladding-mode resonances of the TFBG were tuned by tuning the pumping power to the TFBG, which led to the tuning of the phase shift introduced to the optical carrier of an OSSB-modulated signal located at the resonance bandwidth. A 280° continuously tunable phase shifter at a microwave frequency tunable from 24 to 32 GHz was demonstrated experimentally. The proposed phase shifter has the potential to have a wider phase shift up to 360° if a TFBG with a wider resonance bandwidth and resonance spacing is employed.

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