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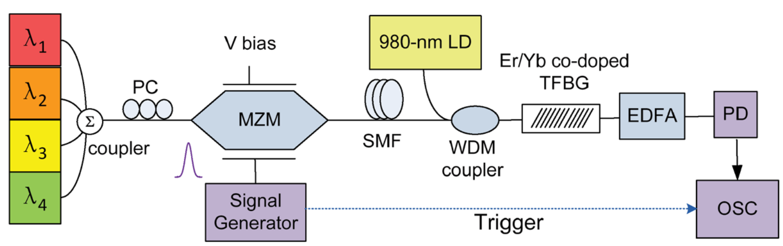

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Continuously Tunable Chirped Microwave Waveform Generation Using a Tilted Fiber Bragg Grating Written in an Erbium/Ytterbium Codoped Fiber

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Abstract: An optical approach to generating continuously tunable chirped microwave waveforms using a tilted fiber Bragg grating (TFBG) written in an erbium/ytterbium (Er/Yb) codoped fiber is proposed. By pumping the TFBG, the magnitude and group delay responses of the cladding mode resonances are changed, which can be used to implement a photonic microwave delay-line filter with increasing or decreasing tap spacing. If an ultranarrow pulse is sent to the photonic microwave delay-line filter, a pulse burst with increasing or decreasing pulse spacing is generated. The photodetection of the pulse burst would lead to the generation of a chirped microwave waveform. The proposed technique is demonstrated by an experiment in which a chirped microwave waveform with a tunable chirp rate from 1.8 to 7 GHz/ns is generated.

Index Terms: Chirped waveform generation, microwave photonics, tilted fiber Bragg grating, tunable time delay.

1. Introduction

Photonic generation of microwave waveforms with a large time-bandwidth product (TBWP) has been a topic of interest recently [1]. Large TBWP waveforms can find numerous applications such as in radar systems where the range resolution can be significantly improved. Large TBWP microwave waveforms can also find applications in wireless communications, medical imaging, and instrumentation. To achieve a large TBWP, the waveforms are usually frequency chirped or phase coded. Chirped microwave waveforms are usually generated in the electrical domain using digital or analog electronics, but with relatively low frequency and small bandwidth. For example, a state-of-the-art electronic arbitrary waveform generator can generate microwave waveforms at a sampling rate of 12 Gs/s and a bandwidth of 5.6 GHz [2], but for many applications microwave waveforms with a bandwidth up to tens of GHz is needed. Thanks to the broad bandwidth and high speed of modern photonics, the generation of chirped microwave waveforms with a large TBWP in the optical domain has been a promising solution. Among the numerous methods [1], [3], [4], those based on pure fiber optics are more interesting since they offer advantages such as smaller size, lower loss, better stability and higher potential for integration [5]–[9]. A chirped microwave waveform can be generated based on spectrum shaping and wavelength-to-time mapping [7]–[9]. In [7], [8], an ultrashort pulse from a femtosecond pulsed laser source is shaped by a two-tap Sagnac loop filter

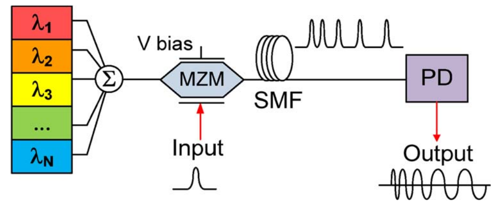

Fig. 1. Chirped microwave waveform generation using a nonuniformly spaced photonic microwave delay-line filter.

that has a sinusoidal frequency response. The spectrum-shaped optical pulse is then sent to a dispersive fiber with higher order dispersion [7] or a nonlinearly chirped fiber Bragg grating (NLCFBG) [8] to perform nonlinear frequency-to-time mapping. The chirp rate can be tuned by changing the nonlinearity of the fiber or the NLCFBG. In [9], a tilted fiber Bragg grating (TFBG) is used as a spectral shaper to generate a chirped microwave waveform. The transmission spectrum of a TFBG has multiple peaks with nonuniformly spaced peak spacing. The limitation of the techniques in [7] and [8] is that the tuning of the chirp rate is difficult, especially in [7], where the nonlinearity of the fiber is tuned by changing the fiber length. The chirp rate may be tuned by tuning the TFBG [9], but the tunability is again very limited. A chirped microwave waveform can also be generated by passing an ultranarrow microwave pulse through a microwave delay-line filter with a quadratic phase response or equivalently a linear group delay response, which can be implemented using a nonuniformly spaced photonic microwave delay-line filter [10]. The limitation of this technique in [10] is that the tuning of the chirped profile is done by tuning the wavelengths of the laser sources, which makes the system complicated and costly.

In this paper, we propose a new technique to generate continuously tunable chirped microwave waveforms using laser sources with fixed wavelengths. The entire system is a photonic microwave delay-line filter with nonuniformly spaced taps. When an ultrashort pulse is applied to the input of the photonic microwave delay-line filter, a pulse burst with nonuniform temporal spacing is generated. The nonuniform time delays are achieved using a TFBG, which is written in an erbium/ytterbium (Er/Yb) codoped fiber. Due to the strong absorption, the refractive index of the Er/Yb codoped fiber is changed when the TFBG is optically pumped. In the proposed system, the wavelengths of the laser sources are located at the different cladding-mode resonance peaks of the TFBG, and the tuning of the time delays is realized by optically pumping the TFBG. Thus, simple but fast tuning is ensured. An experiment is performed. A chirped microwave pulse with a tunable chirp rate from 1.8 to 7 GHz/ns is experimentally demonstrated.

2. Principle

A chirped microwave waveform can be generated using a photonic microwave delay-line filter with nonuniformly spaced taps [10]. When an ultrashort pulse is applied to the input of the photonic microwave delay-line filter, at the output a pulse burst with the temporal spacing depending on the time delays is obtained [10]. By applying the pulse burst to a photodetector (PD), due to the limited bandwidth of the PD a chirped microwave waveform is generated [11]. The operation of a photonic microwave delay-line filter for chirped microwave waveform generation is shown in Fig. 1. The nonuniform time delays can be generated by incorporating a TFBG into the photonic microwave delay-line filter. A TFBG is different from a regular FBG, in which the variation of the refractive index has a tilted angle with the optical fiber, with two different resonances resulted from two different couplings. One is the coupling between the forward and backward core modes and the other is the coupling between the contrapropagating core mode and the cladding modes. As a result, there are multiple resonances at the transmission spectrum of a TFBG. The resonance wavelength corresponding to the self-coupling of the core mode is given by

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

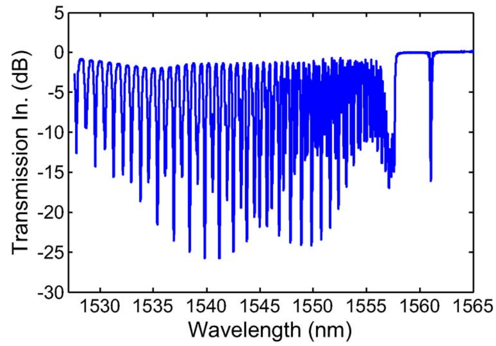

Fig. 2. Transmission spectrum of a TFBG with a tilt angle of 6°, and a Bragg wavelength of 1560 nm.

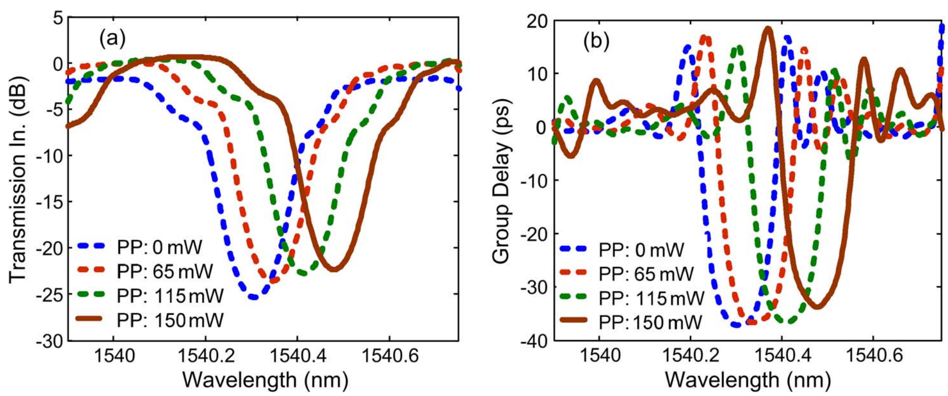

Fig. 3. (a) The magnitude response and (b) the group delay response of one channel of the TFBG shown in Fig. 1. PP: pumping power.

and the resonance wavelengths corresponding to contrapropagating cladding modes are given by

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

where θ is the tilt angle of the TFBG, Λ_g is the nominal grating period, $n_{\text{eff,core}}$ and $n_{\text{eff,cladding}}$ are the effective refractive indices of the core mode and a particular cladding mode, respectively. By locating the wavelengths at the cladding-mode resonance peaks, nonuniform time delays are achieved, which lead to the generation of a chirped microwave waveform. Fig. 2 shows the transmission spectrum of a TFBG with a tilt angle of 6°, and a Bragg wavelength of 1560 nm.

Based on Kramers–Kronig relations, a change in the amplitude results in a change in the phase ($d\varphi/d\omega$), and consequently a change in the group-delay. Thus, within the bandwidth of each resonance, a tunable time delay can be achieved for slightly tuning the wavelength. Since the coupling coefficient is different for different resonances in a TFBG, the range and rate of time tunability are different at different resonances. To achieve tunable time delays, the TFBG is written in an Er/Yb codoped fiber and is optically pumped. Thanks to the high absorption of an Er/Yb codoped fiber, the refractive index of the fiber is changed [12], [13]

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

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 laser diode (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 time delays.

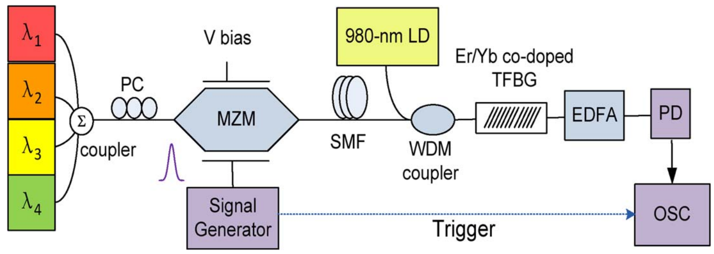

Fig. 4. Experimental setup. LD: laser diode, MZM: Mach–Zehnder modulator, PC: polarization controller, WDM: 980/1550 nm wavelength division multiplexer, PD: photodetector, OSC: oscilloscope.

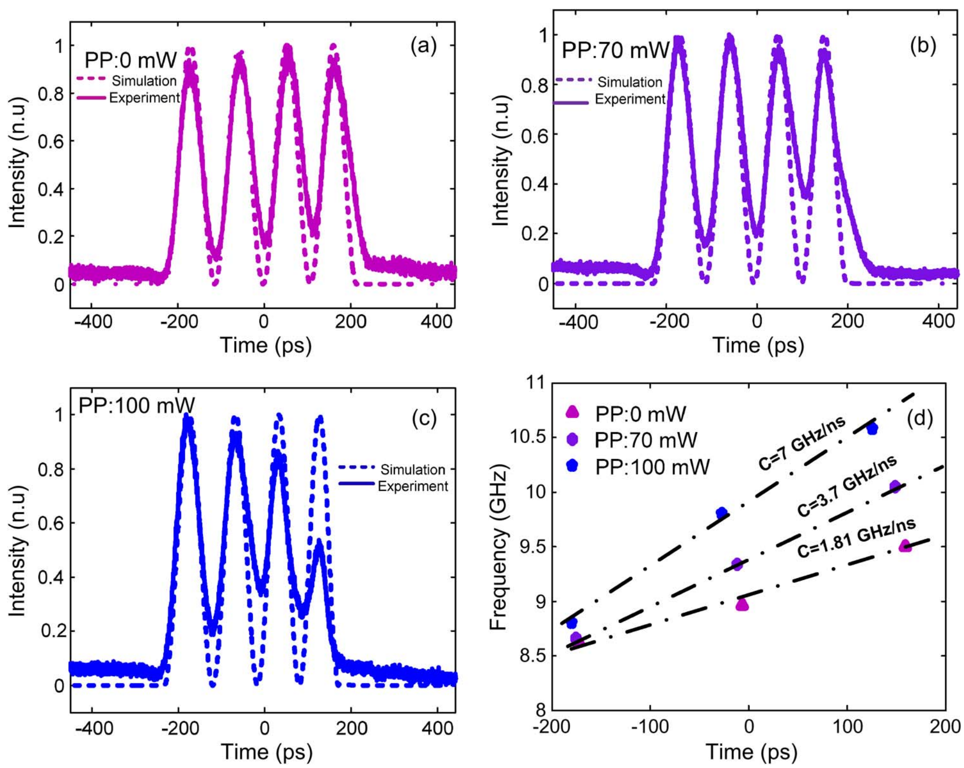

Fig. 5. Experimentally generated (solid) and simulated (dashed) chirped microwave waveforms with a pumping power of (a) 0 mW, (b) 70 mW, and (c) 100 mW. (d) The frequency versus time for the generated chirped microwave waveforms at different pumping power levels. PP: pumping power.

Fig. 3 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 Optical vector analyzer CT_e). By pumping the TFBG, the resonance wavelength is shifted to a longer wavelength and the group delay response is also shifted accordingly. As can be seen in Fig. 2, the coupling coefficients of the resonances within the wavelength range from 1530 to 1540 nm are linearly increasing, and consequently the time delays achieved at different resonances are also linearly increasing, which provides linear chirping.

3. Experiment

The proposed technique for generating a tunable chirped microwave waveform is experimentally studied. The experimental setup is shown in Fig. 4. Four light waves from four tunable laser sources are sent to a 20-GHz Mach–Zehnder modulator (MZM). A Gaussian pulse with a full-width

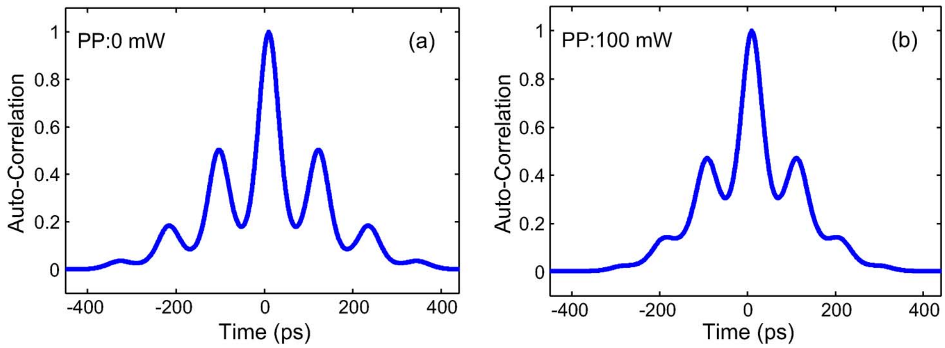

Fig. 6. Autocorrelation of the experimentally generated waveforms with a pumping power of (a) 0 mW, and (b) 100 mW.

at half-maximum (FWHM) bandwidth of 6.7 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 waves. The modulated light waves are sent to a length of single-mode fiber (SMF) of a length of 4.3 km with a total dispersion of 74 ps/nm, to introduce a constant time delay between adjacent channels and then sent to a TFBG to introduce tunable time delays. The TFBG has a tilt angle of 10° and is fabricated using an excimer laser with a uniform phase mask. The tilt angle is introduced by using a focal lens. The fiber used to fabricate the TFBG is a photosensitive Er/Yb codoped fiber (EY 305, Coractive) which is hydrogen loaded for two weeks to further increase the photosensitivity. A pulse burst with the time delays determined by the length of the SMF and the TFBG is generated at the output of the TFBG, which is then applied to a 53-GHz photodetector. The generated chirped waveform is observed by a sampling oscilloscope (Agilent 86100C).

The generated chirped microwave waveforms are shown in Fig. 5. By increasing the pump power (PP), a chirped microwave waveform with an increasing chirp rate is generated, as shown in Fig. 5(a)–(c). The microwave frequency versus time for the chirped waveform with three different chirp rates is shown in Fig. 5(d). As can be seen by increasing the pump power from 0 to 100 mW, the chirp rate is increased from 1.8 to 7 GHz/ns. The experimentally generated waveforms are compared with the simulated waveforms, a good agreement is achieved. The root mean square error (RMSE) is calculated to be 14% between the waveforms shown in Fig. 5(c), which is the largest error for the three generated waveforms. A slight difference in amplitude between the experimentally generated and the simulated waveforms is due to the nonflat frequency response of the MZM and the PD, and the nonuniform powers of the tunable laser sources.

To demonstrate the waveform compression performance, we calculate the autocorrelation of the experimentally generated chirped microwave waveforms, shown as the solid line in Fig. 5(a) and (c). The results are shown in Fig. 6(a) and (b). It is clearly seen that the microwave waveforms are compressed, which confirms that the generated microwave waveforms are frequency chirped. The FWHM temporal width of the correlation peak in Fig. 6(a) is 67 ps while it is 57 ps in Fig. 6(b). This shows that the compression ratio is larger for a pumping power of 100 mW since the corresponding chirp rate is higher. The noise performance is also evaluated. To do so, we add an additive white Gaussian noise (AWGN) to the chirped microwave waveforms. Fig. 7 shows the correlation between the chirped microwave waveforms at different signal-to-noise ratio (SNR) levels of 0 dB, -5 dB, -10 dB, and -12 dB and the reference waveforms. As can be seen, even for an SNR as low as -12 dB, the correlation peak is still detectable. Thus, it is confirmed that the use of the generated chirped microwave waveform would increase the robustness of the system to noise.

4. Conclusion

A novel and simple method to generate continuously tunable chirped microwave waveforms was proposed and experimentally demonstrated. The entire system is considered to be a photonic microwave delay-line filter with nonuniformly spaced taps. When an ultrashort pulse was applied to

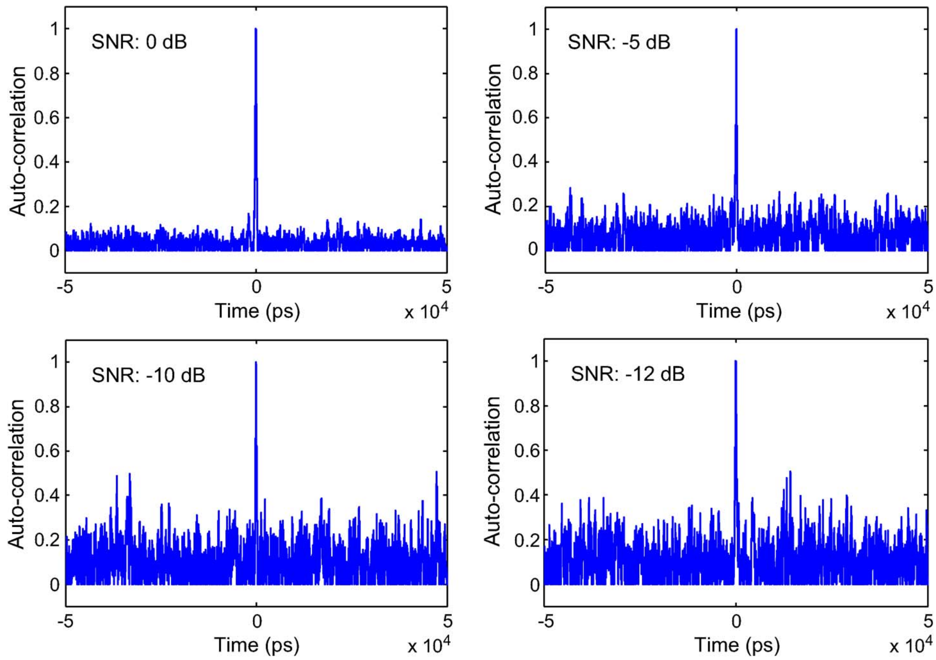

Fig. 7. Correlation between the reference waveforms and the chirped microwave waveforms added with an AWGN with an SNR of (a) 0 dB, (b) −5 dB, (c) −10 dB, and (d) −12 dB.

the input of the photonic microwave delay-line filter, a pulse burst with nonuniform temporal spacing was generated. The key device to achieve nonuniform time delays was the TFBG, which was written in an Er/Yb codoped fiber. By optically pumping the TFBG, the cladding mode resonance wavelengths were changed, leading to the change of the time delays. The proposed approach was experimentally demonstrated. By pumping the TFBG with a pumping power from 0 to 100 mW, a chirped microwave waveform with the continuously tunable chirp rate of 1.8 to 7 GHz/ns was demonstrated experimentally. In the experiment, the bandwidth of the generated chirped microwave pulses was about 2 GHz, which could be increased by increasing the maximum time advancement. In addition, the bandwidth of the MZM and the PD must be sufficiently large to support the generation of the waveforms with the required bandwidth.

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