Photonic Generation of Chirped Microwave Pulses Using Superimposed Chirped Fiber Bragg Gratings

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***Abstract*—A novel approach to generating linearly chirped microwave pulses in the optical domain based on spectral shaping and linear frequency-to-time mapping is proposed and experimentally demonstrated. In the proposed system, the spectrum of a femtosecond pulse generated by a mode-locked fiber laser is spectrum-shaped by an optical filter that consists of two superimposed chirped fiber Bragg gratings (SI-CFBGs) with different chirp rates. The SI-CFBGs form a Fabry–Pérot cavity with a cavity length linearly dependent on the resonance wavelength, thus a spectral response with an increased or decreased free spectral range is generated. A chirped microwave pulse with the pulse shape identical to the shaped spectrum is obtained at the output of a high-speed photodetector thanks to the frequency-to-time mapping in a dispersive device. The proposed technique is experimentally demonstrated, a linearly chirped microwave pulse with a central frequency of 15 GHz and a chirp rate of 0.0217 GHz/ps is experimentally generated.**

***Index Terms*—Chirped fiber Bragg grating, chirped microwave pulse, pulse compression, radar.**

I. Introduction

PULSE compression based on matched filtering using frequency-modulated or phase coded pulses has been widely used in modern radar systems to improve the range resolution [1]. Frequency-modulated or chirped microwave pulses have also found applications in chirped pulse microwave computed tomography [2]. Thanks to the advantageous features such as broad bandwidth and low loss offered by optics, the generation of chirped microwave pulses in the optical domain has been a topic of interest recently. The key advantage of using the optical technique to generate chirped microwave pulses is that high frequency and large time-bandwidth product (TBWP) microwave pulses can be generated.

A few techniques to generate chirped microwave pulses in the optical domain have been proposed recently. In [3], a chirped microwave pulse is generated by beating two chromatically dispersed optical pulses obtained by passing a broadband ultrashort pulse through two chirped fiber Bragg gratings (CFBGs) with different chirp rates in a Mach–Zehnder-interferometer (MZI) geometry. Chirped microwave pulses can also be generated based on optical spectral shaping and nonlinear frequency-to-time mapping in a nonlinear dispersive element [4]–[6]. The dispersive device should have both the first- and second-order dispersions, to generate linearly chirped microwave pulses. The use of either a nonlinear CFBG [4], [5] or a nonlinear optical fiber [6] has been recently demonstrated. Due to the limited nonlinear dispersions of the dispersive devices in [4]–[6], the generated chirped microwave pulses have a limited frequency chirp. On the other hand, chirped microwave pulses can also be generated based on linear frequency-to-time mapping; in this case, the optical filter for spectral shaping should have a spectral response with an increased or decreased free spectral range (FSR), which is called chirped FSR in this letter. Since only linear frequency-to-time mapping is required, the dispersive device can only have the first-order dispersion, such as a length of single-mode fiber (SMF) [7] or a linear CFBG [8]. In this letter, our efforts will focus on the use of an optical filter with a chirped FSR for the generation of linearly chirped microwave pulses. In the proposed system, the optical filter consists of two superimposed chirped fiber Bragg gratings (SI-CFBGs) having different chirp rates. It is known that an SI-CFBG consisting of two spectrally overlapped CFBGs with identical chirp rates could be considered as a Fabry–Pérot cavity with a fixed cavity length, therefore a spectral response with a fixed FSR would be the result, which may find applications for multiband optical filtering [9] and optical pulse repetition-rate multiplication [10]. Recently, an all-fiber Fabry–Pérot filter consisting of two identical superimposed CFBGs with continuously tunable FSR has been reported [11]. To have an optical filter with a chirped FSR, however, the superimposed CFBGs should have different chirp rates to make the Fabry–Pérot cavity have a cavity length linearly dependent on the resonance wavelength, thus a spectral response with a chirped FSR would be obtained. By properly selecting the chirp rates and longitudinal offset of two CFBGs, linearly chirped microwave pulses with high frequency and large chirp rate can be generated after linear frequency-to-time mapping. In addition, since no MZI-based optical interference is involved in the approach, the system is more compact with a better resistance to the environmental changes [3]. A linearly chirped microwave pulse with a chirp rate of 0.0217 GHz/ps and a TBWP as large as 37.5 is experimentally generated. A pulse compression ratio of 62.5 is achieved.

II. Principle

The block diagram of the proposed chirped pulse generation system is illustrated in Fig. 1(a). An ultrashort optical pulse train from a mode-locked fiber laser (MLFL) is spectrally shaped by an SI-CFBG-based optical filter. The spectrally filtered pulse is

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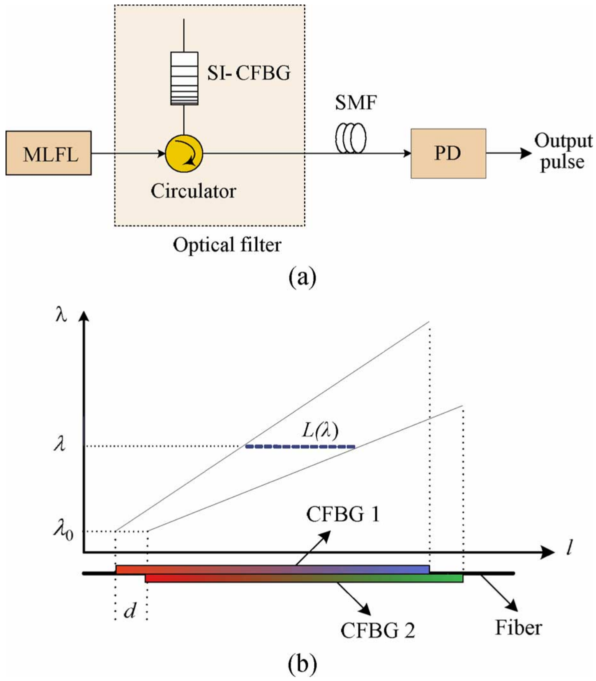

Fig. 1. (a) Schematic diagram of proposed electrical chirped pulse generation system. (b) SI-CFBG-based chirped FSR optical spectral filter.

then sent to a length of SMF to perform the linear frequency-to-time mapping, which leads to the generation of linearly chirped microwave pulses at the photodetector (PD).

To obtain a spectral response with a chirped FSR, the SI-CFBG is designed and fabricated by superimposing two CFBGs with different chirp rates into a same fiber with a small longitudinal offset, as shown in Fig. 1(b). Distributed Fabry–Pérot interference is then produced in the fiber due to the reflections of the two CFBGs. This generates an in-fiber optical filter with an FSR inversely proportional to the cavity length L. Since the two CFBGs have different linear chirp rates, the equivalent cavity length L varies linearly with respect to the wavelength λ. As a result, the FSR is not constant but is increased or decreased with respect to the wavelength.

From Fig. 1(b), we can see the equivalent cavity length L is linearly proportional to the wavelength λ within the filter bandwidth

$$L(\lambda) = \frac{C_1 - C_2}{C_1 C_2}\lambda + d + \frac{C_2 - C_1}{C_1 C_2}\lambda_0 \tag{1}$$

where C_1 and C_2 are the chirp rates of the two CFBGs (in nanometers/millimeters), d is the longitudinal offset, and λ_0 is the start wavelength.

The FSR of the distributed Fabry–Pérot filter is given by

$$\mathrm{FSR} \cong \frac{\lambda_0^2}{2nL(\lambda)} \tag{2}$$

where n is the refractive index of the fiber. After the dispersion-induced linear frequency-to-time mapping, the FSR is mapped to the temporal period of the generated chirped pulse, namely $\Delta\tau$, with a mapping relationship $\lambda \to t/D$, where D (ps/nm) is the total dispersion of the SMF.

For simplicity, the instantaneous radio-frequency (RF) carrier frequency of the generated temporal pulse f_{RF} can be approximated by the reciprocal of the temporal period $\Delta\tau$

$$f_{\mathrm{RF}}(t) \propto \frac{1}{\Delta\tau} \propto 2n\left[\frac{C_1 - C_2}{C_1 C_2}\frac{t}{\lambda_0^2 D^2} + \frac{d}{\lambda_0^2 D} + \frac{C_2 - C_1}{C_1 C_2 \lambda_0 D}\right]. \tag{3}$$

It can be seen that the frequency of the microwave pulse is linearly proportional to time t, therefore it is linearly chirped. For a given length of SMF, the central carrier frequency of the generated chirped pulse at $t = 0$ is only dependent upon the offset d. The chirp rate of generated pulse is determined by the chirp rates of the two CFBGs. Therefore, by appropriately designing the longitudinal offset and the chirp rates of the CFBGs, linearly chirped microwave pulses with a high central frequency and a large chirp rate can be generated.

III. Experiment

The setup shown in Fig. 1 is experimentally evaluated. In the experiment, a transform-limited Gaussian pulse with a full-width at half-maximum (FWHM) of 550 fs generated from an MLFL is sent to the SI-CFBG through a three-port circulator. The central wavelength of the ultrashort pulse is 1558.5 nm, and the 3-dB spectral bandwidth is 8 nm. The SI-CFBG is fabricated using a frequency-doubled argon–ion laser operating at 244 nm. To simplify the fabrication, two CFBGs with equal but opposite chirp rates ($C_2 = -C_1$) are superimposed in a photosensitive fiber, which requires only a single linearly chirped phase mask. In addition, for a given chirped phase mask, the fabrication of two CFBGs with opposite chirp rates would generate chirped microwave pulse with the largest frequency chirp rate. Furthermore, since the effective reflection bandwidth of the SI-CFBG is roughly equal to the common reflection bandwidth of the two CFBGs, superimposing two CFBGs with the same bandwidth would ensure a maximum bandwidth usage. Based on these considerations, two CFBGs with opposite chirp rates of ± 0.1 nm/mm and an identical grating length of 10 mm are written with a longitudinal offset of 12 mm. The center Bragg wavelength of the two CFBGs is 1558.3 nm, which is selected to match the center wavelength of the ultrashort pulse. To produce distributed Fabry–Pérot resonance, each grating has a weak reflection ($\sim$30%). Fig. 2(a) shows the measured normalized reflection spectrum of the SI-CFBG. Simulation results by using the piecewise-uniform matrix approach [12] are also illustrated in Fig. 2(a) for comparison. It is shown that an SI-CFBG with a reflection spectrum having an increased FSR is obtained, which can be used to spectrally shape the spectrum of the broadband ultrashort pulse. Note that the measured spectrum has a limited modulation depth compared with the simulation result. This mainly owes to the limited resolution of our optical spectrum analyzer.

Fig. 2(b) shows the measured group delay response of the SI-CFBG. A nearly constant group delay is observed, which is usually required in a pulse shaping system based on spectral-shaping and frequency-to-time mapping [8]. The result can be understood intuitively by considering the dispersion

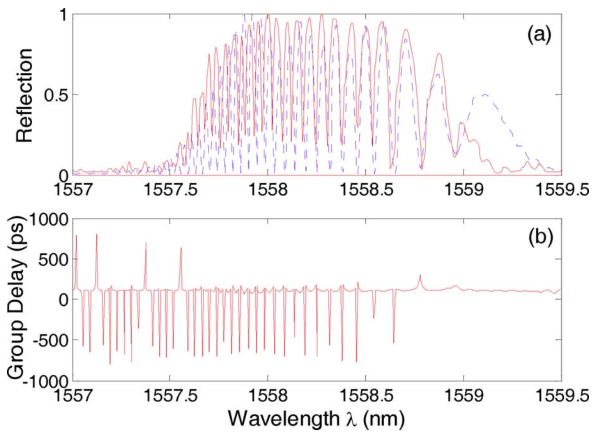

Fig. 2. (a) Measured (solid line) and the simulated (dashed line) reflection spectra and, (b) reflection group delay of the SI-CFBG.

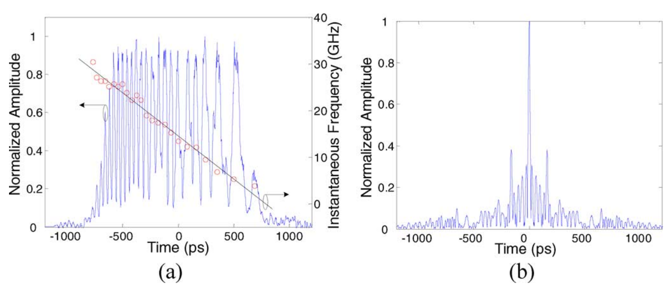

Fig. 3. (a) Measured pulse profile and instantaneous *frequency* of the generated chirped microwave pulse. (b) Autocorrelation *waveform* of the generated chirped microwave pulse.

cancellation due to two CFBGs with equal but opposite chirp rates. One may notice that some group delay peaks at the reflection notch wavelengths are also observed, which is attributed to the very low optical power at the notches. Such group delay noise at the notch wavelengths has negligible impact on the dispersion-induced frequency-to-time mapping.

The incident ultrashort pulse is spectrum-shaped by the SI-CFBG, which is then mapped to a chirped temporal waveform thanks to linear frequency-to-time mapping in a 58-km SMF. A linearly chirped microwave pulse is experimentally generated, as shown in Fig. 3(a). The FWHM of the pulse envelope is around 1250 ps. Fig. 3(a) also shows the instantaneous RF carrier frequency within the main pulsewidth, which is calculated by Hilbert transform [13] and shown by the solid circle curve, with a linear fitting shown by the dotted curve. It is shown that the instantaneous frequency changes almost linearly across the pulse with a central frequency of 15 GHz and a chirp rate of 0.0217 GHz/ps, which agrees very well with the theoretically predicted chirp rate of 0.0238 GHz/ps by (3). A TBWP as large as 37.5 is obtained. To generate a linearly chirped microwave pulse with larger TBWP and higher frequency, two superimposed CFBGs with larger chirp rates and smaller offset should be used. Theoretically, the achievable frequency and TBWP are only limited by the bandwidth of high-speed PD. Fig. 3(b) shows the autocorrelation of the generated pulse, the FWHM of which is around 20 ps. Therefore, a pulse compression ratio of 62.5 is achieved, a much greater compression than those obtained based on nonlinear frequency-to-time mapping in [4]–[6].

IV. Conclusion

A novel approach to generating a linearly chirped microwave pulse based on spectral filtering and linear frequency-to-time mapping was proposed and experimentally demonstrated. The key component in the proposed system is the SI-CFBG, which was fabricated by superimposing two CFBGs with opposite chirp rates in a photosensitive fiber with a small longitudinal offset. By using a linear dispersive device to perform the frequency to time mapping, a linearly chirped microwave pulse with a high frequency and large TBWP was generated. The proposed technique is simple, which can find wide applications in modern radar, communications, and instrumentation systems.

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