Phase-Coded Millimeter-Wave Waveform Generation Using a Spatially Discrete Chirped Fiber Bragg Grating

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***Abstract*— An all-optical approach to generating phase-coded millimeter-wave (mm-wave) waveforms based on optical pulse shaping, using a spatially discrete chirped fiber Bragg grating (SD-CFBG) is proposed and experimentally demonstrated. Since no electro-optical modulator is used, the system is simpler and less costly. In the proposed system, the spectrum of an optical pulse is spectrally sliced by a sinusoidal comb filter. The SD-CFBG is then used as a special dispersive element to map the shaped spectrum to a temporal waveform based on dispersive Fourier transform, and at the same time, to introduce the desired time delay jumps, which are translated to phase shifts. A simplified system without using the comb filter is also studied, in which a single SD-CFBG is employed to simultaneously perform spectral slicing, frequency-to-time mapping, and temporal coding. The proposed technique is validated by two experiments in which two phase-coded mm-wave waveforms at 28.5 GHz and 47.2 GHz with, respectively, a 7-bit and 11-bit Barker code are generated.**

***Index Terms*— Dispersion, fiber Bragg grating (FBG), microwave photonics, optical pulse shaping, phase coding, radar.**

I. INTRODUCTION

MICROWAVE pulse compression has been employed in radar and sonar systems to increase the range resolution [1]. To achieve pulse compression, the microwave pulses are usually frequency chirped or phase coded to increase the time-bandwidth product (TBWP). Thanks to the high frequency and broad bandwidth of modern photonics, the generation of high-frequency and large TBWP microwave waveforms based on photonics has been a topic of interest recently [2]–[7]. One widely used technique for photonic microwave waveform generation is based on optical pulse shaping. For example, reprogrammable synthesis of a phase-coded microwave waveform can be achieved by shaping an optical pulse using a spatial light modulator (SLM) [5], [6]. The advantage of using an SLM is its high flexibility, but the footprint size is large and the loss is relatively high. These problems can be solved by using pure fiber optics. For example, a phase-coded microwave waveform generated using a fiber-optic Mach–Zehnder interferometer (MZI) incorporating a phase modulator has been reported [8]. However, the stability of the system is poor due to the use of an interferometer. Moreover, since a high-frequency phase modulator (PM) is employed, the system cost is high and the carrier frequency of the generated microwave waveform is limited by the bandwidth of the PM.

In this letter, we propose and demonstrate a simple technique to generate a phase-coded mm-wave waveform using a spatially discrete chirped fiber Bragg grating (SD-CFBG), based on spectral pulse shaping and frequency-to-time mapping. In the proposed system, the SD-CFBG provides two functions, to perform 1) frequency-to-time mapping and 2) phase coding. The frequency-to-time mapping is achieved due to the dispersion of the SD-CFBG, and the phase coding is achieved by introducing discrete time delay jumps, which are translated to phase shifts to the generated mm-wave waveform. Note that a similar technique using an SD-CFBG to generate a chirped microwave waveform has been demonstrated in [3]. The key difference is that for phase-coded waveform generation, the SD-CFBG should have multiple time delay jumps, which are produced during the fabrication process by a precise control of the translation stage, while for chirped waveform generation, a smooth group delay response is needed which makes the fabrication greatly simplified.

The proposed technique is validated experimentally. Two phase-coded mm-wave waveforms corresponding to a 7-bit and an 11-bit Barker code with a carrier frequency of 28.5 and 47.2 GHz are generated. Since no PM is needed, the frequency of the generated waveforms can be high and will not be limited by the bandwidth of the PM. In addition, since no fiber-optic MZI is employed, the system is very stable [8]. A simplified scheme without using a separate spectral shaper is also investigated.

II. PHASE-CODED mm-WAVE PULSE GENERATION USING A SD-CFBG

Arbitrary waveform generation based on spectral shaping and frequency-to-time mapping has been extensively studied recently [2]. As shown in Fig. 1(a), an ultra-short pulse from a mode-locked laser is sent to an optical comb filter. The spectrum-shaped pulse is then sent to a dispersive element to perform frequency-to-time mapping. A microwave waveform with its temporal shape that is a scaled version

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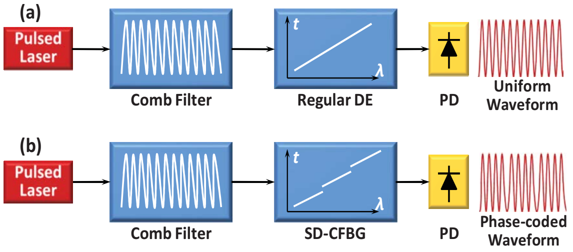

Fig. 1. Microwave waveform generation based on spectral pulse shaping and frequency-to-time mapping. (a) A uniform microwave pulse is generated using a regular dispersive element (DE) and (b) a phase-coded microwave pulse is generated using a SD-CFBG with discrete time delay jumps.

of the shaped spectrum is generated at the output of a photodetector (PD) [9].

To generate a phase-coded microwave waveform, the dispersive element (SD-CFBG) is redesigned to have a group delay response with discrete time delay jumps, as shown in Fig. 1(b). Thanks to the additional time delay jumps, a microwave waveform with the required phase shifts, corresponding to the required phase coding, is generated. The key device in the system is the SD-CFBG [3], which is designed to have a group delay response with user-defined time delay jumps on top of a linear group delay response. The carrier frequency of the generated mm-wave waveform is determined by the free spectral range (FSR) of the comb filter, $\Delta\lambda$, and the group velocity dispersion (GVD) of the SD-CFBG, D, given by

$$fc = \frac{1}{\Delta\lambda \times D}. \tag{1}$$

The phase coding is determined by the positions of the time delay jumps along the grating length. Each jump corresponds to half period of the mm-wave waveform, creating a π-phase shift.

To verify the proposed technique, an experiment is carried out based on the setup shown in Fig. 2. A passively mode-locked laser (MML) is employed as the optical source to generate a Gaussian-like optical pulse with a 3-dB temporal width of 550 fs or a 3-dB spectral bandwidth of 10 nm at a central wavelength of 1558 nm. The optical pulse is first sent to the comb filter, which is implemented by superimposing two identical chirped fiber Bragg gratings (SI-CFBG) in a single optical fiber with a small longitudinal offset, offering greatly improved stability compared with a fiber Mach–Zehnder interferometer [9], [10]. The measured spectral response of the comb filter is shown in Fig. 3(a). The spectrally-shaped optical pulse is then sent to a SD-CFBG, which is designed to have a flat magnitude response and a linear group delay response with three discrete time delay jumps, to generate a 7-bit phase-coded Barker code. The SD-CFBG is fabricated using a linearly chirped phase mask, with the discrete time delay jumps introduced by axially shifting the fiber using a high precision translation stage [3]. The average reflectivity of the SD-FBG is ∼80%, corresponding to an insertion loss of 0.97 dB. Considering that the loss of the circulator is about 1 dB and the splicing loss is about 0.01 dB, the system has an average insertion loss of 2 dB. Fig. 3(b) shows the reflection spectrum normalized to the peak reflectivity and group delay response of the SD-CFBG, measured by an optical vector analyzer (OVA). Three discrete time delay jumps, as indicated by the dashed circles, are introduced on top of the linear group delay response. The jump value (17.5 ps) is chosen to match the half period of the mm-wave waveform at 28.5 GHz.

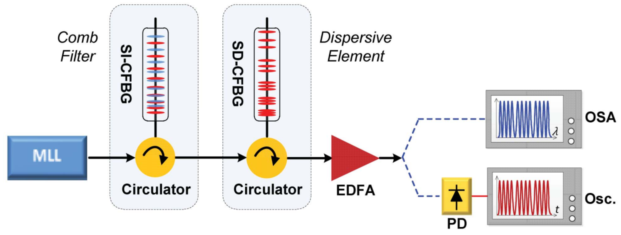

Fig. 2. Experimental setup. An SI-CFBG is employed as a comb filter. EDFA: erbium-doped fiber amplifier. PD: photodetector. OSA: optical spectrum analyzer. Osc.: oscilloscope.

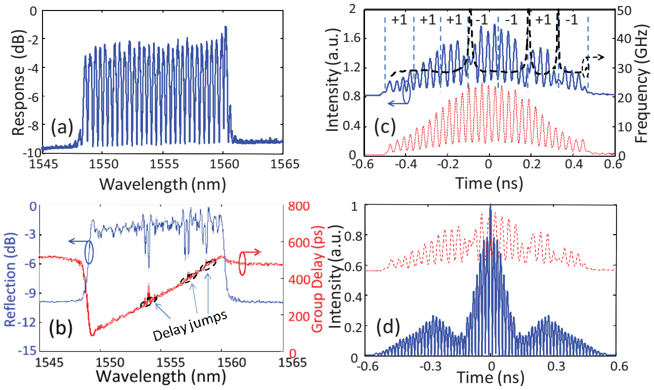

Fig. 3. Experimental results. (a) Spectral response of the comb filter. (b) Normalized reflection spectrum and group delay response of the SD-CFBG. (c) Generated mm-wave waveforms (top: phase-coded waveform, bottom: uniform waveform), and the instantaneous carrier frequency of the phase-coded waveform. (d) Pulse compression of the phase-coded waveform based on auto-correlation (dashed curve: original waveform).

The generated waveform is then detected by a 45-GHz PD and displayed by a 53-GHz digital sampling oscilloscope, which is shown in Fig. 3(c). A phase-coded mm-wave waveform corresponding to a 7-bit Barker code of {+1, +1, +1, −1, −1, +1, −1} with a carrier frequency of ∼28.5 GHz is obtained. The instantaneous carrier frequency is calculated by the Hilbert transform, which is also shown in Fig. 3(c). An mm-wave waveform generated using a linearly chirped FBG without time delay jumps is also shown for comparison.

To evaluate the pulse compression performance [11], we calculate the correlation between the experimentally generated phase-coded mm-wave waveform and the reference which is an ideal 7-bit Barker code, with the result shown in Fig. 3(d). It is clearly seen that the phase-coded mm-wave pulse is compressed. The compression ratio is calculated to be 5.1.

III. SIMPLIFIED SCHEME

The proposed pulse shaping scheme can be simplified using a single SD-CFBG, as shown in Fig. 4(a). Here the SD-CFBG is designed to perform three functions: 1) to uniformly slice the spectrum of an ultrashort optical pulse; 2) to map the

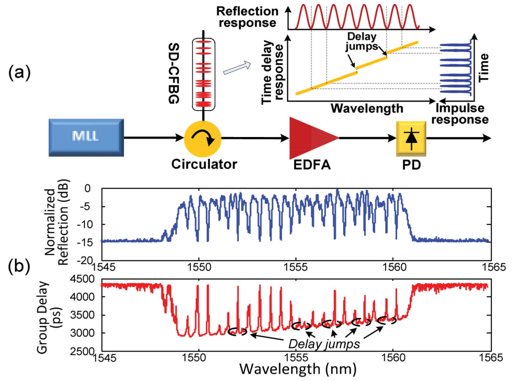

Fig. 4. Simplified scheme. (a) Schematic of the simplified optical pulse shaping system. Inset: principle of the SD-CFBG. (b) Measured normalized reflection spectrum and group delay response of the SD-CFBG.

shaped spectrum to a temporal pulse burst; and 3) to perform pulse coding by introducing discrete time delay jumps to the temporal pulse burst. Therefore, when an ultrashort optical pulse is sent to the SD-CFBG, a pulse burst with user-defined pulse spacing is obtained. With the help of a bandwidth-limited PD, a smooth phase-coded mm-wave pulse is generated from the discrete pulse burst [5]. In the simplified pulse shaping system, only a passive fiber-optic device, the SD-CFBG, is used. The entire system is simplified with better stability and lower cost.

The generation of a phase-coded mm-wave waveform with an 11-bit Barker code using the simplified system is then experimentally evaluated. To fulfill the three functions simultaneously, the SD-CFBG is designed to have a multi-channel spectral response to perform uniform spectrum slicing (as a comb filter) and a linear group delay response with discrete time delay jumps to perform frequency-to-time mapping and to change pulse spacing in the mapped pulse burst, as shown in Fig. 4(a).

The normalized reflection spectrum and group delay response of the SD-CFBG is measured and shown in Fig. 4(b). The SD-CFBG has a spectral response with 22 channels and a linear group delay response with 5 time delay jumps (10.6 ps) as indicated by the dashed circles, corresponding to a 11-bit Barker code of $\{+1, +1, +1, -1, -1, -1, +1, -1, -1, +1, -1\}$. Peaks in the group delay response are measurement errors due to the very low power at the spectral notches, which have negligible impact on the generated waveform [3].

Fig. 5(a) shows the measured impulse response of the SD-CFBG, which is equivalent to the output optical pulse burst. A smooth phase-coded mm-wave waveform with an 11-bit Barker code at a carrier frequency of 47.2 GHz is generated at the output of the PD, as shown in Fig. 5(b). Pulse compression based on correlation is shown in Fig. 5(c). A compression ratio of 10.7 is achieved. The compression ratio can be increased by using a longer Barker code (13 bit) or a polyphase code.

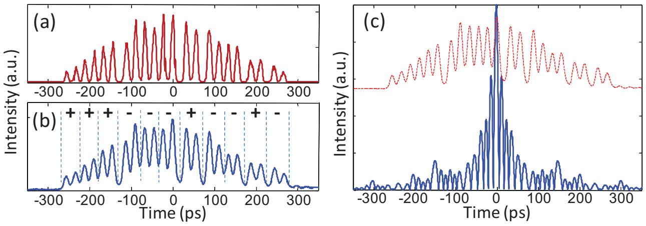

Fig. 5. Experimental results. (a) Measured impulse response of the SD-CFBG. (b) Generated phase-coded mm-wave waveform with 11-bit Barker code. (c) Pulse compression result based on correlation.

Note that the reconfigurability of the system is limited, since the spectral response of the SD-CFBG is fixed once it is made. For practical applications, however, we may use an array of SD-CFBGs. By switching from one to another, we can get the desired phase-coded waveforms with different coding patterns.

IV. CONCLUSION

An approach to generating phase-coded mm-wave pulses based on optical pulse shaping using a SD-CFBG was proposed and demonstrated. Two experiments were performed. In the first experiment, the SD-CFBG was designed to perform two functions: frequency-to-time mapping and pulse coding. In the second experiment, a simplified system using a redesigned SD-CFBG to perform three functions: spectral shaping, frequency-to-time mapping and pulse coding was demonstrated. The key significance of this approach is that phase coding can be done using a SD-CFBG, which would increase the system stability and reduce the footprint size and the system cost.

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