Large Time-Bandwidth Product Microwave Arbitrary Waveform Generation Using a Spatially Discrete Chirped Fiber Bragg Grating

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***Abstract*—We propose and experimentally demonstrate an approach to generating large time-bandwidth product (TBWP) microwave arbitrary waveforms based on optical pulse shaping using a single spatially discrete chirped fiber Bragg grating (SD-CFBG). The SD-CFBG functions to perform simultaneously spectral slicing, frequency-to-time mapping, and temporal shifting of the input optical pulse, which leads to the generation of an optical pulse burst with the individual pulses in the burst temporally spaced by the time delays determined by the SD-CFBG. With the help of a bandwidth-limited photodetector (PD), a smooth microwave waveform is obtained. The SD-CFBG is fabricated using a linearly chirped phase mask by axially shifting the photosensitive fiber to introduce a spatial spacing between two adjacent sub-gratings during the fabrication process. By properly designing the fiber shifting function, a large TBWP microwave arbitrary waveform with the desired frequency chirping or phase coding can be generated. An equation that relates the fiber shifting function and the microwave waveform frequency chirping is derived. The photonic generation of large TBWP microwave waveforms with a linear, nonlinear and stepped frequency chirping is experimentally demonstrated.**

***Index Terms*—Chirp, dispersion, fiber Bragg grating, microwave photonics, optical pulse shaping, phase coding, pulse compression, radar, time-bandwidth product.**

I. Introduction

MICROWAVE waveforms with a large time-bandwidth product (TBWP) have been extensively employed in modern radar systems to improve the range resolution [1]. Large TBWP microwave waveforms can also find other applications such as in spread-spectrum communications [2], microwave computed tomography [3] and modern instrumentation. For radar applications, for example, to achieve a large TBWP, the transmitted microwave waveforms are usually frequency chirped or phase coded, which are usually generated in the electrical domain using digital electronics, but with the limitations of small TBWP and low central frequency. At the current stage of development of modern radar systems, frequency-chirped or phase-coded microwave waveforms with a TBWP of 100 or more and a central frequency up to tens or even hundreds of gigahertz are often required [1].

As a solution to the problems associated with the above electronic methods, photonically assisted techniques have been extensively investigated recently to generate large TBWP microwave arbitrary waveforms based on optical pulse shaping. Photonic generation of frequency-chirped and phase-coded microwave waveforms has been demonstrated in the spatial domain based on direct space-to-time (DST) pulse shaping [4], [5], and in the spectral domain based on spectral pulse shaping using a spatial light modulator (SLM) followed by frequency-to-time mapping in a dispersive element [6], [7]. With the use of the techniques in [4]–[7], a reprogrammable synthesis of a large TBWP microwave arbitrary waveform could be achieved. However, these techniques are all implemented in free space using expensive and complex bulk optical devices, which suffers from various difficulties such as complicated alignment and high coupling losses.

On the other hand, a large TBWP microwave arbitrary waveform can also be generated based on optical pulse shaping using fiber-optic devices. Compared with the techniques using free-space optics, fiber-optics-based optical pulse shaping features a much smaller size, lower loss, better stability and higher potential for integration. For example, a phase-coded microwave pulse can be generated by beating two dispersed optical pulses in an unbalanced Mach–Zehnder interferometer (MZI) with an optical phase modulator incorporated in one arm of the MZI [8]. The same concept can also be applied to the generation of a frequency-chirped microwave pulse [9], [10]. A linearly chirped microwave pulse can be generated by beating two time-delayed chirped optical pulses at a photodetector (PD) in which the two time-delayed optical pulses are dispersed by two linearly chirped fiber Bragg gratings (L-CFBGs) with different chirp rates [9] or by a single nonlinearly chirped fiber Bragg grating (NL-CFBG) [10]. A frequency-chirped microwave pulse can also be generated based on optical spectral shaping using an optical filter with a sinusoidal frequency response followed by nonlinear frequency-to-time mapping. The nonlinear frequency-to-time mapping could be realized in a dispersive element with high-order dispersion [11]–[13]. If a fiber-optic spectral filter with a varying free spectral range (FSR), which was termed a chirped FSR in [14], is used to perform spectral shaping [14], [15], a dispersive element with only the first-order dispersion is required to generate a chirped microwave pulse

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based on linear frequency-to-time mapping. More recently, an approach to generating a chirped microwave pulse using a photonic microwave delay-line filter with a quadratic phase response was reported [16]. By passing a broadband chirp-free microwave pulse through the microwave delay-line filter that has a quadratic phase response, a chirped microwave pulse is generated. The photonic microwave delay-line filter with a quadratic phase response can be realized using a regular uniformly spaced photonic microwave delay-line filter, but the tap coefficients should be complex-valued, making it hard to implement in the optical domain. A much simpler approach to achieving a photonic microwave delay-line filter with a quadratic phase response is to use a delay-line structure with nonuniformly spaced taps, in which the complex coefficients are equivalently generated by nonuniform time delays [16].

The photonically assisted phase-coded and frequency-chirped microwave pulse generation systems reported in [4]–[16] were implemented using multiple optical devices with each performing a different function; the systems were thus complicated, costly and with a high coupling loss. In this paper, we propose, for the first time to the best of our knowledge, a novel all-fiber technique to implement large TBWP microwave arbitrary waveform generation based on optical pulse shaping using a single spatially discrete chirped fiber Bragg grating (SD-CFBG). The SD-CFBG consists of multiple spatially separated sub-gratings that functions to perform simultaneously spectral slicing, frequency-to-time mapping, and temporal shifting. When a broadband transform-limited optical pulse is sent to the SD-CFBG, which is operating in the reflection mode, the power spectrum of the optical pulse is sliced, mapped to the time domain, and then temporally delayed, leading to the generation of an optical pulse burst with a custom-designed amplitude profile and time spacing. With the help of a bandwidth-limited PD, a smooth frequency-chirped or phase-coded microwave pulse is generated. The SD-CFBG is fabricated using a linearly chirped phase mask by axially shifting the fiber to introduce a spatial spacing between two adjacent sub-gratings during the fabrication process. By properly designing the fiber shifting function, a large TBWP microwave waveform with the desired frequency chirping or phase coding would be generated.

Note that the generation of a custom-designed optical pulse burst from a single input optical pulse by using a multi-mirror interferometer has been reported in [17]. Similar architectures have also been successfully applied for coherent optical arbitrary pulse shaping [18] and microwave arbitrary waveform generation based on incoherent optical pulse processing [19], [20]. The key limitation existing in the above systems is the complexity of the interferometer, such as a multi-stage Michelson interferometer used in [18] and a fiber-Bragg-grating-based multichannel interferometer used in [19]. Compared with the optical pulse burst generation systems in [17]–[20], the proposed system has a significantly simplified structure (only one single SD-CFBG is used), which features a smaller size, lower loss, better stability and higher potential for integration.

Some preliminary experimental observations have been recently reported by us [21], where only a nonlinearly chirped microwave pulse was generated. To have a better understanding of the proposed large TBWP microwave waveform generation technique and to investigate its feasibility for practical applications, a comprehensive theoretical analysis and further experimental verifications are needed, which are presented in this paper.

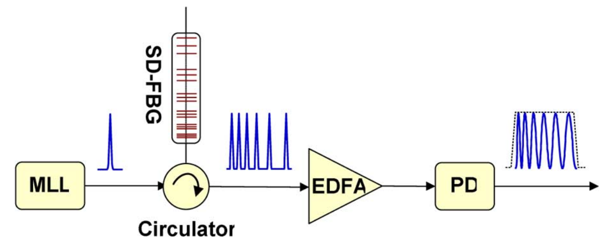

Fig. 1. A large TBWP microwave pulse generator using an SD-CFBG. MLL: mode-locked laser, SD-CFBG: spatially discrete chirped fiber Bragg grating, EDFA: Erbium-doped fiber amplifier, PD: photodetector.

The paper is organized as follows. In Section II, the principle of the proposed SD-CFBG is presented in detail. The SD-CFBG can be produced using a linearly chirped phase mask by axially shifting the fiber to introduce a spatial spacing between two adjacent sub-gratings during the fabrication process. The SD-CFBG-based large TBWP microwave pulse generation system is also described. We show that by properly designing the fiber shifting function, large TBWP microwave arbitrary waveforms with the desired frequency chirping or phase coding can be generated. The relationship between the fiber shifting function and the frequency chirping is derived and analyzed. Then, in Section III, the generation of chirped microwave pulses with different chirping types, such as linear chirp, nonlinear chirp and stepped chirp, is experimentally demonstrated. In Section IV, a discussion on the feasibility of the technique for practical implementation and the adaptability to microwave arbitrary waveform generation is presented. A conclusion is drawn in Section V.

II. Principle

The proposed large TBWP microwave pulse generation system using an SD-CFBG is shown in Fig. 1. A broadband ultrashort optical pulse from a mode-locked laser (MLL) is sent to the SD-CFBG, which is working in the reflection mode. Thanks to the simultaneous spectral slicing, frequency-to-time mapping and temporal shifting performed by the SD-CFBG, an optical pulse burst with the desired time spacing is generated from the single input optical pulse. With the help of a bandwidth-limited PD, a smooth frequency-chirped or phase-coded microwave pulse is generated thanks to the equivalent low-pass filtering process at the PD. By properly controlling the time spacing between the individual seed pulses, large TBWP microwave arbitrary waveforms with the desired frequency chirping or phase coding can be generated.

The key device in the proposed microwave pulse generation system is the SD-CFBG. A diagram showing the principle of the proposed SD-CFBG is illustrated in Fig. 2(a). The SD-CFBG is produced by first dividing a continuous and linearly chirped refractive index modulation function along the fiber axial direction into N seed modulation functions that have identical length and identical apodization profile, and then imprinting these N

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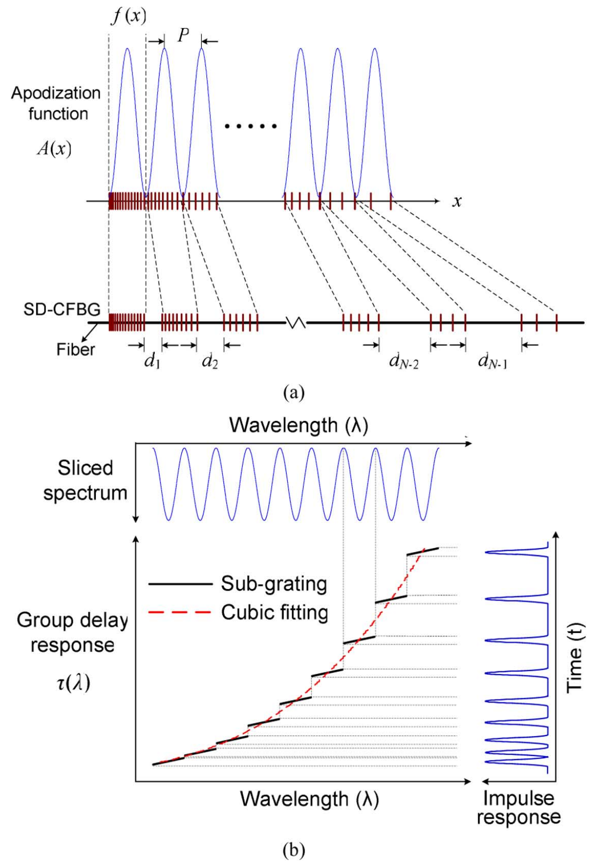

Fig. 2. Illustration of the design and fabrication of an SD-CFBG. (a) An SD-CFBG produced based on axial fiber shifting during the fabrication process. (b) The group delay response and the impulse response of the SD-CFBG. A quadratically increasing fiber shifting function corresponds to a fitted group delay response that is cubically increasing with wavelength.

seed index modulation functions into N spatially separated sub-gratings with a properly designed separation function to achieve the required group delay response for the SD-CFBG. The sub-grating separation function is introduced to the SD-CFBG by axially shifting the photo-sensitive fiber to introduce a spatial spacing between two adjacent sub-gratings during the grating fabrication process.

To produce the SD-CFBG, as shown in Fig. 2(a), a linearly chirped refractive index modulation function is first constructed, which is continuous along the fiber axial direction and is expressed as

$$\Delta n(x) = \Delta n_{\max} A(x) \exp\left(-j\frac{\pi C}{\Lambda_0^2}x^2\right) \exp\left[j\frac{2\pi}{\Lambda_0}x\right], \quad 0 \le x \le L \quad (1)$$

where $\Delta n_{\max}$ is the maximum refractive index change, Λ_0 is the fundamental period of the grating and C (nm/mm) is the chirp rate. Here we consider that the refractive index modulation occurs over a length of L. $A(x)$ describes the normalized apodization function, which is continuous and periodic with a constant period of P,

$$A(x) = \sum_{k=0}^{N-1} f(x - kP) \quad (2)$$

where $f(x)$ is the seed apodization function, i.e., a Gaussian function, within one period of the apodization function, as illustrated in Fig. 2(a).

It is known that when a linearly chirped FBG has a high enough dispersion, its apodization profile can be mapped to the grating reflection spectral response thanks to the space-to-frequency mapping relationship in a weak linearly-chirped FBG [22]. Therefore, a spectral comb filter can be obtained due to the periodic apodization function $A(x)$ introduced to the SD-CFBG. The obtained comb filter can be used to slice the spectrum of the input ultrashort optical pulse.

The continuous and linearly chirped index modulation function in (1) is then imprinted into a photosensitive fiber through UV illumination using a linearly chirped phase mask. During the grating fabrication process, the fiber is axially shifted with an offset of $d_k (k = 1, 2, \ldots, N-1)$ after the kth sub-grating is written with the apodization function $f(x - kP)$. Therefore, an SD-CFBG consisting of N spatially separate sub-gratings is obtained, as illustrated in Fig. 2(a).

The group delay response of the produced SD-CFBG can then be expressed as

$$\tau(\Delta\lambda) = \frac{\Delta\lambda}{C} \times \frac{2n_{\text{eff}}}{c} + \sum_{k=1}^{M} d_k \times \frac{2n_{\text{eff}}}{c} \quad (3)$$

where $\Delta\lambda$ denotes the wavelength offset from the starting wavelength, n_{eff} is the effective refractive index of the fiber core, c is the light speed in vacuum, and M is the number of the involved fiber shifts within the bandwidth of $\Delta\lambda$. The first term in (3), which is continuous, is the original linear group delay contributed by the linear phase mask, and the second term, which is discrete, represents the user-defined group delay response introduced by the fiber shifting function d_k. Therefore, the entire group delay response of the produced SD-CFBG is discontinuous with N linear segments and $N-1$ jumps. The bandwidth of each linear segment is given by $\delta\lambda = C \times P$. The height of the kth jump is determined by the corresponding spacing d_k. The selection of the heights of the jumps provides the flexibility to design an SD-CFBG with an arbitrary discrete group delay response. For example, if the fiber shifting function d_k is increasing quadratically with k, a fitted group delay response that is a cubic function of wavelength can be achieved, which is shown in dashed line in Fig. 2(b).

When a broadband transform-limited (chirp-free) optical pulse is sent to the SD-CFBG, which is operating in the reflection mode, the power spectrum of the optical pulse is first sliced by the SD-CFBG due to the multiple sub-grating responses, as shown in Fig. 2(b). The linear group delay response within each sub-grating channel is then used to perform the dispersion-induced frequency-to-time mapping [23], which leads to the generation of a comb waveform in the time domain. Finally, the mapped waveform is further temporally delayed due to the user-defined group delay jumps in the SD-CFBG, resulting in an optical pulse burst with the desired time spacing between individual seed pulses. Therefore, thanks to the simultaneous spectral slicing, frequency-to-time mapping and temporal shifting by the single SD-CFBG, an optical pulse burst consisting of N seed pulses with the pulse spacing determined by

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the fiber shifting function d_k is generated from a single input optical pulse.

It is important to note that even though the frequency-to-time mapping is a coherent process, the proposed microwave pulse generation system is still operating in the incoherent scheme. The term 'incoherent' refers to the fact that only the amplitude (not the phase) of the generated optical pulse burst is involved in the pulse shifting and combining process. This is because each seed pulse comes from different frequency component of the input broadband optical pulse. There is no interference between different seed pulses. Thus, only the intensity of the pulse burst is considered in our theoretical treatment. Mathematically, the output optical pulse burst is expressed as

$$r(t) = w(t) \times \left\{ s_0(t) + \sum_{k=1}^{N-1} s_0 \left[t - \left(kP + \sum_{1}^{k} d_k \right) \frac{2n_{\text{eff}}}{c} \right] \right\} \quad (4)$$

where $s_0(t)$ is the seed pulse, which is obtained according to the space-to-frequency-to-time mapping in the SD-CFBG [22],

$$s_0(t) \propto g(t) * [f(x)]|_{x=c/(2n_{\text{eff}})\times t} \quad (5)$$

where $g(t)$ is the temporal envelope of the input transform-limited optical pulse. As shown in (5) the seed pulse $s_0(t)$ is determined by both the input optical pulse $g(t)$ and the seed apodization function $f(x)$. Note that the generated optical pulse burst is modulated by a slowly varying envelope $w(t)$, which is determined by the input optical spectrum due to the dispersion-induced frequency-to-time mapping. Since the SD-CFBG has a nonlinear group delay response, according to (3), even though the input optical pulse has a symmetric spectrum, the envelope function $w(t)$ is usually asymmetric due to the high-order dispersion induced pulse shape distortion [24]. This may also be interpreted as a sampled version of the continuous nonlinear frequency-to-time mapping [12], where a continuous nonlinear group delay response is applied. In its sampled version, both the input spectrum and the nonlinear group delay response of the SD-CFBG are sampled by N sub-gratings. As a result, a pulse burst is generated from the sampled (sliced) spectrum thanks to the sampled nonlinear frequency-to-time mapping. The pulse burst is indeed a sampled version with an envelope which can be obtained from the input spectrum according to the continuous frequency-to-time mapping.

The generated optical pulse burst $r(t)$ is then amplified and directed to a high-speed PD for incoherent detection. A properly shaped microwave waveform is obtained at the output of the PD. Since the PD has a limited bandwidth, a smooth microwave waveform is resulted [4], [19], [20].

The instantaneous frequency of the generated microwave pulse is inversely proportional to the seed pulse spacing. The sampled instantaneous microwave frequency f_k, which is determined by both the apodization period P and the sub-grating spacing d_k, can be expressed as

$$f_k = \frac{1}{P + d_k} \times \frac{c}{2n_{\text{eff}}} \quad (6)$$

where P determines the initial instantaneous microwave frequency (the frequency offset) and d_k controls the frequency chirping profile. Thus, we can conclude that by properly selecting the period of the apodization function and designing the fiber shifting function, a large TBWP microwave waveform with the desired frequency chirping or phase coding can be generated.

III. Experiment

In this section, several examples to show the generation of different types of chirped microwave pulses using the proposed technique are experimentally demonstrated. We also show that the proposed system can be easily adapted to realize phase-coded microwave pulse generation. Chirped and phase-coded microwave pulses have been widely applied for many important scientific and industrial applications, such as in modern radar systems to increase the range resolution, in broadband communications systems to increase the signal-to-noise ratio (SNR), and in microwave computed tomography systems to increase the imaging resolution.

In our demonstrations, a periodic apodization function $A(x)$ with a constant period of P and a seed apodization function $f(x)$ with a Gaussian profile are always applied. The desired frequency chirping is then achieved by properly controlling the fiber shifting function d_k.

A. Linearly Chirped Microwave Pulse Generation

In the first example, we demonstrate the generation of a linearly frequency-modulated (LFM) or linearly chirped microwave pulse, which is still commonly used in modern radar systems due to the generation simplicity [25]. Photonic generation of linearly chirped microwave pulses has been intensively investigated and many techniques have been proposed [6], [7], [10]–[16]. To generate a linearly chirped microwave pulse, according to (4), a linearly increasing shifting function d_k is required.

The key device in the proposed microwave waveform generation system is the SD-CFBG. In our experiment, the SD-CFBG is fabricated in a hydrogen-loaded single-mode fiber using a frequency-doubled argon-ion laser (Coherent FreD 300 C) operating at 244 nm. A 50-mm long linearly chirped phase-mask with a chirp rate of $C = 0.24$ nm/mm is employed. The refractive index modulation has a maximum index change of $\Delta n_{\max} = 2.5 \times 10^{-4}$. A strong reflection (up to 90%) is achieved to ensure a high energetic efficiency. The produced grating has a center wavelength of 1558.3 nm, which is selected to match the center wavelength of the input transform-limited optical pulse. The desired linear shifting of the fiber is accurately performed during the grating fabrication process by a computer-controlled high-precision translation stage that has a resolution of 1 μm. In the demonstration, the apodization period is set at $P = 2.78$ mm and the fiber shifting function d_k is selected to be linearly increasing from 0.1 to 2.6 mm, which would lead to the generation of a linearly chirped microwave pulse with 19 cycles.

The group delay response of the fabricated SD-CFBG is first measured using an optical vector analyzer (OVA, LUNA Technologies), with the result shown in Fig. 3. It can be seen that a

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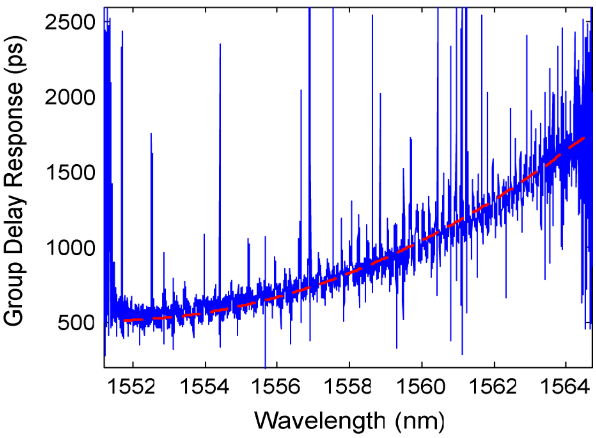

Fig. 3. Experimental result: the measured group delay response of the fabricated SD-CFBG for linearly chirped microwave pulse generation. The dashed line shows the quadratic fitting result.

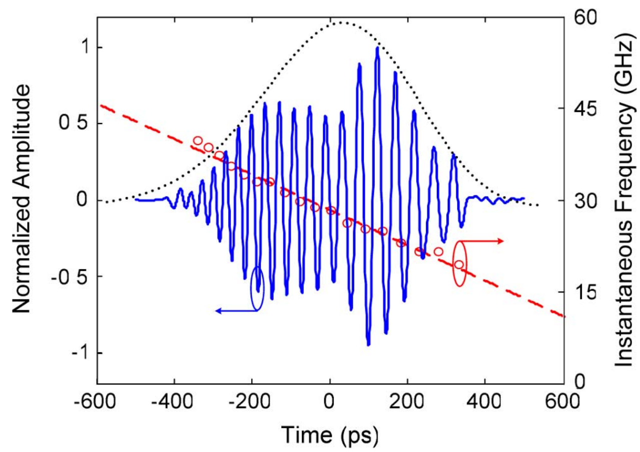

Fig. 4. Experimental result: the generated linearly chirped microwave pulse (solid line) and the instantaneous frequency (circle line). Dashed line: linear curve fitting of the instantaneous frequency. Dotted line: the calculated pulse envelope.

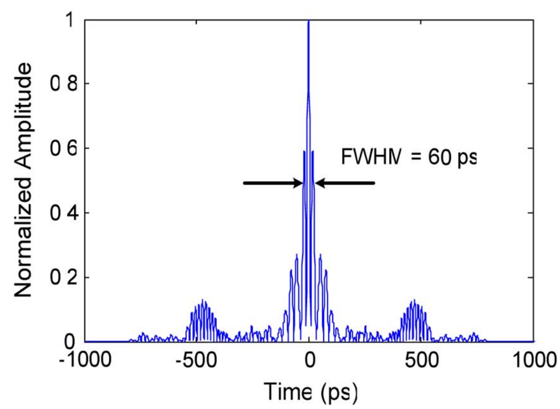

Fig. 5. Calculated autocorrelation between the generated linearly chirped microwave pulse and its reference.

nonlinear (quadratic) group delay response is obtained, which matches well with the theoretical prediction given by (3). A quadratic curve fitting result is also plotted in dashed line. The measured group delay response contains 18 jumps, which, however, are not clearly visible due to the very narrow bandwidth of each segment. One may notice that some group delay peaks are also observed, which are generated from the reflection spectral notches caused by the optical resonance between two adjacent sub-gratings in the SD-CFBG. Due to the very low reflected power at the spectral notches, the group delay response cannot be accurately measured at these notch wavelengths. In fact, such group delay peaks have no impact on the time-domain optical pulse shaping due to the incoherent feature of the system. This issue will be further discussed in Section IV.

The fabricated SD-CFBG is then incorporated into the experimental system shown in Fig. 1, to generate the linearly chirped microwave pulse. In the experiment, the MLL is a passively mode-locked fiber laser source that can generate a transform-limited Gaussian optical pulse train with a repetition rate of 48.6 MHz, a 3-dB pulsewidth of 550 fs, a 3-dB spectrum bandwidth of 8 nm, and an average power of 5 dBm. The broadband ultrashort optical pulse from the MLL is first sent to the fabricated SD-CFBG, which is working in the reflection mode. The SD-CFBG is functioning to slice the spectrum of the input optical pulse, to implement frequency-to-time mapping, and to temporally shift the mapped optical seed pulses. A PD with a bandwidth of 45 GHz is used to perform the optical to electrical conversion. Due to the limited bandwidth of the PD, a smooth microwave pulse is generated. The generated microwave waveform is measured in the time domain using a 53-GHz-bandwidth digital sampling oscilloscope (Agilent 86100 C). A broadband DC block is also used to eliminate the dc component in the generated microwave pulse.

The measured result is shown in Fig. 4. As can be seen, a chirped microwave waveform is generated. The instantaneous frequency of the generated microwave pulse is also plotted in Fig. 4 in circles, which is obtained by calculating the reciprocal of the seed pulse spacing. A linear curve fitting for the measured instantaneous frequency is also performed, which is shown in Fig. 4 in dashed line. It is shown that a linearly chirped microwave pulse is generated. The instantaneous frequency is linearly decreasing from 38 to 17 GHz within the main pulse lobe, with an equivalent frequency chirp rate of 26.25 GHz/ns. According to the experimental results, a TBWP of 16.8 is achieved for the generated linearly chirped microwave pulse.

Given the quadratic group delay response in (3), the waveform envelope $w(t)$ is also numerically calculated by using the Fourier transform method [24], with the result plotted in Fig. 4 in dotted line. Note that the generated pulse envelope does not exactly fit the simulated profile, which is mainly due to the non-ideal (non-flat) spectral response of the SD-CFBG.

In a radar system, a chirped or phase-coded microwave pulse is usually compressed through matched filtering or autocorrelation at the radar receiver [26]. Fig. 5 shows the calculated correlation between the generated linearly chirped microwave pulse and its reference pulse. The autocorrelation peak has a full-width at half-maximum (FWHM) of 60 ps. Considering the FWHM of the generated chirped microwave pulse is 795 ps as shown in Fig. 4, a pulse compression ratio of 13.2 is achieved. It is also shown in Fig. 5 that a peak-to-sidelobe ratio (PSR) of 7.7 is realized.

It is worth noting that a linear frequency chirping is not always the only frequency modulation scheme in a microwave

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radar system. In fact, the frequency chirping can be of any form, provided that the matched filter in the receiver end is designed to match the transmitted chirped microwave pulse. The presented approach can also be used to generate other types of chirped microwave waveforms, such as nonlinearly chirped and step-chirped microwave pulses by properly designing the fiber shifting function d_k. These waveforms can also find applications in spread-spectrum communications [2] and microwave computed tomography [3].

B. Nonlinearly Chirped Microwave Pulse Generation

Although linearly chirped microwave pulses are widely used in pulsed radar systems thanks to the generation simplicity, the autocorrelation of a linearly chirped microwave pulse at a radar receiver usually has relatively high sidelobes which are not expected, especially in an environment with multiple targets and clutter. The autocorrelation sidelobes can be reduced by applying a window function to its reference. However, since the filtering process is no longer exactly matched to the transmitted signal, it will reduce the SNR at the receiver [25]. This problem can be alleviated by using microwave pulses with nonlinear frequency chirping. Nonlinear frequency chirping has an advantageous feature - the pulse spectrum can be tailored to substantially reduce the autocorrelation sidelobes while maintaining the maximum SNR performance [27].

To generate a nonlinearly chirped microwave pulse, i.e., with quadratic frequency chirping, using the proposed approach, a quadratic fiber shifting function d_k is required according to (6). In this second example, the apodization period is set at $P = 2.63$ mm and the fiber shifting function d_k is selected to be quadratically increasing from 0.1 to 4.5 mm, which would lead to the generation of a nonlinearly (quadratically) chirped microwave pulse with 20 cycles.

A second SD-CFBG is fabricated using the same linearly chirped phase mask. The group delay response of the fabricated grating is measured and shown in Fig. 6. A nonlinear (cubic) group delay response containing 19 jumps is obtained, which agrees well with the theoretical prediction given by (3). The cubic fitting curve is also plotted in Fig. 6 in dashed line. Fig. 7 shows the generated nonlinearly chirped microwave pulse by use of the second SD-CFBG. The instantaneous frequency of the generated microwave pulse is also shown in circles in Fig. 7, with the quadratic fitting result shown in dashed line.

As can be seen in Fig. 7, a nonlinearly chirped microwave pulse with an FWHM of 808 ps is generated. The instantaneous frequency is quadratically decreasing from 43 to 14 GHz. The frequency chirp rate of the generated microwave pulse is linearly decreasing from 93.6 to 11.2 GHz/ns. The TBWP of the generated microwave pulse is calculated to be 23.2.

Fig. 8 shows the calculated autocorrelation of the generated nonlinearly chirped microwave pulse with its reference. The autocorrelation peak has an FWHM of 55 ps. Considering the FWHM of the generated chirped microwave pulse is 808 ps, as shown in Fig. 7, a pulse compression ratio of 14.7 is obtained. It is also shown in Fig. 8 that the achieved PSR is 14.3, which is much higher than that when a linearly chirped microwave pulse is employed in the first example. Therefore, the autocorrelation sidelobes are reduced by employing nonlinear frequency chirping. The sidelobe level can be further reduced by finely controlling the envelope of the generated microwave pulse.

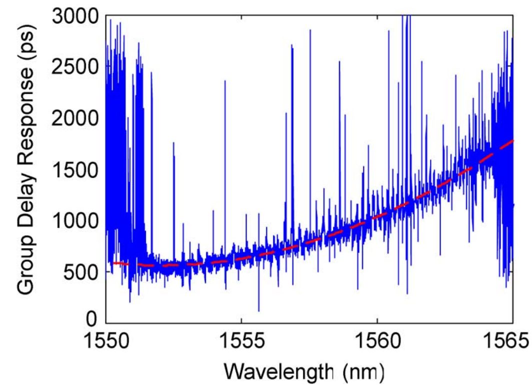

Fig. 6. Experimental result: the measured group delay response of the fabricated SD-CFBG for nonlinearly chirped microwave pulse generation. The dashed line shows the cubic curve fitting result.

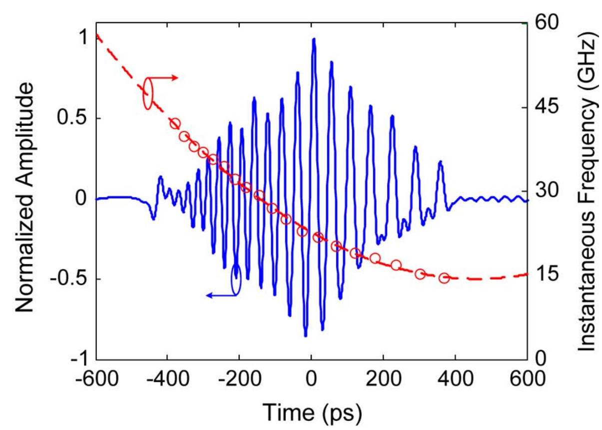

Fig. 7. Experimental result: the generated nonlinearly chirped microwave pulse (solid line) and the instantaneous frequency (circle line). The dashed line shows the quadratic curve fitting of the instantaneous frequency.

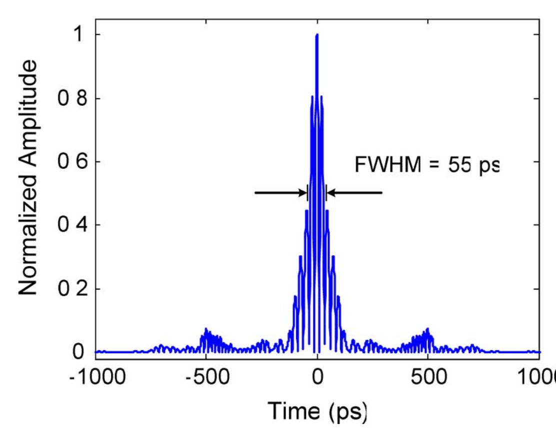

Fig. 8. Calculated autocorrelation bewteen the generated nonlinearly chirped microwave pulse and its reference.

C. Step-Chirped Microwave Pulse Generation

Stepped frequency modulation or microwave frequency-hopping technique is another effective method to improve the range resolution of a microwave radar system. The main advantage of

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this technique is that the instantaneous bandwidth is small compared with the overall bandwidth of a step-chirped microwave pulse, which allows the use of narrowband and low-cost hardware to support the transmission of a microwave waveform with a wide overall bandwidth [28]. Step-chirped microwave waveforms have also been widely used in wireless communications systems due to the advantages of high resistance to narrowband interference, low probability of interception and coexistence with other communications schemes [2].

To generate a step-chirped microwave pulse, the fiber shifting function d_k should be a step function. The apodization period is again set at $P = 2.63$ mm to generate a microwave pulse with 20 cycles. A four-level stepped fiber shifting function ($d_k =$ 0.7, 1.4, 2.1 and 2.8 mm) is designed, as shown in Fig. 9(a), which would lead to the generation of a step-chirped microwave pulse with four different instantaneous carrier frequencies. A SD-CFBG is then fabricated with the designed fiber shifting function that is implemented by shifting the fiber with four different d_k during the grating fabrication process. Fig. 9(b) shows the measured group delay response of the fabricated SD-CFBG. As expected, the entire group delay response consists of four individual linear group delay responses with four different slopes. The fabricated SD-CFBG is then incorporated in the microwave pulse generation system shown in Fig. 1. Again, thanks to the simultaneous spectral slicing, frequency-to-time mapping and temporal shifting in the SD-CFBG, a step-chirped microwave pulse with four carrier frequencies at 18, 21.8, 25.6 and 31 GHz and three frequency jumps within the main pulse lobe is obtained at the output of the PD, as shown in Fig. 9(c). The circles show the instantaneous microwave carrier frequency, which is obtained by calculating the reciprocal of the seed pulse spacing.

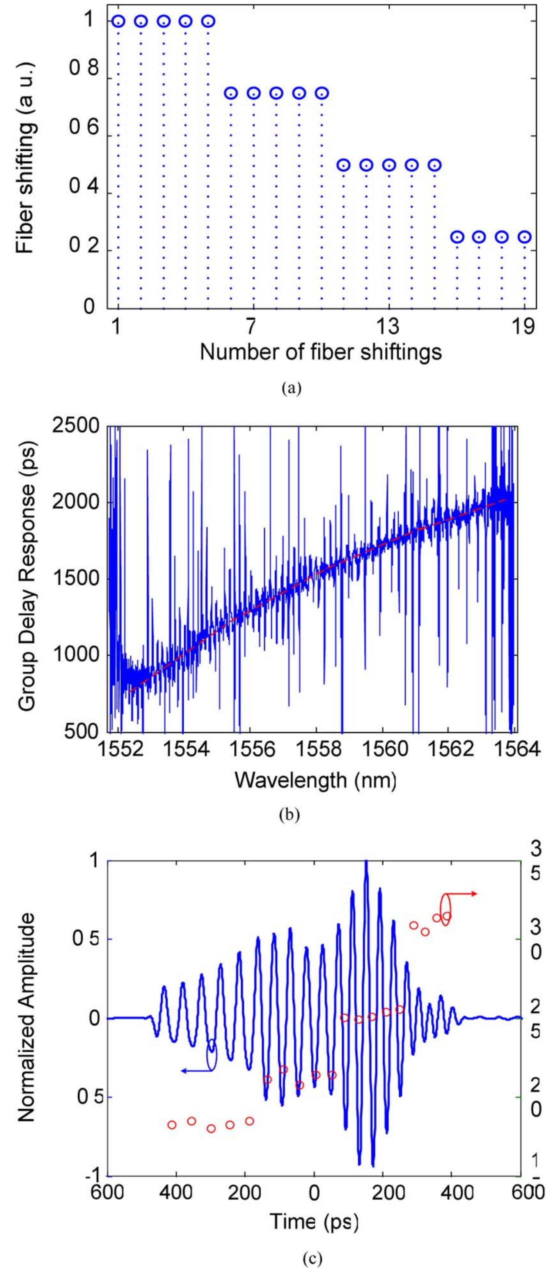

Fig. 9. Step-chirped microwave pulse generation. (a) The designed fiber shifting function. (b) The measured group delay response of the fabricated SD-CFBG. (c) The generated step-chirped microwave pulse (solid line) and the instantaneous frequency (circle line).

D. Phase-Coded Microwave Pulse Generation

Phase coding is another technique to increase the TBWP of a microwave pulse. Phase-coded microwave pulses have been widely adopted in radar and code division multiple access (CDMA) systems. The proposed technique can also be easily adapted for phase-coded microwave pulse generation.

According to (4), the reflected signal from the SD-CFBG is an optical pulse burst with the pulse spacing determined by the fiber shifting function. If the fiber shifting function has uniform spacing, i.e., d_k is a constant for different k, then an optical pulse burst with identical temporal spacing is resulted. To implement phase modulation, a simple solution is to use a fiber shifting function with non-uniform spacing. It was demonstrated recently by Dai and Yao that arbitrary phase modulation can be implemented based on pulse position modulation [20]. If a fiber shifting function is properly designed, the position of the seed pulses is modulated. With the help a microwave bandpass filter, a phase-coded microwave waveform would be generated from the pulse-position-modulated optical pulse burst [20].

IV. Discussion

In the proposed optical pulse shaping system, an optical pulse burst is generated from a single input optical pulse thanks to the simultaneous spectral slicing, frequency-to-time mapping and temporal shifting by a single SD-CFBG. By controlling the temporal pulse spacing, the generation of a large TBWP microwave arbitrary waveform has been demonstrated. In addition to the generation of chirped or phase-coded microwave waveforms, the proposed technique can also be adapted to generate other microwave waveforms. For example, a microwave arbitrary waveform can be synthesized by incoherently superposing a set of seed optical pulses with the proper temporal spacing. This concept has been proved for coherent optical arbitrary pulse shaping [18]. Compared with the approach in [18], the proposed photonic microwave waveform generation system has the key advantage that the pulse shaping process is incoherent, making the

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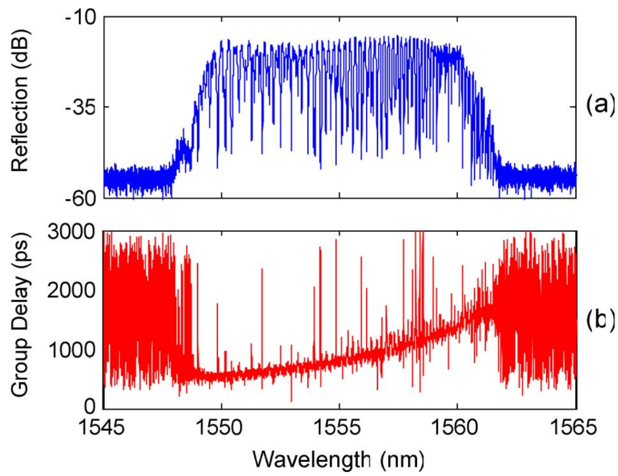

Fig. 10. (a) Measured reflection spectral response and (b) the group delay response of the fabricated SD-CFBG for nonlinearly microwave pulse generation.

process insensitive to the environmental fluctuations. In addition, the ability in performing individual amplitude modulation of each seed optical pulse can also be achieved by controlling the seed apodization function $f_k(x)$, which would provide an additional flexibility in microwave arbitrary waveform generation.

In order to convert a specific optical pulse burst into a smooth microwave waveform, a bandwidth-limited PD is employed, which functions equivalently as a low-pass filter. In addition, a broadband DC block is also used to eliminate the baseband component in the generated chirped microwave pulse. In fact, this is equivalent to using a microwave bandpass filter to select the spectral channel of interest from a multichannel spectral response of a pulse-position-modulated pulse burst, as first reported in [20]. To perform optical pulse shaping and microwave bandpass filtering in an all-optical fashion, the microwave bandpass filter can be a photonic microwave delay-line filter implemented in the optical domain [29].

In the measured group delay responses of the fabricated SD-CFBGs, as shown in Figs. 3, 6 and 9(b), some group delay peaks are observed. These group delay peaks are measurement errors due to the very low power level at the reflection spectral notches [14]. The spectral notches are caused by optical resonance between adjacent sub-gratings in the SD-CFBG [14]. In our proposed SD-CFBG design, the adjacent sub-gratings spatially separated along the fiber form a multi-cavity Fabry–Perot resonator. Ideally, if the sub-gratings have completely separate (no overlapping) spectral responses, no optical resonance would be generated, and a clean comb filter response with a smooth group delay response will be obtained, as illustrated in Fig. 2(b). In practice, however, the spectral crosstalk between the adjacent channels will lead to obvious optical resonance. The reflection spectral response and the group delay response of the SD-CFBG used for nonlinearly chirped microwave pulse generation are measured and shown in Fig. 10. A strong optical resonance is observed in the reflection spectrum. It can be seen that the group delay peaks are all resulted from the spectral notches. A smaller FSR is observed for a longer wavelength, where a longer cavity length (a longer fiber shifting) is set. It is important to note that the group delay peaks due to the optical resonance have negligible impact on the time-domain optical pulse shaping because the optical power reflected from these resonance notches is low and negligible. There is no interference between the adjacent seed pulses in the incoherent scheme. This conclusion has been verified by the experiment, as shown in Figs. 4, 7 and 9(c).

V. Conclusion

In conclusion, we have proposed and experimentally demonstrated a novel all-optical technique to achieving large TBWP microwave arbitrary waveform generation by using an SD-CFBG. The SD-CFBG in the proposed system was functioning to perform simultaneously spectral slicing, frequency-to-time mapping and temporal shifting of the input ultrashort optical pulse, which makes the system have a significantly simplified design and very low insertion loss. The SD-CFBG was produced by UV illumination using a linearly chirped phase mask by axially shifting the fiber to introduce a spatial spacing between two adjacent sub-gratings during the fabrication process. By properly designing the fiber shifting function, an SD-CFBG with different group delay response would be resulted, which can be used to generate a microwave waveform with different frequency chirping or phase coding. Three examples to generate a linearly chirped, a nonlinearly chirped and a step-chirped microwave waveform were experimentally demonstrated. The proposed technique provides a simple and effective solution to the generation of high-speed and large TBWP microwave waveforms with arbitrary frequency chirping or phase coding, which can find wide applications in modern radar and wireless communications systems.

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