Simultaneous Optical Spectral Shaping and Wavelength-to-Time Mapping for Photonic Microwave Arbitrary Waveform Generation

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***Abstract*—Photonic microwave arbitrary waveform generation (AWG) based on simultaneous optical spectral shaping and wavelength-to-time mapping in a single specially designed linearly chirped fiber Bragg grating (LCFBG) is proposed. In the proposed approach, the spectrum of a transform-limited ultrashort optical pulse is spectrally shaped, and at the same time is wavelength-to-time mapped by the LCFBG to generate a microwave pulse with a shape identical to that of the shaped optical spectrum. By designing the LCFBG to have an arbitrary reflection profile, a microwave arbitrary waveform is generated. A simple and effective technique to synthesize the LCFBG with an arbitrary reflection response is proposed. Since amplitude-only index modulation is required, the designed LCFBG can be easily fabricated. Two examples showing the generations of a chirped microwave pulse and an ultra-wideband monocycle pulse are experimentally demonstrated.**

***Index Terms*—Arbitrary waveform generation (AWG), chromatic dispersion, linearly chirped fiber Bragg grating (LCFBG), spectral shaping, wavelength-to-time mapping.**

I. Introduction

High-frequency and large bandwidth (BW) microwave arbitrary waveform generation (AWG) has become an important area that has numerous scientific and industrial applications, such as in ultra-wideband (UWB) and multiple-access communication systems, electronic countermeasures, and pulsed radar systems. Photonically assisted microwave AWG techniques provide the capability of generating high-frequency and large BW microwave arbitrary waveforms which may not be fulfilled by conventional electronic techniques. Several photonics-based pulse shaping techniques have been recently proposed and demonstrated for the generation of microwave arbitrary waveforms, such as direct space-to-time pulse shaping [1] and temporal pulse shaping [2]–[4]. On the other hand, microwave arbitrary pulse shaping can also be implemented in the frequency domain using an optical spectrum shaper followed by a wavelength-to-time mapper [5]–[8]. By properly designing the frequency response of the optical spectral shaper, a microwave pulse with the shape identical to that of the shaped optical spectrum is obtained thanks to the wavelength-to-time mapping in a dispersive medium. Since the spectral shaping and wavelength-to-time mapping are achieved using two separate devices in all the previous approaches [5]–[8], the system becomes complicated, costly, and with high loss. In this letter, for the first time to the best of our knowledge, we propose an all-fiber technique to implement microwave AWG based on simultaneous optical spectral shaping and wavelength-to-time mapping in a single linearly chirped fiber Bragg grating (LCFBG). The LCFBG is designed to have a magnitude response corresponding to the target microwave waveform and a linear group delay response for wavelength-to-time mapping. Compared with the photonic-based microwave AWG systems in [5]–[8], the presented system provides the advantages of smaller size, lower loss, better stability, and potential for integration.

Optical AWG based on Fourier transform pulse shaping using a sampled fiber Bragg grating (SFBG) has been recently proposed [9]. The SFBG can be designed to perform arbitrary spectral shaping, and at the same time to compress the predispersed input pulse. Since the SFBG is fabricated based on reconstruction-equivalent-chirp technique, a simple implementation is ensured. However, the small operational BW of the SFBG (<1 nm) limits its applications to ultrashort optical pulse shaping, where a pulse shaper with a BW up to tens of nanometers is usually required. In this letter, we demonstrate a microwave AWG system based on simultaneous spectral shaping of a femtosecond optical pulse and wavelength-to-time mapping in a single broadband LCFBG (BW $>$ 12 nm). A simple and effective technique to synthesize LCFBG based on an accurate mapping of the grating reflection response to the refractive index apodization is proposed.

II. System Configuration

A diagram showing the proposed photonic microwave AWG system is illustrated in Fig. 1. A transform-limited ultrashort optical pulse from a femtosecond pulsed laser (FSPL) is sent to a specially designed LCFBG working in the reflection mode. The LCFBG, which has a magnitude response corresponding to a scaled version of the target temporal waveform, is used to shape the power spectrum of the input optical pulse. At the same time, due to the linear group delay response, the LCFBG also performs the dispersion-induced wavelength-to-time mapping. A microwave waveform with its shape identical to that of a shaped optical power spectrum is then generated at the output of a photodetector.

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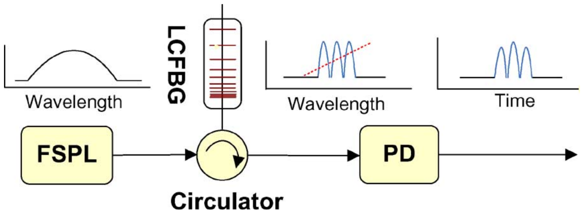


Fig. 1. Schematic diagram showing a microwave arbitrary waveform generator using a single LCFBG. PD: photodetector.

III. LCFBG Design

The key component in the proposed system is the LCFBG, which should be designed to have a magnitude as well as a phase response that can fulfill the requirements for both arbitrary spectral shaping and dispersion-induced wavelength-to-time mapping. Thanks to the inherent linear group delay response, an LCFBG can always act as a linear wavelength-to-time mapper. Therefore, the focus of our work is to synthesize the grating refractive index modulation profile from the target grating magnitude response.

In this letter, we present a simple and effective method to synthesize a highly reflective and largely chirped fiber Bragg grating (FBG) with an arbitrary reflection spectrum based on the accurate mapping of grating reflection response to the refractive index modulation. We can first set up the mapping relationship by applying a linearly increasing index modulation function to a test grating with the use of a linearly chirped phase mask and then measuring the grating reflection spectrum. A linear index modulation function is first constructed, which is expressed as

$$\Delta n_L(z) = \Delta n_{\max}\frac{z}{L}\exp\left(j\frac{2\pi z}{\Lambda_0}\right)\exp\left[-j\frac{2\pi C(z-L/2)^2}{\Lambda_0^2}\right] \tag{1}$$

where Λ_0 is the grating period at the center of the LCFBG, L is the length of the LCFBG, and C is the grating chirp rate. We can imprint the index modulation function in (1) into the test grating using a given linearly chirped phase mask. Then the reflection spectrum $R_{\text{test}}(\lambda)$ of the fabricated test grating is measured. By equally dividing the grating into N consecutive segments with the positions z_i $(1 \leq i \leq N)$, we can get the sampled reflection spectrum $R_{\text{test}}(\lambda_i)$ thanks to the unique mapping relationship between $\Delta n_L(z_i)$ and $R_{\text{test}}(\lambda_i)$.

For a target grating reflection spectrum $R_{\text{target}}(\lambda)$, we can compare it with the test grating response $R_{\text{test}}(\lambda_i)$ wavelength by wavelength and then determine the desired index modulation function $\Delta n_D(z_i)$ by querying the linear index modulation function $\Delta n_L(z_i)$ segment by segment. Therefore, by applying the amplitude-only index modulation $\Delta n_D(z_i)$ under the same experimental condition, a desired LCFBG with the target reflection spectrum can be easily fabricated with the current FBG fabrication technology.

The LCFBG design process can be described using the flowchart shown in Fig. 2. Simulation results for each design step are also plotted to numerically verify the proposed approach. In the simulation, the maximum index modulation of $\Delta n_{\max} = 0.0008$, grating chirp rate of $C = 2.4$ nm/cm, and grating length of $L = 5$ cm are chosen. The designed LCFBG has a target reflection spectrum corresponding to a UWB monocycle pulse [10].

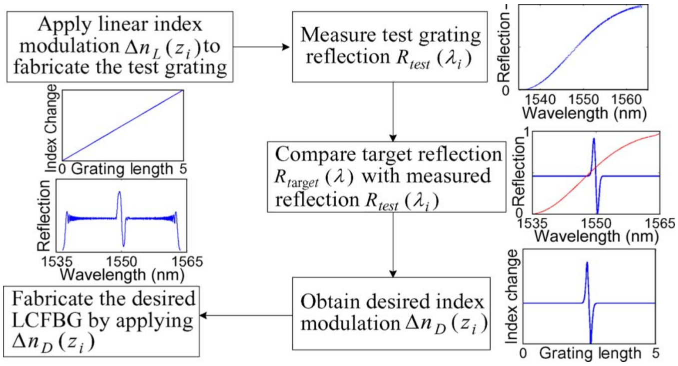
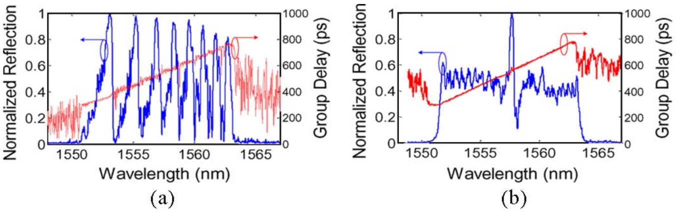


Fig. 2. Flowchart for the design and fabrication of an LCFBG with arbitrary magnitude response.



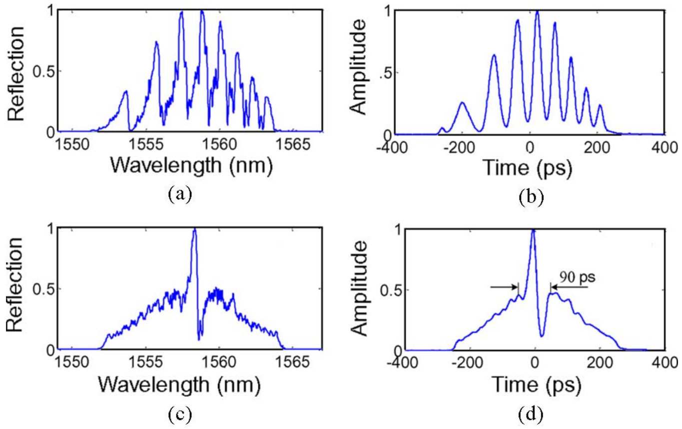
(a) (b)

Fig. 3. Measured reflection spectra and group delay responses of the fabricated LCFBGs for (a) chirped microwave pulse generation and (b) UWB monocycle pulse generation.

IV. Experiment

An experiment based on the setup shown in Fig. 1 is then carried out to verify the proposed approach. The FSPL is a commercial mode-locked fiber laser source that can generate an ultrashort pulse train with a repetition rate of 46 MHz, a pulsewidth of 550 fs, a 3-dB spectrum BW of 8 nm, and an average power of 5 dBm.

Two LCFBGs are first designed following the procedure shown in Fig. 2. The gratings are then fabricated by a frequency-doubled argon–ion laser operating at 244 nm using a linearly chirped phase mask. Due to the nonlinear response of the fiber to ultraviolet (UV) light, one needs to first measure the nonlinear response of the glass and then compensate the nonlinearity with a customized exposure function to produce the desired index modulation function. In fact, for a strong index modulation ($\Delta n_{\max} = 0.0008$), the linear approximation of fiber response to UV energy is well satisfied [11]. The two fabricated gratings both have a length of 5 cm and a chirp rate of 2.4 nm/cm. To ensure a high energy efficiency, the fabricated LCFBGs have a strong reflection as high as 98%. The center wavelength of the LCFBGs is 1558.1 nm, which is selected to match the center wavelength of the input optical pulse. The reflection spectrum and the group delay response of the fabricated LCFBGs are both shown in Fig. 3, which are measured using an optical vector analyzer (OVA, LUNA CTe) with a wavelength resolution of 1 pm. The first LCFBG has a reflection spectrum corresponding to a chirped pulse waveform, as shown in Fig 3(a), and the second LCFBG has a reflection spectrum corresponding to a UWB monocycle pulse, as shown in Fig 3(b). It can be seen from Fig. 3 that, no matter what the index modulation is, the linear group delay responses are always maintained. Therefore, the fabricated LCFBG can be



(a) (b)

(c) (d)

Fig. 4. Experimental results. (a) Shaped spectrum by an LCFBG for chirped microwave pusle generation. (b) Generated chirped microwave pulse. (c) Shaped spectrum by a second LCFBG for UWB monocycle pusle generation. (d) Generated UWB monocycle pusle.

also used to act as a wavelength-to-time mapper to convert the shaped optical spectrum to the target temporal waveform.

The two LCFBGs are then incorporated, respectively, into the experimental system shown in Fig. 1, to generate the desired temporal waveforms. The generated waveforms are measured both in the frequency domain using the OVA and in the time domain using a 63-GHz sampling oscilloscope (OSC). Fig. 4(a) shows the shaped optical power spectrum by the first LCFBG. Thanks to the simultaneous wavelength-to-time mapping in the LCFBG, a linearly chirped microwave pulse is generated, as shown in Fig. 4(b). A high-frequency chirped microwave pulse has been extensively employed in modern radar systems to increase the radar range resolution [12]. Fig. 4(c) shows the shaped optical spectrum by the second LCFBG. The generated temporal waveform, which is a UWB monocycle pulse with a pulsewidth of 90 ps, is shown in Fig. 4(d). To generate a UWB pulse that meets the spectrum requirement regulated by the US Federal Communications Commission (FCC) for indoor wireless communications, the monocycle pulse should have a pulsewidth of about 180 ps [10]. One solution to achieve the desired pulsewidth is to utilize an LCFBG with a larger dispersion (or equivalently a smaller chirp rate of 1.2 nm/cm). For practical applications, the optically generated UWB pulse train can be modulated by a binary sequence using an optical intensity modulator with ON–OFF keying modulation.

As can be seen from Fig. 4, the generated temporal waveform has almost an identical shape to the shaped optical spectrum, which verifies that the wavelength-to-time mapping is perfectly achieved by the LCFBGs. Note that the temporal waveform has a smoother trace compared to the optical spectrum, which is due to the limited BW of the OSC.

V. CONCLUSION

We have proposed and experimentally demonstrated a novel approach to achieving photonic microwave AWG using a single specially designed LCFBG to simultaneously perform optical spectral shaping and wavelength-to-time mapping. A technique to design an LCFBG with an arbitrary magnitude response and a linear group delay response was proposed based on an accurate mapping of the grating magnitude response to the refractive index modulation function. Amplitude-only index modulation is required to produce the designed LCFBGs. Two LCFBGs were designed and fabricated. The use of the LCFBGs for the generation of a chirped microwave pulse and a UWB monocycle pulse was experimentally demonstrated. Compared with the systems in [5] and [6], the main limitation of the technique for practical applications is that the system is not reconfigurable. A potential solution to improve the reconfigurability is to use a strain-gradient beam tuning technique [12].

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