Fourier Transform Ultrashort Optical Pulse Shaping Using a Single Chirped Fiber Bragg Grating

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***Abstract*—Fourier transform ultrashort optical pulse shaping using a single linearly chirped fiber Bragg grating (LCFBG) is proposed and experimentally demonstrated in this letter. The LCFBG in the system performs three functions: temporally stretching the input ultrashort pulse, shaping the pulse spectrum, and temporally compressing the spectrum-shaped pulse. The impulse response of the entire pulse shaping system is equal to the Fourier transform of the square of the grating power reflectivity function. By appropriately designing the grating reflection response, a temporal optical waveform in the subpicosecond regime can be accurately synthesized. An example to show the synthesis of a triangular optical pulse with a full-width at half-maximum of 2 ps is demonstrated.**

***Index Terms*—Chromatic dispersion, fiber Bragg grating (FBG), Fourier synthesis, optical pulse shaping.**

I. Introduction

FOURIER synthesis, also known as Fourier transform pulse shaping, is one of the most commonly used techniques for optical pulse shaping in the subpicosecond regime [1]. In a Fourier transform pulse shaping system, as shown in Fig. 1(a), a pair of dispersive elements with opposite chromatic dispersions is used to temporally stretch and compress the input optical pulse, and a spectral shaping device is incorporated between the two conjugate dispersive elements to realize optical spectral shaping in the Fourier domain. The optical spectral shaping can be implemented in the spatial domain using a programmable liquid crystal modulator (LCM) [2] or in the time domain using an electrooptic modulator (EOM) [3], [4]. For the latter case, the system is usually called a temporal pulse shaping (TPS) system. On the other hand, Fourier transform pulse shaping in the frequency domain has also been investigated. Two linearly chirped fiber Bragg gratings (LCFBGs) were used in [5] to perform Fourier transform pulse shaping, with the first LCFBG serving as a spectral shaper and the other as a dispersion compensator. To cancel completely the dispersion introduced by the first LCFBG, the second LCFBG must be precisely fabricated to have an exact opposite chirp, which would significantly increase the fabrication complexity and cost. In addition, the LCFBGs in

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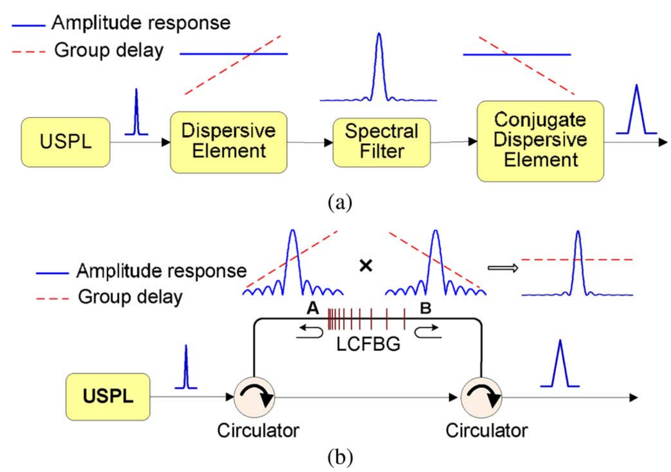

Fig. 1. Schematic diagrams showing: (a) a conventional Fourier transform optical pulse shaping system and (b) the proposed optical pulse shaping system using a single LCFBG. USPL: ultrashort pulsed laser and LCFBG: linearly chirped fiber Bragg grating.

[5] were designed based on the weak coupling (Born) approximation [6], making the LCFBGs have a very low energy efficiency.

In this letter, we propose and experimentally demonstrate a novel Fourier transform pulse shaper that uses only a single LCFBG. In the system, an input ultrashort optical pulse is first temporally stretched by the LCFBG, and then completely compressed by the same LCFBG by directing the dispersed pulse into the LCFBG from an opposite direction. Therefore, a perfect dispersion cancellation is obtained. At the same time, the LCFBG also acts as an optical spectral shaper, which is designed to have a user-defined spectral reflection response according to the target temporal waveform. The impulse response of the entire system is equal to the Fourier transform of the square of the LCFBG power reflectivity function.

The key device in the system is the LCFBG, which should be designed to have a strict linear group delay response and a user-defined reflection amplitude response. In this letter, we propose to use a simple and effective method based on an accurate mapping of the grating reflection response to the refractive index apodization to synthesize and produce the required LCFBG [7]. It is different from the design based on the Born approximation which makes the LCFBGs have a very low energy efficiency; the method here can make the grating have a high reflectivity, leading to an improved energy efficiency [5]. Since an amplitude-only index apodization is required, the LCFBG can be easily realized with the current phase-mask-based FBG fabrication technology.

II. Principle

A schematic diagram showing the proposed Fourier transform optical pulse shaping system is illustrated in Fig. 1(b). The system consists of a single LCFBG and two three-port optical circulators. The two ports of the LCFBG (A and B) are connected by the circulators to route the input optical pulse to enter the LCFBG from the two ports. The LCFBG can be modeled as a linear, time-invariable (LTI) system, with a transfer function given by $H_A(\omega) = |H_A(\omega)| \exp[j\Phi_A(\omega)]$ if the input pulse enters the LCFBG from port A and is then reflected by the LCFBG, where $|H_A(\omega)|$ and $\Phi_A(\omega)$ are the amplitude and the phase response, respectively. Under the first-order dispersion approximation, which is always true for an LCFBG with very low higher order dispersion, the transfer function becomes [8]

$$H_A(\omega) = R(\omega) \exp(\frac{-j\ddot{\Phi}_A \omega^2}{2}) \qquad (1)$$

where ω is the offset frequency from the optical central frequency ω_0, $R(\omega)$ is the grating power reflectivity, and $\ddot{\Phi}_A = d^2\Phi_A/d\omega^2|_{\omega=0}$ is the first-order dispersion coefficient. Similarly, the LCFBG has a transfer function $H_B(\omega)$ if the input optical pulse enters the LCFBG from port B and is then reflected by the LCFBG

$$H_B(\omega) = R(\omega) \exp(\frac{-j\ddot{\Phi}_B \omega^2}{2}) \qquad (2)$$

where $\ddot{\Phi}_B = d^2\Phi_B/d\omega^2|_{\omega=0}$ is again the grating first-order dispersion coefficient. Due to the linear group delay response of the LCFBG, we have $\ddot{\Phi}_A = -\ddot{\Phi}_B$. Therefore, the impulse response of the entire system is given by

$$h(t) = \tilde{F}\left[H_A(\omega)H_B(\omega)\right] = \tilde{F}\left[R^2(\omega)\right] \qquad (3)$$

where $\tilde{F}(\cdot)$ denotes the Fourier transform operation. As can be seen, the impulse response of the entire system is equal to the Fourier transform of the square of the grating power reflectivity.

For a temporal waveform $y(t)$ to be synthesized, the desired grating power reflectivity function is determined by

$$R(\omega) = \sqrt{\frac{Y(\omega)}{G(\omega)}} \qquad (4)$$

where $Y(\omega)$ and $G(\omega)$ are the Fourier transforms of the target output pulse $y(t)$ and the input pulse $g(t)$, respectively.

An accurate grating synthesis technique is required to synthesize the grating refractive index modulation profile from the desired LCFBG power reflectivity function given by (4). It was reported in [6] that when an LCFBG has a large dispersion, the grating apodization profile can be linearly mapped to its spectral response. Our recent study shows that the mapping relationship is unique, but not always linear, depending on the grating parameters such as the refractive index modulation coefficient, the grating chirp rate, and the bandwidth [7]. In this letter, the desired LCFBG is synthesized and produced using a simple and effective technique based on an accurate mapping of the grating reflection response to the refractive index apodization [7]. In the applied technique, a calibration process is performed first by fabricating and measuring a test grating to determine the accurate mapping relationship, which offers a better accuracy as compared with the approach in [5].

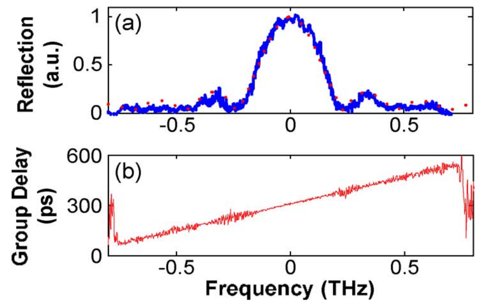

Fig. 2. (a) Reflection spectrum and (b) group delay response of the fabricated LCFBG. Solid line: measured spectrum and dotted line: desired spectrum.

III. Experiment

To prove the concept, an experiment to generate an ultrashort optical triangular waveform is carried out. The technique can be extended to generate other types of ultrashort waveforms. In our design, the input optical pulse is assumed to be an ideal Dirac impulse function with $G(\omega) \approx 1$. The target temporal waveform $y(t)$ is a triangular optical pulse with a full-width at half-maximum (FWHM) of 2 ps. Therefore, the desired LCFBG power reflectivity function, according to (4), is given by

$$R(\omega) = \sqrt{Y(\omega)/G(\omega)} = \sqrt{Y(\omega)} \propto |\mathrm{Sinc}(\omega/B)| \qquad (5)$$

where B is the spectral bandwidth of the LCFBG, which has a value of $2\pi \times 0.25$ THz. The selected bandwidth is determined by the desired pulsewidth. To synthesize a shorter optical pulse, an LCFBG with a broader bandwidth is required. In practice, the LCFBG bandwidth is limited by the pitch range of the phase mask. The fabrication of an ultra-broadband LCFBG with a bandwidth of more than 400 nm $(2\pi \times 50$ THz$)$ has been reported recently [9].

The LCFBG with the desired reflection response given by (5) is first designed by applying the presented grating synthesis technique [7]. The grating is then fabricated using a linearly chirped phase mask. The fabricated LCFBG has a length of 5 cm, a chirp rate of 2.4 nm/cm, and a strong reflection (the maximum reflectivity is around 90%). The center wavelength of the LCFBG is selected to match the central wavelength of the input optical pulse. The reflection spectrum and the group delay response of the fabricated LCFBG are measured using an optical vector analyzer (OVA, Luna Technologies). The measured reflection profile matches well with the desired reflection profile, as shown in Fig. 2(a). The linearity of the group delay response is also achieved, as shown in Fig. 2(b).

The fabricated LCFBG is then incorporated into the experimental setup, shown in Fig. 1(b), to perform optical pulse shaping. The system performance is measured in both the frequency domain and the time domain using the OVA. The measured system spectral response, including the amplitude response and the group delay response, is shown in Fig. 3. A system amplitude response corresponding to $|\mathrm{Sinc}(\omega/B)|$ is obtained, as shown in Fig. 3(a). The desired amplitude response is also shown as dotted line in Fig. 3(a) for comparison. A constant system group delay response is observed, as shown in Fig. 3(b), which confirms the perfect dispersion cancellation.

Fig. 4(a) shows the system impulse response measured by the OVA. Due to the limited temporal resolution of the OVA, the details of the impulse response are not fully shown. To evaluate

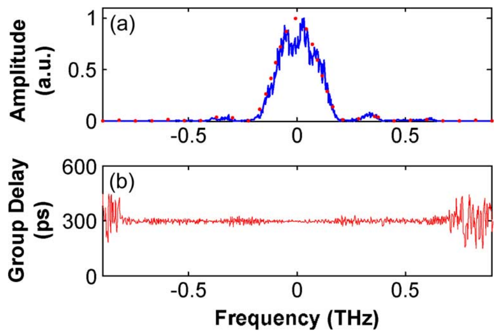

Fig. 3. (a) Amplitude response and (b) group delay response of the entire pulse shaping system. Solid line: measured amplitude response and dotted line: desired amplitude response.

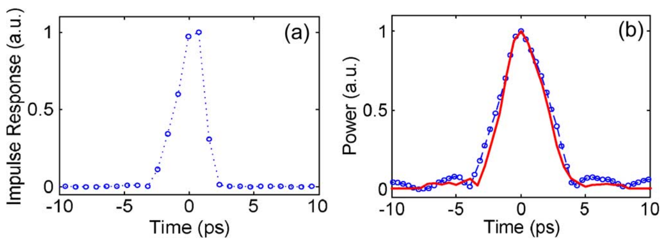

Fig. 4. Experimental results. (a) Measured system impulse response. (b) Synthesized triangular waveforms obtained from the measured LCFBG spectral response (circle line) and from the measured phase response with ideal amplitude response (solid line).

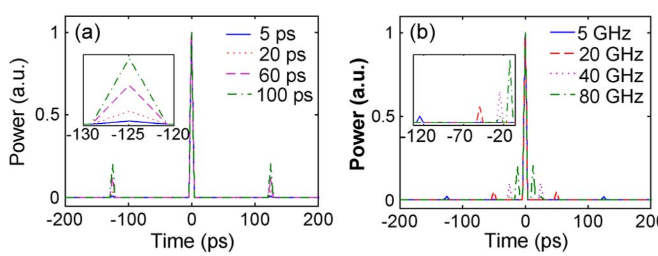

Fig. 5. Synthesized waveforms with different sinusoidally distributed GDRs. (a) GDR frequency is 8 GHz with different amplitudes. (b) GDR amplitude is 6 ps with different frequencies. (Inset: the sidelobes).

the system performance more accurately, the measured system spectral response, including its amplitude response and phase response, is used to calculate the system impulse response, with the result shown in Fig. 4(b) (circle line). A triangular-shaped impulse response with more details is obtained. The synthesized waveform obtained from the measured grating phase response and the ideal amplitude response is also shown in Fig. 4(b) (solid line). It is shown that the pulse shaping errors are resulted in part from the inaccuracy of the LCFBG amplitude response, which can be improved by refining the fabrication process.

The group delay ripples (GDRs) in the LCFBG may also have an impact on the pulse shaping accuracy. To evaluate the impact of the GDRs on the pulse shaping performance, the synthesized triangular waveforms based on an ideal grating amplitude response and different sinusoidally distributed GDRs are calculated, with the results shown in Fig. 5. For the measured grating response in Fig. 2, the frequency and the amplitude of the grating GDRs are estimated to be around 8 GHz and 6 ps, respectively. According to the results in Fig. 5, the corresponding waveform has a peak-to-sidelobe intensity ratio of 100, which is usually acceptable for practical pulse shaping applications. Therefore, the proposed LCFBG-based optical pulse shaping system is tolerant to the grating GDRs. A comprehensive study on the tolerances of an optical pulse compression system against the GDR can be found in [10].

Note that in the synthesis of the triangular pulse, the input optical pulse was assumed to be a Dirac impulse function. For practical pulse shaping with a higher accuracy, the nonzero input pulsewidth should be taken into consideration. Then the LCFBG should be designed with a reflection power spectrum given by $\sqrt{Y(\omega)/G(\omega)}$.

IV. Conclusion

A novel technique to implement ultrashort optical pulse shaping based on Fourier spectrum synthesis using a single LCFBG was proposed and experimentally demonstrated. The LCFBG in the system was functioning as a spectrum shaper, and at the same time, as a conjugate dispersive element pair to perform pulse stretching and pulse compression. The use of a single LCFBG guarantees an exact cancellation of the dispersions, making the pulse shaping system have a simplified structure with a better pulse shaping accuracy [11]. An experiment to demonstrate the generation of a triangular pulse with an FWHM of 2 ps was performed.

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