

1 053-nm all-fiber pulse multi-pass stretcher using a linear chirped fiber Bragg grating

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An all-fiber optical laser pulse multi-pass stretcher using a chirped fiber Bragg grating (CFBG) is demonstrated. Pulses from a 1 053-nm mode-locked fiber seed oscillator are stretched by multiple passing through a chirped fiber grating set in a fiber regenerative amplifier structure. We stretch the pulse from 16 ps to 1.855 ns after it transmits seven loops in the stretcher. The main factors that affect the stretching results are discussed.

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In 1974, the chirped-pulse amplification (CPA) technique was adopted to develop high power laser pulses^[1] and acquire terawatt-class ultrashort pulses^[2–4]. Since 1993, this technique has become an important solution for boosting pulses to high energy levels in a fiber system^[5,6]. In a CPA system, a stretcher is applied to stretch optical pulses and a compressor recompresses the pulses after amplification. Conventional diffraction grating pairs are commonly used as stretchers and compressors, but they are difficult to fabricate because of their high cost. When bulk optics and gratings are used in optical systems, they require free space propagation and alignment. A dispersion compensating fiber can work as a pulse stretcher but it must be very long (~ 100 m)^[7] and may need a special design^[8] to achieve proper dispersion. In recent years, air-core photonic band gap fibers have been used as a new type of compressor in CPA systems to obtain very high peak power pulses^[7,9]; however, they are difficult to manufacture. The chirped fiber Bragg grating (CFBG) is another outstanding stretcher or compressor because it is easy to obtain and small enough to play an important role in miniaturizing high-power laser systems. As such, CFBGs have become a research hotspot both in theory and various fields of application in recent years^[10,11]. Using CFBG and an Er- or Yb-doped optical fiber amplifier in the CPA technique yields an all-fiber system through which the application fields of CPA may be expanded. In 1995, Minelly et al.^[12] acquired 20-nJ femtosecond pulses using CPA and a cladding-pumped fiber amplifier. As a stretcher, a 5-mm-long CFBG with a bandwidth of 15 nm can stretch 200-fs seed pulses derived from a Kerr-mode-locked fiber laser to a width of ~ 50 ps. Galvanauskas et al.^[13,14] employed a 12-cm-long linear CFBG with a 9.8-nm bandwidth to compress initial 200-ps and 2-ns pulses and obtained 1.9-ps pulses with 300-nJ energy after recompression.

Fast ignition is a new igniting scheme for inertial confinement fusion. An effective CPA system for fast ignition requires pulses to be first stretched from 1–2 ns and then recompressed to 1–10 ps after amplification^[15].

However, the scheme requires the CFBG to provide a large enough dispersion as a stretcher. One of the solutions to this problem is to fabricate a very long CFBG, as reported in 2009^[16], where a 30-cm CFBG was used to stretch pulses to 2.5 ns. Another solution is to connect several CFBGs together for increased dispersion^[17]. However, long CFBGs are difficult to fabricate and very expensive. Moreover, connecting several CFBGs complicates the stretcher configuration and different characteristics between the gratings may affect the quality of stretched pulses. If we can use the CFBG in a flexible manner, the stretching and compression parameters may be tailored to meet the application requirements. Reusing one CFBG to realize multi-pass stretching and multi-pass compressing will be feasible for it. Fiber optical amplifiers based on rare-earth-doped fibers have been investigated for decades^[18–20]. All-fiber regenerative amplifiers circulate optical pulses in a fiber cavity for amplification. Pulses from a Yb-fiber laser are stretched to ~ 450 ps by a CFBG with ~ 1 -nm bandwidth and become amplified in a subsystem including a regenerative amplifier^[21].

In this letter, we demonstrate a 1 053-nm all-fiber optical laser pulse multi-pass stretcher using a CFBG. We stretched pulses from 16 ps to 1.855 ns after seven cycles of reflection by a 4.5-cm-long CFBG with a bandwidth of 7.8 nm, which can provide a 394.6-ps time delay for one reflection. The main factors that affect the stretching results and a practicable compressor are discussed.

A nonlinear polarization rotation (NPR) passively mode-locked Yb-doped fiber laser demonstrated by our research group delivers 16-ps positive-chirped pulses^[22]. The measured spectral bandwidth of this laser is 7.1 nm with a center wavelength of 1 053 nm and has a repetition rate of 17 MHz and a calculated transform limited pulse duration of 567 fs. An autocorrelator (Angewandte Physik & Elektronik GmbH) was used to measure pulses that theoretically fit a Gaussian pulse profile. The measured full-width at half-maximum (FWHM) delay of the autocorrelation trace is 23.2 ps, as shown in Fig. 1. The real FWHM time (T_{FWHM}) for the pulse was calculated

to be 16 ps for the Gaussian pulse^[23]. To obtain the 1-Hz seed pulses we desire, an acousto-optic modulator (AOM) was used to select pulses from the 17-MHz pulse train. The dispersion length L_D in single-mode fiber is given by^[24]

$$L_D = \frac{T_0^2}{|\beta_2|}, \quad (1)$$

$$T_{\text{FWHM}} = 2(\ln 2)^{1/2} T_0 \approx 1.665 T_0, \quad (2)$$

where T_0 is the half-width of the pulse, T_{FWHM} is the FWHM power of the pulse, and β_2 is the second-order dispersion parameter of fiber. When $T_{\text{FWHM}} = 16$ ps and $\beta_2 = 35$ ps²/km, L_D is calculated as 2.64 km. For the stretcher in this letter, the total pulse path length $L \ll L_D$, so the group delay dispersion (GDD) of the fiber may be ignored in discussions of pulse stretching.

A phase mask was designed to fabricate the CFBG, which can provide a delay of ~ 400 ps per reflection. The fabricated CFBG had a grating length of 4.5 cm, linear chirp of 1.2 nm/cm, and center period of 724.1 nm. CFBGs with different lengths and reflectivity were fabricated from B/Ge doped fibers irradiated by a 248-nm KrF excimer laser through the phase mask. Taking into account the n_{eff} , the chirp of the CFBG became 1.75 nm/cm with a center wavelength of 1 053 nm. CFBGs with different lengths have different dispersion. If a CFBG has a smooth reflection spectrum distribution, the stretching results of pulses are mostly determined by the group delay provide by the CFBG.

We disregard the high-order dispersion to simplify the calculation of an approximately linearly CFBG. The dispersion d can be given by

$$d = \frac{2n_{\text{eff}}L}{c \cdot \Delta\lambda}, \quad (3)$$

where n_{eff} is the effective refractive index, $\Delta\lambda$ is the bandwidth of CFBG, c is the velocity of light, and L is the length of the CFBG.

The experimental setup of the pulse multi-pass stretcher is shown in Fig. 2. The 1-Hz seed pulse was inputted to a multi-pass stretcher using a CFBG in an all-fiber regenerative amplifier structure^[25]. The CFBG was introduced by a 3-port fiber optic circulator. To compensate the insert loss caused by the CFBG and other components in the cavity, a 3.2-m section of Yb-doped single-clad fiber with a mode field diameter of

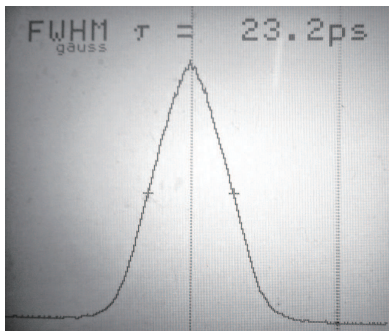


Fig. 1. Autocorrelation trace for the seed pulse delivered by the 1 053-nm NPR mode-lock laser.

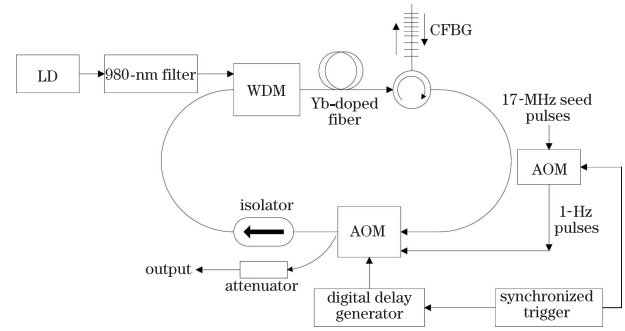


Fig. 2. 1 053-nm all-fiber pulse multi-pass stretcher using a CFBG.

3.6 μm was used as the gain medium. The gain medium was counter-pumped by a 980-nm laser diode (LD) through a 980/1 053-nm wavelength division multiplexer (WDM). A 2×2 AOM switch was used to control the built-in output port.

The AOM was controlled by a digital delay generator that had been synchronized to the seed pulses. When it was turned off, the pulse was first amplified when it passed through the doped fiber and into the CFBG through the circulator. The pulse reflected from the CFBG then passed through the turn-off-state AOM to the output end. The system provides single-pass stretch to pulses. When the AOM is turned on, the pulse transmits in the closed loop and gains multi-pass stretching by the CFBG. The duration of time the AOM is opened was calculated and controlled to determine over how many passes the pulses are stretched before they are exported. An isolator is employed to prevent reverse light in the cavity. Output pulses are converted into electrical signals by a positive intrinsic negative (PIN) photoelectric diode. Final electrical signals are observed and measured by an oscilloscope.

We chose two CFBGs to carry out experiments. Figure 3 shows the transmission spectra of 1.4 (No. 1) and 4.5-cm (No. 2) long CFBGs. The bandwidth of CFBG 1 is 2.4 nm while that of CFBG 2 is 7.8 nm; as well, their insertion losses are 1.6 and 1.2 dB, respectively. According to Eq. (3), CFBG 1 can provide a total time delay of about 136.3 ps and a seed pulse bandwidth is 7.1 nm, which is smaller than that of CFBG 2. As such, the time delay of CFBG 1 was calculated as 394.6 ps. The transmission curves of these two CFBGs are not adequately smooth. For CFBG 1, the reflectivity bulges at the long-wave end, but CFABG 2 has a better reflection distribution.

By changing the time during which the AOM is opened, we changed the total pulse transmission time in the cavity and stretched and amplified the pulses for different times. The pump power was set to 170 mW. An attenuator was applied at the output port to modulate the intensity of pulses to the same scale for comparison. The oscilloscope recorded the waveform after the pulse transmitted different numbers of loops in the cavity. The stretching results using CFBG Nos. 1 and 2 are shown in Fig. 4. When CFBG 1 is applied, the pulse is stretched from 16 to 155 ps in the first loop. CFBG 1 provides a 131 ps delay per reflection, which corresponds to the calculation result of 136.3 ps. The largest pulse duration

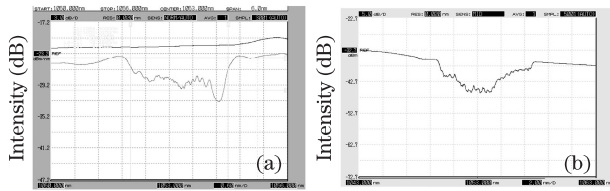


Fig. 3. Transmission spectra of CFBG Nos. (a) 1 and (b) 2.

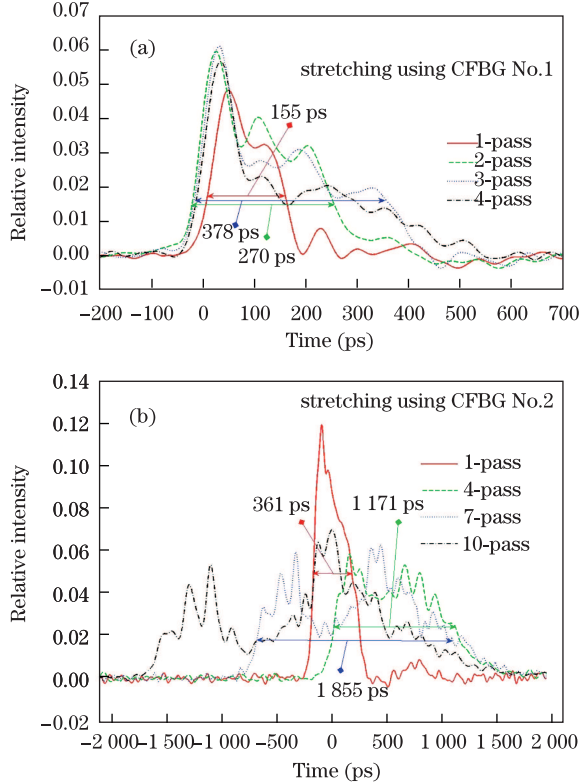


Fig. 4. Pulse stretching results of stretcher using CFBG (a) No.1 with 1, 2, 3, and 4 passes and (b) No. 2 with 1, 4, 7, and 10 passes.

of CFBG 1 after three reflections is 378 ps. When the pulse transmits more than three laps in the cavity, the pulse waveform widens. The bottom width of the pulse is over 500 ps in the fourth loop but distorts significantly, and the T_{FWHM} of the pulse can no longer be measured by the oscillograph. When CFBG 2 is used, the pulse is stretched from 16 to 361 ps in the first loop. CFBG 2 provides a 345-ps delay, which corresponds to the calculation result of 394.6 ps. The largest pulse duration of 1.855 ns is obtained 378 ps after seven reflections from the CFBG. The pulse transmits as much as 10 loops in the cavity but the T_{FWHM} cannot be measured by the oscillograph after over 7 loops. Uneven reflection spectral distribution of the CFBG is the key factor that affects the stretched pulse waveform distortion and limits the number of stretching passes. If a CFBG with better quality is fabricated, we can obtain better stretching results.

The leading edge of stretched pulses appears to be amplified most. To discuss this inference completely, we carried out contrast experiments without a CFBG in the regenerative amplifier structure. The results are shown in Fig. 5 and compared with those obtained from

experiments using CFBG No. 2. The pulse leading edge exhibits maximum amplification. Figure 6 shows the emission spectra of the 3.2-m Yb-doped fiber. The gain curve of the fiber amplifier is flat near 1 053 nm, and the gain narrowing effect does not cause unbalanced amplification. A pump power of 170 mW is high for this amplifier, which causes the amplifier work in saturated conditions and induces the gain saturation effect. The leading edge runs faster than the trailing edge and gains more amplification. It will be obvious when the pulse gets more than 1 time amplification. We can further optimize the parameters of the amplifier and run it in unsaturated conditions to avoid this effect. The group delay ripple (GDR) from CFBGs is also a barrier that may yield better pulse quality for the stretcher^[26]. A GDR usually behaves as a peak-to-peak variation in the stretched pulse waveform and originates from random and systematic errors introduced during CFBG fabrication, which is difficult to completely avoid. Further modification of the CFBG fabrication process can help us reduce the effect of GDR.

A double-passed Treacy compressor, which consists of a conventional grating pair, was designed as an available compressor scheme to recompress the stretched pulse to

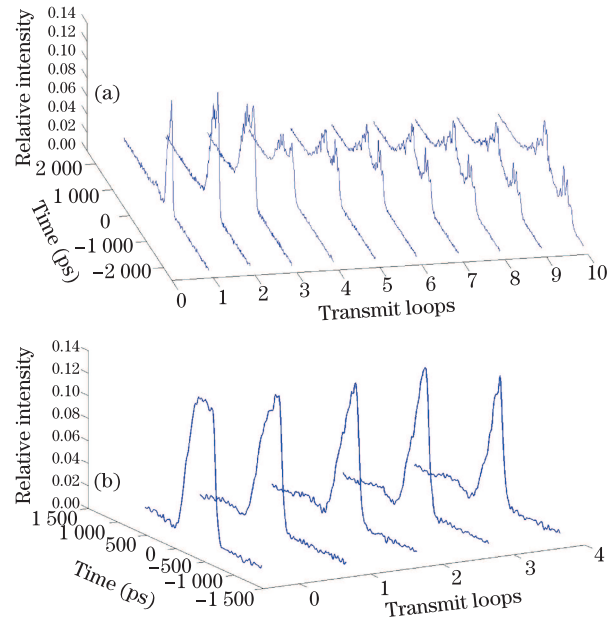


Fig. 5. (a) Stretched pulses after transmission from 1 to 10 loops in a stretcher using CFBG No. 2; (b) pulse amplification results without a CFBG in the amplifier structure; pulses are transmitted from 0 to 4 loops.

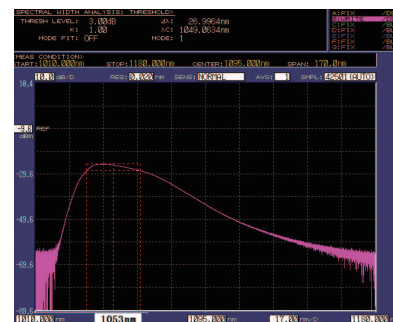


Fig. 6. Emission spectrum of the 3.2-m Yb-doped fiber.

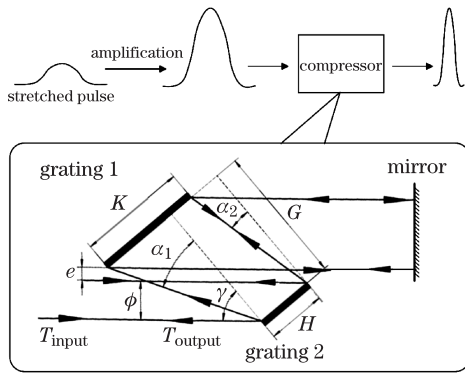


Fig. 7. Schematic of the double-passed Treacy compressor that may be used to recompress stretched pulses.

a narrow duration, as shown in Fig. 7. A double pass through the pair yields a spatial-chirp-free beam^[27]. The perpendicular distance between the two gratings is G , which satisfies^[28,29]

$$G = \frac{cd^2}{\lambda_0 \delta \lambda} \cdot \frac{\delta T}{2} \left[1 - \left(\frac{\lambda_0}{d} - \sin \gamma \right)^2 \right]^{\frac{3}{2}}, \quad (4)$$

where γ is the incident angle of the input stretched pulse, $\delta \lambda$ is the bandwidth of the input pulse, λ_0 is the central wavelength of it, d is the grating constant, and δT is the width difference between the input and output pulses. Considering the actual application requirements and geometrical restriction conditions, such as $e = [(\tan \gamma - \tan \alpha_1)G - H] \cos \gamma \geq 0$, where e is the gap between the input beam and edge of grating 1 and H is the minimum width of grating 2, we can use 1780 lines/mm gratings and set the compressor parameters as $\gamma = 74$ and $G = 146\text{--}1460$ mm to compress 1.85 ns pulses to 1–10 ps pulses. The effect of high-order dispersion from the grating pair was determined from the compressor geometry. A typical example of this compressor is $\text{GDD} = -379.26 \text{ ps}^2/\text{rad}$ and $\text{TOD} = 5.84 \text{ ps}^3/\text{rad}$, which could be compensated by fabricating CFBGs with specific GDDs and TODs^[26].

In conclusion, we demonstrate an optical laser pulse multi-pass stretcher using CFBG. The stretcher can stretch pulses from the picosecond scale to the nanosecond scale by reusing a normal CFBG, which can meet the requirements for fast ignition when combined with a double-passed Treacy compressor. Compared with other stretcher types, CFBG has a simpler structure with adjustable stretching parameters. Moreover, CFBG is easy to obtain and inexpensive. The 16-ps pulses delivered by a NPR mode-lock laser is used as the seed signal. We stretched pulses from 16 to 378 ps after the reflections from a 1.4-cm-long CFBG and to 1.855 ns after seven reflections from a 4.5-cm CFBG. Uneven reflection of the CFBG causes waveform distortion of the stretched pulse and limits the stretching results. The gain saturation effect can result in unbalanced amplification of the pulse, which is another main factor that affects the multi-pass stretching results. In future studies, we will continue to optimize the multi-pass stretcher for better pulse quality, which may include promotion of the fabrication process of the CFBG and modification of the stretcher structure.

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