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An All-Fiberized Chirped Pulse Amplification System Based on Chirped Fiber Bragg Grating Stretcher and Compressor

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We report an all-fiberized chirped pulse amplification system without any bulk devices. The stretcher and compressor are chirped fiber Bragg gratings inscribed in a 6/125 μm single-mode fiber and a 30/250 μm large-mode-area fiber. The fabrication system of chirped fiber Bragg gratings was designed and built by ourselves. The width of the linear exposure spot was controlled according to the different fiber sizes to improve the fabrication quality, and the parameters of chirped fiber Bragg gratings were fine-tuned during the fabrication to achieve the overall system's spectral matching. Two fiber circulators with the same fiber sizes as the chirped fiber Bragg gratings were employed to auxiliarily achieve the pulse stretching and compression. The dispersion accumulations provided by the stretcher and compressor are 129.8 ps and 90.8 ps. The power amplifiers were composed of the two-stage 10/130 μm fiber pre-amplifier and the 30/250 μm fiber main amplifier. The proposed chirped pulse amplification system with no spatial light is the true sense of an all-fiberized chirped pulse amplification structure and shows the main trend in development of ultrashort pulse fiber lasers.

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Fiber chirped pulse amplification (FCPA) technology is one of the effective methods to avoid the nonlinear effects of fiber that are excited by the high peak power in ultrashort pulse fiber lasers.[1–4] Due to the special performance requirements of pulses stretcher and compressor, most FCPA systems are not real all-fiberized structures. They are composed of bulk stretchers and compressors which have insurmountable defects of poor stability and large volume.[5–8] Thus, the key to constructing a real all-fiberized FCPA system without any bulk devices is that the pulse stretcher and compressor should be fiberized.

An optical fiber, especially a single-mode fiber (SMF), has often been used to stretch pulses, while laser pulses generally need to travel through a longer fiber to obtain adequate dispersion accumulation because of the small dispersion, which will cause some undesired effects.[9,10] Chirped fiber Bragg grating (CFBG), which has a large grating dispersion and length of millimeters to provide the dispersion accumulation as same as the SMF of kilometers, has become a better choice of fiber stretchers.[11,12] Müller *et al.*[13] designed a set of CFBGs to stretch the pulse duration of an fs-oscillator to 5 ns. Denisa Štěpánková *et al.*[14] employed a stretcher of single CFBG with grating dispersion of 205 ps/nm to stretch the pulse duration from sub-picosecond to 0.5 ns. Yu *et al.*[15] stretched laser pulses from 3.5 ps to 617 ps by a CFBG stretcher with the grating dispersion of 65 ps/nm. The numerous outstanding results indicated that CFBG is an excellent fiber device for laser pulse stretching and is instrumental in building real all-fiberized FCPA systems. The compressors, however, are still bulk devices in these works, which are the bottleneck.

Photonic bandgap fiber has been proposed as compressor[16–18] and the special air hole distribution leads to the dispersion reaching a maximum of 940 ps/(nm·km), which is much larger than the SMF. However, compared with the CFBG of millimeters, a photonic bandgap fiber of meters is still longer and the dispersion is still not large enough.[18] Consequently, CFBGs were directly employed as the compressors with CFBG stretchers for the preliminary research of constructing the all-fiberized FCPA system.[19–22] Galvanauskas *et al.*[21] reported on an FCPA system based on two CFBGs that were fused to the system in opposite directions as the stretcher and compressor. The dispersion accumulations provided were 29.7 ps and 29.6 ps. D. Taverner *et al.*[22] designed an all-fiberized-annular FCPA system with only one CFBG for better spectral matching. Laser pulses were stretched by reflection from one end of the CFBG and compressed by reflection from the other. The values of dispersion accumulations in stretching and compressing were theoretically the same. The successful construction of the FCPA system with the CFBG stretcher and compressor shows a novel method to build the real all-fiberized FCPA structure. However,

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the CFBGs employed were all inscribed in SMF which has no advantage in power increase. N. G. R. Broderick *et al.*[23] described an FCPA system, the output peak power was around 500 kW at the compression pulse duration of 5 ps. Although the compressor was a CFBG inscribed in a large-mode-area (LMA) fiber and improved the output power, a series of bulk devices was also employed to separate the reflective light from the compressor achieving the pulse compression. Therefore, it is not a true sense of the all-fiberized FCPA system with a compressor of CFBG inscribed in an LMA fiber. On the other hand, the lack of the LMA fiber circulator also limits the development of the CFBG compressor. To our best knowledge, the output power of the CW fiber laser with CFBGs inscribed in the LMA fiber as the Raman filter without fiber circulator has reached 5 kW,[24,25] which shows that the CFBG inscribed in the LMA fiber has satisfactory stability at high power.

We built an FCPA system based on a CFBG inscribed in the 6/125 μm SMF, a CFBG inscribed in the 30/250 μm LMA double-cladding fiber, and two fiber circulators of the same fiber sizes as CFBGs. The CFBGs were fabricated through a system built by ourselves and the width of the exposure linear spot was adjusted according to the fiber size to increase the fabrication quality. The parameters of CFBG were fine-tuned during the fabrication to achieve the spectral matching of the overall system. The dispersion accumulations of 129.8 ps and 90.8 ps were obtained and the output pulse duration is 73 ps with an average power of 10.1 W. The proposed FCPA system based on the CFBG stretcher inscribed in SMF and CFBG compressor inscribed in LMA fiber is a real all-fiberized structure and has no spatial light, which is the tendency to the future development of ultrashort pulse fiber lasers.

Design and Fabrication of CFBG Stretcher and Compressor. According to the coupled-mode theory, the reflective Bragg wavelength λ_{Bragg} of uniform fiber Bragg grating (FBG) is[26]

$$\lambda_{\mathrm{Bragg}} = 2n_{\mathrm{eff}}\Lambda, \tag{1}$$

where Λ is the period of FBG and n_{eff} is the effective index. It is clear from Eq. (1) that the λ_{Bragg} is proportional to n_{eff} in the uniform FBG with a constant period Λ. Unlike the uniform FBG, the period of CFBG is linearly chirped along the grating, so that λ_{Bragg} of CFBG is linearly varied along the grating, which means that the light with different wavelengths is reflected at different locations of CFBG, as shown in Fig. 1.

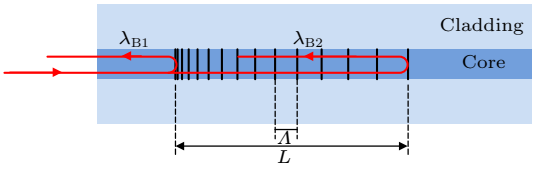

Fig. 1. Schematic diagram of the reflection in CFBG.

The time delay between the reflective light separated by unit wavelength is expressed as[27]

$$D = \frac{2n_{\mathrm{eff}}L}{c}\left(\frac{1}{\Delta\lambda_{\mathrm{B}}}\right), \tag{2}$$

which is also the grating dispersion in units of ps/nm. Here, L is the length of CFBG, c is the speed of light in vacuum, and $\Delta\lambda_{\mathrm{B}}$ is equal to $\lambda_{B2} - \lambda_{B1}$ that is the difference between the reflected wavelengths at two ends of CFBG. In ultrashort pulse lasers, the common dispersion parameter is the group velocity dispersion (GVD) β_2, which is related to the grating dispersion D by[26]

$$\beta_2 = \frac{\lambda^2}{2\pi c}D. \tag{3}$$

Table 1. Parameters of fibers for the simulation.

	Core diameter (μm)	Cladding diameter (μm)	GVD β_2 ($\mathrm{ps^2{\cdot}km^{-1}}$)	Nonlinear coefficient γ ($\mathrm{W^{-1}{\cdot}m^{-1}}$)
Pre-amplifier	10	130	25	0.00196
Main amplifier	30	250	19	0.00022

We set $\Delta\lambda'$ as the compensation bandwidth, the dispersion accumulation provided by CFBG should be $D \cdot \Delta\lambda'$ in units of ps. When the reflective bandwidth of CFBG is smaller than the spectrum width of the laser, $\Delta\lambda'$ equals the reflective bandwidth of CFBG, and conversely, $\Delta\lambda'$ equals the spectrum width of the laser. On the other hand, as shown in Fig. 1, the CFBG has the characteristics of bidirectional transmission. When laser pulses are coupled into CFBG from the long-period end, the dispersion accumulation is positive and the pulses are stretched, but from the short-period end, the dispersion accumulation is negative and the pulses are compressed.

In the FCPA system, the dispersions should be matched between the seed source, the stretcher, the fiber amplifier, and the compressor. The pulse duration of the seed source is 34 ps. Based on the generalized nonlinear Schrödinger equation,[3] we simulated the spectrum and pulse duration evolutions in fiber amplifiers. The simulation results, as shown in Fig. 2, show that the spectrum is broadened to roughly 2 times with the average power increasing to 40 W,

but the variation of pulse duration is only femtosecond scale. When the duration of the laser pulse is the hundred-picosecond scale, such variation can be ignored. Therefore, the pulse duration of seed source 34 ps plus the dispersion accumulation provided by the CFBG stretcher should be equal to that provided by the CFBG compressor. Since the CFBG stretcher and compressor will be inscribed through the same phase mask, the grating dispersions are the same. Thus, at stretching, the laser spectral width should be adjusted narrow to provide small dispersion accumulation. Then, the spectrum is broadened through the fiber amplifier. At final compressing, the wide compensation bandwidth can provide large dispersion accumulation to achieve the dispersion matching of the entire FCPA system. The difference in spectral width between the stretcher and compressor should be 34 ps/(53.3 ps/nm) = 0.64 nm.

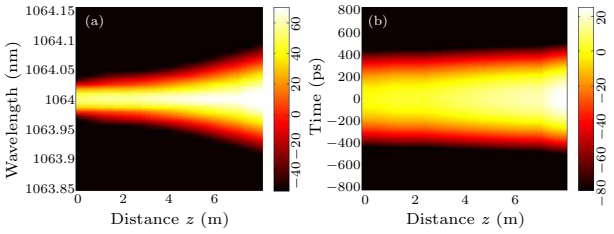

Fig. 2. Variation simulations of (a) spectral width and (b) pulse duration with transmission distance in the fiber amplifier.

The phase mask (Ibsen) we used to fabricate the CFBG stretcher and compressor is designed with a central period of 732.37 nm, a chirp rate of 1.25 nm/cm, and a grating area of 20 × 10 mm^2. According to the theory of phase mask,[28] the central period and chirp rate α of the CFBG inscribed through such a phase mask should be 366.185 nm and 0.625 nm/cm. From Eq. (1), we get $\Delta\lambda' = 2n_{\text{eff}}(\alpha L)$, when $n_{\text{eff}} = 1.45$, the spectral bandwidth $\Delta\lambda'$ is around 3.6 nm, which is proportional to the chirp rate α and the grating length L. Combining Eqs. (1) and (2), the grating dispersion of 53.3 ps/nm is obtained. We designed and built the fabrication system for CFBG, as shown in Fig. 3. A 213 nm laser source (UV, Impress 213, Xiton photonics) produced 6.1 ns pulses at 12.5 kHz as the fabrication source. The output average power is 0–140 mW and the elliptical laser spot has diameters of 770 µm and 890 µm at 110 cm from the laser head. Two cylindrical lenses were set to shape the exposure spot according to the transformation equation of the Gaussian beam through a lens.[29] The cylindrical lens 1 with a focal length of 46 mm is fixed and the photosensitive fiber is always located at its focus. The cylindrical lens 2 with a focal length of 168 mm is movable, by adjusting its location, the long diameter of the elliptical spot irradiated on cylindrical lens 1 is controlled, thus the width of the focused linear spot on the photosensitive fiber can be shaped to match with the different sizes of fibers to improve the fabrication quality.

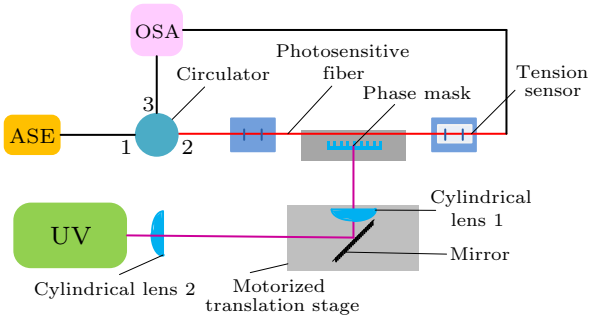

Fig. 3. Diagram of the fabrication system for CFBGs. UV: ultraviolet laser; ASE: amplified spontaneous emission source; OSA: optical spectrum analyzer.

Since the gain fiber of the main amplifier in a high-power fiber laser is commonly an LMA fiber. The compressor after the main amplifier should be a CFBG inscribed in the LMA fiber to increase the efficiency, while the stretcher before the amplifier is a CFBG inscribed in SMF. The LMA fiber is different from SMF in fiber structure and index profiles, which leads to a different mode distribution and index modulation. However, the reflective light of CFBG in 1-µm wavelength only travels through the fiber core, which is unrelated to the modes. We simulated the reflective spectrums of CFBGs in a PS1060 fiber (SMF, Nufern) and an LMA-GDF-30/250-M fiber (Nufern) according to the coupled-mode theory.[26] The length of simulated CFBGs is 2 cm with a central period of 366.185 nm and a total chirp of 1.25 nm. The reflective spectrum of CFBG in the LMA fiber is similar to that in SMF as shown in Fig. 4(a). There are no obvious multimode characteristics in the spectrum of CFBG in the LMA fiber and the 3 dB reflective bandwidths are all around 3.4 nm, which is almost equal to the result of 3.6 nm calculated from Eq. (1). According to the above discussion, when stretching, the laser spectrum should be adjusted to slightly smaller than 3.4 nm − 0.64 nm = 2.76 nm to achieve dispersion matching and meanwhile to provide adequate dispersion accumulation.

Before fabrication, we computed the location of the cylindrical lenses 1 and 2. The cylindrical lens 1 is always located from the laser head 1000 mm. When the cylindrical lens 2 is located at 110 mm from the laser head, the final width of the focused linear spot is about 6 µm to match with SMF. When it is located at 735 mm, the final width is about 30 µm to match with the LMA fiber. The fiber of LMA-GDF-30/250-M (Nufern) was pretreated with hydrogen loading for 25 days, and the total exposure time was around 160 s at 140 mW. After fabrication, the CFBG was annealed at 120 ℃ for 15 h. The diffusion of the excess hydrogen molecules in the fiber led to the blue shift of re-

flective wavelength during the annealing.[30] The stabilized spectrum of CFBG in the LMA fiber is shown by the red dashed curve in Fig. 4(b), the central wavelength is located at around 1063.5 nm. Therefore, during the fabrication of CFBG in SMF, we stretched PS1060 fiber by tension sensor with roughly 50 g to fine-tune the spectrum matching with the CFBG in the LMA fiber.[31] The total exposure time is around 80 s at 140 mW. As shown in Fig. 4, the reflective spectrums of homemade CFBGs are located at the same waveband and the 3 dB bandwidths are all 3.4 nm, as same as the simulated results. Meanwhile, it is visible that the height of the reflective spectrums is decreased with the increase of the fiber size. That is, under the same exposure intensity, the fiber with a larger size is irradiated with the lower average dose density, leading to the smaller reflectivity of CFBG.

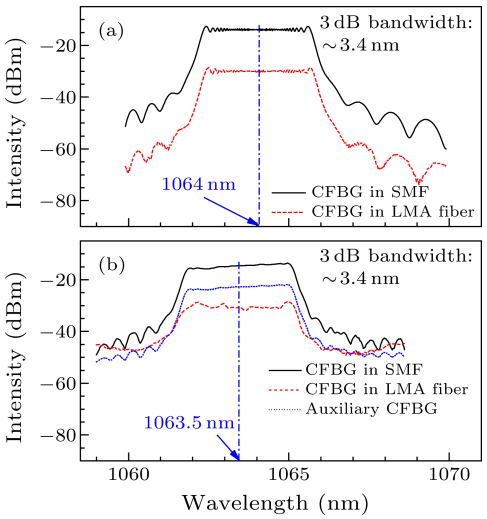

Fig. 4. Reflective spectrums of (a) the simulated and (b) homemade CFBGs.

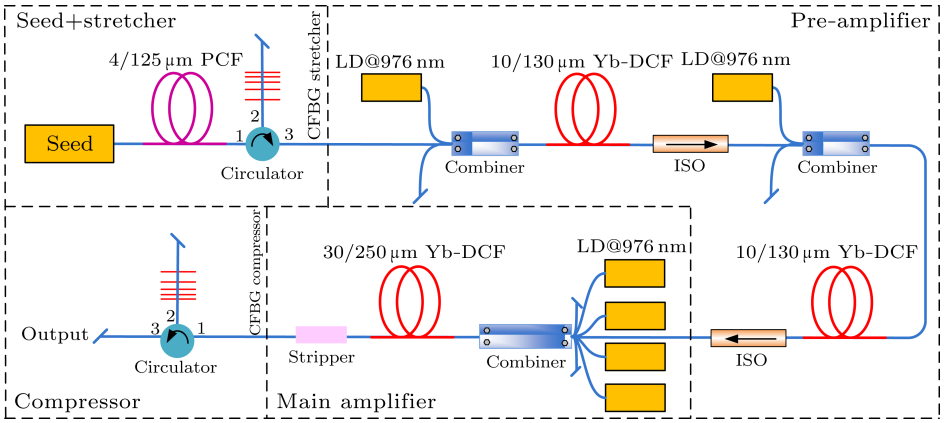

Fig. 5. Schematic diagram of the all-fiberized FCPA system. PCF: photonic crystal fiber; LD: laser diode; Yb-DCF: ytterbium-doped double cladding fiber; ISO: isolator.

Experiment of the All-Fiberized FCPA System and Its Results. Based on the homemade CFBGs, we built an all-fiberized FCPA system as shown in Fig. 5. We employed an SESAM passively mode-locked fiber laser with a pulse duration of 34 ps, an average power of 150 mW, and a repetition rate of 18.1 MHz as the seed source. The pulse duration was measured by an autocorrelator (FR-103XL, Femtochrome) as shown in Fig. 6(a), and the spectrums were measured by an optical spectrum analyzer (OSA, AQ6370D, Yokogawa) with a resolution of 0.02 nm as shown in Fig. 6(b). The black solid curve in Fig. 6(b) shows that the 3 dB bandwidth of the seed source is around 0.34 nm, which is smaller than the reflective bandwidth of the CFBG stretcher inscribed in SMF. The dispersion accumulation provided by such a narrow compensation bandwidth is only 18 ps from the dispersion theory given above. The pulse duration will be stretched from 34 ps to just 52 ps, which is too small to effectively amplify the power. A 12-m-long PCF is set after the seed source to solve this problem. The PCF of 4/125 µm has high nonlinearity with a solid core and five loops hexagonal arrangement of air holes, but the loss is relatively large. While the 3 dB bandwidth of spectrum is broadened to about 2.5 nm which is slightly smaller than the discussed result of 2.76 nm, the power is decreased to 47 mW. The output spectrum as the red dashed curve is shown in Fig. 6(b). Then, the stretcher was fused to the end of the PCF through a circulator and the total insertion loss is about 2 dB. The average power of laser pulses was decreased to 29 mW after stretching. The dispersion accumulation provided with the compensation bandwidth of 2.5 nm is theoretically 133.3 ps. The pulse duration will be stretched from 34 ps to 167.3 ps.

However, the pulse duration between 90–200 ps is beyond the accurately measurement range of the existing laboratory instruments. We fabricated another CFBG in SMF as the auxiliary device to indirectly measure the pulse duration after stretcher. The reflective spectrum is shown by the blue dotted curve in Fig. 4(b). The two ends of the auxiliary CFBG were successively connected with the stretcher and made the pulses after the stretcher was stretched and compressed with the same value of dispersion accumulation. The stretched and compressed pulse dura-

tions were measured by a digital oscilloscope (LeCroy, sampling rate: 13 GHz) and the autocorrelator (FR-103XL, Femtochrome), respectively. As shown in Figs. 6(c) and 6(d), the measured results are 271 ps and 56.5 ps. We set the pulse duration after stretcher as x and the dispersion accumulation of the auxiliary CFBG as y,

$$x + y = 271, \qquad x - y = 56.5. \tag{4}$$

The solution to Eqs. (4) is

$$x = 163.8, \qquad y = 107.3, \tag{5}$$

where the pulse duration after the stretcher is 163.8 ps, which is very close to the theoretical result of 167.3 ps. Thus, the dispersion accumulation provided by the CFBG stretcher inscribed in SMF should be 163.8 ps − 34 ps and equals 129.8 ps.

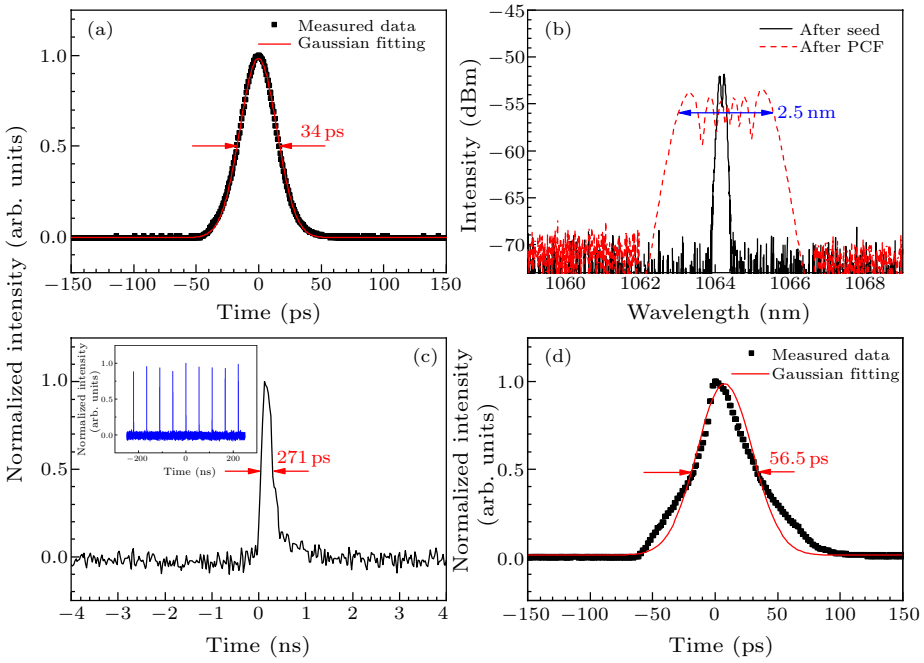

Fig. 6. (a) Pulse duration of seed source; (b) spectrums after seed and PCF; (c) stretched and (d) compressed pulse duration through the auxiliary SMF-CFBG. (inset: the pulse sequence).

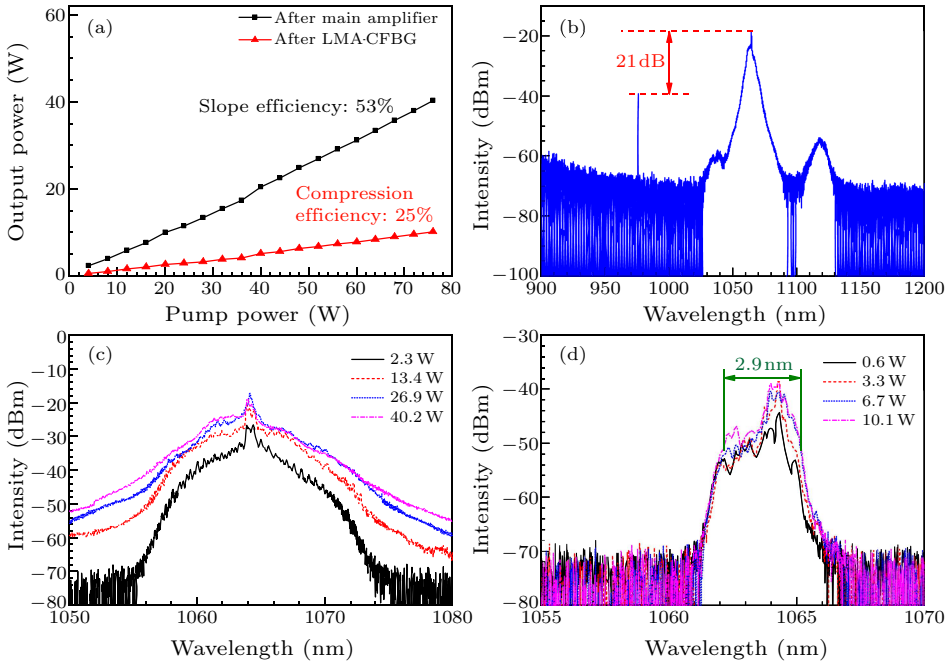

Fig. 7. (a) The average output power versus the pump power; (b) the spectrum of maximum output power after the main amplifier with an abscissa from 900 nm to 1200 nm; (c) the evolution of spectrums after the main amplifier; (d) the evolution of spectrums after the compressor.

The 163.8 ps pulses are then coupled into a two-stage pre-amplifier. The gain fibers are 10/130 μm ytterbium-doped double cladding fibers (Yb-DCFs) with the core absorption coefficient of 4.1 dB/m at 976 nm. The lengths are 0.5 m and 4 m, while the average powers are amplified to 60 mW and 1.2 W, respectively. The main amplifier with the gain fiber of 30/250 μm Yb-DCFs is set after the pre-amplifier. The 1-m-long gain fiber has a core absorption coefficient of 9 dB/m at 976 nm and is coiled with a radius of roughly 160 mm on a thermoelectric cooler (TEC) of 350 × 350 mm^2 for heat dissipation. A 0.5-m-long 30/250 μm passive fiber was fused to the end of the main amplifier. By recoating the cladding with high-index polymer, the residual pump light can be stripped. Limited by the threshold of the 30/250 μm circulator (AFR) in the compressor, the maximum power is amplified to 40.2 W when the pump power is 76 W. The amplified slope efficiency and the output spectrum at 40.2 W are shown in Figs. 7(a) and 7(b). Figure 7(b) shows that the wavelength of the signal light is located at around 1064 nm and the difference between the signal light and the pump light is about 21 dB, while the amplified spontaneous emission (ASE) around 1030 nm is observed. According to the Raman frequency shift of 13 THz (around 51 nm at 1064 nm) in a silica fiber,[32] the envelope centered around 1115 nm is stimulated Raman scattering (SRS) generated by the nonlinear effects of fiber. Although we reduced the length of the gain fiber in the main amplifier to raise the threshold of SRS, it was still excited at the average power above 10 W. This indicates that the effect of pulse stretching with a CFBG stretcher of such parameters can not suppress the SRS better in the LMA-30/250 fiber and the stretcher with large grating dispersion should be developed. Figure 7(c) shows the evolution of the output spectrum after the main amplifier and the spectrum is broadened and raised with the power increase. The spectrums are not smooth and show oscillation, which are caused by the multi-transverse-mode structure of the beam.[33] The spectrums were collected and delivered to the OSA by a 105/125 μm multimode fiber.

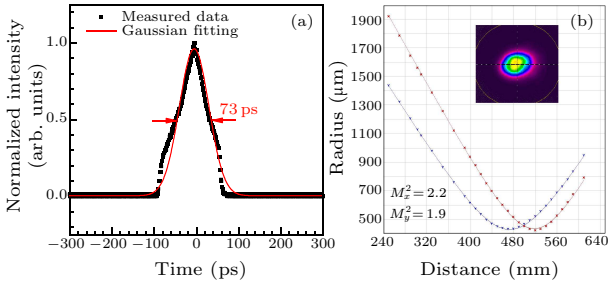

Fig. 8. (a) The compressed pulse duration; (b) M^2 measurement of the output beam after compression.

Finally, the amplified pulses with an average power of 40.2 W are injected into the homemade CFBG compressor inscribed in the LMA-GDF-30/250-M fiber (Nufern) with the 30/250 μm circulator (AFR). The temperature of the compressor remained constant indicates that the homemade CFBG compressor in the LMA fiber has higher power durability. Due to the filtering effect of CFBG, the laser pulses outside the reflective bandwidth are directly filtered out, which leads to the maximum output compressed average power of only 10.1 W obtained, and the compression efficiency is 25%. The pulse duration after compression was measured by the autocorrelator (FR-103XL, Femtochrome). The measured data and Gaussian fitting curve are shown in Fig. 8(a). The 3 dB width of the fitting curve is about 73 ps. As shown in Fig. 7(d), ignoring the highest little peak around 1064 nm, the FWHM of the compressed spectrum at 10.1 W is roughly 2.9 nm. From the time-bandwidth product (TBP) $\Delta t \cdot \Delta \nu \geqslant 0.441$, the limit pulse duration is around 574 fs, which is far less than the experimental result of 73 ps. This is mainly due to the fact that the insertion loss affects the performance of CFBG for dispersion accumulation.[26] The lower the reflectivity, the larger the insertion loss, and the worse the compression effects, just like the auxiliary CFBG shown in Fig. 4(b). Although it has the same grating dispersion, fiber size, and reflective bandwidth as the CFBG stretcher, the lower reflectivity results in the less dispersion accumulation of only 107.3 ps, constructing to the dispersion accumulation of CFBG stretcher 129.8 ps. Therefore, from Fig. 4, the lowest spectrum of the CFBG compressor in LMA fiber provides the least dispersion accumulation of 163.8 ps − 73 ps = 90.8 ps. Meanwhile, the measured data do not show a perfect Gaussian shape because the pulses of the system are stretched by both the linear chirp of the CFBG stretcher and the nonlinear effects of the fibers in the system, but compressed only by the linear chirp of the CFBG compressor. The insufficient dispersion compensation leads to an irregular pulse profile. Based on the pulse duration of 73 ps and average power of 10.1 W, the single pulse energy is calculated to be about 0.56 μJ and the peak power is around 7.7 kW. Figure 8(b) shows the beam quality measured by a laser beam analyzer (M^2-200, Ophir-Spiricon). The beam quality factor M^2 values of 2.2 and 1.9 are obtained in horizontal and vertical directions. Although the beam profile still presents an ellipse, there should be a few high order modes in the LMA-30/250 fiber, which leads to M^2 close to 2.[34]

In summary, we have proposed a novel all-fiberized FCPA system with a CFBG inscribed in SMF as pulse stretcher and a CFBG inscribed in an LMA fiber as pulse compressor. The CFBGs were fabricated using the fabrication system built by ourselves. The width of the linear exposure spot was adjusted according to

the fiber size and the parameters of CFBGs were fine-tuned during the fabrication to achieve the spectral matching with the entire system. The pulse duration was stretched from 34 ps to 163.8 ps, and the average power was amplified from 15 mW to 40.2 W. Finally, as a compression result of the CFBG in the LMA fiber, a pulse duration of 73 ps with an average output power of 10.1 W was obtained, corresponding to the peak power of 7.7 kW. The dispersion accumulations provided by the CFBG stretcher in SMF and the CFBG compressor in the LMA fiber are 129.8 ps and 90.8 ps, respectively. The lower reflectivity and the mismatch between the reflective spectrum and the laser spectrum lead to the dispersion compensation effect of the CFBG compressor being slightly smaller than the CFBG stretcher. The proposed FCPA system based on the CFBG stretcher and compressor, with fiber circulators of the same fiber size as CFBGs, is a novel all-fiberized structure and provides the experimental support for the future development of ultrashort pulse fiber lasers. In the future, the CFBG stretcher with larger grating dispersion should be fabricated to increase the dispersion accumulation and to reduce the peak power achieving the better suppression of SRS at high peak power. Meanwhile, the CFBG inscribed in the LMA fiber with larger grating dispersion, higher reflectivity, and wider spectral bandwidth should be developed to increase the compression effects and to construct a femtosecond all-fiberized FCPA system without any bulk devices.

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