Femtosecond Yb-fiber chirped-pulse-amplification system based on chirped-volume Bragg gratings

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A 100 W amplified (75 W compressed) femtosecond (650 fs) Yb-fiber chirped-pulse-amplification system is demonstrated using broadband chirped-volume Bragg gratings (CVBGs) for the stretcher and compressor. With a 75% compression efficiency, the CVBG-based compressor exhibits an excellent average power handling capability and indicates the potential for further power scaling with this compact and robust technology. © 2009 Optical Society of America

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Real-world applications such as high power terahertz pulse generation [1], rapid high-precision micromachining [2], and hard x-ray generation [3] have led to rapid advances in power scaling of fiber chirped-pulse-amplification (CPA) systems [4]. Because standard metal-coated gratings can withstand only average powers below 10 W, current high-power CPA techniques rely on the use of dielectric diffraction-grating based pulse compressors [5]. Unfortunately, such dielectric gratings still share the same critical disadvantages with their metal-coated counterparts, such as large size, polarization sensitive, and high complexity of the optical setup, which offset the inherent compactness and monolithic architecture offered by fiber technology itself. To overcome these limitations, we have developed large-aperture chirped-volume Bragg grating (CVBG) technology based on photothermorefractive (PTR) glass as what we believe to be novel pulse stretchers and compressors for compact fiber CPA systems [6].

We have demonstrated several CVBG-based fiber CPA systems for the most common wavelengths: 1.55 μm (Er doped) [6,7] and 1 μm (Yb doped) [8]. Although we have achieved 200 μJ energy pulse compression using a 2-cm-long CVBG at 1053 nm in [8], CVBG’s capability of handling a high average power has not yet been explored. This is particularly important at 1 μm, where Yb-doped fiber lasers possess an excellent power scalability. Additionally, the compressed pulses obtained in all of these demonstrations were restricted to a 1–5 ps range owing to the narrow reflection bandwidth or to the strong transverse-spatial chirp of the employed CVBGs. In the current work, to implement the femtosecond CPA, we have fabricated 6 nm bandwidth (centered at 1.063 μm) CVBGs with significantly reduced transverse-spatial chirp compared with those samples in previous demonstrations. The 2.5-cm-long CVBG with a square transverse aperture of 5 mm × 5 mm was recorded onto a PTR glass using interference between two curved-wavefront writing beams.

The experimental setup is illustrated in Fig. 1. It consists of a seed oscillator, two CVBGs for the stretcher and the compressor, two Yb-doped fiber amplifiers, and two pieces of hollow core photonic-bandgap fibers (PBGFs). It is noteworthy that the two CVBGs for the stretcher and the compressor are cut from the same sample and have a dispersion of 42 ps/nm. They are arranged with opposite orientations to ensure temporal reciprocity, leading to an automatic dispersion matching between the stretcher and the compressor. To compensate for the residual normal dispersion along the optical path, two pieces of PBGF (3 and 0.7 m) are introduced to provide an anomalous dispersion of 120 (ps/nm)/km at 1.063 μm. Additionally these two PBGFs only accommodate the propagation of single transversal mode and enable the single-mode excitation inside the subsequent amplifiers constructed with multimode fibers. In the experiment, we cut back the second piece of the PBGF to minimize the recompressed pulse duration.

The fiber CPA system is seeded with 110 fs pulses at 1.063 μm generated from a passively mode-locked...
Nd:glass oscillator operating at 72 MHz with 130 mW average power. The CVBG stretcher slices out a 6-nm-wide spectrum from this broadband seed with an average power of 35 mW. A combination of a polarization beam splitter and a quarter-wave-plate separates the stretched pulse from the input and the separated pulse is then coupled into 3 m of the PBGF. The stretched pulse with a 5 nm spectrum width (FWHM) is launched into two cascaded fiber amplifiers. The first stage is constructed using a 6.3 m standard polarization-maintaining 30 μm core-diameter large-mode-area (LMA) Yb-doped fiber (fabricated by NUFERN) with a 0.06 NA Yb-doped core and a 400 μm 0.46 NA hexagonal-shaped inner cladding. This amplifier is pumped at 976 nm in a counter-propagating configuration. The second amplifier, pumped also in a counter-propagating scheme at 940 nm, uses a 6 m LMA fiber (fabricated by LIEKKI) with a 65 μm 0.06 NA core and a 400 μm 0.46 NA hexagonal-shaped inner cladding.

In the experiment, the power after the first amplifier is fixed at 7 W to seed the second amplifier after the second PBGF, which has a 75% throughput. The output power versus the pump power of the second Yb-fiber amplifier is shown in Fig. 2(a). With an 80% slope efficiency with respect to the launched pump power, up to 100 W of amplified average power is obtained. For compression, the output from the second amplifier, with a diameter of 1 mm, is injected into the angle-tilted CVBG compressor. The recompressed power reflected from the CVBG compressor versus the incident power is plotted in Fig. 2(b), showing that the compressor has an efficiency of 75% independent of the input power. Up to 75 W of recompressed average power is achieved. The measured spectrum and the corresponding autocorrelation trace of the recompressed pulses are plotted in Fig. 3. The transform-limited pulse corresponding to the spectrum in Fig. 3(a) has a duration of ~550 fs. By comparing the measured autocorrelation trace for the recompressed pulse [thick solid curve in Fig. 3(b)] and the autocorrelation trace calculated from the transform-limited pulse [thin solid curve in Fig. 3(b)], we estimated that the recompressed pulse is about 100 fs longer than the transform-limited pulse given by the amplified pulse spectrum. This deviation might be caused by the residual higher-order dispersion mismatch between the PBGF and the gain fibers (e.g., the third-order dispersion adds up for all these fibers owing to the same sign).

An ideal CVBG should be homogenous across the plane perpendicular to the direction of the refractive index modulation. However, the imperfect writing process may induce inhomogeneity, which leads to the reflection of different frequency components at slightly different angles and consequently gives rise to spatial chirp. Figure 4 illustrates the setup capable of measuring the dependence of the reflection angle on wavelength that quantitatively indicates the strength of a CVBG’s spatial chirp. The output of a CW tunable fiber laser is adjusted by a half-wave-plate so that a slight portion of the CW power goes to a spectrum analyzer to monitor the operating wavelength, while most of the power is injected into the CVBG under test. The reflected beam is directed into a CCD camera that measures the position of the beam centroid. As a result of the spatial chirp, the image on the CCD camera moves continuously as we tune the operating wavelength of the fiber laser. The spatial chirp, characterized as the wavelength-dependent reflection angle, can be calculated as the ratio between the relative shifts read from the CCD camera and the distance from the CCD camera to the CVBG.

Figure 5(a) plots the measured spatial chirps of the CVBG employed in our fiber CPA system in both the horizontal and vertical directions in terms of milliradians. Clearly, the CVBG possesses a stronger spatial chirp in the horizontal direction. The inset shows the effect of the spatial chirp on the reflected beam profile of a broadband input pulse.
It is worth noting that a trade-off between the power and spectrum-width couplings exists owing to the spatial chirp. For this 6 nm CVBG, we are able to couple 5 nm of bandwidth into a single-mode PBGF with a 60% coupling efficiency. To have a diffraction-limited beam that is required for many applications, it is highly desirable to develop spatial-chirp-free CVBGs. Recently, our CVBG writing process has been improved to enable writing CVBGs with negligible spatial chirp. For example, Fig. 5(b) illustrates the spatial chirp measurement for such a CVBG designed for 1050 nm with a 17 nm bandwidth which can accommodate 300 fs recompressed pulses.

In conclusion, we have demonstrated an Yb-doped fiber CPA laser system producing 650 fs pulses at 75 W based on broadband CVBG stretchers and compressors that exhibit a 75% reflection efficiency. This constant unsaturated reflection efficiency evidently reveals the potential for further power scaling. As a matter of fact, our system is running far below a CVBG’s damage threshold for average power, which is at least 100 kW/cm² [9]. Given 1 mm beam diameter, a CVBG is capable of handling approximately kilowatt average power. However, at this power level, the slight IR absorption of the PTR glass might cause temperature rising of the CVBG compressor and therefore degrade the dispersion match between the stretcher and the compressor. The effect of absorption on such a CPA system is currently under investigation.

References