Large-aperture chirped volume Bragg grating based fiber CPA system

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Abstract: A fiber chirped pulse amplification system at 1558nm was demonstrated using a large-aperture volume Bragg grating stretcher and compressor made of Photo-Thermal-Refractive (PTR) glass. Such PTR-glass based gratings represent a new type of pulse stretching and compressing devices which are compact, monolithic and optically efficient. Furthermore, since PTR glass technology enables volume gratings with transverse apertures which are large, homogeneous and scalable, it also enables high pulse energies and powers far exceeding those achievable with other existing compact pulse-compression technologies. Additionally, reciprocity of chirped gratings with respect to stretching and compression also enables to address a long-standing problem in CPA system design of stretcher-compressor dispersion mismatch.

OCIS codes: (050.0050) Diffraction and gratings; (140.3510) Lasers, fiber.

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#79812 - $15.00 USD Received 7 Feb 2007; revised 24 Mar 2007; accepted 29 Mar 2007; published 6 Apr 2007

1. Introduction

The absence of compact and robust ultrashort pulse stretchers and compressors has been a significant hindrance for practical use of chirped pulse amplification (CPA) laser systems. Currently used high energy and high power CPA systems are still relying on diffraction grating based stretchers and compressors [1] which require complex alignment, have limited long-term stability, and are relatively large. This constitutes a particularly important technological limitation for fiber based CPA systems, since fiber-based laser systems can be made very compact and robust. Moreover, high average power cw and pulsed fiber laser systems can now provide several hundreds to more than kilowatt of output power [2] and one of the main obstacles for scaling ultrashort pulse systems into this range is associated with power handling limitations and relatively low efficiency of standard diffraction-grating technology. Several alternative approaches for the compact pulse compression technology has been explored, including linearly chirped fiber gratings [3], linearly chirped quasi-phase-matching structures [4], and hollow-core photonic crystal fiber pulse compressors[5], but none of these technologies can handle pulse energies above ~1-μJ level and, consequently, can not fully replace diffraction gratings when high pulse energies are required. Volume gratings have been suggested as a potential technological path towards compact high energy compressors [6], however this initial demonstration of a volume chirped Bragg grating pulse compressor in a hydrogen-loaded fused-silica photo-sensitive glass was limited to relatively small transverse apertures of only ~300-μm in depth due to the strong absorption of UV writing beam in the sample. This volume grating technology proved to be unsuitable for achieving larger transverse apertures.

We report demonstration of a fiber CPA (FCPA) system based on a linearly chirped millimeter-large transverse aperture volume Bragg grating (CVBG) written in Photo-Thermal-Refractive (PTR) glass. PTR glass technology [7] enables large and homogeneous transverse apertures because this glass has a relatively low absorption of the UV writing beam, thus permitting this writing beam to penetrate deep into the PTR glass sample with negligible transverse variation in the beam power. In this work we use 5-mmx5-mm aperture CVBG to achieve 6-W of average output power 1.1-ps duration recompressed pulses from a fiber-based CPA system at 1558nm.

2. Chirped volume Bragg gratings in PTR glass

The principle of pulse stretching and compression using a CVBG is identical to the chirped fiber Bragg grating (CFBG): different spectral components experience different delays when reflected from different longitudinal positions at which Bragg condition ($\lambda_B = 2n_e\Lambda(z)$) is locally satisfied [8]. The essential difference between a CVBG and a CFBG is that CVBG is written in a bulk material and the propagating beam inside a CVBG is unguided, while CFBG is written in a fiber core and the propagating beam is a guided fiber mode. Therefore, the transverse aperture size of a CFBG is limited by the maximum achievable single-mode core size to approximately 10-μm in diameter at best, while the transverse aperture of a CVBG is only limited by the grating writing technology and, for a PTR glass technology, potentially can be in the range from several millimeters to several centimeters. Consequently, energy handling capability for recompressed pulses in a pulse compressor is vastly different for these two devices. For example, considering that nonlinearity-induced limit for femtosecond-pulse compression in CFBG has been shown to be ~40-nJ [9], one might expect that CVBG with an aperture of several millimeters should be able to handle pulse recompression at approximately ~1-mJ level (and higher for larger apertures). CVBG, however, retains essential advantage of CFBG over other compact compressor technologies of being suitable to compress stretched pulses of the same duration as diffraction-grating compressors. Indeed, 100-ps to 1-ns long stretched pulses, sufficient to extract saturation-limited pulse energies from fiber and majority of other types of amplifiers, require 1-cm to 10-cm long CVBG, which are achievable with PTR-glass technology.

#79812 - $15.00 USD Received 7 Feb 2007; revised 24 Mar 2007; accepted 29 Mar 2007; published 6 Apr 2007

PTR glass is a stable multi-component sodium-zinc-aluminum-silicate glass doped with cerium, silver, and fluorine. Its refractive index decreases after UV exposure followed by a high temperature thermal annealing process. The recorded grating pattern in the PTR glass is stable under optical illumination and can withstand high temperature elevation up to 400 ºC [10]. The achievable modulation of refractive index is in the range of 10^{-3}, which is approximately equal to that achievable in conventional fiber Bragg gratings UV-imprinted in fused silica [8]. Consequently, broad chirp bandwidths of few 10's of nanometers should be possible, similar to what has been demonstrated in chirped fiber Bragg gratings. PTR glass has low absorption within 350 nm to 2700 nm spectral window, which enables PTR glass based gratings to withstand high average powers in this spectral window [10]. The measured PTR glass surface damage threshold of 20 J/cm^2 [11] (measured at 1054 nm for 1-ns pulse duration) is similar to that of fused silica. This high damage threshold and low absorption makes PTR glass based CVBG very attractive for high energy and high average power FCPA systems.

The grating pattern inside the PTR glass sample was recorded by holographic method using a CW radiation of a He-Cd laser at 325 nm. The UV writing beam was split into two arms and then redirected to cross each other with one arm collimated and the other arm diverging after a cylindrical lens. In this configuration, a tilted chirped interference pattern was created. The PTR glass sample was then placed at the beam crossover position with same slant angle as the interference pattern so that chirped pattern was parallel to the input and output surfaces. A post-recording annealing process was used to reveal the grating.

3. Experimental setup and results

Experiment setup of a fiber CPA system is shown in Fig. 1. The distinctive feature of the setup is that a single CVBG has been used both for stretching and compressing of optical pulses. Advantage of this configuration is that it ensures temporal reciprocity between pulse stretching and compression [3]. This automatically compensates for any dispersion mismatch between the stretcher and compressor, thus eliminating the problem of stretcher-compressor mismatch typical in conventional CPA systems. It also eliminates pulse distortions associated with chirped Bragg grating dispersion ripple, as has been demonstrated in the past with chirped fiber gratings and 300-fs pulses [12]. The separation between incident and reflected beams at both stretching and compressing ports were arranged using quarter wave-plates and polarizing beam splitters (PBS), as shown in the figure. In order to avoid cross-talk between amplifier system input and output, stretcher and compressor beams were offset laterally within the grating.

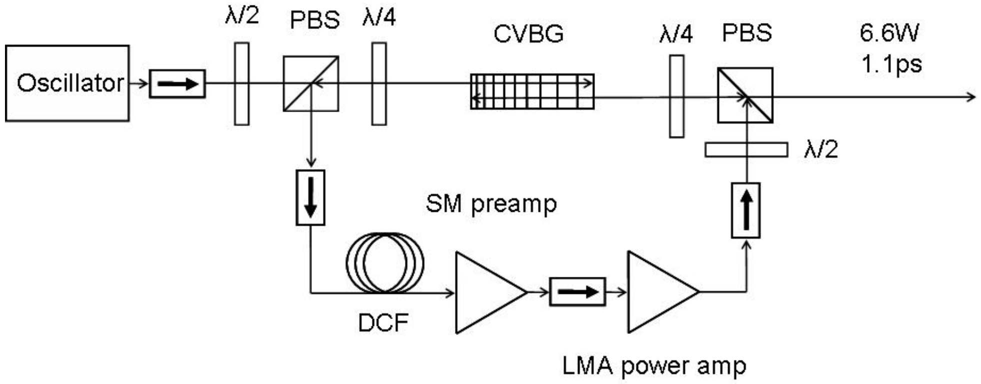

Fig. 1. Setup for the CVBG based FCPA system. Reciprocal setup is adapted for the volume grating to match the stretching and compression phase chirp.

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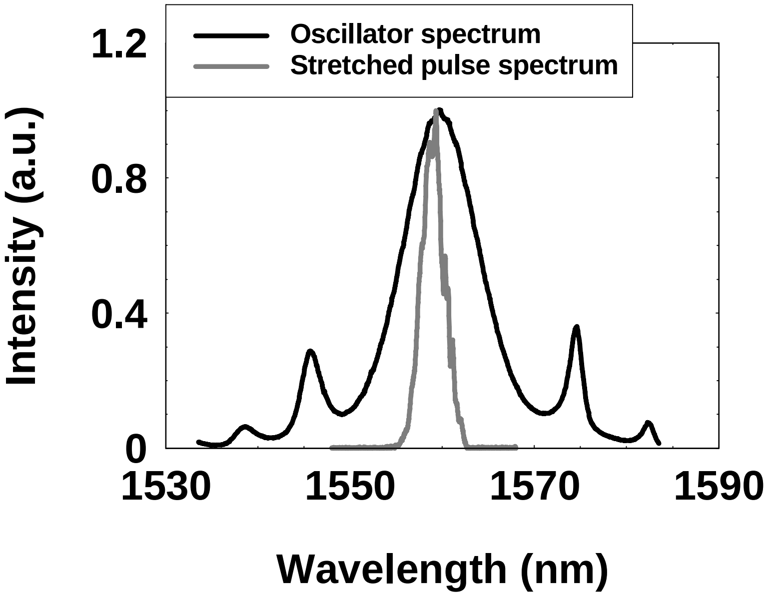

Fig. 2. Measured incident/reflected spectra. The reflected spectrum is centered at 1558-nm with 3-nm bandwidth.

The seed pulses for the CPA system have been generated with a mode-locked fiber oscillator producing 300-fs pulses at 1558 nm with 10mW of average power and 40-MHz pulse repetition rate. We verified with autocorrelation measurements that these seed pulses were bandwidth-limited prior to the injection into the CPA system. In Fig. 2 the spectrum of these seed pulses measured directly after a mode-locked laser is shown. This figure also shows the 3-nm bandwidth spectrum that was injected into fiber amplifier system after stretching pulses in the chirped volume Bragg grating, indicating that seed pulses have bandwidth which is larger that the CVBG bandwidth. The CVBG used in this experiment has a square transverse aperture of 5 mm x 5 mm and its length is 13 mm. Grating reflection efficiency was 70%. Beams of up to 1-mm in diameter have been propagated in this CVBG. Stretched pulse duration was ~100-ps, as measured with a 50-GHz detector and sampling oscilloscope. Stretched pulses were coupled into dispersion compensating fiber (DCF) at the beginning of fiber amplifier system. Purpose of this DCF fiber was to compensate the fiber dispersion in the rest of amplification path, thus ensuring that bandwidth-limited pulses are achieved after recompression.

Fiber amplifier consisted of two amplification stages. Optical isolators were used between the stages to prevent cross-talk, as well as at the input and the output of the amplifier system to avoid parasitic external feedback through the counter-propagating stretched/recompressed beams in CVBG. The first stage consisted of a 10-m long Er-doped standard single-mode (SM) fiber, in-core pumped with 450-mW SM pump diode at 980-nm. Amplified output power after this stage was 100-mW corresponding to 2.5 nJ per pulse. The second stage consisted of a 10-m long Er/Yb co-doped polarization maintaining (PM) large-mode-area (LMA) fiber. The fiber was a double-cladding fiber with 18-μm, 0.17-NA core and 250-μm, 0.46-NA cladding. The amplifier was pumped with 75-W average power at 975 nm in a counter-propagate pumping configuration. Amplified output from this second stage reached up to 15-W of average power at 40-MHz, corresponding to 375-nJ per pulse. After passing the optical isolator and PBS at the output end of the second amplifying stage, the remaining 9.4-W of the amplified signal was launched into the CVBG for pulse recompression. The recompressed pulse average power reflected through the second pair of a quarter wave-plate and a PBS was 6.6 W, corresponding the reflectivity of the CVBG compressor port of 70% (the same as at the stretcher port). To verify the absence of thermal effects in CVBG we had measured this compressor-port reflectivity at all amplified signal powers, which remained constant at ~70% through the complete range of measured output powers, as shown in Fig. 3.

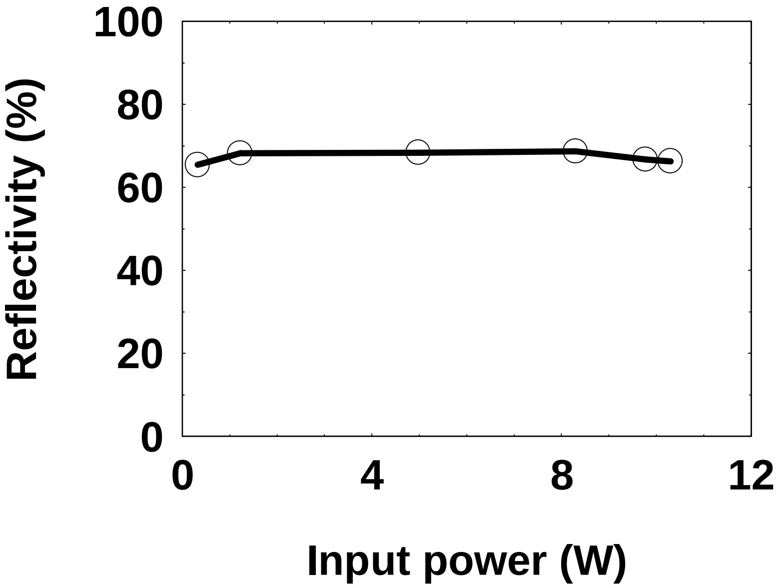

Fig. 3. Reflectivity of the CVBG remains constant (70%) for the entire incident power testing range up to 9.4 W.

The measured autocorrelation trace of the 6.6-W recompressed pulses is shown in Fig. 4(a). Pulse duration corresponding to this trace is 1.1ps. In order to verify reciprocity of the used stretcher and compressor configuration we calculated bandwidth-limited autocorrelation trace of the measured recompressed-pulse spectrum, shown in Fig. 4(b). Indeed, as evident from the overlaid measured and calculated BW traces, both pulse shapes are identical everywhere except small mismatch in the “wings” of the pulses. This confirms that reciprocal pulse stretching and compression has been achieved in this CVBG based fiber CPA systems. Of course, due to the limited grating bandwidth, sensitivity of the recompressed pulses to the higher-order dispersion terms is relatively small in this demonstration. Note, however, that in previous work with chirped fiber Bragg grating reciprocal stretching and compression pulse durations as short as 300-fs have been demonstrated [12].

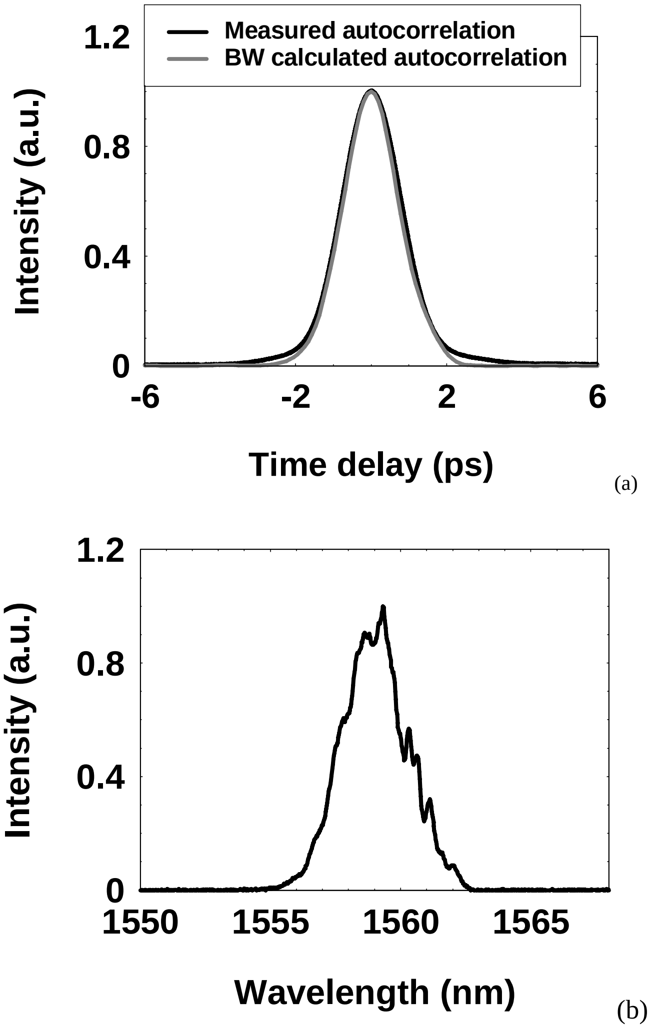

Fig. 4. (a) Measured and calculated autocorrelation traces showed that recompressed pulses were 1.1-ps transform limited pulses. (b) Spectrum of the recompressed pulse.

4. Discussion and summary

In summary, we have demonstrated the first FCPA system using PTR glass based CVBG as pulse stretcher and compressor. In this demonstration a CVBG compressor exhibited a constant 70% efficiency at all tested power levels producing transform limited 1.1-ps duration recompressed pulses at up to 6.6-W of average power. The power achieved in this experimental setup is not limited by the CVBG technology in PTR glass but by the combination of the available pump power and the limited efficiency of the used Er/Yb doped fiber in the last stage (slope efficiency of 20%). Additional power limitation is also posed by the free-space isolator used at the output of the last amplification stage, which was necessary due to the particular scheme used to separate amplified and back-reflected compressed beam from CVBG. We are currently investigating an alternative scheme, which does not require an isolator at the output and, thus, could facilitate scaling to much higher output powers. Generation of higher pulse energies is also possible with PTR-glass CVBG compressors, but has not been attempted in this experiment, since it would require much more complex CPA setup, which is currently being considered for future work. It also would require of much larger core fibers which are currently being developed.

Distinct advantage of the PTR-based CVBG technology is that millimeter-large homogeneous transverse apertures have been demonstrated (and larger apertures are possible), due to the low absorption of PTR glass to the UV writing beam. Indeed, transverse aperture refractive-index homogeneity measurements over 5-mm transverse aperture show refractive index variation of only ~10-ppm.

Important question associated with this technology is related to the maximum achievable CVBG bandwidths and, consequently, to the shortest pulse durations. In terms of the grating parameters, broader bandwidth requires larger refractive-index modulation depth. Preliminary studies indicate that there is a trade off between the grating strength and the scattering loss due to the precipitation of nano-particles during thermal development stage, which appears to strongly depend on the conditions of the post UV-exposure annealing process. Experimental characterization of separately fabricated test samples indicate that currently chirp rate of 5nm/cm can be achieved with induced scattering losses of approximately 2.5%/cm, which for 2 – 5 cm long CVBG structures could provide 10 – 25 nm chirp bandwidth with absolute reflection efficiencies of 80% to 90%.

CVBG are robust, compact and easy to align devices, which have a high throughput efficiency compared to traditional diffraction grating stretchers and compressors. Therefore, the demonstrated PTR-glass chirped volume Bragg grating technology provides with a very promising avenue towards developing compact and highly practical high power ultrashort pulse lasers.

#79812 - $15.00 USD Received 7 Feb 2007; revised 24 Mar 2007; accepted 29 Mar 2007; published 6 Apr 2007