Vector-dispersion compensation and pulse pedestal cancellation in a femtosecond nonlinear amplification fiber laser system

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We report on a femtosecond nonlinear amplification fiber laser system using a vector-dispersion compressor, which consists of a transmission grating pair and multipass cell based Gires–Tournois interferometer mirrors. The mirror is designed with nearly zero group-delay dispersion and large negative third-order dispersion. As a result, the third-order dispersion of the compressor can be adjusted independently to compensate the nonlinear phase shift of amplified pulses to reduce the pulse pedestal. With this scheme, the system outputs 44 fs laser pulses with little wing at 26.6 W output average power and 531 nJ pulse energy, corresponding to 10.8 MW peak power. © 2011 Optical Society of America

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Ultrashort pulse fiber lasers and amplifiers [1–4] have many advantages over conventional bulk solid-state systems, such as compact design, high optical pumping efficiency, and outstanding thermo-optical properties. The ultrashort pulse amplification in doped fibers is challenging due to the high intensity confined in the fiber core over a long propagation length, which evokes nonlinear pulse distortions, mainly by self-phase modulation (SPM). Fiber chirped-pulse amplification [1] and nonlinear pulse amplification [2] are widely used as the most intuitive and common approaches to alleviate this issue. In these two schemes, the grating pair is a very favorable compressor to supply group-delay dispersion (GDD) and third-order dispersion (TOD) to compensate the nonlinear phase shift ($\Phi_{NL}$) [3,4], but its fixed ratio between the GDD and TOD cannot compensate the $\Phi_{NL}$ very accurately [5] and always leads to a pedestal in the pulse shape. For many applications it is desirable and necessary to modify the pulse form in a well-defined manner. To obtain clean ultrashort pulses, larger stretched pulse durations of the seed pulse will increase the compression quality due to lower $\Phi_{NL}$ accumulation [1]. Another alternative direction is applying more accurate dispersion compensation, such as liquid crystal spatial light modulation, acousto-optic programmable dispersive filters, and electro-optic phase modulators [6–8], which are too complex to be applied in a compact system and cannot support high average power operation.

In this Letter, we propose a vector-dispersion compressor (VDC), consisting of transmission gratings and multipass cell (MPC)-based TOD Gires–Tournois interferometer mirrors (G-T mirrors). The TOD G-T mirror is designed to have nearly zero GDD and large negative TOD (the grating pair supplies positive TOD). The total TOD of G-T mirrors can be easily tuned by the number of bounces on the MPC, while the influence on the GDD of the compressor can be neglected. Thus, an adjustable dispersion vector (i.e., the ratio of TOD to GDD) features this compressor. According to the dispersion vector analysis theory [9], the vector dispersion of our VDC can be expressed as

$$\vec{D}_c = \left[ \begin{array}{c} D_{2c} \\ D_{3c} \end{array} \right] = \left[ \begin{array}{cc} D_{2g} & D_{2m} \\ D_{3g} & D_{3m} \end{array} \right] \left[ \begin{array}{c} l \\ n \end{array} \right],$$

where $l$ is the grating separation, $n$ is the bounce number on G-T mirrors, and $D_{2m}$, $D_{3g}$, and $D_{2c}$ represent the $x$th-order dispersion of the G-T mirrors, grating pairs, and VDC, respectively. Since $D_{2m} \approx 0$, $D_{2c}$ can be written as

$$D_{2c} = D_{2g} l.$$

Note that the total GDD of the compressor is determined only by $l$, and the TOD can be adjusted independently by $n$. With this adjustable TOD design, the compressor can compensate the $\Phi_{NL}$ of amplified pulses perfectly and compress the laser pulse with little pedestal, even at a high output-power level.

A schematic of the experimental setup is shown in Fig. 1(a). The oscillator and amplifier are all based on the identical single-polarization double-cladding Yb3+-doped large mode area photonic crystal fiber (LMA-PCF) [10]. The fundamental mode diameter of the LMA-PCF is 29 $\mu$m. The microstructure and polarization maintaining elements built in the inner cladding guarantee diffraction-limited beam quality and single-polarization operation within a 100 nm bandwidth centered at 1060 nm. Both fiber ends are fused and polished at $8^\circ$ to suppress parasitic lasing. The seed source is a passively mode-locked LMA-PCF femtosecond laser [11], which generates 554 fs pulses with ~6 nm bandwidth around 1040 nm at 50 MHz repetition rate. The seed pulses are directly coupled into the amplifier after the isolator in a stretcher-free configuration. The amplifier is counterdirectionally end-pumped with a
100 W fiber-coupled laser diode emitting at 976 nm. Amplification of laser pulses in this configuration is accompanied by spectral broadening and $\Phi_{NL}$ accumulation due to SPM. As shown in earlier work [2-4], high-peak-power ultrashort laser pulses are supported in this regime, since a limited $\Phi_{NL}$ of pulses can be compensated by an appropriate negative dispersion component following the amplification stage. This strategy of perfect short-pulse generation, however, requires a precise balance between the gain, nonlinearity, and dispersion. Otherwise, the output laser pulses always have a pedestal, limiting the corresponding peak power.

Numerical simulations were performed to find an optimization for compression. The split-step Fourier algorithm was applied to solve the extended nonlinear Schrödinger equation with similar parameters to the experiment. Increasing the output pulse energy up to 540 nJ, the directly output pulse duration is 2.7 ps. With optimization of the GDD and TOD, the results from the VDC show a better temporal quality than those from the grating compressor alone in Fig. 2.

The VDC experiment setup is shown in the dotted frame in Fig. 1(a). The amplified laser pulses first pass through a pair of 1250 lines/mm transmission gratings in fused silica with a 40° incident angle and then interfere on G-T mirrors. The grating pair supplies $\sim 0.725 \times 10^3 \text{ fs}^2$ GDD and $\sim 3 \times 10^3 \text{ fs}^3$ TOD with $\sim 5$ nm separation in experiment. The throughput efficiency is 74% with double-pass geometry. The concave G-T mirrors are aligned with a Herriott-type multipass configuration to maintain beam quantity fidelity [the beam spot pattern on the mirror is shown in the inset of Fig. 1(a)]. The dispersion of the G-T mirror is specially designed, and Fig. 1 shows the measured GDD and TOD curves. There is less than $\pm 100 \text{ fs}^2$ GDD and $-1 \times 10^4 \text{ fs}^3$ TOD around 1040 nm wavelength. Around 40 bounces on G-T mirrors can roughly balance the TOD of the gating pair and gain fiber in the system, while the introduced GDD is too low to influence the total GDD. The mirrors’ reflectance is 99.9% (950 ~ 1140 nm), and hence the total compression efficiency of the VDC is $\sim 71\%$. A long-scan-range autocorrelator (APE Pulse-Check) and a high-resolution spectrometer (Ando 6315A) were used to measure the pulse shape and spectrum, respectively.

During amplification, the laser pulses are broadened spectrally and temporally, while accumulating $\Phi_{NL}$ due to SPM. Over 50 nm bandwidth of amplified pulses is obtained [shown in Fig. 3(c)], as the output average power is increased up to approximately 37.4 W and the output pulse is stretched up to 2.7 ps. Meanwhile, the spectral asymmetry appears [shown in Figs. 3(a)–3(c)] because of the impact from the asymmetric gain spectral shape, which is enhanced, especially for the optical spectrum outside the gain bandwidth [12]. With the bandwidth increasing, the FWHM of the compressed pulses’ duration is reduced from 73 fs to 44 fs. With the assistance of TOD G-T mirrors, the laser pulses are compressed in a well-defined manner, resulting in a peak power of 10.8 MW (95% energy in the main pulse peak, and assuming a Gaussian profile).

For comparison, the VDC and the grating-pair compressor were employed respectively in the experiment. The measured autocorrelation (AC) traces of the compressed pulses with different output average power are summarized in Figs. 3(d)–3(f). As shown in these figures, the dramatic variation in the pulse quality and duration is observable as $\Phi_{NL}$ is varied. The VDC can supply a more adjustable dispersion vector than the grating pair to match the $\Phi_{NL}$. When the pulses are amplified up to 11.8 W, the spectrum is broadened to $\sim 40$ nm, and the chirped pulse duration is $\sim 73$ fs. Here the traces have a low pedestal [shown in Fig. 3(d)], regardless of whether the G-T mirrors are used or not, because long-duration pulses are insensitive to residual TOD to make the advantage of G-T mirrors unobvious. As the output power
scales up, the dechirped pulse duration decreases, and the TOD-optimized effect of the G-T mirrors is more obvious. When the laser output power rises to 27.1 W with a pulse duration of 54 fs, the pulses compressed by the VDC show lower wing structure than those compressed only by gratings [shown in Fig. 3(e)]. The advantage of the VDC on pedestal suppression is more observable, when the average power rises up to 37.4 W with a pulse duration as short as 44 fs, as shown in Fig. 3(f).

To analyze semiquantitatively, the RMS width of the autocorrelation trace is used to evaluate the pulse temporal quality. For the same value of FWHM, smaller RMS width implies better pulse quality with a lower pedestal. The RMS and FWHM widths of the AC traces versus pulse average power are summarized in Fig. 4. At different output power, the bounce number on the G-T mirrors (shown in Fig. 4) and the distance of the gratings are optimized. The FWHM of AC traces of pulses obtained by both compressors are nearly the same and decrease monotonically with average power increase. However, the VDC does not only compress the laser pulses as the grating pair does, but it also keeps a good RMS width. With the power scaling up, the mismatch between $\Phi_{NL}$ and the TOD of the grating compressor increases and makes the RMS width increase. In contrast, the G-T mirrors can optimize the TOD in the system to follow the increase of $\Phi_{NL}$ and even reduce the RMS width. However, restricted by the bandwidth of the G-T mirrors, the pulse cannot be compensated over the whole spectrum at the high output power. As a result, the RMS width stays around 45 fs, not going down as the FWHM curves, and is accompanied by little pedestal [shown in Fig. 3(f)].

In conclusion, we have demonstrated a VDC in a non-linear amplification femtosecond fiber laser system. The TOD of the compressor can be controlled independently of the GDD, so that it can accurately compensate the $\Phi_{NL}$ in fiber. With this scheme, the amplifier generates 44 fs pulses with little pedestal of 26.6 W average power (71% compression efficiency of 37.4 W output power from the amplifier) and 50 MHz repetition rate, corresponding to 10.8 MW peak power. This scheme is suitable for even higher power fiber laser systems, and with a broader bandwidth, a high quality femtosecond laser pulse with a shorter duration can be obtained.

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