Temporal contrast enhancement by nonlinear elliptical polarization rotation in a multi-pass cell

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Abstract: We demonstrate the simultaneous temporal contrast improvement and pulse compression of a Yb-doped femtosecond laser via nonlinear elliptical polarization rotation in a solid state multi-pass cell. The temporal contrast is improved to 10⁹, while the pulse is shortened from 181 fs to 36 fs, corresponding to a compression factor of 5. The output beam features excellent beam quality with $M^2$ values of 1.18 $\times$ 1.16. The total efficiency of the contrast enhancement system exceeds 50%. This technique will have wide applications in high temporal contrast ultra-intense femtosecond lasers.

Key Words: temporal contrast, pulse compression, nonlinear elliptical polarization rotation, multi-pass cell

1. Introduction

High peak power femtosecond lasers based on the chirped pulse amplification (CPA) and optical parametric chirped pulse amplification (OPCPA) technology have developed rapidly in the last few decades[1-5]. Laser systems with the peak power of 10 petawatt (PW, 1PW=10¹⁵ W) have also been reported in recent years[6], which have become powerful tools for the investigation of laser matter interactions. During amplification, unwanted amplified spontaneous emission (ASE) and pre-pulses can be generated and amplified, which deteriorate the temporal contrast of the high peak-power femtosecond pulse. When the intensity of amplified spontaneous emission (ASE) or pre-pulses reaches 10¹³ W/cm², they can ionize the target material and generate pre-plasma before the main pulse reaches the target, which would seriously affects the laser matter interactions.

To eliminate negative impact of the undesired pre-pulses and ASE, several temporal pulse cleaning technologies have been proposed and demonstrated, such as cross polarize wave generation (XPW)[7, 8], optical parametric amplification (OPA)[9, 10], self-diffraction (SD)[11, 12], nonlinear elliptical polarization rotation (NER)[13-15], plasma mirrors[16-18], nonlinear fourier filtering[19, 20] and so on. Among the temporal contrast improvement technologies mentioned above, XPW based on BaF₂ crystal is widely implemented in ultra-intense femtosecond laser facilities worldwide[5, 21], as it improves the temporal contrast several orders of magnitude and shortens the pulse by a factor of $\sim$1.73 at the same time. Therefore, XPW is good for obtaining higher peak power after amplification. Nevertheless, the total efficiency of XPW is typically only about 20%,
focused intensity of the femtosecond pulse on the BaF$_2$ crystal is at 10$^{12}$ W/cm$^2$ level, which implies that the damage of BaF$_2$ crystal is unavoidable after long term operation. So, it is necessary to shift the position of BaF$_2$ crystal periodically. As for NER, it also features temporal cleaning and spectral broadening simultaneously. Moreover, the spectral broadening capability of NER exceeds that of XPW. Based on NER, the generation of high temporal contrast pulses with few-cycle pulse duration have been reported. In 2019, N. Smijesh et al demonstrated the generation of high temporal contrast sub-4 fs pulses by integrating NER into a spectral broadening device of argon filled hollow-core fiber (HCF)[22]. In 2020, N G Khodakovskiy et al demonstrated the generation of high temporal contrast 5 fs pulse by NER in a HCF compressor[23]. But the HCF suffers from low transmittance and more complex alignment requirements. Another spectral broadening device called multi-pass cell (MPC) has been widely investigated in recent years[24-33]. It consists of two concave mirrors and nonlinear elements between them. The pulse roundtrips inside MPC can induce dramatic spectral broadening. Compared with HCF, the MPC features high efficiency, excellent energy and power scalability and low requirement for pointing stability of the input laser. In 2021, Viktor Pajer et al simulated the simultaneous nonlinear spectral broadening and temporal cleaning of the femtosecond pulses by NER in a MPC device. In their simulations, the 10$^3$ temporal contrast enhancement with a 50% internal efficiency is realized[34]. Recently, Yanik Pfaff et al demonstrated temporal contrast improvement by NER in a gas filled MPC device, and the temporal contrast is enhanced by more than a factor of 50 with an optical efficiency of 56%[35].

In this article, the temporal cleaning and compression are experimentally achieved simultaneously by integrating NER into a solid plate based MPC device. The pedestal of the input pulse is cleaned effectivevily with a total efficiency higher than 50%, while the pulse duration is shortened from 181 fs to 36 fs, corresponding to a compression factor of 5. The beam quality after temporal filter is excellent with $M^2$ values reaching 1.18×1.16.

2. Experimental setup

Fig.1 Layout of the experimental setup. HWP, half wave plate, TFP1-TFP2, thin film polarizers, L1-L4, lenses, GL1-GL2, Glan prisms, QWP1-QWP2, quarter wave plates, CM1-CM2, concave mirrors, FS, fused silica plate.

The layout of the experimental setup is depicted in Fig.1. An ytterbium (Yb)-doped femtosecond amplifier is employed as the driving laser, which delivers 2 mJ pulse energy and 181 fs pulse duration at 1 kHz repetition rate. The central wavelength and the spectral full width at half maximum (FWHM) of the driving laser are 1036.8 nm and 9.3 nm, respectively. A small portion of pulse
energy is used for our proof of principle experiment. The mode matching between Yb-doped driving laser and eigenmode of the MPC is realized by utilizing three lenses (L1-L3). A Glan prism (GL1) is used to improve the linear polarization degree. The pulse energy after GL1 is 29 μJ. Then the polarization of the input laser is converted to elliptical through a quarter wave plate (QWP1). The MPC cavity consists of two concave mirrors with 50.8 mm diameter and 300 mm radius of curvature. The MPC mirrors are low group delay dispersion (GDD) coated at the spectral range of 950 nm-1110 nm. The distance between the MPC mirrors is 525 mm, so the eigenmode diameter of the MPC is 2w₀=0.36 mm in the middle of the MPC. A 5 mm thick fused silica plate coated with high transmittance at 1 μm is used as Kerr medium. As material dispersion of the fused silica plate is not compensated inside MPC, the pulse duration broadens after multiple round trips. And the single pass nonlinear phase shift will decrease gradually. Therefore, a small number of round trips (13 times) is proposed, corresponding to laser pulse propagation 0.13 m in fused silica and 13.5 m in air. It is obvious that the propagation length is much shorter than the respective dispersion lengths of fused silica $L_{D,FS}=0.64$ m and air $L_{D,air}=725$ m. The accumulated total material dispersion inside MPC is calculated to be 2630 fs², which just broadens the input pulse from 181 fs to 185 fs. As a result, the nonlinear phase shift is barely affected by material dispersion. The pulse coupling in and out of the MPC is performed with a rectangle mirror with 3 mm width. The output beam is collimated with a lens L4. Then output pulses are delivered through QWP2 to eliminate the retardation generated by QWP1. The pulse temporally filtered by NER is discriminated by a high extinction ratio ($>2\times10^5$) GL2.

3. Experimental results

The output power measured before GL2 is 27.5 mW, corresponding to a transmission efficiency of 95% in the MPC. The QWP1 whose optical axis is rotated by an angle $\gamma$ with respect to the polarization of the input pulse is employed to set the original ellipticity, while the QWP2 is rotated with an angle of $90^\circ+\gamma$. The fused silica plate is positioned 14 cm, 16 cm, 18 cm and 20 cm away from CM2 respectively, corresponding to the eigenmode diameter at the position of the plate reducing from 574 μm to 427 μm while ignoring the Kerr lens effect. Therefore, the peak intensity on the plate is estimated to be $10^{11}$ W/cm² level. The total efficiency of the NER filter is investigated as a function of angle $\gamma$, and results are described in Fig.2 (a). The total efficiency is given by $\eta=\frac{P_2}{P_1}$, where $P_2$ denotes the power after GL2 and $P_1$ denotes the power after GL1. As the angle $\gamma$ increases from 0° to 44°, the total efficiency first increases and then decreases. When the fused silica plate is 14 cm and 16 cm away from the CM2, the angle $\gamma$ corresponding to maximum efficiency is 14°. And angle $\gamma$ for maximum efficiency shifts to 12° for the plate at 18 cm and 20 cm away from the CM2. Figure.2(b) summarizes the optimal total efficiency when the plate is placed at different positions. The highest total efficiency 53% is obtained when the plate is placed 18 cm away from CM2.
By placing the plate at different positions, the spectra after GL2 are measured at maximum total efficiency, as presented in Fig.3 (a). As the plate moves away from the CM2, stronger spectral broadening occurs because the nonlinear phase shift increases gradually. The spectral bandwidth at the intensity of -20 dB is broadened from 94.1 nm to 131.6 nm, as summarized in Fig.3(b) (red line), and the corresponding Fourier transform limit (FTL) pulse duration is shortened from 44.2 fs to 31 fs, as shown in Fig.3(b) (blue line). At the strongest spectral broadening condition, the total efficiency of the system is 52%.

After ejected from the MPC, the positive chirp of the pulse accumulated with propagation through the MPC is compensated by utilizing chirped mirrors. The pulse duration is characterized by using a homebuilt second harmonic frequency-resolved optical gating (SHG-FROG) device. A pulse duration of 36 fs is obtained when the compensated GDD is -3200 fs², corresponding to a compression factor of 5. The measured and retrieved traces are shown in Fig.4(a)-(b). The spectral intensity and phase are shown in Fig.4(c). The input pulse, compressed pulse and calculated FTL pulse duration are presented in Fig.4(d).
Fig. 4 SHG-FROG characterization of the filtered pulse. (a) Measured and (b) retrieved SHG-FROG traces (0.45% FROG error on a 512×512 grid). (c) Measured spectrum (red line) and spectral phase (blue line). (d) Input pulse duration (blue dashed line), retrieved pulse duration (red line) and calculated FTL pulse duration (black line).

Fig. 5 Beam quality after MPC device.

The beam quality ($M^2$) of the temporal cleaned pulse is measured to be $1.18 \times 1.16$ by employing a commercial $M$-squared factor meter (BSQ-SP300, Ophir Spiricon), which is shown in Fig. 5. Compared with the $M^2$ of the input laser, the beam quality is almost maintained.
The energy of temporally cleaned pulse is no more than twenty microjoules, which is insufficient to perform temporal contrast measurement with a commercial third-order cross-correlator device. So, a Yb: KGW based chirped pulse amplifier was built to boost the filtered pulse energy. The schematic of the amplifier is depicted in Fig.6. The stretcher and compressor share one transmission grating. One Ng-cut Yb: KGW crystal with a size of $3\times3\times5$ mm$^3$ is employed as gain medium in the regenerative amplifier. The dumped pulse energy of the regenerative cavity is 800 $\mu$J. Limited by the emission spectral bandwidth of the Yb: KGW crystal and gain narrowing, the spectral bandwidth of the amplified pulse is narrowed to 4.8 nm, as shown in Fig.7 (a). Assuming a Sech$^2$ shaped pulse, the compressed pulse duration is 457 fs, as shown in Fig.7 (b).

Figure.8 shows the measured temporal contrast of the amplified pulse (red line), which is $10^9$. As a comparison, the temporal contrast is $10^7$ when the amplifier is seeded by a semiconductor saturable absorption mirror (SESAM) mode-locked fiber oscillator (black line). It can be seen that the fluctuation of the ASE intensity increases dramatically when employing the temporally cleaned pulse as the seed. This is because the distance between the Yb-doped driving laser and the homemade Yb: KGW regenerative amplifier is around 10 m, which deteriorates the energy stability of the amplified pulse.
4. Conclusion

In conclusion, the temporal contrast of a Yb-doped femtosecond laser is enhanced to nearly $10^9$ by integrating NER into a solid state MPC device. The pulse duration is compressed from 181 fs to 36 fs, corresponding to a compression factor of 5. The beam quality after MPC is excellent with a $M^2$ value of 1.18×1.16. The total efficiency of the MPC based temporal contrast enhancement device is higher than 50%. Benefitting from excellent power and energy scalability of the MPC device, we believe that this scheme can be applied to high energy pulses cleaning system.

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