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Spectral-Phase-Modulated Cross-Polarized Wave for Chirped Pulse Amplifier with High Contrast Ratio *

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We demonstrate a high-quality cross-polarized-wave filter based on spectral phase modulation. Driven by well-compressed spectral-phase fully-compensated fundamental laser pulses, the filter stretches the pulse bandwidth from 35 nm to 70 nm with a conversion efficiency of 20%. After implementing the filter into a femtosecond TW Ti:sapphire laser system, we generate 40 mJ output pulse energy with pulse duration of 18.9 fs. The temporal contrast of the compressed pulse is enhanced to 10^9.

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Chirped-pulse amplification (CPA) technology[1] has been revolutionary to allow the generation of ultrahigh-peak-power pulses for strong-field physics since the 1980s. Laser intensity as high as 10^{22} W/cm^2 has been demonstrated for applications of high-field physics research in the relativistic regimes.[2,3] Such high-peak-power laser offers more possibilities to the research of light-matter interactions. As one of the crucial characteristics of high-peak-power lasers, temporal pulse contrast represents the ratio between the peak intensity of the main pulse and the other noises in the temporal structure, such as the amplified spontaneous emission (ASE) and the pre-pulses.[4] Higher contrast ratio is one of the most demanding parameters for the mitigation of pre-plasma dynamics, which would not only reduce the effective on-target energy but also make the experimental analysis more difficult. The requirement is even more stringent in laser–solid matter interaction experiments because solid targets have much lower ionization threshold than gas targets.[5,6]

ASE is the main cause of the contrast degradation. Several pulse-cleaning methods have been developed to control the ASE to a lower level, such as the utilization of saturable absorbers,[7] double CPA,[8] plasma mirrors[9] and the cross-polarized wave generation (XPW).[10] The XPW filter is an ideal solution to achieve a high-peak power laser system due to its inherent pulse cleaning effects,[11,12] as well as its superior spectral broadening capabilities.[13] The XPW method also utilizes simple all-solid-state setup, which introduces negligible instabilities into the whole laser system if the qualities of driving pulses are well controlled.

In this Letter, we demonstrate a cascaded XPW filter based on controlled spectra-phase modulations. This technique is subsequently implemented into a home-built 2 TW, 40 mJ CPA laser system. The recompressed pulse duration is as short as 18.9 fs and the contrast ratio is enhanced by three orders of magnitude.

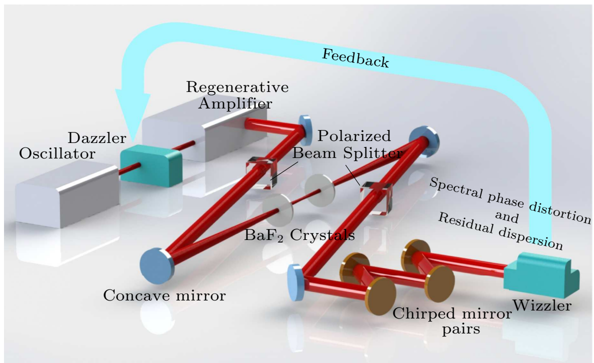

Fig. 1. Detailed structure design of the cascaded XPW filter.

The detailed structure of the XPW filter is illustrated in Fig. 1. The driving laser pulse comes from a spectral phase-modulated CPA system with a regenerative amplifier. Prior to the amplification, the 3.8 nJ, 15 fs seed pulse from a homemade mode-locked Ti:sapphire oscillator is first stretched, and the pulse shaper (DAZZLER, Fastlite Inc) is deployed to compensate for the residual dispersion and to control the spectral phase of the whole system. The output pulse from the regenerative amplifier is recompressed by a Treacy-type grating compressor to 33 fs, which is then focused onto two 2-mm-thick BaF_2 crystals under vacuum conditions by a concave mirror.

The XPW pulse is collimated by another concave

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mirror with the same radius of curvature. Chirped mirrors are utilized to compensate for the dispersion introduced by the polarizers and the optical windows. During the XPW process, the high-intensity main pulses reach the nonlinear threshold and become converted to XPW pulses, while the ASE and pre-pulses are not intense enough, and will be rejected by the crossed polarizer. Moreover, the spectral bandwidth is greatly expanded due to the self-phase modulation, cross-phase modulation as well as the pulse steepening effects in the crystal. Therefore, the pulse would possess greater potential to be compressed to a shorter temporal scale.

The XPW conversion efficiency and spectral characteristics have a strong dependence on the spatial and temporal qualities of the input driving pulses. Since the XPW process is a third-order nonlinear interaction process,[14] any spatial defects would be enhanced during the conversion, which will subsequently deteriorate the beam quality of the output pulses. Furthermore, the input pulse duration should be compressed to near Fourier transform limit (FTL) and the minimal residual spectral phase distortion is required, which has dominant influence on the conversion efficiency and the spectral broadening. Therefore, the spatial and temporal qualities must be precisely controlled.

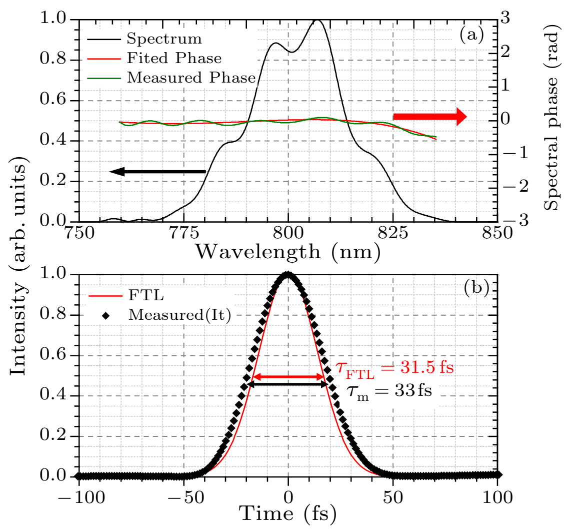

Fig. 2. Spectral and temporal properties of the XPW driving pulses. (a) Black curve: measured spectrum; red curve: fitted spectral phase; and green curve: measured spectral phase. (b) Black dot: measurement of the pulse duration before the XPW; and red line: FTL pulse duration calculated from the spectrum.

The first CPA laser system for driving the XPW process is designed to have balanced the second- and third-order dispersions. However, the complete compensation of higher-order phase distortions is beyond the capability of the stretcher and compressor. We therefore implement an adaptive close-loop optical system to achieve a flat spectral phase. As mentioned above, we use an acousto-optic programmable dispersive filter (DAZZLER, Fastlite Inc.) to actively control the spectral phase. A self-referenced spectral interferometer (Wizzler, Fastlite Inc.) characterizes the pulses and the error signal would be fed back to the DAZZLER. This type of feedback could be executed with several iterations until the spectral phase is flat and the pulse duration is compressed to the FTL (Fig. 2(a)). The optimized pulse duration is 1.05 times of the FTL. The result is shown in Fig. 2(b).

The M^2 factor measurement of the regenerative amplifier (compressed) is shown in Fig. 3. It is around 1.3 for both the directions, which is sufficient to obtain moderate conversion efficiency.

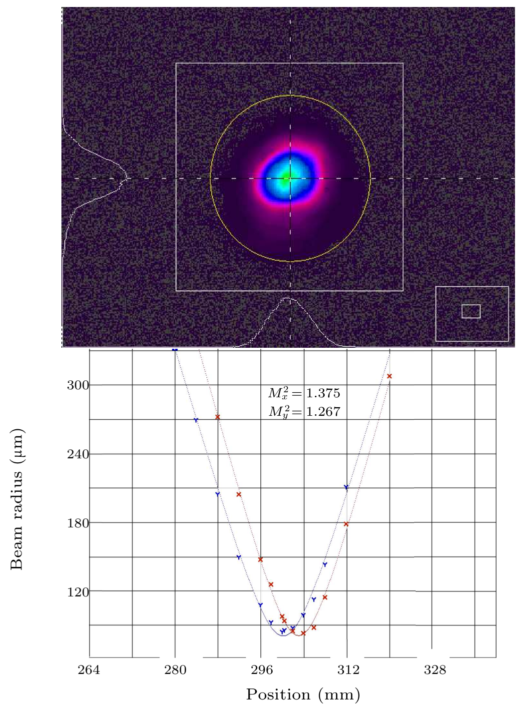

Fig. 3. The M^2 factor measurement result of the regenerative amplifier (compressed).

In the focusing geometry of the XPW filters, we use a concave mirror with 2-meter radius of curvature to focus the driving pulse and to keep the slow longitudinal variation of the beam sizes through two pieces of BaF_2 crystals (2-mm-thick, [011] orientated). Reflective concave mirrors are free of material dispersion and nonlinear effects compared with transmissive focal lenses. To have adequately high intensity but not reaching the damage threshold, the laser beam diameter ($1/e^2$) is controlled to be approximately 800 μm by placing the first crystal 40 mm before the focal point. The actual peak power density is $8.4 \times 10^{12}\,\mathrm{W/cm^2}$.

We then place the second BaF_2 crystal symmetrically 40 mm after the focal point, and choose two pieces of the 2-mm-thick BaF_2 crystals instead of one piece of a 4 mm crystal to increase the conversion efficiency. The cascaded structure offers more flexibility to adjust the relative angles between the crystalline axis and the pulse polarization vector for both the crystals.[15] Since the pulse intensity at the focus is strong enough to break down the air and to distort the

XPW output, we place the two BaF_2 crystals under vacuum conditions. With input fundamental energy of 1.4 mJ, we achieve 280 µJ XPW energy output with a conversion efficiency of 20%.

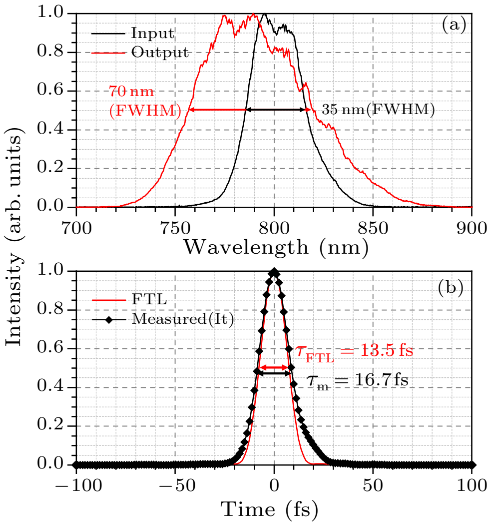

Fig. 4. Spectral and temporal properties of XPW pulses. (a) Black curve: measurement of the spectrum at the regenerative amplifier (compressed), with the FWHM of 35 nm. Red curve: measurement of the spectrum after the XPW, with the FWHM of 70 nm. (b) Black dot: measurement of the pulse duration of the compressed XPW output. Red line: FTL pulse duration calculated from the spectrum.

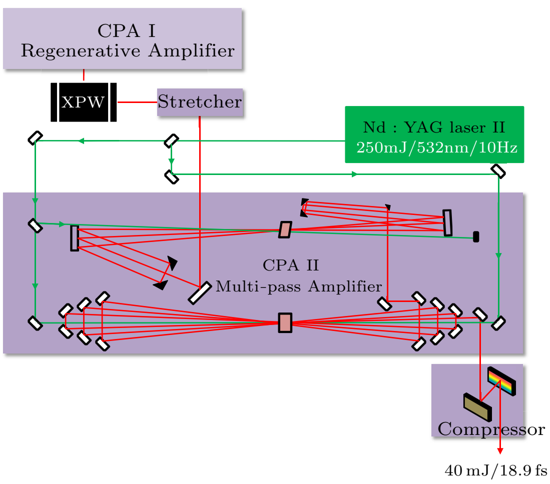

Fig. 5. Schematic diagram of XPW built in the double-CPA system with the peak-power of 2 TW.

We measure the broadening of the XPW spectrum. As shown in Fig. 4(a), the spectral bandwidth (FWHM) of the output is broadened from 35 nm to 70 nm. It could potentially support pulse duration as short as 13.5 fs. The center of the XPW spectrum is blue shifted due to the residual higher-order spectral phase of the seed pulse.[16] After compression, we measure the compensated pulse duration and the result is 16.7 fs, as shown in Fig. 4(b).

The high-contrast and broadband seed pulses from the XPW filter are injected into the second CPA stage, as illustrated in Fig. 5. The clean seed pulse is stretched to ~200 ps and an electro-optic pulse-picker steps down the repetition rate from 1 kHz to 10 Hz. The pulse energy is subsequently boosted to 55 mJ by two stages of multi-pass amplifiers pumped by a 250-mJ 10-Hz Nd:YAG laser. Due to the limited coating bandwidth of optics and the gain-narrowing effect in the amplifiers, the spectral bandwidth is reduced by 10 nm during the amplification. As shown in Fig. 6, the recompressed pulse duration is 18.9 fs and the energy from the compressor is 40 mJ, leading to a peak power higher than 2 TW.

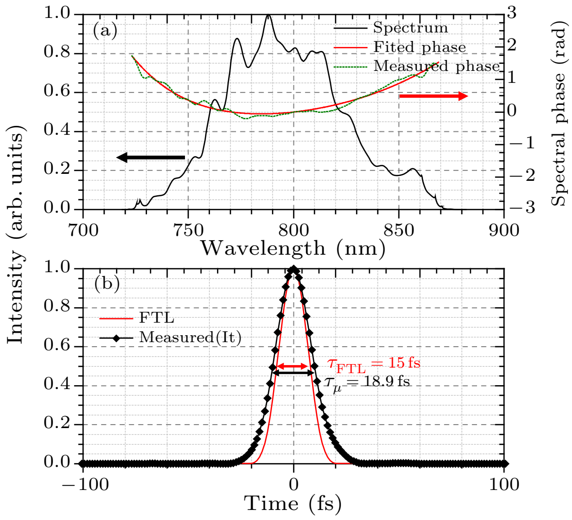

Fig. 6. Spectral and temporal properties of the amplified XPW pulses. (a) Black curve: measured spectrum; red curve: fitted spectral phase; and green curve: measured phase. (b) Black dots: measurement of the pulse duration. Red line: FTL calculated from the spectrum.

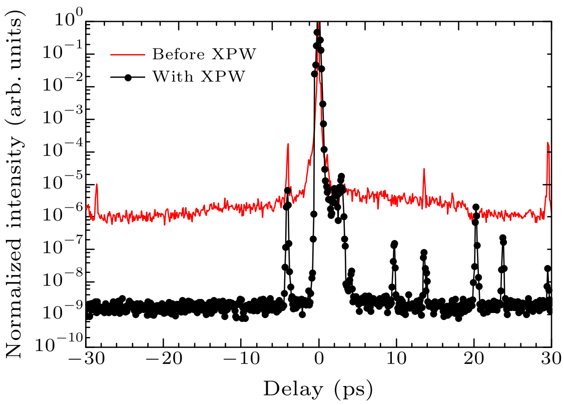

Fig. 7. Third-order cross-correlation measurement of the pulses before XPW (red line) and the TW system output pulses after XPW (black dotted line).

The temporal pulse contrast ratio of the DCPA system is characterized by using a high dynamic third-order cross correlator (Sequoia 800, Amplitude Technologies). The measurement results both before and after the implementation of the XPW filter are shown in Fig. 7. The measurements are conducted under the time scale of ±30 ps. The red curve represents the contrast before cleaning, which is about 10^6, and there is a pre-pulse existing at 4 ps prior to the main pulse. The cleaned result is shown by the dotted curve, which is higher than 10^9, and the pre-pulse is suppressed by two orders of magnitude. It can be obtained that the XPW filter enhances the contrast of the laser pulse at least by three orders of magnitude.

The third-order cross correlator has the best performance for ultrafast pulses with duration from 40 fs to 200 fs, while the actual pulse duration is below 20 fs, much shorter than the standard requirement. In this situation, the peak position of the main pulse is difficult to capture accurately by the photo detector in the third-order cross correlator (Sequoia 800, Amplitude), which means that the contrast ratio between the main pulse and the continuous pedestal may be under-estimated. The real contrast result could be 1–2 orders of magnitude better than the measurement result. This hypothesis is also supported by the device manual[17] as well as the extinction ratio (10^6) measurements of the alpha-BBO polarizers.

In conclusion, we have demonstrated a pulse cleaning filter based on high-quality double-crystal XPW generation, which is subsequently applied to a self-built TW laser system. The contrast ratio reaches 10^9 with a pulse duration as short as 18.9 fs. The cascaded XPW filter has enhanced the contrast ratio by three orders of magnitude and broadens the bandwidth by over two times. This is an ideal front-end for a petawatt laser facility for high-field physics research. A higher-peak-power CPA laser system (>200 TW) with shorter pulse duration (15 fs) and high contrast (10^{10}) is in development.

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