Recent progress in the development of high intensity ultrashort pulse lasers at SIOM

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We report the recent progress in the development of high intensity ultrashort pulse lasers at the State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics (SIOM). Based on the concept of optical parametric chirped pulse amplification (OPCPA), a 16.7 TW/120 fs laser at 1064 nm was developed. Some new nonlinear optical materials, such as quasi-phase-match crystals, were investigated as new OPCPA gain media. The investigation of broadband OPCPA near 780 nm was also carried out. On the other hand, based on the scheme of chirped pulse amplification (CPA), the Ti:sapphire laser system with a peak power of 0.89 PW and a pulse width of ~29.0 fs has been developed. The high gain amplification was achieved in a large aperture amplifier by cladding with refractive-index matched liquid doped with absorber to suppress the parasitic lasing.

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The development of high intensity ultrashort pulse laser is an important research field. Possible applications from laboratory astrophysics to medical therapy with high energy particles demand laser pulses with higher intensity, shorter pulse width and higher contrast ratio. In recent years, there has been rapid progress in the development of terawatt-class and even petawatt-class ultrashort pulse lasers with tens of femtoseconds pulse width based on chirped pulse amplification (CPA) technique[1,2]. The Nd:glass laser system with peak power above 1 PW and pulse width of several hundreds of femtoseconds has also been obtained[3]. The Ti:sapphire laser systems, limited by the size of the crystal, can reach near petawatt peak power with a pulse duration of ~30 fs[4], and the focused intensity has reached 10^{22} W/cm^2[5]. In the research field of ultrashort pulse laser technology, near 10-fs pulse with lower energy per pulse has been achieved using different pulse compression techniques[6].

There are some limitations for the CPA technique. For example, the contrast ratio of the laser pulse is typically low due to the amplified spontaneous emission (ASE) and the pulse width in a terawatt-class or more powerful laser system is usually several tens of femtoseconds due to gain narrowing effect. Optical parametric chirped pulse amplification (OPCPA) scheme[7] possesses several advantages over CPA, such as higher pulse contrast ratio and higher gain with wider gain bandwidth which can support sub-10-fs pulse amplification[8]. OPCPA scheme has therefore been considered as a promising method which may leads to a new generation of high peak power, ultrashort-pulse lasers[9−14]. Currently the main difficulty of OPCPA scheme is the lack of suitable pump sources dedicated for different OPCPA designs.

In this paper, we report the recent progress in the development of high intensity ultrashort pulse lasers at Shanghai Institute of Optics and Fine Mechanics (SIOM). Based on the concept of OPCPA, a 16.7 TW/120 fs laser at 1064 nm was developed. Some quasi-phase-match (QPM) crystals were investigated as new OPCPA gain media and the investigation of broadband OPCPA near 780 nm was also carried out. On the other hand, the Ti:sapphire laser system with a peak power of 0.89 PW based on the scheme of CPA has been developed.

In the compact 10-TW-class OPCPA laser system, near-degenerated and near-collinear OPCPA was designed. The broadband signal laser wavelength is near 1064 nm, and the pump laser wavelength is at 532 nm. A Nd:YAG and Nd:glass hybrid laser system was utilized as pump source. The system consists of a femtosecond Ti:sapphire oscillator, a pulse stretcher, a Nd:YAG-Nd:glass hybrid amplifier chain as the pumping laser, an optical parametric amplification (OPA) chain and a pulse compressor. The OPA stages and the pumping laser share the same seed source. The oscillator generates ~150 mW pulses at 1064 nm with the pulse duration of ~100 fs. One part of the femtosecond pulse is stretched to ~ 300ps by an Offner stretcher as the chirped signal pulse of the subsequent OPA stages. And the other part is used as the seed of the pumping laser of the OPA stages.

The pumping laser is a Nd:YAG-Nd:glass hybrid amplifier chain consisting of a Nd:YAG regenerative amplifier, three Nd:YAG pre-amplifiers and four Nd:silicate-glass amplifiers. With an etalon in the regenerative amplifier cavity, the ~800 ps output pulse was obtained.

The OPA chain consists of three OPA amplifiers with a 15-mm-long, an 18-mm-long LBO crystals and a final large aperture 20-mm-long LBO crystal as power amplifier. All the OPA stages operate in type I OPA process (oo→e) with slightly noncollinear configuration. In the final OPA stage, using a pumping energy of 12 J and pumping intensity of ~4.1 GW/cm^2, the signal laser pulse is amplified to about 3.1 J with an energy conversion efficiency of 25.5%. By using a grating compressor, 2.0 J/120 fs (full-width at half-maximum (FWHM)) pulses are achieved, corresponding to a peak power of 16.7 TW.

The signal pulse gain is very sensitive to the pump intensity in the process of OPCPA. In order to obtain high, broadband and stable OPCPA gain, the pump laser pulse needs to match the signal laser pulse exactly in temporal, spatial and spectral regimes. The parametric conversion efficiency of the OPCPA process is another issue of concern, which is relatively poor and unstable[15,16] due to the poor spatial and temporal features of the Q-switched pump laser pulses. In order to keep high and stable con-

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version efficiency, we developed a new technique to make the signal and pump pulses match each other in spectral and temporal domains[17]. The signal pulse and pump pulse came from the same oscillator in our OPCPA laser system, the time jitter between the signal and pumping pulses could be less than 10 ps. In the regenerative amplifier of the pumping laser, the duration of the narrow bandwidth laser pulse was adjustable to match the signal pulse duration[18]. The time jitter effect on the output stability was investigated[19]. It is shown in Fig. 1 that a 200-ps time jitter can generate 50% fluctuation in the output.

Figure 2 shows that the bandwidth of the amplified signal pulse increases obviously with saturated OPA, and the top of the spectrum grows flat. This is obviously different from many other amplifiers in which spectral narrowing occurs due to the gain narrowing.

Because strong optical parametric generation (OPG) should be separated from the chirped signal pulse, a saturated OPA is not suitable for the first OPA stage in a multi-stage OPCPA system. However, at the last stage, the saturated amplification is desired for higher energy conversion efficiency and lower energy fluctuation.

We have investigated the performance of novel crystals as the OPA medium. CLBO is a new kind of crystal available in very large size, and with higher damage threshold and higher nonlinear coefficient compared with KDP crystal[8,20]. We demonstrated a broadband OPCPA using CLBO both theoretically and experimentally[21]. In the experiment, the intensity gain with CLBO is much higher than the gain with KDP under the same condition. And the pulse duration of the compressed signal pulse was ~123 fs for the ~100-fs oscillator. Based on theoretical calculations, the gain bandwidth of CLBO for type I phase matching in degeneracy can reach 130 nm supporting a pulse shorter than 15 fs at 1064 nm. Considering the higher OPCPA gain and higher damage threshold of CLBO compared with KDP, CLBO crystal has a great potential to replace KDP crystal as the final amplifier for terawatt or petawatt level OPCPA laser system.

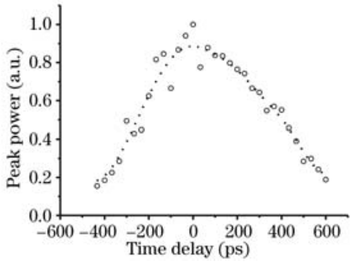

Fig. 1. Intensity of the amplified signal pulse in OPCPA stage as a function of the relative time delay between the signal pulse and the pumping pulse (dotted curve is the fitting curve).

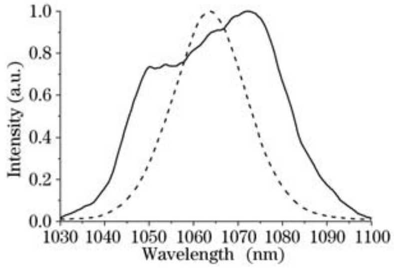

Fig. 2. Spectra of the input signal pulse (dashed, the bandwidth is ~20 nm) and the signal pulse after saturated amplification using two crystals (solid, the bandwidth is ~37 nm).

In comparison with LBO and BBO crystals, QPM materials such as PPKTP and PPLT have much higher nonlinear coefficient and have been used in OPCPA laser system recently[22−25]. In our experiments, using PPLT (0.5 × 5 × 15 (mm)), we obtained higher than 10^7 broadband gain, as shown in Fig. 3. PPLT was temperature controlled, the accepted temperature bandwidth of PPLT was 3.6 °C at 119 °C, and the accepted angle bandwidth was 2.7° (3 times of that of BBO). Due to the high gain, the QPM crystal is very suitable for compact OPCPA laser system of high repetition rate, or for the front OPCPA stage in high intensity ultrashort pulse OPCPA laser system. With optimum design, the accepted variation in angle and temperature is larger for QPM crystal. Using QPM crystal, different phase matching can be realized with a temperature control for broadband high gain OPCPA.

The investigation of OPCPA at 800 nm with QPM materials was carried out too. We found that PPKTP is suitable for the OPCPA at 800 nm pumped with 532 nm laser, with a gain bandwidth of 130 nm.

In order to stretch gain bandwidth, a series of techniques were also developed, not only for the wavelength near 1064 nm, but also near 800 nm[26−28]. We explored the 800-nm OPCPA laser in the similar geometry to that of the 1064-nm OPCPA laser system, in which 400-nm pump pulse seeded by the same oscillator was used[29]. As we know, under same pumping condition, higher gain with broad bandwidth can be obtained by near-degenerative near-collinear phase matching OPCPA

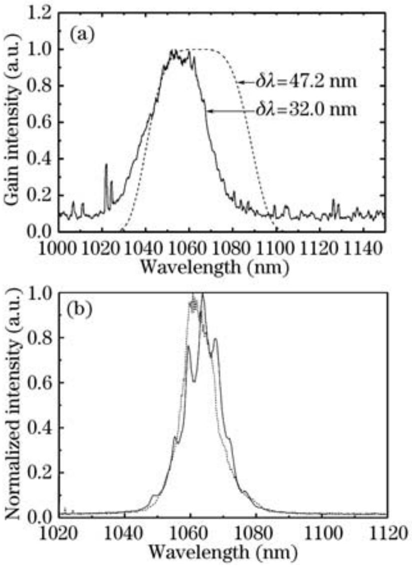

Fig. 3. (a) Measured (solid line) and calculated (dashed) spectra of OPG, which can support the amplification bandwidth for a 50-fs pulse at 1064 nm. (b) Signal spectra of seed (dashed) and amplified (solid) pulses. Signal pulse is near 1064 nm (~18-nm bandwidth, ~300 ps, ~20 pJ), pump laser pulse is at 532 nm (~800 ps, 0.63 mJ, I_p = 400 MW/cm^2). The crystal is PPLT. Amplified signal is ~35 μJ (~18-nm bandwidth) and the single-pass signal gain is ~1.7×10^6.

than that based on non-degenerative non-collinear phase matching with 532-nm pumping pulse. In the experiment, type-I near-degenerative near-collinear broadband OPCPA near 800 nm was demonstrated with a LBO crystal as nonlinear crystal. The results are shown in Fig. 4. For the broadband chirped signal pulse (~40-nm bandwidth, FWHM), the amplified chirped signal pulse with ~412-μJ energy and ~71-nm bandwidth (FWHM) was obtained with ~15-mJ pumping laser energy and ~4.5-GW/cm^2 pumping intensity respectively, and the total OPCPA gain is higher than 3.7×10^6, as shown in Fig. 5. The experimental results are in agreement with the calculated results which indicates a gain bandwidth of ~72 nm.

According to the theoretical and experimental results, the OPCPA based on near-degenerative near-collinear phase matching geometry can offer enough gain bandwidth to support the amplification for sub-20-fs or even sub-10-fs laser pulses. We have developed the related techniques, such as spectral and temporal shaping technique and accurate temporal synchronization technique, to obtain the required pumping pulse around 400 nm from Ti:sapphire laser. It is more complicated than the generation of synchronized 532-nm pumping pulse. In practice, a suitable pumping laser, which can generate pulse around 400 nm, could be chosen as pumping laser for convenience, such as iodine laser. Taking the advantage of more precise pulse shaping techniques, such as spatial light modulation (SLM), to compensate the phase aberration from OPCPA, OPCPA with near-degenerative near-collinear phase matching could be used in terawatt, even petawatt laser system to generate sub-20-fs ultra-intense pulse with high signal-noise contrast ratio[30].

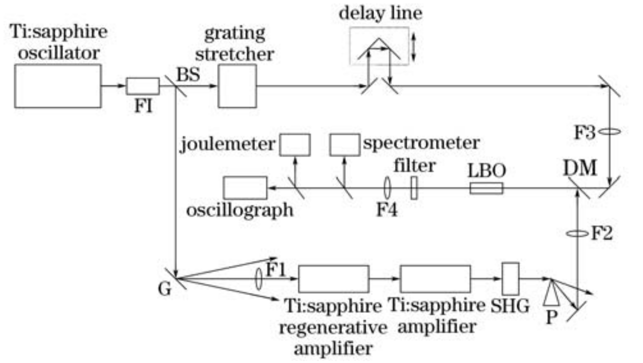

Fig. 4. Experimental setup of LBO-I near-degenerated near-collinear broadband OPCPA. FI is Faraday isolator; BS is 50 : 50 beam splitter near 780 nm; DM is dichromatic mirror; G is 1700-l/mm ruled grating; P is prism; F1—F4 are lenses.

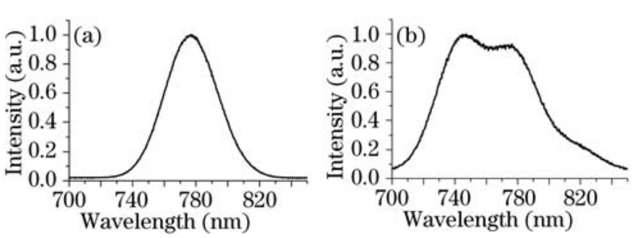

Fig. 5. Spectra of the chirped signal pulse. (a) Input signal pulse spectrum, bandwidth is ~38 nm (FWHM); (b) amplified signal pulse spectrum by LBO-I OPCPA, bandwidth is ~71 nm (FWHM).

The Ti:sapphire laser system with a peak power of 0.89 PW based on the CPA scheme has been developed.

This petawatt class laser system is a typical CPA laser system using Ti:sapphire amplifiers. It consists of a self-mode-locked 10-fs Ti:sapphire oscillator, an AOPDF[31], a stretcher, a regenerative amplifier, three stages of multi-pass amplifiers and a four-grating compressor. The schematic layout of this laser system is shown in Fig. 6.

The regenerative amplifier and the multi-pass preamplifier were pumped by commercially available 10-Hz Q-switched Nd:YAG lasers. The pump laser for the last two amplifiers is a home-made Nd:glass laser system with the maximum output energy of ~100 J (at 527 nm after frequency doubling) and the pulse duration of 20 ns.

Special measures were taken to suppress the parasitic lasing in the power and booster amplifiers, which results from the significant Fresnel reflection at transverse surfaces of the crystals[4]. The Ti:sapphire crystal used in this booster amplifier is a commercially available circular disk (Crystal System, Inc.), 80 mm in diameter and 32 mm thick. In order to keep the uniformity of the amplified beam, the laser beam was image-relayed between every two passes. The beam diameters were 60 and 50 mm for pump and seed laser beams. We used a refractive index-matched liquid as the index matching media for cladding to suppress the parasitic lasing, which is easy to bond with the crystal surface. This method can effectively remove the air at the side surface of the crystal. In the experiment, we found that the doped absorber could be bleached with the exposure time and it was easy to renew.

With the pump energy of 70 J, the output laser energy of 35.9 J is achieved with a conversion efficiency of higher than 50%. The output laser beam from the final booster amplifier was expanded to 150 mm and image-relayed to a four-grating compressor. After compression, the pulse duration was 29.0 fs, and the auto-correlation trace is shown in Fig. 7. The corresponding peak power of the laser pulse is 0.89 PW[32]. We found that the AOPDF was necessary for good pulse compression with the correction of third- and fourth-order dispersion

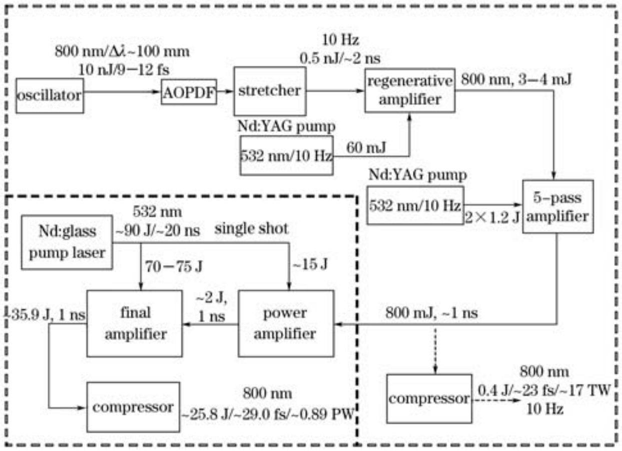

Fig. 6. Schematic layout of the femtosecond petawatt CPA laser system.

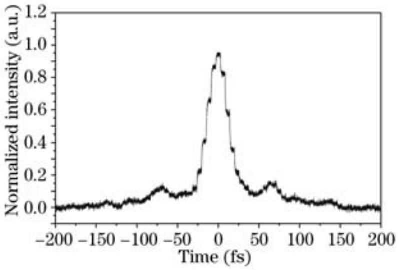

Fig. 7. Measured autocorrelation trace of the compressed laser pulse.

(TOD and FOD). The Fourier transformation of the measured laser spectra suggested that the compressed pulse duration is nearly transform limited.

In summary, we have developed a 16.7 TW/120 fs laser system at 1064 nm based on the concept of OPCPA, in which an all-optical synchronization scheme for the pump and signal beams was used. Some new nonlinear optical materials including QPM crystals were investigated as new OPCPA gain media. We also carried out the investigation of broadband OPCPA at 780 nm. Based on the CPA scheme, we have developed the Ti:sapphire laser system with a peak power of 0.89 PW. The high gain amplification was achieved in a large aperture amplifier by cladding with refractive-index matched liquid doped with absorber to suppress the parasitic lasing.

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