High-power output from a compact OPCPA laser system

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With a tabletop hybrid Nd:YAG-Nd:glass laser as pump source, a compact optical parametric chirped pulse amplification (OPCPA) laser system with a peak output power of 16.7 TW and a pulse duration of 120 fs has been demonstrated. Chirped pulses are amplified from 50 pJ to more than 3.1 J with an energy gain of above 6×10^{10} by three LBO optical parametric amplifiers with a pump energy of 12.4 J at 532 nm. After compression, a final output of 2.0-J/120-fs pulse is obtained. To the best of our knowledge, it is the highest peak output power from an OPCPA laser so far. In addition, a practical design of 1-PW laser system based on the technique of OPCPA is also proposed.

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A Nd:glass laser system with a peak power of above 1 PW and a pulse duration of several hundreds of femtoseconds has been obtained[1]. The Ti:sapphire laser systems, limited by the size of Ti:sapphire crystal, can reach a peak-power of above 500 TW with pulse durations of sub-20 fs[2]. However, the level of amplified stimulated emission (ASE) and the amplified pre-pulse of the existing chirped pulse amplification (CPA) laser system may significantly perturb the target prior to the arrival of the main pulses in the experiments of laser-matter interaction. In recent years, there has been much interest in the study on high power laser systems based on the technique of optical parametric chirped pulse amplification (OPCPA)[3]. The concept of OPCPA, proposed by Dubietis *et al.*[4], offers ultra-broad gain bandwidth which can support a pulse duration of ~10 fs. OPCPA possesses several advantages over CPA[3]. First, in OPCPA process, the pre-pulse intensity can be reduced to lower level. Second, due to the high energy gain in the OPA process, the OPCPA-based laser system may be tabletop in size. These advantages make it possible that the laser system based on OPCPA generates sub-10-fs pulse with high energy or acts as an alternative of regenerative or multi-pass Ti:sapphire amplifier in the ultra-high power laser system.

The studies on OPCPA have been reported in several papers[5−10]. In this paper, we report the high power output from a compact OPCPA laser system. With a tabletop hybrid Nd:YAG-Nd:glass laser as pump source, a compact OPCPA laser system with a peak output power of 16.7 TW has been demonstrated. To the best of our knowledge, it is the highest output power from an OPCPA laser so far. Based on the theoretical and experimental study on OPCPA scheme, we propose a new design of 1-PW OPCPA laser system.

The intensity gain G of the amplified signal beam can be obtained by solving the coupled wave equations. We assume that there is no significant pump depletion and that the crystal losses and the group velocity mismatch (GVM) are neglected, the intensity gain G of the amplified signal beam is given by[11]

$$G = 1 + (\gamma L)^2 (\sinh A/A)^2, \tag{1}$$

where

$$A = [(\gamma L)^2 - B^2]^{1/2},$$

$$B = \Delta k L/2,$$

$$\gamma = 4\pi d_{\mathrm{eff}} (I_p / 2\varepsilon_0 n_{\mathrm{p}} n_{\mathrm{s}} n_{\mathrm{i}} c \lambda_{\mathrm{s}} \lambda_{\mathrm{i}})^{1/2}, \tag{2}$$

where $\Delta k = |\Delta k_\omega|$ is the phase mismatch.

Based on the numerical solution of the above equations, we designed a compact multiterawatt OPCPA laser system. Recently, the compact OPCPA laser system with a peak output power of 16.7 TW has been demonstrated.

The experimental setup is illustrated in Fig. 1. The system consists of a Mira900 Ti:sapphire oscillator, a pulse stretcher, a tabletop hybrid Nd:YAG-Nd:silicate glass pump laser, an OPA chain and a compressor. The Ti:sapphire oscillator generates ~ 150-mW pulses at 1064 nm with a pulse duration of ~ 100 fs. A fraction of the femtosecond pulse is expanded to about 300 ps by an all-reflective Öffner triplet pulse stretcher as the seed of the OPA chain. The remaining of the femtosecond pulse is used as the seed of the pump laser system. Since the OPA stages and the pump source use the same oscillator, the shot-to-shot timing jitter of < 10 ps between the signal and pump pulse has been obtained.

The pump laser is a tabletop Nd:YAG-Nd:silicate glass amplifier chain consisting of a Nd:YAG regenerative amplifier, three Nd:YAG pre-amplifiers and four Nd:silicate-glass amplifiers. In the Nd:YAG regenerative amplifier with an étalon in the cavity, the energy of the injecting pulse is increased from 1 nJ to ~ 3 mJ and the output pulse duration is about 800 ps. The pulse is then injected to the first Nd:YAG pre-amplifier. The output light of the second Nd:YAG pre-amplifier is converted to the second harmonic at 532 nm by a type-II KDP crystal and a green light with an energy of ~ 20 mJ

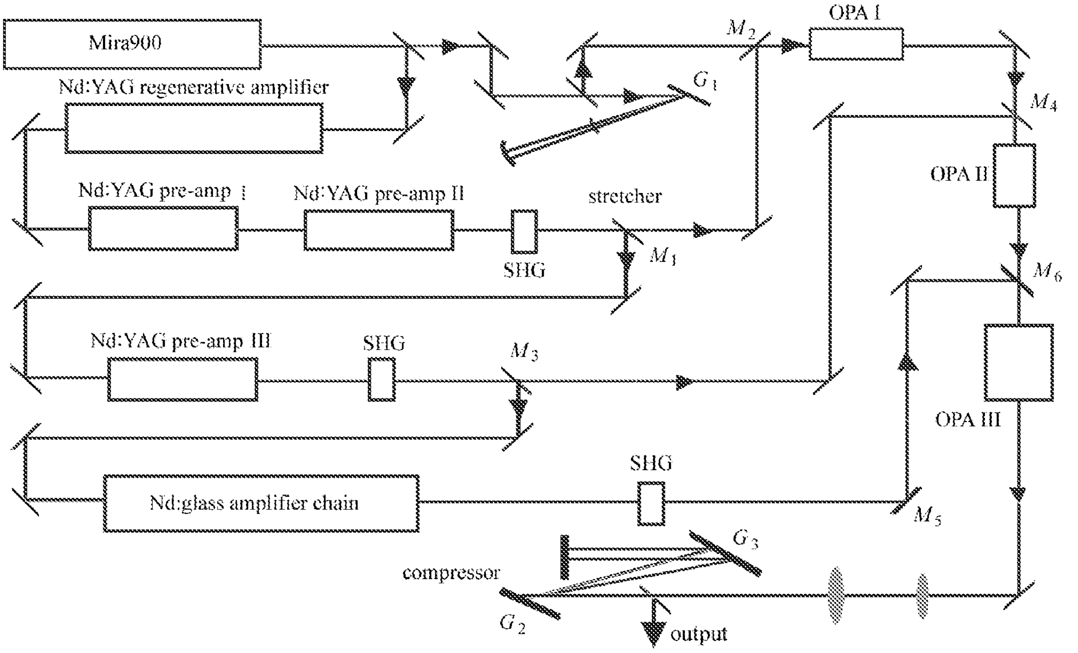

Fig. 1. Experimental setup of the 16.7-TW/120-fs OPCPA laser system. $G_1 - G_3$ are 1200-line/mm gold-coated holographic gratings. Mirrors $M_1 - M_6$ are dichroic mirrors coated for HR at 532 nm and AR at 1064 nm.

is achieved. The green light is split from the fundamental light by a dichroic mirror M_1 to pump the first OPA stage. The residual fundamental light is injected to the third Nd:YAG pre-amplifier and its energy is amplified to ~ 300 mJ. With a KDP frequency doubler, a green light with an energy of ~ 100 mJ is obtained and is split by a dichroic mirror M_3 to pump the second OPA stage. The remaining fundamental light passes through a spatial filter and then is injected to the Nd: silicate glass amplifier chain and the energy is amplified to ~ 25 J. The second harmonic with a pulse energy of about 12.3 J, generated in a 3-cm KDP crystal, is split by a dichroic mirror M_5 to pump the final OPA stage.

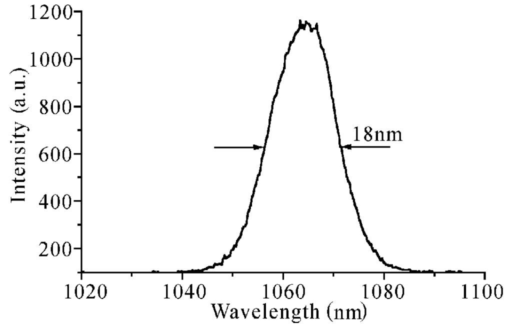

Fig. 2. Measured spectrum of the input seed pulse.

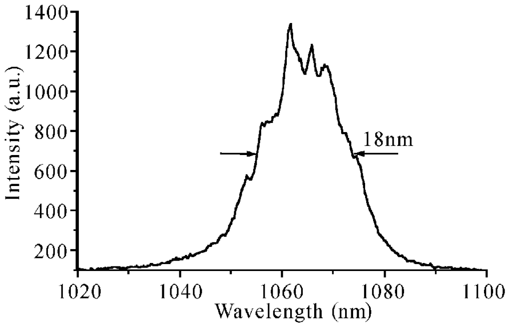

Fig. 3. Measured spectrum of the amplified pulse after the final OPA stage.

The OPA chain consists of two OPA preamplifiers with 15-mm-long and 18-mm-long LBO crystals, and a final large aperture OPA power amplifier with a 20-mm-long LBO crystal. All the OPA stages operate in close to degeneracy for type I OPA process (oo→e) in a slightly noncollinear configuration. The pump-signal angle is 0.5 degree for each amplifier, resulting in the separation of both the idler and the residual pump beam from the signal beam. In each OPA stage, the pump and the signal beams are

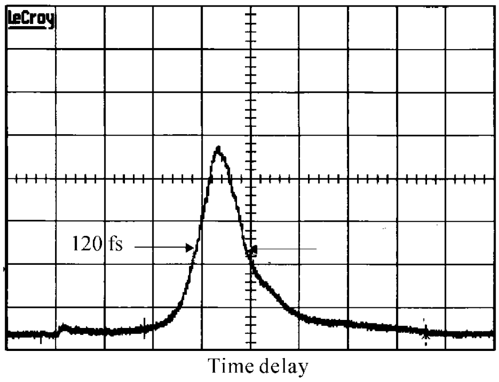

Fig. 4. Measured autocorrelation trace of the recompressed amplified pulse.

image-relayed to the crystal at desired beam sizes by telescopes. The pump beams are injected into the OPA crystals by dichroic mirrors M_2, M_4 and M_6, respectively.

The input signal energy of the first OPA stage is about 50 pJ and its bandwidth is $\sim$ 18 nm (FWHM). With a pump intensity of $\sim$ 3 GW/cm^2, the signal energy is amplified to 4 μJ with an energy gain of $\sim 10^5$ in the first LBO OPA stage. The amplified signal is then injected to the second OPA stage with a beam expander. With a pump intensity of $\sim$ 4 GW/cm^2 in the second OPA stage, the signal energy rises to $\sim$ 10 mJ with an energy gain of $\sim 2 \times 10^3$ and an energy conversion of $\sim$ 10%. After traveling through a long delay line, the signal is injected into the final OPA stage. With the pump energy of 12.3 J and the pump intensity of $\sim$ 4.1 GW/cm^2, the signal is amplified to more than 3.1 J in the final OPA stage, with an energy conversion of 25.5%.

The amplified pulses are collimated and then sent to a pulse compressor employing a pair of 1200-line/mm gold-coated holographic gratings. The grating separation is 98 cm, and the incident angle is 54.25°. The net compression efficiency (include mirrors in the compressor) is 64%, resulting in a compressed pulse with an energy of 2.0 J.

The spectrum of the seed pulse and the amplified pulse is measured with a SP-308 Spectrometer. Figure 2 shows the measured seed pulse spectrum with a bandwidth of 18 nm (FWHM). After the final OPA stage, the bandwidth of the amplified signal is a little bit larger than $\sim$ 18 nm due to the saturation amplification effect, as shown in Fig. 3. The pulse duration of the recompressed pulse is measured with a single shot autocorrelator. The autocorrelation trace for the recompressed amplified pulse is shown in Fig. 4. The amplified pulse has a pulse duration of 120 fs (FWHM). Shorter compressed pulse is expected by precisely aligning the compressor or using the combination of gratings and chirped mirrors or prisms.

Based on the theoretical and experimental study on OPCPA, we designed a practical 1-PW OPCPA laser system. The layout of the designed scheme is shown in Fig. 5. The system consists of a femtosecond oscillator, a high-power Nd:glass pump source, two LBO-I OPA stages and a final KDP-I OPA stage. The femtosecond oscillator generates 50-fs pulses at 800 nm. With a Ti:sapphire regenerative amplifier and then noncollinear type I OPA and a compressor[12], 20-fs pulses at 1053 nm will be obtained as seed pulses. These pulses are temporally expanded to 500 ps and will be used as the seed of the pump source and the OPA stages. Since the OPCPA stages and the pump source use the same oscillator, the jitter between the signal and the pump should be very small.

The pumping source is a Nd:phosphate glass laser system consisting of a Nd:phosphate glass regenerator, two Nd:phosphate glass pre-amplifiers and a Nd:phosphate glass power amplifier chain. The pumping source will deliver up to 400 J of energy with a pulse duration of 800 ps at 1.053 μm. The beam is frequency doubled and the pulse energy of about 200 J at 527 nm should be obtained.

The two LBO stages operate close-to-degeneracy for type I OPA process (oo→e) in a near-collinear configuration, while the final large size KDP stage operates close-to-degeneracy and slightly noncollinear to enable the separation of the pump and the signal beams. Table 1 gives the parameters of the OPCPA system obtained from the numerical simulation. To obtain high

Table 1. Parameters of the Amplifiers in the Designed 1-PW OPCPA Laser System

	OPA I LBO-I (oo→e)	OPA II LBO-I (oo→e)	OPA III KDP-I (oo→e)
Input Signal Energy	0.5 nJ	10 μJ	100 mJ
Signal Beam Diameter	1.4 mm	5.8 mm	86 mm
Pump Energy	50 mJ	1 J	200 J
Pump Fluence	2.5 J/cm^2	3.2 J/cm^2	3.1 J/cm^2
Pump Intensity	3.1 GW/cm^2	4 GW/cm^2	3.9 GW/cm^2
Crystal Length	18 mm	15 mm	30 mm

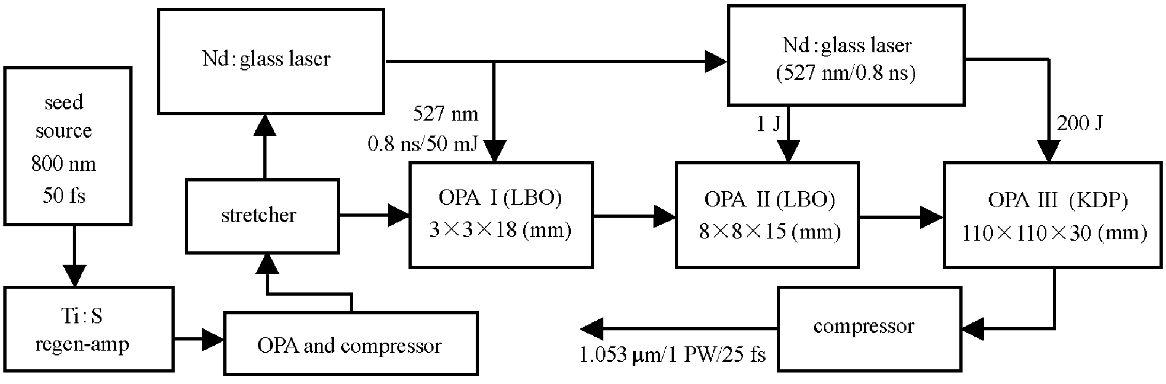

Fig. 5. Layout of the designed scheme for 1-PW OPCPA laser system.

gain or high energy-conversion efficiency, the three amplifier stages require a pump intensity of $3-4$ GW/cm^2. Assuming that an energy extraction efficiency of 25% can be achieved in the final OPA stage, an amplified chirped pulse with an energy of 50 J is expected. After compression, the final output pulse energy of 25 J with a pulse duration of 25 fs will be available, corresponding to the peak power of 1 PW.

In summary, we have demonstrated a compact high-power laser system based on the technique of OPCPA. The chirped pulse has been amplified from 50 pJ to more than 3.1 J in two LBO pre-amplifiers and a final LBO power amplifier with a pump energy of 12.4 J at 532 nm. An energy gain of above 6×10^{10} has been obtained. After compression, we obtained a final output pulse with a peak power of 16.7 TW. Based on the theoretical and experimental study on OPCPA, we also designed a practical 1-PW OPCPA laser system.

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