Broadband, high gain two-stage optical parametric chirped pulse amplifier using BBO crystals for a femtosecond high-power Ti:sapphire laser system

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Abstract

We design a two-stage non-collinear optical parametric chirped pulse amplifier using BBO crystals for a high-power Ti:sapphire laser system, and numerically analyze the output characteristics of the OPCPA system. We find optimal phase-matching conditions and calculate the parametric gains as a function of pump intensity and interaction length. By constructing a two-stage OPCPA system using two BBO crystals, we obtain 12 mJ output energy corresponding to a high gain of $10^7$, a pulse duration of 37 fs, and a contrast ratio of $5 \times 10^{-8}$.

1. Introduction

Since the development of chirped pulse amplification (CPA) technique, femtosecond high-power Ti:sapphire laser systems have been rapidly introduced around the world, and an 1 PW (petawatt) CPA Ti:sapphire laser system has been recently demonstrated [1]. High-power laser pulses exceeding tens of terawatts is a key tool for laser–matter interaction experiments, such as proton beam generation, electron beam generation, high harmonic generation, and so on. In these experiments using high-power laser systems, the temporal contrast of laser pulses is very important, because the prepulse can cause preformed plasma generation before main pulse arrives.

Several techniques were proposed for improving the temporal contrast [2–7]. Among them, optical parametric chirped pulse amplification (OPCPA) [8], which combines advantages of CPA and optical parametric amplification (OPA), is an emerging and promising amplification technique. Advantages of the OPCPA technique include broad gain bandwidth, high temporal contrast, extremely high gain in a thin crystal, less accumulation of nonlinear effects, a negligible thermal load on a nonlinear crystal, and the tunability of the gain spectral range [9]. On the other hand, OPCPA technique is very sensitive to the phase-matching angle and the pump beam intensity fluctuation. Thus, a pump source operated in a single longitudinal mode is highly required for the stable amplification. For the near infrared OPCPA, Q-switched frequency-doubled Nd:YAG laser is commonly used as a pump source. As a nonlinear crystal, the BBO ($\beta$-barium borate) crystal is commonly used due to its high nonlinear coefficient. In addition, it is well known that OPCPA in a non-collinear geometry (NOPCPA) provides a broader gain bandwidth than collinear one. To date, several NOPCPA systems based on BBO crystals using Ti:sapphire oscillator were reported; Witte et al. [10], Kiriyama et al. [6] and Wnuk et al. [11] have obtained pulse energy of 15.5 mJ, 122 mJ and 49 mJ, respectively.

Although OPCPA system offers high gain, the conversion efficiency from pump energy to signal energy is not so high, because nonlinear crystal cannot store pump energy unlike common laser medium. To improve the conversion efficiency in OPCPA systems, hybrid systems combining OPCPA with conventional CPA have been reported by several researchers [7,12,13]. In this case, OPCPA is used for front-end part using commercial pump laser, and CPA is used for power amplifier. A 80 TW hybrid system with three-stage OPCPA front-end was reported by Kiriyama et al. [7]. Another approach to improve the conversion efficiency is the temporal beam shaping of pump pulses. Using pump pulse whose duration is close to a seed pulse’s, the efficiency of the OPCPA can increase [14,15]. In addition, it is effective to reduce parametric fluorescence and increases damage threshold of optical components.

In this paper, we design and construct a two-stage single-pass OPCPA front-end system using BBO crystals for efficiently enhancing output energy of signal pulses to over 10 mJ. For
a broadband amplification, we design and numerically analyze a non-collinear OPCA scheme using BBO crystals in the spectral range from 750 to 850 nm. Based on the design and numerical analysis, a two-stage single-pass OPCA system with 12 mJ output energy is constructed, and its output characteristics are investigated. To our knowledge, high output energy exceeding 10 mJ from a two-stage single-pass OPCA front-end system was not reported yet, although such a high output energy was demonstrated with multi-pass [10,16] or three- or four-stage [6,11] OPCA front-end systems. In Section 2, optimal phase-matching angles are found under the pump beam depletion condition and parametric gains are calculated as a function of the pump intensity and the interaction length. In Section 3, the construction of a two-stage OPCA system using BBO crystals is described, and the output characteristics of the OPCA system are investigated and compared to numerical calculations. In Section 4, the conclusion of the paper is given.

2. Design and numerical analysis of two-stage OPCA system

Optical parametric process is three-wave nonlinear interaction process. In optical parametric amplification (OPA), the high-intensity pump wave interacts with a weak signal wave, and the pump wave is converted to the signal and the idler waves according to energy conservation \(E_p = E_s + E_i\), where \(E_p\), \(E_s\), and \(E_i\) indicate angular frequencies of the pump, signal, and idler waves, respectively. Then, the coupled three-wave equations governing the optical parametric amplification can be given by [17]

\[
\begin{align*}
\frac{\partial \tilde{E}_s}{\partial z} &= -i \left( \frac{\nu_s}{n_p} \right) d_{\text{eff}} E_p \tilde{E}_i \exp(-i\Delta k z), \\
\frac{\partial \tilde{E}_i}{\partial z} &= -i \left( \frac{\nu_i}{n_s} \right) d_{\text{eff}} E_p \tilde{E}_s \exp(-i\Delta k z), \\
\frac{\partial \tilde{E}_p}{\partial z} &= -i \left( \frac{\nu_p}{n_e} \right) d_{\text{eff}} E_p \tilde{E}_i \exp(i\Delta k z),
\end{align*}
\]

where \(d_{\text{eff}}\) is the effective nonlinear coefficient; \(n_p\), \(n_s\), and \(n_e\) are refractive indices for pump, signal, and idler waves, respectively; and \(\Delta k\) is the wave vector mismatch given by \(\Delta k = k_p - k_s - k_i\). Subscripts \(p\), \(s\), and \(i\) mean the pump, signal, and idler waves, respectively. Assuming that there is no pump beam depletion, the parametric gain can be expressed by [18]

\[
G = 1 + (\gamma L)^2 \left( \frac{\sin h g L}{g L} \right)^2
\]

\[
g = \sqrt{\gamma^2 - \left( \frac{\Delta k}{2} \right)^2}, \quad \gamma = 4\pi d_{\text{eff}} \frac{I_p}{2\alpha n_p n_s c \lambda_s^2 c_i^2}
\]

Here, \(G\) is the parametric gain, \(L\) is the interaction length, \(I_p\) is the pump beam intensity, and \(\lambda\) is wavelength. Fig. 1 shows a typical non-collinear phase-matching configuration for a uniaxial nonlinear crystal. In Fig. 1, \(\theta\) is the phase-matching angle between the pump wave direction and the optic axis; \(\alpha\) is the non-collinear angle between pump and signal wave directions in the crystal; and \(\beta\) is the angle between signal and idler waves. For broadband phase-matching, the group velocity matching condition between the signal and the idler waves should be satisfied as well as the phase-matching condition [17]. By introducing a non-collinear angle, it is possible to satisfy both the phase-matching and the group velocity matching conditions in a nonlinear crystal. Eqs. (3) and (4) imply the phase-matching and the group velocity matching conditions, respectively.

\[
k_p \sin \alpha = k_s \sin \beta, \quad k_p \cos \alpha = k_s + k_i \cos \beta
\]

\[
v_{gs} = v_{gi} \cos \beta
\]

Here, \(v_{gs}\) and \(v_{gi}\) denote the group velocities of signal and idler waves, respectively. From Eqs. (3) and (4), the expression for the optimized non-collinear angle is obtained by [19]

\[
\sin \alpha = \left[ 1 - \left( \frac{v_{gs}/v_{gi}}{2} \right)^2 \right]^{1/2}
\]

In addition, using Eqs. (3)–(5), we can calculate \(k_p\) for the broadband phase-matching condition. For type-I (oo-e) phase-matching, the signal and the idler waves are ordinarily polarized, and the pump wave is extraordinarily polarized. For negative uniaxial crystals, the analytical formula for type-I phase-matching in a non-collinear geometry can be given by [20],

\[
\sin \theta = \frac{n_{pe}}{k_p} \left[ \frac{2\pi^2}{\gamma} \frac{I_p}{\alpha n_p n_e c \lambda_s^2 c_i^2} \right]^{1/2}
\]

Here, \(n_{pe}\) and \(n_{pe}\) denote the principal (ordinary and extraordinary) values of the refractive indices at a pump wavelength. Therefore, optimal non-collinear angle and phase-matching angle for broadband OPA can be obtained by Eqs. (5) and (6).

For a type-I BBO crystal with a pump wave at 532 nm and a signal wave at 800 nm, the phase-matching angle (\(\theta\)) and the non-collinear angle (\(\alpha\)) are 23.84° and 2.39°, respectively. Fig. 2 shows the simulation results of the gain profile and phase mismatch in case of \(\alpha = 23.84°\) and \(\alpha = 2.39°\). The parametric gain is calculated using Eq. (2) under the conditions of a pump beam intensity of 340 MW/cm² and a crystal length of 19.5 mm. In this case, it is shown that broadband amplification is obtained, and the phase mismatch is almost zero in the spectral range of 750–940 nm. Using these phase-matching angles, numerical analysis on the output characteristics of a two-stage OPCA system was carried out. The configuration of the OPCA system used for simulation is shown in Fig. 3; the same pump source for each stage is used. Eq. (2) is used for calculating the gain in the first stage of the OPCA system because the pump beam depletion is very small. However, it is not appropriate for calculating the second stage gain because the pump beam depletion cannot be ignored in the second stage. Therefore, to solve coupled equations, Eqs. (1) for the second stage, numerical method, such as Runge-Kutta method, should be used.
First, the parametric gain as a function of the interaction length is calculated for $\lambda_s = 800$ nm. For numerical simulations, we assume the use of two 19.5-mm-long BBO crystals ($L_1 = L_2 = 19.5$ mm), pump power of 340 MW/cm², and seed power of 9.7 W/cm². Fig. 4(a) and (b) show the parametric gain with respect to the interaction length in the first and the second stages, respectively; the parametric gain increases exponentially as signal beams propagate in BBO crystals. Fig. 4(c) shows the signal, idler, and pump intensities with respect to the propagation length in the second stage. The signal and idler beam intensities increase exponentially as beams propagate, and pump beam intensity starts to be depleted at around 12 mm, and is almost depleted at the end of crystal (19.5 mm). This is because the pump energy is transferred to the signal and the idler beams, as beams propagate along the nonlinear crystal. If beams propagate further along nonlinear crystal, back-conversion from signal into pump would occur.

Next, the parametric gain with respect to the pump beam intensity is calculated under the conditions of two 19.5-mm-long BBO crystals ($L_1 = L_2 = 19.5$ mm), $\lambda_s = 770, 800, \text{ and } 850$ nm, and $\lambda_p = 532$ nm. Fig. 5(a) shows the parametric gain in the first stage; parametric gain exponentially increases with the pump intensity. Fig. 5(b) shows the parametric gain for the two-stage OPCPA system. Parametric gains also exponentially increase with the pump beam intensity, but gain saturation occurs at certain pump beam intensities (385 MW/cm² for $\lambda_s = 770$ nm, 360 MW/cm² for $\lambda_s = 800$ nm, and 340 MW/cm² for $\lambda_s = 850$ nm); saturation pump intensity increases with decreasing signal wavelength. Saturation pump intensity is required for efficient energy extraction and stable amplification. However, back-conversion into the pump beam occurs after reaching saturation pump intensity. Fig. 6(a) and (b) show the gain profiles for the first stage and the total OPCPA system at pump beam intensities of $I_p = 320, 340, 360$ MW/cm². Both the first stage and the total system have broad spectral gain profiles in the range of 750–940 nm. In the second stage, back-conversion is observed at long wavelength region as increasing of pump intensity. Therefore, it can be concluded from our numerical simulation that output signal beam having a gain of over $10^7$ in a broad spectral bandwidth (from 750 to 940 nm) can be obtained by using these parameters.
3. Output characteristics of two-stage OPCPA system using BBO crystals

Two-stage OPCPA system has been constructed based on design parameters obtained in numerical simulations. The schematic diagram of the two-stage OPCPA system is shown in Fig. 7. A 75-MHz mode-locked Ti:sapphire oscillator (Femtolasers, Synergy) generates seed pulses having a pulse duration of 25 fs and an energy of several-nanojoule per pulse. Before amplification, an Offner-triplet-type stretcher with a 1400 grooves/mm grating temporally expands the seed pulses up to 400 ps. The repetition rate of 75 MHz is converted into 10 Hz by pulse selection using a Pockels cell (5046ER, Fast Pulse Tech. Inc.). The stretched 10 Hz seed pulses are then incident into the two-stage OPCPA amplifier comprised of two type-I BBO crystals. Dichroic mirrors (high reflection coating for signal wave and anti-reflection coating for pump wave) are used to overlap signal pulse with pump pulse in BBO crystals. The pump pulses are provided by a commercial Q-switched, frequency-doubled Nd:YAG laser (Thales laser, SAGA); it gives a maximum energy of 900 mJ with 6.5 ns pulse duration at 10-Hz repetition rate. The pump laser is operated in the single longitudinal mode for the temporal pulseform without intensity modulation. Pump energy is controlled by a pair of half-wave plate (HP) and polarizing beam splitter (PBS). Then, using a high speed Pockels cell (PC) with 500 ps rising time and a PBS, Gaussian pulse with 6.5 ns duration is sliced into quasi-rectangular pulse with 2 ns

![Diagram](image_url)
duration, and converted into p-polarized wave. Temporal pump pulse shaping can both increase the damage threshold of optical components, and improve the temporal contrast. A pump beam diameter of 12.5 mm is reduced into 4 mm by a beam reducer to be matched to the seed beam diameter of 4 mm. For a simple configuration, one common pump beam is used for pumping two OPCPA stages. In the experiment, two 19.5-mm-long BBO crystals whose cross sections are $7_{\mu}m^2$ are used. Two crystals have a $\frac{1}{14}$ wedge on their output faces to suppress superfluorescence. The seed and pump pulses are temporally synchronized by an electronic device (ISEO, Thales laser). The amplified pulse was recompressed by using a grating compressor with 75% throughput efficiency.

Fig. 8 shows the experimental and simulation results for the parametric gains of the first stage and the total OPCPA system. Horizontal axis indicates the pump energy before pulse slicing. For simulation, we assumed a seed pulse with spectrum of 750–850 nm and 0.5 nJ energy. For a pump energy of 300 mJ (before pulse shaping), the first stage shows a parametric gain of about $5 \times 10^4$ as shown in Fig. 8(a), and the total OPCPA system shows the saturation gain of about $3 \times 10^7$ in Fig. 8(b). The general trends in the parametric gain agree well with the simulation results. In the experiment, the maximum output energy from the two-stage OPCPA system was 12 mJ, and output beam exhibits the good beam quality ($M^2 < 2.0$).

To our knowledge, high output energy exceeding 10 mJ from a two-stage single-pass OPCPA front-end system was not reported yet, although such a high output energy was demonstrated with multi-pass [10,16] or three- or four-stage [6,11] OPCPA front-end systems. To obtain output energy over 10 mJ, we carefully designed amplification conditions. Long BBO crystals of 19.5 mm length were used, although BBO crystals below 15 mm length have been usually used to obtain good spatial overlap between pump and signal beams. A stretched pulse with 0.5 nJ energy and 400 ps duration was also used. In these conditions, a saturated gain of $2.4 \times 10^7$, corresponding to 12 mJ output energy, was obtained with a pump intensity of 360 MW/cm$^2$. Kiriyama et al. also used 19.5 mm BBO crystals [7], but they used a weak seed pulse (0.1 nJ pulse energy and 1 ns duration). According to numerical simulations for these conditions, strong pump intensity of 450 MW/cm$^2$ is required for saturation amplification, and the saturated gain is $4 \times 10^8$. Since the pump intensity of 450 MW/cm$^2$ is too high, they used low pump intensity of 250 MW/cm$^2$, and added one more amplification stage ($L = 16$ mm), and consequently 15 mJ output energy was obtained.

We also examined the change in output spectrum, because the output spectrum determines the pulse duration and the pulse profile after pulse compression. Fig. 9 shows the input and the amplified spectra, and simulation result of parametric gain ($I_p = 340$ MW/cm$^2$).
output spectrums measured after the second stage. In order to compare the seed and the output spectrums, their amplitudes have been normalized. Although input spectrum remains same during amplification, output spectrum is slightly broadened by $\pm 10$ nm especially in the long wavelength range. As shown in Fig. 9, the short wavelength component below 750 nm was suppressed by the parametric gain profile, and the long wavelength component over 820 nm was enhanced because the pulse wings are more amplified than the pulse peak in the saturation regime. The recompressed pulse duration was measured with a single-shot spectral interferometry for direct electric field reconstruction (SPIIDER). Fig. 10 shows that the typical pulse duration is 37 fs (FWHM).

For evaluating the temporal contrast, we characterized the output beam by using a third-order cross correlator (Amplitude Technologies, Sequoia). Fig. 11 shows the typical contrast measurements; contrast level is about $5 \times 10^{-8}$. The contrast deterioration is due to the amplification of parametric fluorescence (superfluorescence). It was well known that the superfluorescence deteriorates the pulse temporal contrast ratio in the low seed energy case, such as nanjoule level oscillator beam [21]. Therefore, a straightforward way to improve the contrast ratio would be to use stronger seed source. There are several ways to reduce superfluorescence background; the control of the pump pulse duration [14], and the reduction of parametric gain [7]. etc. In this research, for improving the temporal contrast, pump pulse duration was controlled by using high speed Pockels cell with 2 ns temporal window. To investigate the effectiveness of the pump pulse shaping, we measured the energy of superfluorescence background when the seed pulse was blocked with or without pump pulse shaping. Measured energy of superfluorescence was 0.31 mJ in the presence of the pump pulse shaping, and 1.1 mJ in the absence of the pump pulse shaping. By pump pulse shaping, therefore, about 72% of the superfluorescence background was efficiently removed.

4. Conclusion

We have designed a two-stage non-collinear OPCPA system using BBO crystals and numerically analyzed the output characteristics of the system. The optimized phase-matching angles which could support the phase-matching in the range of 750–940 nm were $\theta = 23.84^\circ$ and $\alpha = 2.39^\circ$. The signal beam intensity exponentially increases with respect to the interaction length, and pump beam is depleted at the second stage of the system. In addition, the parametric gain increases with respect to the pump intensity, but back-conversion occurs after certain pump beam intensity. A two-stage OPCPA system has been constructed based on design parameters obtained from numerical simulations. For a simple configuration, a Q-switched, frequency-doubled Nd:YAG laser was used for pumping two stages in the system. This system can efficiently boost the signal energy from 0.5 nJ to 12 mJ (before compression), which corresponds to high gain of about $10^7$, and support broadband amplification (in the range of 750–850 nm) without spectral narrowing.

Acknowledgement

This work was supported by the Ministry of Knowledge and Economy of Korea through the Ultrashort Quantum Beam Facility Program.

References