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Optical Parametric Chirped-pulse Amplification of Femtosecond Ti:sapphire Laser Pulses by Using a BBO Crystal

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We have characterized the optical parametric chirped-pulse amplification of femtosecond Ti:sapphire laser pulses by using a BBO crystal. It is numerically verified that a high gain and a broad gain bandwidth can be obtained with a 532-nm pump laser. The dependence of the gain profile of OPA on phase matching angles, pump intensity, and crystal length is numerically investigated. Experimental results shows that the temporal fluctuation of a pump laser causes the modulation of an amplified spectrum in OPCPA.

OCIS codes : 140.3590, 140.3280, 320.7090, 320.1590.

I. INTRODUCTION

Ultrashort high-power lasers have greatly contributed to the advent of new research fields such as high-harmonic generation, nano-scale nuclear fusion, laser-driven particle acceleration, and relativistic nonlinear optics because they provide an unprecedented unique physical environment where a very intense field lasts only for a extremely short period. The great advance of ultrashort high-power lasers has been driven by the technique of chirped-pulse amplification (CPA) during the last decade, and a petawatt level has been reached [1]. As the power level increases, however, it has been recognized that another factors such as amplified spontaneous emission (ASE) and preceding pulses undermine the utility of ultrashort high-power lasers because they change the target property prior to the arrival of main pulses and yield unexpected results. Therefore, one needs to find another way or to modify the CPA technique to achieve a high-peak power with the sufficient reduction of ASE and preceding pulses [2,3].

Optical parametric chirped-pulse amplification (OPCPA) has been noticed as a promising alternative to CPA because OPCPA can simultaneously provide a high gain and a broad bandwidth in a relatively short length of nonlinear medium, leading to a significant reduction of gain narrowing and nonlinear wavefront distortion [4]. In contrast to CPA using conventional gain material such as Ti:sapphire and Nd:glass, the amplification in OPCPA takes place only when the pump and the signal pulses directly interact with each other in a nonlinear medium. Therefore, the amplification of preceding pulses can be effectively excluded in OPCPA by using a pump pulse shorter than the separation of signal pulses. Other attractive characteristics of OPCPA are the potential of lower ASE compared with conventional CPA and the negligible heat load associated with little absorption of interacting lasers. On the other hand, OPCPA has a shortcoming of a low conversion efficiency with widely used commercial pump lasers because it is difficult to achieve precise spatial and temporal match between pump and signal lasers. Recently, a hybrid CPA combining OPCPA with conventional CPA has been introduced to increase the overall efficiency [5].

For the practical realization of optical parametric amplification (OPA), a nonlinear crystal, a phase matching scheme, and a pump source should be carefully prepared. It has been numerically shown that noncollinear OPA provide a broader gain bandwidth than collinear ones and that many nonlinear crystals can be used in OPA for various kinds of femtosecond pulses. Because a pump laser for OPA should be easily available and have a sufficiently high power, Q-switched frequency-doubled Nd:YAG lasers are most widely used for the OPA of near infrared laser pulses. A BBO crystal is known to be the most compatible with the OPA of femtosecond Ti:saphire laser pulses because it can give a high gain and a broad bandwidth around the gain peak of Ti:sapphire with a 532-nm pump laser. In this paper we numerically analyze the characteristics of OPA for femtosecond Ti:sapphire lasers with a BBO crystal. The gain profile of OPA is calculated as pumping condition and phase matching angles are varied. Finally, basic experimental results showing the importance of temporal quality of a pump laser are given.

II. NUMERICAL ANALYSIS

1. Basic formulas

The signal gain during optical parametric amplification (OPA) can be given by solving coupled wave equations. In the condition of a slowly varying envelope approximation and no pump depletion the intensity gain is given by following formulas [6].

$$I_{out}/I_{in} = 1 + (gL)^2 \frac{\sinh^2(\sqrt{(gL)^2 - (\Delta kL/2)^2})}{(gL)^2 - (\Delta kL/2)^2} \quad (1)$$

$$g = 4\pi d_{\text{eff}} \sqrt{\frac{I_p}{2\epsilon_0 n_p n_s n_i c \lambda_s \lambda_i}} \quad (2)$$

where L is the crystal length, I_p the pump intensity, d_{eff} the effective nonlinear coefficient, c the speed of light, n_p, n_s, and n_i the refractive indices of pump, signal and idler, λ_s, λ_i the vacuum wavelengths of signal and idler, and Δk the phase mismatch ($|\boldsymbol{k}_p - \boldsymbol{k}_s - \boldsymbol{k}_i|$).

The phase mismatch can be expressed by

$$\begin{aligned}\Delta k &= |\boldsymbol{k}_p - \boldsymbol{k}_s - \boldsymbol{k}_i| \\ &= |\boldsymbol{k}_p - \boldsymbol{k}_s - \boldsymbol{k}_{ip} + \boldsymbol{k}_{ip} - \boldsymbol{k}_i| = |k_{ip} - k_i|,\end{aligned} \quad (3)$$

where $\boldsymbol{k}_p$, $\boldsymbol{k}_s$, and $\boldsymbol{k}_i$ are the wave vectors of pump, signal, and idler, and $\boldsymbol{k}_{ip}$ the required wave vector of idler for the perfect phase matching. Because BBO is an uniaxial crystal the phase matching condition is relatively simple. For the case of type-I phase matching ($e \to o + o$), the k_{ip} is given by following formulas.

$$k_{ip}^2 = k_p^2 + k_i^2 - 2\cos\alpha\ k_p k_i = (2\pi)^2 \left[\left(\frac{n_p}{\lambda_p}\right)^2 + \left(\frac{n_s}{\lambda_s}\right)^2 - 2\cos\alpha \frac{n_p n_s}{\lambda_p \lambda_s} \right] \quad (4)$$

$$\frac{1}{n_p^2} = \frac{\cos^2\theta}{n_{op}^2} + \frac{\sin^2\theta}{n_{ep}^2} \quad (5)$$

where θ is the angle of the pump relative to the optic axis, α the noncollinear angle between the signal and the pump in the crystal, n_{op} and n_{ep} the principal ordinary and extraordinary refractive indices at the pump wavelength. Because the idler is an ordinary wave, k_i can be easily calculated from the condition of energy conservation ($\omega_p = \omega_s + \omega_i$). By calculating Δk with respect to the signal wavelength one can obtain the gain profile of signal from Eq. (1).

We have found that the phase-matching condition and the gain characteristics are very sensitive to the Sellmeier equation of BBO crystal used in the numerical calculation. Following are the Sellmeier equations of the principal refractive indices that we used in our calculations [7].

$$n_o^2(\lambda) = 2.7359 + \frac{0.01878}{\lambda^2 - 0.01822} - 0.01471\lambda^2 + 0.0006081\lambda^4 - 0.00006740\lambda^6 \quad (6)$$

$$n_e^2(\lambda) = 2.3753 + \frac{0.01224}{\lambda^2 - 0.01667} - 0.01627\lambda^2 + 0.0005716\lambda^4 - 0.00006305\lambda^6 \quad (7)$$

2. Dependence of gain profile on phase matching anlges

It has been known that the noncollinear OPA gives a broader amplification bandwidth than the collinear one [4]. Because the type-I noncollinear phase matching is determined by two angles, the angle of pump direction relative to the optic axis (θ) and the angle between pump and signal (α), the dependence of OPA characteristics on these angles should be investigated. Fig. 1 shows the gain profile of OPA calculated by using Eq. (1) as θ and α are varied. The pump in-

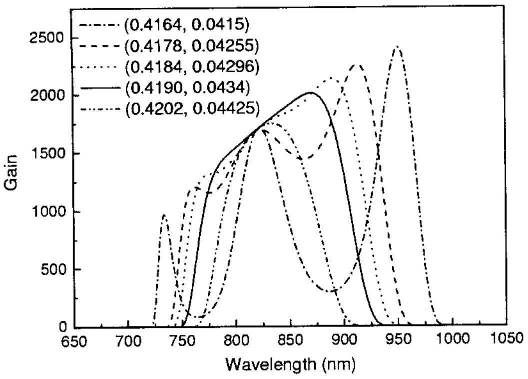

FIG. 1. The calculated gain profiles of OPA with a 15-mm-long BBO crystal and a 532-nm pump laser of 400 MW/cm^2. The numbers in the parenthesis are θ and α. Fore each θ, α is optimized to generated as smooth a gain profile as possible.

tensity, I_p, is 400 MW/cm^2, the BBO crystal length, L, 15 mm, and the effective nonlinear coefficient, d_{eff}, 2.02 pm/V. The pump wavelength is chosen to 532 nm because frequency-doubled Q-switched Nd:YAG lasers are the most widely used for the OPA of femtosecond Ti:sapphire lasers. At each value of θ, α is adjusted to generate as broad a gain profile as possible. It can be verified that the bandwidth increases with the decrease of θ. However, the broader gain profile shows the more significant modulation of gain shape. Because the severe modulation of gain profile yields a degradation of amplified pulse quality such as satellite pulses and background pedestals in the temporal pulse shape, one should make a proper compromise between the bandwidth and the modulation of gain profile. With $\theta = 0.4184$ rad and $\alpha = 42.96$ mrad, a relatively smooth gain profile with a broad bandwidth of more than 150 nm can be obtained, and the transform-limited pulse duration calculated from the gain profile is ~12 fs. Because the average gain over the bandwidth is more than 1500, ~ 10^6 gain can be realized by only two series of 15-mm-long BBO crystals, which is very ideal for the preamplification of femtosecond Ti:sapphire pulses.

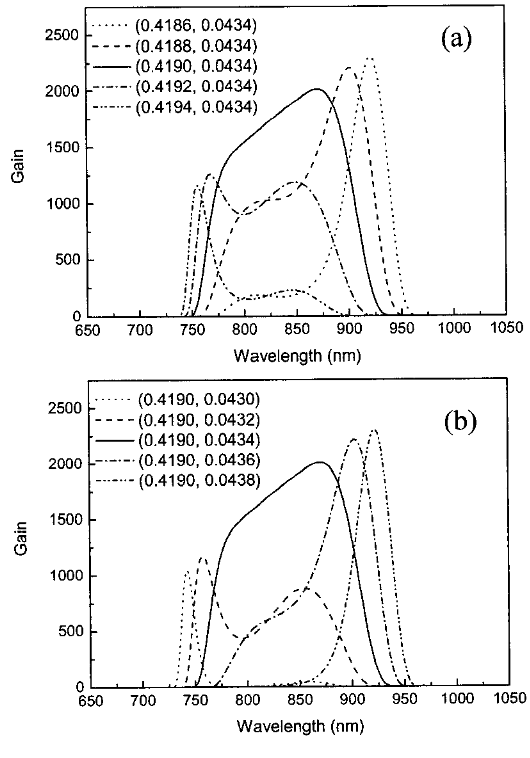

FIG. 2. The dependence of the gain profile of OPA on (a) θ and (b) α. The numbers in the parenthesis are θ and α. I_p and L are 400 MW/cm^2 and 15 mm, respectively.

The sensitivity of OPA to the phase matching angles should be checked for the practical use of OPA. Fig. 2(a) (2(b)) shows the gain profiles as θ (α) is varied by 0.2-mrad step from $\theta = 0.4186$ rad ($\alpha = 43.0$ mrad) with a fixed value of $\alpha = 43.4$ mrad ($\theta = 0.419$ rad). All other parameters used in the calculations are the same as those in Fig. 1. As shown in the figure, the gain profile is rapidly distorted as θ and α deviate from the optimal values. Therefore, θ and α should be very precisely controlled with an angle resolution of better than 0.1 mrad to obtain a desired gain profile.

3. Effect of pumping laser

The pump intensity is a very critical factor that determines the overall gain of OPA. Although a higher pump intensity is required for a higher gain, the pump intensity cannot be increased indefinitely due to the damage of optics and the available pump energy at a required beam size. Eq. (1) shows that one can obtain a high gain at a low pump intensity by increasing crystal length. As crystal length increases, however, the spatial overlap between pump and signal beams becomes more difficult, especially, for the noncollinear OPA. Furthermore, Eq. (1) indicates that the modulation of gain profile at a same gain level becomes more severe with the increase of crystal length because the phase mismatch term (ΔkL) becomes more dominant than the fixed gain term (gL). To verify this phenomenon, we numerically calculated gain profiles with $\theta = 0.4178$ rad and $\alpha = 42.55$ mrad as the crystal length is varied. The overall gain is adjusted to the nearly same value of ~1500 by varying the pump intensity. As shown in Fig. 3, a longer crystal leads to a more severe modulation of gain profile, indicating that a shorter crystal is more preferred to obtain a smooth gain profile. On the other hand, shortening

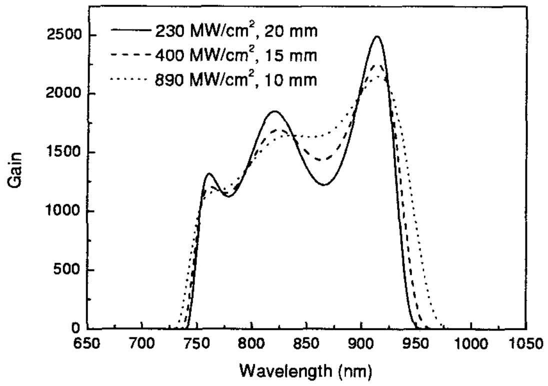

FIG. 3. The effect of pump intensity and crystal length on the modulation of OPA gain. θ and α are 0.4178 rad and 42.55 mrad, respectively.

the crystal length leads to the rapid increase of the pump intensity required to achieve the same gain level because g is proportional to the square root of pump intensity. Therefore, a proper compromise between the crystal length and the pump intensity should be made.

We used the pump wavelength of 532 nm in above calculations of gain profiles of OPA because that wavelength is the most commonly available from frequency-doubled Nd:YAG lasers. As shown in Fig. 1, however, the gain profiles of OPA with a 532-nm pump wavelength are centered around 830 nm, which is shifted from the gain peak of Ti:sapphire (~790 nm). It has been reported that other crystals such as LBO and KDP yield even a longer center wavelength of gain profile unless the gain bandwidth is sacrificed [4]. Therefore, the pump wavelength should be changed in the OPA with a BBO crystal for a better match of OPA gain with the gain curve of Ti:sapphire. Fig. 4 shows the gain profiles of OPA as the pump wavelength is varied. θ and α are adjusted to generate a similar shape of gain profile for each pump wavelength, while I_p is fixed to 400 MW/cm^2. It can be found that the gain profile gets red-shifted with the decrease of pump wavelength and that the gain profile of OPA very well matches with the gain band of Ti:sapphire with a pump wavelength of 510 nm. Although 510 nm is not as easily available as 532 nm, we believe that efficient 510-nm laser sources will be developed in near future by using Yb-doped gain material, which is being intensively studied as a promising alternative to Nd-doped material.

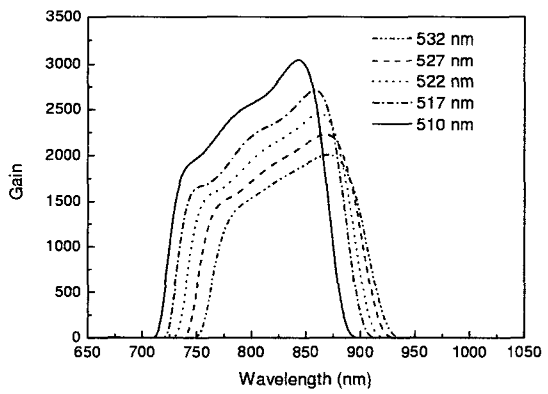

FIG. 4. The effect of a pump wavelength on the gain profile. I_p and L are 400 MW/cm^2 and 15 mm, respectively. θ and α are adjusted to generate a similar shape of gain profile for each pump wavelength.

III. EXPERIMENTAL RESULTS

The signal pulses for OPA are generated from a Kerr-lens mode-locked Ti:sapphire laser oscillator pumped by a frequency-doubled Nd:YVO$_4$ laser (Spectra-Physics, Millennia Vs). The oscillator operates at a repetition rate of ~100 MHz, and the average output power is 350 mW at 3-W pump power. The output spectrum is centered around 800 nm with a bandwidth of more than 150 nm. The pulse duration measured by an autocorrelator is ~15 fs. The pulses from the oscillator are stretched to ~200 ps by an Öffner-type pulse stretcher and selected by an Pockels cell synchronized with a pump laser. Fig. 5 shows the spectra measured before and after the stretcher. One can see that the spectrum is slightly clipped and modulated after the stretcher. The pump laser is a Q-switched frequency-doubled Nd:YAG laser operating at 10 Hz, and the pules duration of the pump laser is ~10 ns.

The BBO crystal used in our experiments is 15-mm long and cut at $\theta = 0.428$ rad. Both end faces are polished and protection-coated with a reflection of less than 2% over the signal and the pump wavelengths.

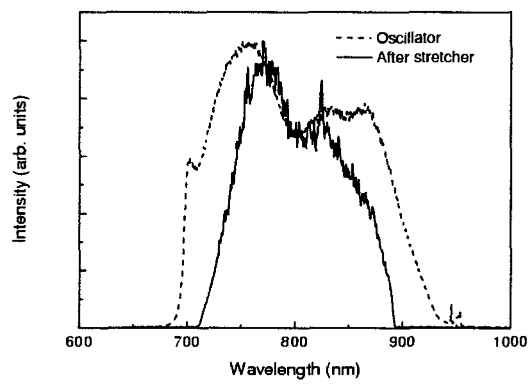

FIG. 5. The output spectrum of the Kerr-lens mode-locked Ti:sapphire laser and the spectrum after the stretcher.

As explained in the previous section, the noncollinear type-I phase-matching configuration is used. The pump laser is injected normally to the end face of the BBO crystal with the pump polarization parallel to the X-Z plane of the crystal (extraordinary polarization). The signal laser is crossed with the pump at an angle of ~43 mrad in the crystal, and the polarization of the signal is normal to the Z axis of the crystal (ordinary polarization). The angles of pump and signal lasers to the crystal axis are precisely adjusted with a resolution of less than 0.1 mrad. The pump laser with an energy of 50-60 mJ is focused to a ~2-mm diameter by a plano-convex lens of 1-m focal length, yielding pump intensity of 160-200 MW/cm^2. Currently, the pump intensity is limited by the available pump energy from our Q-switched Nd:YAG laser. The signal laser is collimated to ~1 mm of diameter and carefully overlapped with the pump in the crystal. In addition to the spatial overlap between the pump and the signal lasers, the temporal overlap is very important. We actively control the Q-switching of the pump laser to precisely synchronize the pump pulse with the signal. The temporal jitter between the pump and the signal lasers is measured to less than 1 ns.

The above configuration of OPA leads to a sufficient signal gain of ~100, and the single-shot measurement of the amplified spectrum is possible. Fig. 6(a) shows the single-shot spectra of amplified Ti:sapphire laser pulse measured by a fiber-coupled spectrometer (Ocean Optics, USB2000). As shown in the figure, the amplified spectrum is severely modulated and shows irregular spectral shape. Only small fractions that are randomly distributed over the input spectrum are strongly amplified by OPA, and the amplified pulse energy fluctuats very much. Such a irregular spectral shape has not been observed in other OPCPA of a similar configuration to ours [5,8]. On the other hand, the average spectrum measured by accumulating 200 shots shows a relatively uniform spectral shape as shown in Fig. 6(b). Such results can be explained in terms of the temporal fluctuation of the pump laser used in our OPA. Generally, many longitudinal modes are simultaneously generated from a Q-switched laser, and the beating among these longitudinal modes yields many random spikes in the temporal pulse shape. Because those spikes have much higher intensity than the average power over the pulse, strong OPA takes place around those spikes. In OPCPA, the signal pulses are strongly chirped before amplification, and the spectrum of the pulse is arranged in time domain. Therefore, only the small random portions of the spectrum where the spikes of the pump laser are temporally overlapped are strongly amplified. To avoid such a problem, a pump laser operating in a single longitudinal mode should be used.

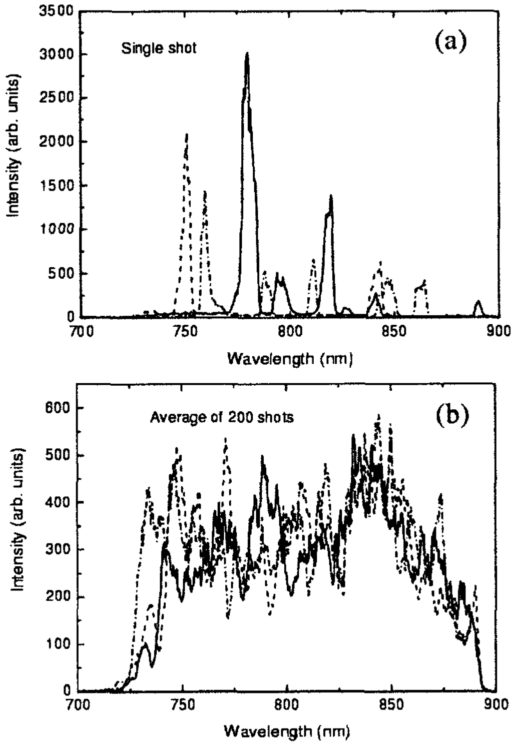

FIG. 6. (a) The single-shot and (b) the averaged spectra amplified by OPCPA with the Q-switched frequency-doubled Nd:YAG laser operating in a multi longitudinal mode.

IV. CONCLUSION

We have investigated the characteristics of OPA of femtosecond Ti:sapphire lasers by using a BBO crystal. Our numerical calculations shows that a high gain of more than 1000 and a broad gain bandwidth of more than 150 nm can be simultaneously obtained with a single BBO crystal pumped by a 532-nm pump laser. Because a broader gain profile has a more severe gain modulation with respect to the signal wavelength, proper compromise between the bandwidth and the uniformity should be made. The gain profile of OPA are found to be very sensitive to the phase matching angles, and an angle resolution of better than 0.1 mrad is required to realize the desired gain profile. The pump intensity and the crystal length determine the overall gain of OPA. To obtain a smooth gain profile with a high gain, the pump intensity needs to be maximized within the damage threshold of optics, and the crystal length should be as short as possible. It has been shown that a better match between the gain profiles of Ti:sapphire and the OPA with a BBO crystal can be achieved by using a shorter pump wavelength of 510 nm.

The experiments of OPCPA based on the numerical analysis have been performed to amplify the femtosecond laser pulses from the home-made Kerr-lens mode-locked Ti:sapphire laser. It has been found that the temporal quality of the pump laser is very critical to obtain a smooth amplified spectrum in OPCPA because the temporal modulation of the pump laser directly affects the amplified spectrum of the chirped pulses. Therefore, a pump laser of a single longitudinal mode should be used to obtain a smooth gain profile in OPCPA. Although the amplified spectrum in our OPCPA experiment is severely modulated by the multi-mode pulse laser, the average spectrum shows that a broad gain bandwidth can be obtained by OPCPA with a BBO crystal. In the future, the preamplification of femtosecond Ti:sapphire laser pulses by OPCPA will be performed by using a more energetic single-longitudinal-mode pump laser.

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