Analysis of 808nm Centered Optical Parametric Chirped Pulse Amplifier Based on DKDP Crystals

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ABSTRACT

The non-collinear phase-matching in Potassium Dideuterium Phosphate (DKDP) crystal is analyzed in detail with signal pulse of center wavelength at 808 nm and pump pulse of wavelength at 526.5 nm. By numerical analysis, parametric bandwidths for various DKDP crystals of different deuteration level are presented. In particularly for DKDP crystals of 95% deuteration level, the optimal non-collinear angles, phase-matching angles, parametric bandwidths, walk-off angles, acceptance angles, efficiency coefficients, gain and gain bandwidths are provided based on the parameter concepts. Optical parametric chirped pulse amplifier based on DKDP crystal is designed and the output characteristics are simulated by OPA coupled wave equations for further discuss. It is concluded that DKDP crystals higher than 90% deuteration level can be utilized in ultra-short high power laser systems with compressed pulses broader than 30fs. The disadvantage is that the acceptance angles are small, increasing the difficulty of engineering regulation.

Keywords: nonlinear optics, OPCPA, non-collinear phase-matching, ultra-broadband, DKDP

1. INTRODUCTION

Owing to meet the demands of study on strong field physics and high energy density physical issues, ultra-short high power laser technology has been developed rapidly in recent years. Such developments result from three aspects. Firstly, many gain mediums of high quality are invented with advanced manufacturing processing improved, such as large aperture nonlinear crystals (DKDP, YCOB, and LB0), large aperture Ti: sapphire, and Nd: glasses; secondly, many advanced laser technologies are proposed and proved to be mature enough for engineering application, including OPCPA and regenerative amplification technology; thirdly, for the researches on laser Inertial Confinement Fusion (ICF), a large number of laser facilities have been built as the driver to generate high energy high power nanosecond-class pulses, which provide high quality pump resources and large aperture reliable optical components.

At present, femtosecond-class lasers have realized ultra-short pulses with peak power from hundreds of terawatts (TW) to one Petawatt (PW), and the new generation constructions of lasers with peak power up to sub-Exawatt (EW) have been taken into schedule, for example, the Extreme Light Infrastructure (ELI) planed by 13 countries in Europe and the Exawatt Center for Extreme Light Studies (XCELS) designed by Russian. Both of ELI and XCELS are designed to realize ultra-short laser pulses of peak power up to 200PW. What’s more, one beam 10PW-class laser device is also proposed by Rutherford Appleton Laboratory based on the Vulcan facility in UK, and the similar device named Appllon is under construction in France. Compared with the standard CPA, OPCPA has some very important advantages, including broad gain bandwidths supporting amplification of few-optical-cycle light pulses, high gain quantity in short nonlinear crystals, small B-integral, large Signal to Noise Ratio (SNR), small thermal loading effects, and high beam quality. Front ends of all the devices above are designed to adopt OPCPA, which is also proposed to be utilized in the main amplifiers of all the devices except for ELI.

Although the technology of nonlinear crystal growth has made great progress, the construction of one beam 10PW optical parametric amplifier still faces with two problems in the respect of nonlinear crystals. Firstly, the broad gain bandwidth. According to Fourier transformation, pulses of a shorter width in temporal domain have the broader spectrum, and amplification systems centered at 808nm demand gain bandwidth exceeding 50nm (FWHM) to support amplification of 20fs pulse compressed. Secondly, considering the substantial loss of the compressor, the damage
thresholds of both the nonlinear crystals and the optical element film layers, diameters of the main amplifier of the last stage has to be larger than 200mm to achieve ultra-short pulse of hundreds of joules. As a result, the acquisition of large-caliber nonlinear crystals, which are of high damage threshold, is another problem. Large-caliber nonlinear crystals available in 808nm optical parametric amplifiers are reported currently, including LBO and YCOB, and the diameters are 80mm and 63mm, respectively. Crystals of larger diameter are under grown, but it is difficult to achieve diameter exceeding 200mm in short term. DKDP is adopted in the devices of UK and Russian, centered at 910nm, and at present it is the only nonlinear crystal that can be grown rapidly with diameter up to 400mm and high damage threshold. What is more, DKDP of different deuteration levels have various matching characteristics. But the potential utilization of DKDP crystals in OPA centered at 808nm has not been reported yet to our knowledge.

In this paper, the type I (o+o=e) non-collinear OPA centered at 808nm in DKDP crystals of different deuteration levels is discussed by numerical simulation. The phase matching parameters are presented, including the optimal non-collinear angles, phase-matching angles, parametric bandwidths, walk-off angles, acceptance angles, efficiency coefficients, gain and gain bandwidths. Optical parametric amplifier based on DKDP crystal is designed and the output characteristics are simulated by OPA coupled wave equations in detail, which would be instructive in practice.

2. NONCOLLINEAR PHASE MATCHING OF DKDP CRYSTALS

2.1 Dispersion formulas and transmittance of DKDP crystals

Phase matching parameters in OPA can be calculated based on the Dispersion formulas of nonlinear crystals. Dispersion formulas of DKDP crystals are associated with deuteration levels, and can be described in the form:

$$n_{o,e}^2(D, \lambda) = n_{o,e}^2(0.96, \lambda) + 0.04n_{o,e}^2(0, \lambda) D + (1 - D) n_{o,e}^2(0, \lambda)$$

in which, $n_{o,e}(D, \lambda)$ is the spindle refractive of DKDP crystal with deuteration ratio $D$ at wavelength $\lambda$, and $n_{o,e}^2(0.96, \lambda)$ as well as $n_{o,e}^2(0, \lambda)$ are obtained by experimental data and expressed as Eq.(2) and Eq.(3).

$$n_{o,e}^2(0.96, \lambda) = 2.240921 + \frac{2.246956 \lambda^2}{\lambda^2 - 11.26591^2} + \frac{0.009676}{\lambda^2 - 0.124981^2}$$

$$n_{o,e}^2(0, \lambda) = 2.126019 + \frac{0.784404 \lambda^2}{\lambda^2 - 11.10871^2} + \frac{0.008578}{\lambda^2 - 0.109505^2}$$

$$n_{o,e}^2(0, \lambda) = 2.259276 + \frac{13.00522 \lambda^2}{\lambda^2 - 400} + \frac{0.01008956}{\lambda^2 - (77.26408)^2}$$

$$n_{o,e}^2(0, \lambda) = 2.132668 + \frac{3.2279924 \lambda^2}{\lambda^2 - 400} + \frac{0.008637494}{\lambda^2 - (81.42631)^2}$$

Figure 1. Internal transmittance of DKDP for different deuteration level
Compared with BBO, LBO and YCOB crystals, DKDP crystals have much higher loss in the infrared domain and the loss is different for crystals of various deuteration levels. Internal transmittance of DKDP for different deuteration level is measured experimentally and the transmittance curves for 50mm crystals of deuteration level 0, 70% and 95% are presented in Figure 1, which is the most detailed data reported currently to our knowledge. The idler pulses generated in the OPA with signal pulse centered at 808nm will be suppressed because of the high loss for wavelength longer than 1200nm.

2.2 Noncollinear phase matching

The type-I phase matching vectors of noncollinear geometric configuration are indicated in Figure 2(a), in which, $k_s$, $k_i$ and $k_p$ are the wave vectors of the signal, idle, and pump respectively, $Z$ is the optical axis, the symbol $\alpha$ is the noncollinear angle, $\theta$ is the phase matching angle, $\beta$ is the angle the angle between the pump and idle vectors. In the negative uniaxial crystals, as shown in Figure 2(b), $k_o$ and $k_e$ are the vectors of the ordinary light and the extraordinary light, and $\rho$ is the angle between Poynting vector ($s_e$) and wave vector ($k_e$), that is to say, the walkoff angle.

![Figure 2. Noncollinear phase-matching vectors (a) and walkoff angle in negative uniaxial crystals (b)](image)

Based on the momentum conservation and energy conservation in OPA, the phase matching angle for type-I is expressed as Eq. (4), and the wave vector mismatch is expressed as Eq. (5)

$$\theta_{pm} = \arcsin \left[ \sqrt{\frac{n_p^2 / \lambda_p^2 - \left(n_o^2 / \lambda_o \cos \alpha + n_i^2 / \lambda_i \cos \beta \right)^2}{n_p^2 - n_e^2}} \right] \frac{n_p^*}{n_o / \lambda_o \cos \alpha + n_i / \lambda_i \cos \beta}$$

$$\Delta \vec{k} = 2\pi n_p / \lambda_p - 2\pi n_i \cos \alpha / \lambda_i - 2\pi n_o \cos \beta / \lambda_o$$

where, subscripts s, i and p are marks for signal, idle and pump, $n_o$ and $n_e$ are spindle refractive of ordinary light and extraordinary light, $n_o$, $n_i$ and $n_p$ are the refractive of signal, idle and pump along azimuth angles ($\theta$, $\phi$), respectively, and the angle $\beta$ can be expressed as $\beta = \arcsin(n_i / n_s) \cdot (\lambda_i / \lambda_o) \cdot \sin \alpha$.

![Figure 3. Parametric bandwidths versus noncollinear angles in 30mm DKDP crystals of various deuteration levels.](image)
The concepts of parameters of phase matching in OPA are unnecessary to be repeated in this paper, and they have been described in Ref.22. With Eq. (4) and Eq. (5), we adopt an identical method from Ref.22, and parameters of phase matching in OPA of 808nm-centered signal pulses and 526.5nm-centered pump pulses are calculated for various deutronation DKDP crystals. In 30mm DKDP crystals, parametric bandwidths versus noncollinear angles for deutronation levels 30%, 70%, 85%, 90%, 93% and 95% are presented in Figure 3. Curves in Figure 3 indicate that there are optimal noncollinear angles ($\alpha_{\text{opt}}$) that enable the parametric bandwidth the largest values ($\Delta \lambda_{p}$). Corresponding to the optimal noncollinear angles, the parametric bandwidths for crystals of the different deutronation levels ($\alpha_{\text{opt}}, \Delta \lambda_{p}$) are ($0^\circ, 5\text{nm}$), ($0^\circ, 13\text{nm}$), ($0^\circ, 37\text{nm}$), ($0.13^\circ, 57\text{nm}$), ($0.376^\circ, 58\text{nm}$) and ($0.473^\circ, 59\text{nm}$), respectively. The maximal parametric bandwidth for DKDP crystals of deutronation ratio lower than 85% in NOPA are always smaller than 40nm, which indicates that such crystals are not capable to support the amplification of <50fs pulses, when certain engineering redundancy is taken into account. DKDP crystals to be discussed are confined to those of deutronation ratio higher than 90%. Phase-matching angles for the optimal noncollinear angles in DKDP crystals are presented in Figure 4 corresponding to deutronation ratios 90%, 93% and 95%, and the phase matching angles at 808nm are 36.89°, 36.80°, 36.73°, respectively.

![Matching angle $\theta$ vs. Wavelength $\lambda$](image)

Figure 4. Phase-matching curves for the optimal noncollinear angles in DKDP crystals of various deutronation levels.

![Acceptance angle $\Delta \theta$ vs. Noncollinear Angle $\alpha$](image)

![Walkoff angle $\rho$ vs. Noncollinear Angle $\alpha$](image)

Figure 5. Acceptance angles (a), and walkoff angles (b) versus noncollinear angles in 30mm DKDP crystal of various deutronation levels.

Acceptance angles versus noncollinear angles in 30mm DKDP crystal of various deutronation levels are provided in Figure 5(a). For 95% deutronation 30mm DKDP crystal, the acceptance angle is 0.46mrad, which is much smaller compared with BBO, LBO, YCOB crystals of different length (0.37mrad, 15mm), (1.95mrad, 20mm), (0.78mrad, 20mm). More precise adjustment is required for DKDP crystals when utilized in OPA devices. Walkoff angles versus noncollinear angles in 30mm DKDP crystal of various deutronation levels are provided in Figure 5(b), and the value for 95% deutronation 30mm DKDP crystal at optimal noncollinear angle is -25.4mrad, which is close to the values of -57.81mrad for BBO, 8.40mrad for LBO, and -19.79mrad for YCOB. The reduction on conversion efficiency because...
of walkoff effects is associated with walkoff length, and for the amplification systems with beam aperture larger than 100mm, the walkoff length corresponding to the DKDP walkoff angle is calculated about 6m, which is much larger than crystal length, ten-odd millimeters as usual, utilized in practice. As a result, for DKDP crystal of large aperture used in main amplifier, the walkoff effect can be ignored.

The nonlinear coefficient of the 96% deuteration DKDP crystal is measured at 1064nm, $d_{36}(1.064\mu m)=0.37\text{pm/V}$, and the effective coefficient of type-I phase matching is calculated $d_{\text{eff}}=0.2213\text{pm/V}$ by the relation $d_{\text{ooe}}=d_{36}\sin\theta\sin2\phi$ when the angle $\phi$ is 45°. So we can get conclusion based on the phase matching parameters as follows: parametric bandwidths of >90% deuteration 30mm DKDP crystals are about 60nm, which support amplification of 16fs Fourier transform limited Gaussian pulses. The disadvantage is the small acceptance angle, which requires more precise adjustment in practice. Phase matching parameters for 95% deuteration DKDP crystals are presented in Table 1.

Table 1. Phase matching parameters in DKDP crystals of deuteration level 95%.

<table>
<thead>
<tr>
<th>Para.</th>
<th>$L$/mm</th>
<th>$\alpha_{\text{opt}}$/$(^\circ)$</th>
<th>$\theta$/$(^\circ)$</th>
<th>$\Delta \theta$/mrad</th>
<th>$\rho$/mrad</th>
<th>$d_{\text{eff}}$/($\text{pm/V}$)</th>
<th>$\Delta \lambda_p$/nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>30</td>
<td>0.473</td>
<td>36.73</td>
<td>0.46</td>
<td>-25.4</td>
<td>0.2213</td>
<td>59</td>
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3. COUPLED WAVE EQUATIONS SIMULATION IN TEMPORAL DOMAIN

3.1 Coupled wave equations and chirped pulse compression

The coupled wave equations are numerically simulated to analyze the loss effect and group velocity mismatch (GVM) effect, and it is also required for the discussion of the output waveform, the conversion efficiency and the compression. In the ultra-short ultra-high power devices, the 526.5nm pump pulses of super Gauss temporal-spatial profile are provided by the second harmonic generation (SHG) of fundamental frequency pulses from Nd: glass lasers, and the 808nm signal pulses are reshaped to be super Gauss temporal-spatial profile to realize higher conversion efficiency. The complex amplitude of square beam pulses is given by Eq. (6)

$$\tilde{A}_{(x,y,t)} = A \exp \left( -\frac{x^2}{2x_0^2} \right) \exp \left( -\frac{y^n}{2y_0^n} \right) \exp \left( -\frac{T^n}{2T_0^n} \right) \exp \left[ -i \left( \frac{CT^2}{2T_0^2} + \alpha_0 T \right) \right]$$

in which, symbols $m$ and $n$ are the super-Gauss-orders in temporal domain and spatial domain, $\omega_0$ is the center circular frequency corresponding to the center wavelength $\lambda_0$, $C$ is a cons reflecting the chirped ratio of the pulse, $T_0$, $x_0$ and $y_0$ are half of the values of duration in temporal domain and width in spatial domain bounded by e$^{-1}$ peak intensity, generally we set $x_0=y_0 = t_0$. But in practice, the time duration as well as the beam caliber ($\tau_0$ and $R_0$) are defined as the domain of intensity higher than 1/2 peak (Full Wave at Half Maximum, FWHM). The parameters relation are expressed $R_0=2(\ln2)^{1/4}\tau_0$ and $\tau_0=2(\ln2)^{1/4}T_0$. In FWHM style, apertures of the incident signal pulses and pump pulses are 150mm and 145mm, duration are 2ns and 2.2ns, energy are 20J and 1000J, respectively. The power intensity of the pump pulse is about 2GW/cm$^2$. The chirped ratio of signal pulses is fixed $C_1=1.040\times10^5$, which is essentially equivalent to 2ns/60nm. All the parameters above are presented in Table 2.

Table 2. Laser parameters of incident laser beams.

<table>
<thead>
<tr>
<th>Para.</th>
<th>$\lambda_0$/nm</th>
<th>E/J</th>
<th>n</th>
<th>m</th>
<th>$\tau_0$/ns</th>
<th>$R_0$/mm</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>808</td>
<td>20</td>
<td>$4^n$</td>
<td>$4^n$</td>
<td>2</td>
<td>150</td>
<td>1.040$\times10^5$</td>
</tr>
<tr>
<td>Pump</td>
<td>526.5</td>
<td>1000</td>
<td>$6^n$</td>
<td>$4^n$</td>
<td>2.2</td>
<td>145</td>
<td>0</td>
</tr>
</tbody>
</table>

To discuss the compression of the amplified chirped signal pulses in detail, the nanosecond laser pulses must be discrete in step of a few femtoseconds, which is confined by the Sampling theorem. As a result, a large amount data is calculated in the simulation, and the simulation is confined in temporal domain. The coupled wave equations are expressed by Eq. (7) $^{21}$ Nonlinear gain has a positive sign in Eq. (7), while a negative sign in Ref.23. The difference derives from the monochromatic phase definition $\exp(-i\omega_0 T)$ in Eq.(6).
in which, the left side refers to the laser transmission along the crystal, the first item of the right side is associated with the nonlinear gain, the second is the GVM effect, and \( V_{gs}, V_{gi} \) and \( V_{gp} \) are group velocities of signal, idle and pump pulses, and they are obtain by \( V_{g}=(\omega / k) \) \( |\omega_{0} \), the third is the loss, and \( \alpha \) is the loss factor, which is the function of wavelength as indicated in Figure 1 and given by Eq. (8).

\[
\alpha(\lambda) = \left[ \frac{1}{2} \ln \left( \frac{T}{T_{0}} \right) \right]
\]

where, \( T \) is transmittance, \( L_{0}=50\text{mm} \) used in Figure 1. The coupled wave equations are numerically simulated by Difference method and \(^{4}\text{th} \) order Runge-Kutta method\(^{24, 25} \). Pulses waveform output from the compressor, which provides second-order dispersion \( \phi(\omega) \), are obtained by Eq. (9)\(^{26} \).

\[
B_{r} = \text{fft}^{-1} \left\{ \exp \left[ i \phi(\omega) \right] \text{fft} \left[ A_{r} \right] \right\}
\]

### 3.2 Chirped pulse amplification and compression

Normalized intensity of amplified pulses in OPA is achieved by numerical simulation of coupled wave equations with parameters in Table 2 substituted, and the waveform is shown as the solid line in Figure 6. It indicates that the duration of amplified pulse is a bit smaller than that of incident pulse, and the value is about 1.76ns. The chirped characteristic keep the identical when high order dispersion are ignored, and the spectrum bandwidth is proportional to duration. So the spectrum bandwidth of amplified pulse is about 52nm, which is almost equal to the parametric bandwidth 54.5nm for 35mm DKDP crystals. The conversion efficiency is defined as the ration between the amplified signal pulse energy and all of the incident pulses energy, and it is presented by the solid line in Figure 7. The 49% conversion efficiency indicated that the pump energy has been converted to signal pulse effectively. The compressed pulse waveform is shown by the solid line in Figure 8, and the duration is 30fs, compared with duration 24fs of the compressed incident pulse. Duration of compressed pulse is extended by ratio 25% because of amplification.

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**Figure 6.** Normalized intensity of incident pulses and output pulses in OPA: incident pump pulse (dot line), incident signal pulse (dot dash line), amplified signal pulse of chirped ratio C1=1.040×10^5 (solid line), amplified signal pulse of chirped ratio C2=1.663×10^5 (dash line).
In contrast, with identical numerical simulation and incident parameters except for a different chirped ratio C2 = 1.663 \times 10^5, waveform of the amplified pulse is presented as the dash line in Figure 6. Spectrum bandwidth of the incident signal pulse of chirped ratio C2 is 96nm, which is much larger than parametric bandwidth. Duration of the amplified pulse is about 1.3ns, which is much smaller than that of the incident pulse, while the spectrum bandwidth is about 62nm, which is larger than parametric bandwidth. The conversion efficiency curve is plotted by dot dash line in Figure 7, and the maximal value is 37%, much smaller than that of C1 chirped pulse. It is due to the phase mismatching in the two sides and the pump energy can’t be converted effectively. The compressed waveform of the amplified pulse and the incident pulse are plotted by dot dash line and dot line in Figure 8, respectively, and the durations are 24fs and 15fs, the duration of compressed pulse is extended by ratio 60% because of amplification. It is concluded that duration of the compressed pulse is almost broader than 20fs, and DKDP crystals is unsuitable for 808nm OPCPA aimed at <20fs compressed pulses. At last, to confirm the impact of loss on the OPA, the conversion efficiency is calculated without loss effect in coupled wave equations. As shown by the dot line in Figure 7, the conversion efficiency is 1% higher than that loss included, and it indicated that loss factor from Figure 1 has little impact on the amplification.

4. CONCLUSIONS

Optical parametric chirped pulse amplifier based on DKDP crystals are researched with 526.5nm pump pulse and 808nm centered signal pulse in this paper. Phase matching characteristic are presented by numerical simulation for DKDP crystals of various deuteration levels, and the amplification as well as the compression are analyzed by coupled wave equations. In conclusion, DKDP crystals of >90% deuteration can provide broad gain bandwidth and high gain to support optical parametric amplification systems >30fs compressed pulse centered at 808nm. The high loss in idle pulse
has little impact on the conversion efficiency. The disadvantage is the small acceptance angle, which indicated more precise adjustment in practice.

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