Noncollinear optical parametric amplification in lithium triborate seeded by a cw Ti:sapphire laser☆

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Abstract

Experimental investigations of a type-I noncollinear phase-matched optical parametric amplification based on lithium triborate, which was pumped by a 5-ns second-harmonic pulses from a Q-switched Nd:YAG, seeded by a cw Ti:sapphire laser at 800 nm, was presented. The experiments generated 2-ns signal output pulses at 800 nm, the maximum signal output pulse energy reached 19 μJ, the corresponding parametric gain was 44 dB. Furthermore, the experiments demonstrate that the 65 nm-FWHM parametric fluorescence gain spectrum could also be observed. A quantitative account of the ultrabroadband parametric fluorescence gain spectrum was given with our theory. The experimental measurements are in agreement with theoretical calculations.

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1. Introduction

The optical parametric amplification (OPA) has been widely recognized as a versatile source of tunable laser radiation [1–5]. A current interesting research is centered on a seeded optical parametric amplification [5–7]. The advantage of this source is that it provides efficient and simple conversion of a pump laser (pulsed) to new frequencies with single passes. In other words, an OPA presents an interesting route toward control of the output spectrum simply by choice of an appropriate seeding source, and can be used to generate pulses shorter in duration than the pump. Tuning and spectral control of the OPA are then much simpler to implement than in an OPO, and the lack of cavity mirror makes those devices more robust, with potentially more stable output characteristics. In addition, OPAs offer small-signal gains that are several orders of magnitude larger than are typically obtained in solid-state laser media. Noncollinear parametric interaction in OPAs can be used to extend the tunability of the collinear process, to separate the interacting wavelengths more easily, and to effectively increase the interaction length by compensating the Poynting vector walk-off. Moreover, noncollinear parametric interaction is quite attractive to modify the phase-matched condition as well as the amount of the GVM in a straightforward and simple way for the spectral broadening in an OPA, it can realize the group-velocity matching between the signal and idler, which is equivalent to an achromatic phase matching with the spectral angular dispersion of the idler, and the broadest bandwidth can be attained [8,9].

In this article, a cw-seeded noncollinear optical parametric amplification (NOPA) experiment was carried out in an LiB3O5 (LBO) OPA pumped by a 5-ns laser second-harmonic output of Nd:YAG laser, and seeded by a cw Ti:sapphire laser at 800 nm. For the first time to our knowledge, we demonstrate that the 2-ns signal output pulses at 800 nm and signal energy of 19 μJ with a one-pass gain of 44 dB for a 5-ns LBO-NOPA could be obtained by use of a seeding energy of 0.8 nJ. It was noted that the simultaneous generation of 65 nm (FWHM) ultrabroadband parametric fluorescence gain spectrum is observed in our experiment. A quantitative account of the ultrabroadband parametric fluorescence gain spectrum bandwidth was
carried out using general mathematical expressions for evaluating parametric bandwidth and gain bandwidth of arbitrary three-wave mixing parametric amplifications, which had been earlier developed by us. The experimental measurements are in agreement with our theoretical calculations.

2. Experimental arrangement and experimental results

A schematic of our experimental setup is shown in Fig. 1, in which the NOPA is pumped by the 5-ns second-harmonic generation output of a Q-switched Nd:YAG laser at 1064 nm, operating at 10 Hz. The seed laser source was a cw Ti:sapphire laser system at 800 nm, its output spectrum FWHM bandwidth is about 1 nm as shown in Fig. 5(a). For NOPA we used a dimensions $4 \times 4 \times 15 \text{mm}^3$ LBO type-I crystal cut at $\theta = 90^\circ$, $\phi = 12.6^\circ$. The 532-nm pump beam was reduced to a 1-mm diameter by a $3 \times$ telescope. The pump beam was polarized vertically, the 800-nm signal beam polarized horizontally was reduced to a 500 $\mu$m diameter by a $5 \times$ telescope and then directed into the LBO crystal at an interior angle of $1.112^\circ$ respect to the pump beam. The phase matching angle of the LBO crystal was aligned to central signal wavelength.

The nanosecond pulses from the Nd:YAG pump laser were mixing with the cw seed from the Ti:sapphire, and the seed power was 400 mW. The amplified output signal from the LBO-NOPA at 800 nm had a temporal width of $\sim 2$ ns FWHM as shown in Fig. 2, this translates into equivalent seed pulse energy of 0.8 nJ [6]. The temporal profile of output pump pulse was measured as shown in Fig. 3. The output characteristics of the NOPA are illustrated in Fig. 4. The maximum generated signal pulse energy was 19 $\mu$J at 3.5 GW/cm$^2$ pumping intensity, corresponding to a single-pass gain of almost 44 dB, which, to our knowledge, is the highest gain for 5-ns OPA. The maximum achievable gain arises primarily from the damage threshold of the crystal. In our experiment no evidence of surface or bulk damage could be observed with a 3.5 GW/cm$^2$ pumping intensity at 5-ns pulse width. The effective pump energy corresponding to the 3.5 GW/cm$^2$ pump intensity is 34 mJ. The lower parametric conversion efficiency is due to the LBO’s lower nonlinear coefficient $d_{\text{eff}}$, which is only 0.83 pm/V. This is the main disadvantage of LBO being used in nanosecond OPA.

The measured spectrum of the input signal is illustrated in Fig. 5(a). The measured spectrum of the amplified output 2-ns pulse signal from OPA pumped with 3.5 GW/cm$^2$ of intensity and seeded with 0.8 nJ of energy from the Ti:sapphire
Fig. 4. The output signal pulse energy versus pump intensity in the LBO-NOPA. Squares, experiment; solid curve, theoretical calculation. The seed pulse energy is equivalent to 0.8 nJ.

laser is shown in Fig. 5(b). As can be seen, the NOPA simultaneously generated the amplified broadband parametric fluorescence [3,10]. The amplified parametric fluorescence gain spectrum bandwidth is 65 nm FWHM at $\alpha = 1.112^\circ$, the gain extending all the way from 680 to 900 nm. Of particular interest is that the radiation covered a wavelength range that is not readily accessible by passively Q-switched YAG laser. Because of the ultrabroad gain bandwidth, we could achieve wavelength tuning of the OPA by tuning the Ti:sapphire laser. As a comparison, the amplified signal spectrum at $\alpha = 0^\circ$ was also measured as shown in Fig. 5(c). The amplified parametric fluorescence gain spectrum bandwidth is $\sim 13$ nm FWHM. This implies that the parametric fluorescence gain spectrum bandwidth is strongly dependent on the noncollinear angle $\alpha$. This kind of phenomenon has been observed in an OPA experiment. In fact, the simultaneous generation of the amplified broadband parametric fluorescence is a process of optical parametric generation and amplification (OPG-OPA) [10]. Since OPG has many similar features as OPA and because they are both the nonlinear three wave interaction processes in the nonlinear crystal, we will give a quantitative account of the ultrabroadband parametric fluorescence gain spectrum using our theory in the following section.

3. Theoretical analyses and discussion

3.1. Parametric bandwidth of the OPA

The out signal spectrum bandwidth of OPA is primarily limited by the parametric bandwidth, namely,
phase-matching bandwidth, which determines the maximum achievable gain bandwidth. The parametric bandwidth \( \Delta \lambda \) (FWHM) of OPA can be evaluated with the following expression [9]:

\[
\Delta \lambda = \begin{cases}
\frac{\lambda^2 |n_{s\lambda}|}{c \ I_c^{0.5}} , & 1 - \frac{n_{si}}{n_{si}} \neq 0,
\frac{0.8 \lambda^2}{c} \sqrt{\frac{1}{I_c} \ |g_{si}|} , & 1 - \frac{n_{si}}{n_{si}} = 0
\end{cases}
\]

with

\[
g_{si} = \left[ \frac{1}{2 \pi c^2} \tan(\alpha + \beta) \sin \left( \frac{\lambda_s - \lambda_i \cos(\alpha + \beta)}{n_i} \right) ight] ,
\]

\[
g_m = \left( \frac{\varepsilon^2 k_m}{c n^2_m} \right)_{\alpha = \alpha_m} , (m = s, i),
\]

\[
\beta = \arcsin \left( \frac{n_s \lambda_i}{n_i \lambda_s} \sin \alpha \right). 
\]

Here, \( n_s \) and \( n_i \) is the signal group-velocity (GV) and idler group-velocity, respectively. \( g_m \) is the GV dispersion (GVD), \( l_c \) is the effective length of the nonlinear crystal. \( \alpha \) and \( \beta \) are the noncollinear angles that the signal and the idler make with the pump, respectively.

As can be seen from Eq. (1), the parametric bandwidth strongly depends on noncollinear angle \( \alpha \), and there exists an \( \alpha \) where the maximum parametric bandwidth was obtained. Here a broadband amplification is expected, which is attributed to the GV matching between the signal and idler, when the signal GV is equal to the component of the idler GV projected to the signal direction, namely,

\[
v_s = v_i \cos(\alpha + \beta). 
\]

According to Eq. (3), we can calculate the optimized noncollinear angle \( \alpha \). For an LBO (in \( x-y \) plane, type-I) OPA pumped by 532 nm, and seeded by 800 nm at noncollinear geometry, the optimized noncollinear angle \( \alpha \) is 1.112°. Fig. 6(a) demonstrates the variation of the parametric bandwidth of the LBO (\( l_c = 15 \) mm) OPA versus noncollinear angle \( \alpha \) with \( \lambda_p = 532 \) nm and \( \lambda_s = 800 \) nm. From Fig. 6(a), we can see that the parametric bandwidth of the OPA is only 15 nm FWHM at \( \alpha = 0° \), but increases to 70 nm FWHM at \( \alpha = 1.112° \). Fig. 6(b) shows the variation of the parametric bandwidth versus signal wavelength with \( \lambda_p = 532 \) nm for noncollinear geometry when the GV between the signal and idler pulses are matched.

3.2. Gain bandwidth of the OPA

A first estimate of the noncollinear phase-matching parametric gain and the necessary pump intensity can be made from the simple relations that are available under the assumption of an undepleted pump. For high gains [11]

\[
G = 0.25 \exp \{2[I_0^2 - (\Delta k/2^2)^2]^{0.5} l_c) \},
\]

where

\[
I_0 = 4 \pi d_{eff} \sqrt{I_p/(2 \varepsilon_0 n_p n_s c \lambda_s \lambda_i \cos(\beta - \rho))}.
\]

With \( I_p \) being the pump intensity, \( n \) the refractive indices, and \( d_{eff} \) the effective nonlinear coefficient, \( \rho \) is the Poynting vector walk-off angle.

The gain bandwidth is defined at the points for which \( G = \frac{1}{2} G(\Delta k = 0) \). The gain bandwidth \( \Delta \lambda \) (FWHM) of OPA is expressed as follows [9]:

\[
\Delta \lambda = \begin{cases}
\frac{0.53 \lambda^2}{c} \sqrt{\frac{I_0}{l_c}} |u_{si}| , & 1 - \frac{n_{si}}{n_{si}} \neq 0,
\frac{0.58 \lambda^2}{c} \left( \frac{I_0}{l_c} \right)^{0.4} \sqrt{\frac{1}{|g_{si}|}} , & 1 - \frac{n_{si}}{n_{si}} = 0.
\end{cases}
\]
The $u_{si}$, $g_{si}$ and $g_{mi}$ are the same as those of the Eq. (2). As can be seen, gain bandwidth $\Delta \lambda$ of the OPA increases as the pump intensity $I_p$ increases since $P_{0}^2$ is proportional to $I_p$. The gain bandwidth is also sensitive to the noncollinear angle $\alpha$. For an LBO (in $x$–$y$ plane, type-I) OPA with 532-nm pump pulse and 800-nm seed pulse, the maximum gain bandwidth is also expected at $\alpha = 1.12^\circ$. Fig. 7(a) demonstrates the dependence of the gain bandwidth of the LBO ($l_c = 15$ mm) OPA on the noncollinear angle $\alpha$ with $\lambda_p = 532$ nm and $\lambda_s = 800$ nm at $I_p = 3.5$ GW/cm$^2$. Fig. 7(a) shows that the gain bandwidth increases rapidly from 19 nm FWHM at $\alpha = 0^\circ$ to 79 nm FWHM at $\alpha = 1.12^\circ$. Fig. 7(b) shows the variation of the gain bandwidth of the LBO ($l_c = 15$ mm) OPA versus signal wavelength with 532 nm pump wavelength at $I_p = 3.5$ GW/cm$^2$ for noncollinear geometry when the GV between the signal and idler pulses are matched.

Since the maximum possible gain bandwidth depends on the parametric bandwidth, which is determined by the allowable phase-mismatch of parametric process, the gain bandwidth will increase with the increase of pump intensity within the range of the maximum parametric bandwidth, until the gain bandwidth was saturated into the parametric bandwidth. For that reason, with reference to Figs. 6(a) and 7(a), we know that the maximum gain bandwidth of the LBO (in $x$–$y$ plane, type-I) OPA with $l_c = 15$ mm, $\lambda_p = 532$ nm and $\lambda_s = 800$ nm is 15 nm FWHM at $\alpha = 0^\circ$, and increases to 70 nm FWHM at $\alpha = 1.12^\circ$. The experimental measurements of the parametric fluorescence gain spectrum bandwidth in the Section 2 are 13 nm FWHM at $\alpha = 0^\circ$ and 65 nm FWHM at $\alpha = 1.12^\circ$, they are very close to these theoretical calculation results.

To demonstrate the validity of the above conclusion, we investigated how the gain bandwidth of the NOPA depends on the pump intensity via the simultaneous generation of parametric fluorescence gain spectrum along the signal beam direction. Fig. 8 shows the variation of the gain bandwidth as a function of pump intensity with $\alpha = 1.12^\circ$, $l_c = 15$ mm, $\lambda_p = 532$ nm and $\lambda_s = 800$ nm. As expected from the theory, the pump intensity can affect the gain bandwidth significantly.

With increasing pump intensity the gain bandwidth increases to a saturated value, which is equal to the maximum parametric bandwidth of the OPA. The correspondence between the experimental measurements and the theoretical calculations is good; the subtle discrepancy is probably due to inaccuracy of the refractive indices used in the calculations. Moreover, this implies that Eqs. (1) and (6) are reliable and can be used to provide useful guidance for better design of the broadband OPA. In our experiment, the maximum gain bandwidth is determined by the parametric bandwidth, which is mainly limited by the crystal length, undoubtedly a larger gain bandwidth could be achieved by minimizing the crystal length, but this leads to decreasing of the conversion efficiency. In particular, we can achieve both high gain and large gain bandwidth by maximizing the pump intensity and minimizing the crystal length. However, for longer pulses, especially nanosecond pulses, the damage threshold requires a reduction in the pump intensity and an increase in the crystal length, leading to reduced gain bandwidth.
A variety of applications are expected to benefit from the ultrabroadband OPA. It is well known that a wide gain bandwidth is desirable for the generation of ultrashort pulses, since our experiments demonstrated that the 44 dB gain of 800 nm signal and the 65 nm FWHM gain bandwidth exhibited by the parametric amplified fluorescence can be obtained; this NOPA can be used to amplify a transform-limited signal pulse as short as 10-fs. Furthermore, use of the noncollinear amplification geometry offer new possibilities in extending the OPA gain bandwidth, and the combination of these methods in the meantime become a widely recognized technique for the white light continuum amplification. This kind of NOPA can also be used to amplify chirped pulses for the production of sub-10 fs pulses, as well as for the development of ultrahigh peak power laser sources [12–16].

4. Conclusions

In conclusion, we have investigated a cw-seeded noncollinear OPA. The amplification of 800 nm radiation from a cw Ti:sapphire laser in a noncollinear LBO parametric amplifier pumped by a 5-ns Q-switched frequency-doubled Nd:YAG laser has been experimentally demonstrated. The maximum single-pass signal gain was 44 dB at 3.5 GW/cm² pump intensity, and signal pulse energy was 19 µJ. In addition, the simultaneous generation of 65 nm FWHM ultrabroadband parametric fluorescence gain spectrum has been observed and quantificationally analyzed using our theory together with a comparison with theoretical calculations. The experimental measurements were well in agreement with the theory.

References