High-power nanosecond optical parametric oscillator based on a long LiB₃O₅ crystal


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Abstract

We report on a compact high average power optical parametric oscillator (OPO) pumped by an all-solid-state nanosecond 532 nm laser. Based on the merit of non-critically phase-matched crystal without walk-off effect, a 50-mm-long LiB₃O₅ (LBO) crystal is used as OPO nonlinear crystal to enhance the conversion efficiency and increase the output power. With the available mirror set, continuous tuning from 778 to 1036 nm for signal wave is obtained by changing LBO phase-matching temperature. The maximum average power of signal output is up to 9.4 W at 900 nm for pump power of 18 W inside the LBO crystal, corresponding to a conversion efficiency of 52% only for the signal output. This is, to the best of our knowledge, the highest signal average power generated by nanosecond OPO in single bulk LBO.

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Optical parametric oscillators (OPOs) pumped by intense laser pulses are powerful sources because of their coherence, broad tuning range, and high conversion efficiency [1]. Tunable laser pulses in the infrared are of interest for numerous applications in science and technology including time-resolved spectroscopy, the diagnostics of materials as well as the characterization of various optical components [2]. The development of BBO, LBO, CBO and KTP as effective nonlinear optical crystals has made such devices a practical reality [3]. Among them, the LBO is particularly attractive. The nonlinear material LBO has several advantageous properties for the nonlinear frequency conversion. It is characterized by a high optical damage threshold, wide optical transmission, moderate nonlinear coefficients and sufficient birefringence to provide phase matching from near ultraviolet (UV) to the near infrared (IR). An

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important advantage is the non-critical phase matching (NCPM) of 532 or 355 nm pumped OPOs. The NCPM configuration allows a good OPO conversion efficiency even with poor-beam-quality pump lasers. It avoids spatial walk-off between the incident and generated waves and thus optimizes the interaction length and angular acceptance, so the efficiency is not compromised by the use of tightly focused beams. Therefore, large available crystal size allows the generation of high average power. In addition, the temperature acceptance is small [4,5], which results in a wide wavelength tuning of the signal and idler waves by changing the crystal’s temperature.

For most of the LBO-OPOs reported so far, the output power is less than 1 W with the LBO crystal lengths of 10–30 mm [6–10]. Recently, Ruffing et al. [11] have obtained high average signal power of 5 W from a picosecond OPO in a 18 mm LBO pumped by the third harmonic of a cw diode-pumped modelocked Nd:YVO4 oscillator-three amplifier stages system. Here, we represent highest average signal output up to 9.4 W by using a compact nanosecond LBO-OPO system with a single 50-mm-long LBO crystal. Detailed investigations of the performance of our single idler-resonant LBO-OPO include the wavelength tunability, the optimum crystal length, and the dependence of the output power and efficiency on the pump power. The measured performance is compared with the results of a numerical analysis.

Fig. 1 shows diagram of our compact LBO-OPO system. The OPO pump source is a 532 nm green laser with a pulse width of 50 ns and a repetition rate of 10 kHz. The details of the green laser have been described in our previous paper [12]. Briefly, it is generated by frequency doubling of an all-solid-state nanosecond infrared pulse ($\lambda = 1064$ nm) which is delivered by a Q-switched diode-pumped Nd:YAG laser. The maximum average power of the green radiation is $\sim 30$ W with a beam quality of $M^2 = 3.9$. It is collimated by the AR-coated lens L1 and coupled into the confocal OPO cavity through the lens L2 after passing an optical isolator.

The two OPO cavity couplers M3 and M4 are spherical mirrors with a radius of curvature of $r = -75$ mm. The input mirror M3 has partial transmission of 65% for the pump laser with our available mirror set. It is highly reflective for the signal and idler waves. Its reflectivities, centered at 900 and 1300 nm with 200 nm bandwidths, are 99.9% and 99.8% for the signal and idler, respectively. The output mirror M4 is anti-reflective for the signal and highly reflective for the pump and idler waves. For signal, its transmission is 94.5% at 900 nm and $>83\%$ in the range 750–1040 nm. It has reflection coefficients of 99.7% for the pump and 99.8% centered at 1300 nm with a 200 nm bandwidth for the idler. The OPO is single idler-resonant cavity.

The LBO crystal (provided by Fujian Castech Crystals, Inc. China) in the middle of the two couplers is cut for non-critical ($\theta = 90^\circ$, $\phi = 0^\circ$) type-I ($e \rightarrow o + o$) phase matching and is AR coated for the pump and parametric waves. The LBO is mounted in a temperature controlled oven with precision of 0.1 °C. A prism is placed outside the mirror M4 to separate the OPO output beams.

Starting from the coupled amplitude equations for the parametric three-wave interaction, the OPO output energy (power), pulse profile, beam spatial distribution and the dependence of the OPO conversion efficiency on the LBO crystal length are numerically simulated by means of fourth-order Runge–Kutta method [13]. Here, only the dependence of the signal efficiency on the LBO length is presented as shown in Fig. 2. The parameters used in calculation are the same with those in our experiment. As seen from this figure, the efficiency increases at the beginning and then...
decreases with the lengthening of the LBO crystal and it has a maximum value at 65 mm. In our experiment, a 50 mm long LBO crystal is used. Thus, the cavity physical length is 93.8 mm as a confocal cavity for 75 mm radius of curvature mirrors, giving waist of 157 \( \mu \text{m} \) for an optimally mode-matched pump calculated by the standard ABCD method and the embedded fundamental mode \([14]\) for \( M^2 = 3.9 \). The actual pump beam waist is 160 \( \mu \text{m} \) in the LBO crystal. It suggests an excellent mode matching.

The output of the OPO is mainly signal wave with approximately 1\% of pump and idler waves together in our experiment due to the transmissions of output mirror M4. Fig. 3 shows the signal output power at 900 nm and the conversion efficiency versus the pump power. As indicated in Fig. 3 the signal output power and the conversion efficiency increase along with the increasing of the pump power. The signal power as high as 9.4 W is obtained at pump power of 18 W inside LBO crystal. This corresponds to an internal conversion efficiency of 52\% which agrees well with the calculated value at 50 mm in Fig. 2. It can be seen from Fig. 3, the LBO-OPO threshold average power is 5.8 W, corresponding to the threshold peak power density of 29 MW/cm\(^2\).

The formula for pump threshold of single-resonant OPO pumped by long laser pulses is given by \([15]\)

\[
I_{\text{th}} = \frac{2.25}{k g_{s} l^{2} (1 + \gamma)^{2}} \left[ \frac{33L}{2 \tau_{p} c} + 2x l + \ln \frac{1}{\sqrt{R}} + \ln 4 \right]^{2},
\]

(1)

where

\[
k = \frac{8\pi^{2} d_{\text{eff}}^{2}}{\lambda_{s} \lambda_{i} n_{s} n_{i} n_{p} \tau_{p} c}
\]

(2)

and \( g_{s} \) is the signal spatial mode coupling coefficient defined by

\[
g_{s} = \frac{1}{1 + \left(w_{s}/w_{p}\right)^{2}}.
\]

(3)

In (1) \( l \) is the LBO crystal length; \( \gamma \) is the ratio of the backward to forward pump field amplitude inside the crystal (\( \gamma = 0.99 \) in this calculation); \( L \) is the optical length of the OPO cavity; \( \tau_{p} \) is the \( 1/e^{2} \) intensity half width of the pump pulse; \( z = 0 \) is the absorption coefficient of the crystal; and \( R \) is the reflectivity of the output coupler at idler. In (2) \( d_{\text{eff}} = 0.85 \text{ pm/V} \) is the effective nonlinear coefficient; \( n_{s} \), \( n_{i} \), \( n_{p} \) are refractive indices of the nonlinear crystal at signal, idler and pump, respectively, and \( \lambda_{s} = 900 \text{ nm} \), \( \lambda_{i} = 1300 \text{ nm} \) are wavelengths of signal and idler respectively. In (3) \( w_{s} \) and \( w_{p} \) are the Gaussian mode electric field radii of signal and pump respectively. The calculation gives the threshold peak power density of 20.5 MW/cm\(^2\), which is near our measured value of 29 MW/cm\(^2\).

The wavelength of the OPO can be tuned by changing the temperature of the LBO crystal. For NCPM, there is a wide wavelength tuning of the
signal wave. Fig. 4 shows the signal wavelength as the function of the crystal temperature. The squares represent the measured data. For a temperature change from 106 to 149 °C the wavelength of the signal radiation tunes from 778 to 1036 nm, corresponding to an idler tuning range of 1094–1683 nm. The solid line represents the wavelengths calculated from improved Sellmeier equations [4]. The spectral linewidth of the signal wave is measured by spectrometer MS9710B with a resolution of 0.1 nm and it is 4.8–9.6 nm in the range of 778–1036 nm. The narrow linewidth can be achieved with etalon, prism or grating combination [15].

The average signal output power as function of the wavelength for a pump power of 18 W is shown in Fig. 5. The characterization of the power would be attributed to the transmittance bandwidth of the AR-film coated on the OPO output mirror and on the LBO crystal. The signal power has high value more than 8 W in the range of wavelength from 860 to 1020 nm and has a maximum value up to 9.4 W. High average output power OPO is also an efficient tunable pump source. As an application of this OPO, we generated tunable blue radiation by frequency doubling of the OPO signal wave in the new nonlinear crystal BiB₃O₆. At OPO signal power of 6 W with beam quality of $M^2 < 3.2$ in the horizontal plane and $M^2 < 2$ in the vertical plane, Watt level tunable blue pulse in the wavelength range of 450–495 nm is obtained. The details of the frequency doubling in BiB₃O₆ will be published in elsewhere. In principle, Ti:sapphire laser can be tuned in the 680–1100 nm range and can provide radiation in a range from 340 to 550 nm by frequency doubling. However, the output power of mode-locked Ti:sapphire laser is typically 2 W, and the power of the generated visible laser is below 1 W [10].

To summarize, non-critically phase-matched nanosecond OPO using a single 50-mm-long LBO can generate as high as 9.4 W average signal output at 900 nm and its efficiency is 52%. Through changing the temperature of the crystal from 106 to 149 °C, the signal tuning range of 778–1036 nm has been measured. The higher signal output power can be obtained by increasing the pump power and/or length of nonlinear crystal LBO. Actually, up to 13.5 W signal average power is obtained for a pump power of 27 W at present. The detail investigation is being carried out.

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References