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High pulse energy and symmetrical far field from an optical parametric oscillator in the red spectral range

Gunnar Rustad Norwegian Defence Research Establishment (FFI), P.O.Box 25, NO-2027 Kjeller, Norway
gunnar.rustad@ffi.no

Øystein Farsund Norwegian Defence Research Establishment (FFI), P.O.Box 25, NO-2027 Kjeller, Norway

Red pulses with ›30 mJ energy and ‹ 0.6 nm bandwidth have been demonstrated using a type 2 phase matched optical parametric oscillator pumped at 532 nm. A symmetrical signal beam with beam diameter-divergence product of 3 mm·mrad was obtained by applying KTA and BBO crystals in the same resonator [DOI: http://dx.doi.org/10.2971/jeos.2011.11058]

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1 INTRODUCTION

Remote sensing applications often require high energy laser-like beams with narrow bandwidth and low divergence at wavelengths that cannot be reached directly with ordinary laser materials. The common way of generating such wavelengths is through optical parametric oscillators (OPOs), sum- or difference frequency generators, or a combination of these. For the new beam to be generated with high conversion efficiency and good beam quality, careful design of the nonlinear optical conversion stage is necessary, in particular with respect to beam size, nonlinear crystal length, and in the case of an OPO, resonator length and output coupling. For an OPO with narrow beams it is usually possible to obtain a good beam quality with a simple resonator because the small gain region provides enough spatial filtering to suppress higher order modes. The interplay between pump beam size and crystal length also is important both for the conversion efficiency and the beam quality. The pump beam size affects the pump intensity, and if this is reduced, the nonlinear crystal must be longer to have sufficient conversion. On the other hand, if the crystal is too long or the pump intensity is too high, then back-conversion (the reverse of the desired nonlinear process) will reduce both the conversion efficiency and the beam quality. For a plane-wave (or top-hat) pump beam it is fairly straight-forward to find the optimal combination of beam size and crystal length, but as most pump beams have a strong transversal and temporal variation of their intensity, finding the optimal OPO parameters becomes increasingly difficult.

For higher pulse energies, the beams need to be larger to keep the intracavity fluence below the threshold for optical damage. It is difficult to obtain good beam quality from such OPOs because the wide gain region offers little spatial filtering. Previously, we have found [1] that for an OPO with flat mirrors pumped by a pulsed beam, the gain and resonator provide sufficient spatial filtering to obtain good beam quality if the resonator Fresnel number, F, is less than or approximately equal to the number of round-trips in the OPO resonator during the pump pulse, N_{rt},

$$\frac{F}{N_{rt}} = \frac{\omega^2/\lambda L}{\tau_p c/2L} \leq 1 \Rightarrow \omega \leq \sqrt{\frac{\tau_p c \lambda}{2}} \tag{1}$$

where ω is the beam radius, λ is the wavelength of the resonating wave, L is the mirror spacing, τ_p is the pump pulse length and c is the speed of light. For a given pump beam, Eq. (1) can be used to estimate if a good OPO beam quality is possible without additional spatial filtering. In this work, the pump pulse length is ≈5 ns, and the OPO signal wavelength is 665 nm. The maximum pump beam radius for good beam quality is then ≈0.7mm. If the pump fluence is restricted to 1 J/cm^2 to avoid optical damage, we find that good beam quality can be expected from this OPO only if the pump energy is limited to ≈15 mJ.

There are various methods to obtain high beam quality even for higher pump energies. The master-oscillator power-amplifier (MOPA) geometry uses a low energy oscillator to generate good beam quality at the expense of a considerably increased complexity. Unstable resonators can improve the beam quality at the expense of the conversion efficiency [2]. Another approach is to use the natural filtering of the signal far field that is a result of the limited acceptance angle of the nonlinear process in the OPO. This acceptance angle is usefully small only if there is walk-off between the signal and idler beams in the nonlinear crystal, hence type 2 phase matching (PM) is required for collinear phase matching. As the acceptance angle for type 2 PM is highly asymmetric (much larger in the direction of noncritical PM than in the direction of critical PM), the far field of the signal beam from a type 2 phase matched OPO with a large beam diameter is highly asymmetric. Means to work around this include the RISTRA geometry [3] and the use of non-collinear phase

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matching [4]–[6]. In this work we have used another approach in which the far field is improved in both directions (and hence the beam asymmetry is reduced) by using two different nonlinear crystals in the same OPO [7]. Both crystals are type 2 phase matched for the same set of wavelengths, but with orthogonal critical planes the far field narrowing occurs in both directions.

2 Experiment

A major challenge in designing an OPO using the principle of orthogonal critical planes is to find adequate nonlinear crystals, both in terms of nonlinearity and the magnitude and direction of walk-off. Different from most other OPOs, a large walk-off angle is desirable in this design because the acceptance angle is inversely proportional to the walk-off angle. The walk-off direction is either parallel to the slow (signal) or the fast (idler) axis. Crystals in the KTP-family are good choices for the slow-axis walk-off as they both have high nonlinearities and large walk-off angles. In this work we have used a 16 mm long KTA crystal. This length was chosen after simulations of the OPO. There are less good alternatives to choose from for the fast-axis walk-off crystal, but BBO has both a fairly high effective nonlinearity for type 2 phase matching **and** a large walk-off angle. To have a symmetrical signal beam far field, the acceptance angle should be approximately the same in both directions. For the wavelengths in consideration in this work (532 nm pump and 665 nm signal), the acceptance interval for the signal angle in BBO is approximately equal to that of KTA at ≈6 mm · mrad ($L\delta\theta$, crystal length x acceptance angle). Hence we chose a BBO crystal of the same length as the KTA crystal (16 mm) in the experiment. The main draw-back of BBO it that it has significant absorption at the 2660 nm idler wavelength, but we have previously shown that for low pulse rate lasers, this can actually be an advantage for the signal beam quality [1].

The pump laser was a frequency-doubled flash-lamp pumped Nd:YAG laser (Quantel Brilliant B) delivering 5 ns pulses at 10 Hz pulse rate. The pump beam was resized to 4 mm diameter with a telescope, and the pump energy was varied from 0-100 mJ with a half-wave plate and a polarizing beam-splitter. The KTA and BBO crystals both had 8 x 8 mm^2 cross sections. The 40 mm long singly resonant OPO consisted of flat mirrors, the pump was double-passed and the signal output coupling was 42%. The OPO setup is sketched in Fig. 1. For comparison and initial alignment, the OPO was also run with the same mirror spacing, but without the BBO crystal.

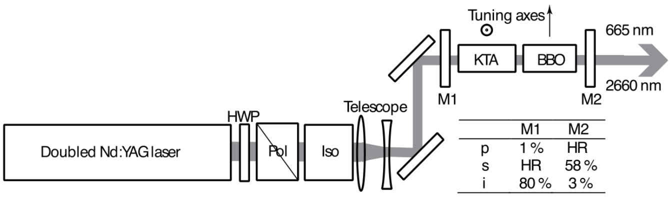

FIG. 1 OPO experimental setup. Pol: Polarizer, Iso: Optical isolator, HWP: Half-wave plate. The directions of the tuning axes are indicated above the KTA and BBO crystals. The table lists the reflectivities of the OPO mirrors at the wavelengths of the pump (p), signal (s) and idler (i)

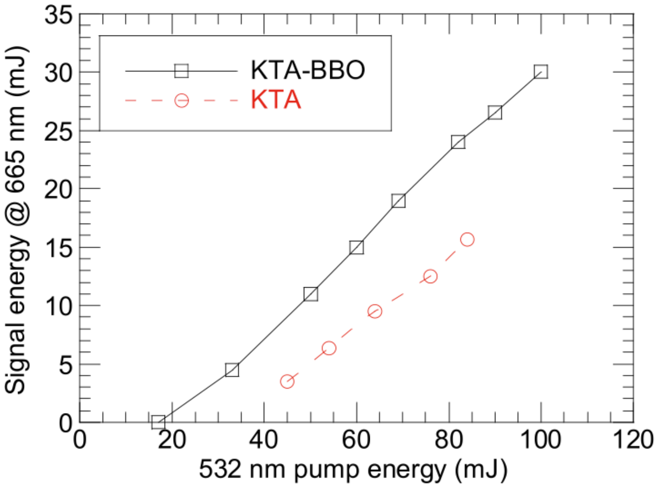

FIG. 2 Signal energy at 665 nm vs. pump energy for the OPO with and without the BBO crystal

3 Results

The signal output energies of the OPO with only the KTA crystal and with both KTA and BBO crystals are shown in Figure 2. Up to 30 mJ was obtained for the KTA-BBO OPO when the OPO was pumped with 100 mJ. It is interesting to note that the BBO crystal clearly contributes to the performance of the OPO although the absorption at the 2660 nm idler is 70 m^{-1}. The width of the signal spectrum was narrow and the measurement was limited by the 0.6 nm spectral resolution of the Thorlabs CCS175 spectrometer.

The near and far fields of the pump and signal beams were measured with a CCD camera, the far field in the focal plane of a 2 m focal length lens. The images are shown in Fig. 3, and Table 1 lists the calculated beam diameter divergence product measured with 85% energy in bucket. The enhancement in beam quality between the KTA OPO and the KTA-BBO OPO is notable. The beam quality is limited by the width of the far field. This width is about 1 mrad for the KTA-BBO OPO, which is in reasonable agreement with the 0.4 mrad signal acceptance angle in 16 mm KTA and BBO. This divergence is a kind of intrinsic property for this OPO. The beam quality will therefore depend strongly on the pump beam diameter; if the pump beam diameter doubles the mm·mrad product and hence the M^2 value can be expected to be doubled, and vice versa for a smaller pump beam. Further improvement in beam quality with this technique could be obtained by using longer crystals.

TABLE 1 Calculated beam diameter divergence products calculated with 85% energy in bucket from the images in Fig. 3

	532 nm Pump	665 nm KTA-BBO OPO	665 nm KTA OPO
mm·mrad	1.1×1.2	3×2.6	3×12

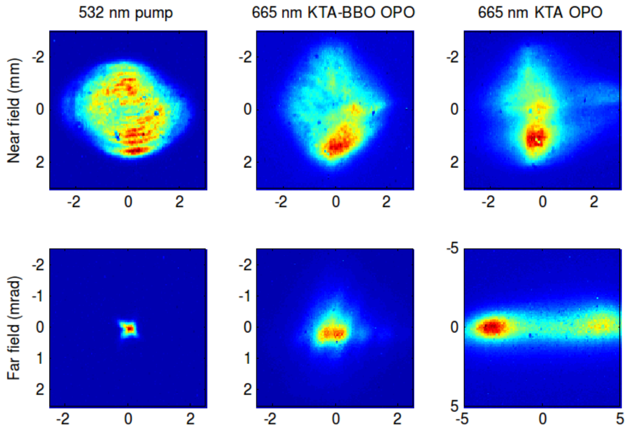

FIG. 3 Measured near (top row) and far (bottom row) fields of the pump (left column) and signal beams from both the KTA-BBO OPO (middle column) and the KTA OPO (right column). Note the different scale in the lower right hand figure.

4 Conclusions

In summary, more than 30 mJ in a symmetrical beam with narrow spectral bandwidth at 665 nm has been obtained from an OPO with two type 2 phase matched crystals with orthogonal critical planes. The beam quality of $\approx$3 mm · mrad compares favorably with commercial products, e.g. [8]. Scaling to higher pulse energies is possible by using larger pump beams, while maintaining the narrow signal beam far field divergence angle.

References

[1] G. Rustad, G. Arisholm, and O. Farsund, “Effect of idler absorption in pulsed optical parametric oscillators” Opt. Express **19**, 2815-2830 (2011).

[2] S. Pearl, Y. Ehrlich, S. Fastig, and S. Rosenwaks, “Nearly Diffraction-Limited Signal Generated by a Lower Beam-Quality Pump in an Optical Parametric Oscillator” Appl. Optics **42**, 1048-1051 (2003).

[3] A. V. Smith and M. S. Bowers, “Image-rotating cavity designs for improved beam quality in nanosecond optical parametric oscillators” J. Opt. Soc. Am. B **18**, 706-713 (2001).

[4] G. Anstett, G. Goritz, D. Kabs, R. Urschel, R. Wallenstein, and A. Borsutzky, “Reduction of the spectral width and beam divergence of a BBO-OPO by using collinear type-II phase matching and back reflection of the pump beam” Appl. Phys. B **72**, 583-589 (2001).

[5] C. D. Nabors and G. Frangineas, “Optical parametric oscillator with bi-noncolinear, porro prism cavity” in *OSA Trends in Optics and Photonics vol 10*, C. R. Pollock and W. R. Bosenberg, eds., 90-93 (Optical Society of America, Washington, DC, 1997).

[6] V. Pasiskevicius, H. Karlsson, F. Laurell, R. Butkus, V. Smilgevicius, and A. Piskarskas, “High-efficiency parametric oscillation and spectral control in the red spectral region with periodically poled $KTiOPO_4$” Opt. Lett. **26**, 710-712 (2001).

[7] O. Farsund, G. Arisholm, and G. Rustad, “Improved beam quality from a high energy optical parametric oscillator using crystals with orthogonal critical planes” Opt. Express **18**, 9229-9235 (2010).

[8] Ekspla, “NT340 series”, www.ekspla.com, 2011.