

Narrowband optical parametric amplifier for efficient conversion of high-energy pulse with high beam quality

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Received March 17, 2014; accepted May 22, 2014; posted online August 25, 2015

In a two-stage optical parametric amplifier based on KTiOAO_4 crystals, we apply beam-overlapping technique to nanosecond signal pulse amplification, which results in high conversion efficiency and good beam quality. A signal pulse energy of 66 mJ at 1.572 μm wavelength is generated with 220 mJ of pump pulse input. A maximum gain of 66 and a maximum pump depletion of as high as 44% are determined. The spectral linewidth of the amplified signal pulse is around 50 MHz, and the beam quality factor of M^2 is less than 2.3.

OCIS codes: 140.3280, 190.4410.
doi: 10.3788/COL201412.091401.

Nanosecond optical parametric oscillator (OPO)/optical parametric amplifier (OPA) is an optimally nonlinear frequency conversion technique for airborne and spaceborne differential absorption lidar applications^[1-4]. In order to achieve high-energy pulse with good beam quality, a multi-stage, large-aperture OPA system is usually employed to amplify the signal pulse from an OPO^[1-7]. For generating wavelength near 1572 nm, potassium titanyl arsenate (KTA) crystal is often chosen as the nonlinear material due to its much lower absorption in the idler spectral range (~ 3300 nm) compared with that of KTP crystal. In 2011, a typical work of nanosecond multi-stage KTA OPAs system was reported by Fix *et al.*^[3], a maximum gain of 18 with maximum pump depletion of 38.5% was achieved, the energy of signal pulse was 3 mJ, and the incident pump pulse was 192 mJ.

In a multi-stage OPAs system, generally, high gain would easily induce undesired back conversion in the nonlinear crystals, so a trade-off between the conversion efficiency and the beam quality is required^[8]. Since the signal gain mainly depends on the pump intensity, the high-intensity parts of the pump pulse will be depleted ahead of the low-intensity parts of pump pulse. Thus, any attempt to obtain high gain within the low-intensity parts of pump pulse will unfortunately result in back conversion in the high-intensity parts of pump pulse. The back conversion process will distort the spatial profile of the signal beam, and even more, it will result in sharp distribution in intensity of all three beams, finally bulk damage of nonlinear crystals will be induced. Therefore, for a high-energy OPAs system, it is important to depress the back conversion, and idler radiation isolated between OPA stages is proven a most effective way^[3,7].

Due to an exponential shape of the gain profile in the OPAs system, the beam diameter and the pulse width of the signal and idler will be reduced during the propagation along the crystals, so that the critical condition of beam-overlapping in spatial and temporal will be deteriorated, and the conversion efficiency will become considerably lower^[9,10]. For achieving good beam quality and high conversion efficiency simultaneously, the deterioration of beam-overlapping should be overcome. It has been proven that temporal variation of the pump pulse and signal beam expanding between the OPA stages are effective methods^[5,7,10]. However, these methods need a relatively complicated optical path^[5].

We propose a compact configuration of 4-KTA OPAs with walk-off compensation. For simplicity, the beam size of the seed signal is expanded to be bigger than that of the pump pulse at the front end of the first KTA crystal, and the signal pulse is adjusted slightly ahead of the pump pulse in time, thus peak-to-peak overlap of pulses is avoided, and pulse narrowing phenomenon could be reduced. Finally, a maximum gain of 66 with total pump depletion of 44% is obtained, the signal beam quality of M^2 is less than 2.3. To the best of our knowledge, it is the highest gain for a nanosecond single-longitudinal mode OPAs architecture based on KTA crystals with considerable high beam quality.

Figure 1 shows the optical arrangement of our KTA OPAs system. A home-built diode-pumped narrowbandwidth Nd:YAG slab laser with capability of output 240 mJ pulse at 1064 nm is used as the pump source of the OPO and OPA. The master oscillator is a diode-pumped injection seeded single-frequency Q-switched Nd:YAG laser^[11]. For obtaining a narrower

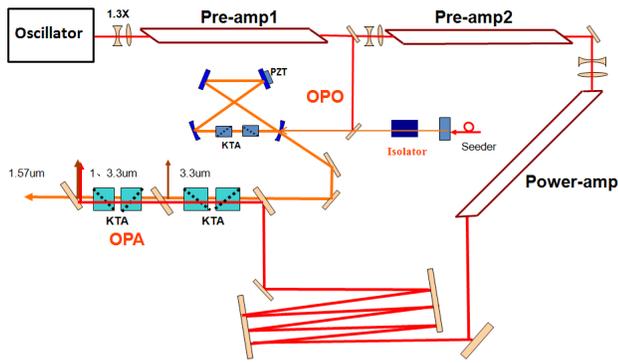


Fig. 1. Schematic of the narrowband KTA OPO/OPAs system.

bandwidth signal pulse from OPO, the pump pulse width is extended to 17 ns. In experiments, about 10 mJ of pump energy with beam quality of M^2 around 1.6 was used to pump the OPO crystal. The OPO setup was designed to be a four-mirror single-pass ring cavity for stable operation^[12], and two identical type II phase-matching KTA crystals cut at $\theta = 74.5^\circ$ and $\varphi = 0^\circ$ were employed for walk-off compensation, as shown in Fig. 1. While pumped by 1.064 μm wavelength beam, a signal radiation at 1.572 μm and idler wave at 3.30 μm could be obtained. The surfaces of the crystals were optically polished and coated for antireflection of the interaction waves. The radius of curvature of the two plano-concave mirrors was same as 1000 mm. The output coupler with transmission $T > 0.99$ for the pump and reflection $R \approx 0.5$ for the signal was chosen for single-pass pumping. The rear mirror of the cavity was mounted onto a piezo actuator (PZT). A distributed feedback laser was used for injection seeder of the OPO, and the modified ramped-hold-fire technique was applied to achieve reliable single-longitudinal mode oscillating^[13]. In order to obtain better spectral property, the seed signal pulse output from OPO was set at the desired 1 mJ level, the pulse width of the seed signal was around 12 ns, and the beam quality factor M^2 was less than 2.0.

Four KTA crystals cut at $\theta = 74.5^\circ$ and $\varphi = 0^\circ$ were oriented in line for walk-off compensation in this OPAs system, a pair of 20-mm-long crystals was used in the first stage and another pair of 15-mm-long crystals was used in the second stage. The optical path of pump pulse to the first OPA stage was 3.3 m longer than that of OPO, which was designed to compensate the built-up time of signal pulse lasing in OPO. In such case, the pump pulse was somewhat delayed in time, and peak-to-peak overlapping between pump pulse and signal pulse could be effectively avoided.

The pump beam and the seed signal beam were independently collimated by telescope systems. A trade-off was made between the beam divergence angle and the beam spot size. In experiments, the pump beam size incident to the OPA was approximately 3.6×4.0 (mm), corresponding to 127 MW/cm² power density. The

seed signal beam size was set to 4.6×5.0 (mm) with 0.5 MW/cm² peak power density. The beam divergence angle of both the pump beam and the signal beam was adjusted to be around 1.0 mrad^[14,15]. Both beam waists of the pump beam and the signal beam were on the front end of the first crystal of the OPAs system. The idler radiation was isolated by a dichroic mirror inserted between the OPA stages to decrease back conversion.

Spatial overlapping between the pump beam and the signal beam in KTA crystals played an important role in optical conversion, so the effective radius of the amplified signal beam coming out from every crystal was measured in detail. A 5-mm signal beam was reduced to near 3.3 mm in diameter after amplified by 70-mm-long KTA crystals, as shown in Fig. 2. The results revealed that seriously shrinking of the signal beam diameter would happen with increasing crystal length. Therefore, experimentally, the initial diameter of the signal beam in the first crystal should be reasonably bigger than that of the pump beam. With both beams co-propagating along the crystal, the shrunk signal beam would well match with pump beam in size, and high optical conversion could be obtained.

We determined the performance of the two-stage KTA OPAs system by measuring the amplification under different crystal lengths. Figure 3 shows the output

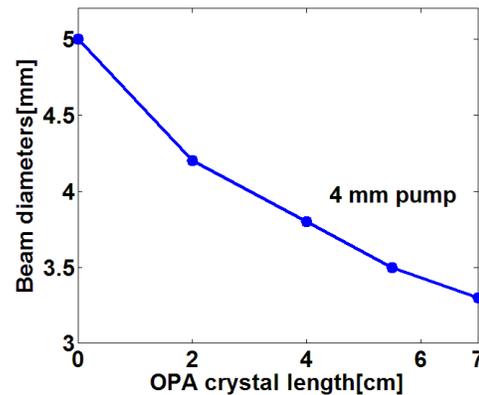


Fig. 2. Evolution of signal beam size versus the length of crystal.

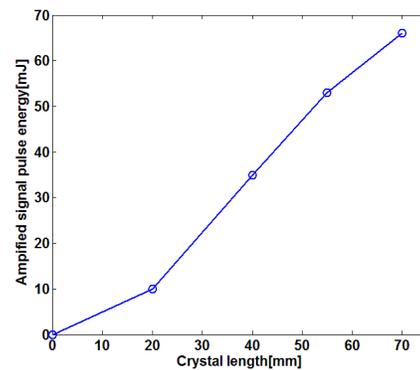


Fig. 3. OPA signal pulse energy increasing with crystal length.

signal energy from the KTA OPAs as a function of the crystal length. The maximum OPAs signal energy of 66 mJ was achieved at a gain length of 70 mm on the conditions of 220 mJ pump energy incident and 1 mJ seed signal pulse input. The total conversion efficiency was up to 44%. The temporal trace of the amplified signal pulse was detected, shown in Fig. 4. The pulse width of the OPAs signal was about 12.4 ns, compared with that of OPO signal pulse, no further narrowing in pulse duration was observed.

The characteristic of the signal beam profile was measured with a lens of $f = 1000$ mm in focal length. The far-field beam spot recorded by a CCD is shown in Fig. 5(a). The beam quality M^2 of the amplified signal pulse from the two-stage KTA OPAs with maximum output energy of 66 mJ was around $M_x^2 = 2.3$ and $M_y^2 = 2.2$, respectively, as shown in Fig. 5(b).

The spectral linewidth of the amplified signal pulse at 1572 nm was derived by a fast Fourier transform (FFT) of the heterodyne beat spectrum of signal^[16].

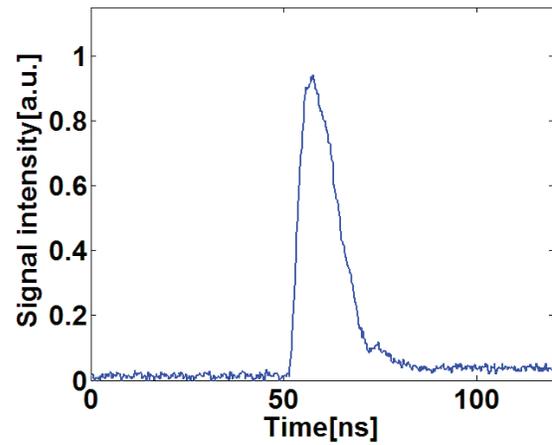


Fig. 4. Temporal profile of the amplified signal pulse.

A typical heterodyne beat spectrum, recorded and digitized by an oscilloscope with 1-GHz analog bandwidth is shown in Fig. 6(a). The spectral intensity profile of

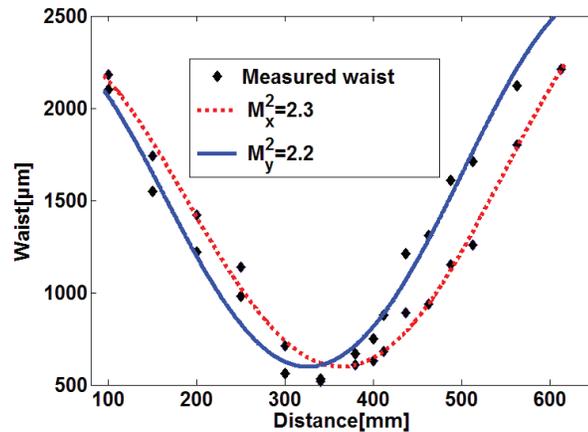
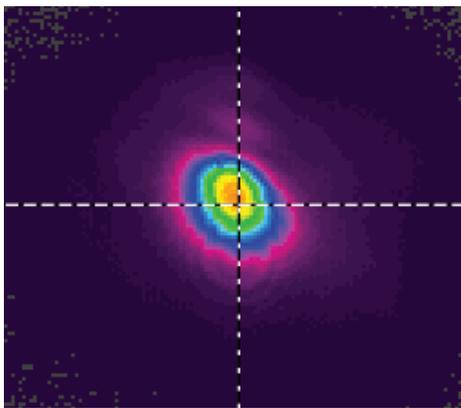


Fig. 5. (a) Far-field image of the amplified signal beam and (b) measurement of signal beam parameter M^2 .

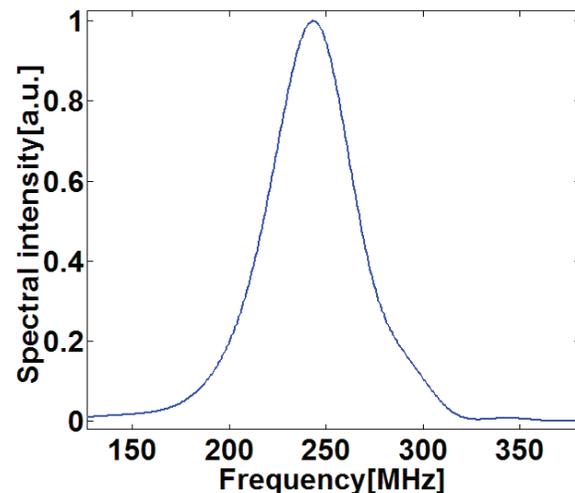
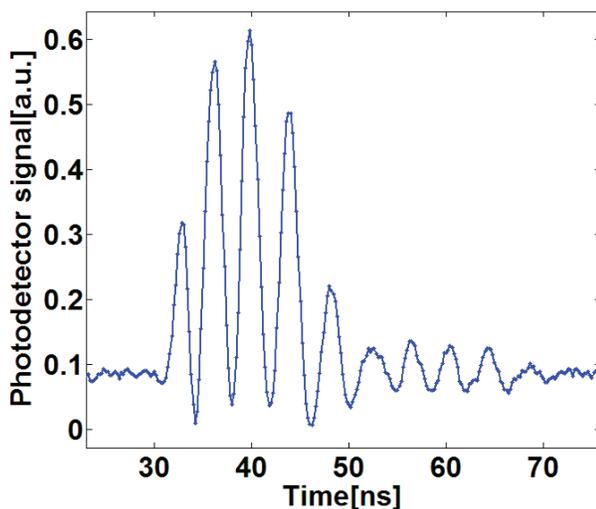


Fig. 6. (a) Heterodyne beat spectrum of signal pulse and (b) power spectrum derived from beat signal.

the OPA signal pulse produced by FFT algorithm using the Hanning window type is depicted in Fig. 6(b). The center frequency was about 245 MHz, and the spectral linewidth (full width at half maximum) was measured to be about 50 MHz, which is close to the Fourier transform limit.

In conclusion, we present a simple structure of two-stage OPA based on KTiOAO_4 crystals. This two-stage KTA OPAs is capable of obtaining high pulse energy with narrow spectral linewidth and good beam quality at the same time. With 220 mJ pump pulse input, we demonstrate the maximum output of the amplified signal pulse up to 66 mJ and the total signal energy extraction efficiency (from pump to signal) obtained is around 30%.

References

1. M. Raybaut, T. Schmid, A. Godard, A. K. Mohamed, M. Lefebvre, F. Marnas, P. Flamant, A. Bohman, P. Geiser, and P. Kaspersen, *Opt. Lett.* **34**, 2069 (2009).
2. A. Amedie, A. Fix, M. Wirth, and G. Ehret, *Appl. Phys. B* **92**, 295 (2008).
3. A. Fix, C. Büdenbender, M. Wirth, M. Quatrevalet, A. Amediek, C. Kiemle, and G. Ehret, *Proc. SPIE* **8182**, 818206 (2011).
4. R. J. Foltynowicz and M. D. Wojcik, *Appl. Remote Sensing* **6**, 053510 (2012).
5. A. Fragemann, V. Pasiskevicius, G. Karlsson, and F. Laurell, *Opt. Express* **11**, 1297 (2003).
6. J. C. McCarthy, R. C. Day, and E. Chicklis, in *Proceedings of Advanced Solid State Lasers* 656, (2001).
7. G. Arisholm, N. Ørnulf, and G. Rustad, *Opt. Express* **12**, 4189 (2004).
8. A. V. Smith and M.S. Bowers, *Opt. Soc. Am. B* **18**, 706 (2001).
9. T. Nishikawa and N. Uesugi *J. Appl. Phys.* **78**, 6361 (1995).
10. G. Arisholm, R. Paschotta, and S. Thomas, *J. Opt. Soc. Am. B* **21**, 578 (2004).
11. J. Wang, R. Zhu, J. Zhou, H. Zang, X. Zhu, and W. Chen, *Chin. Opt. Lett.* **9**, 081405 (2011).
12. B. Yao, X. Liu, X. Yu, X. Duan, Y. Ju, and Y. Wang, *Chin. Opt. Lett.* **11**, 031405 (2013).
13. T. Walther, M. P. Larsen, and E. S. Fry, *Appl. Opt.* **40**, 3046 (2001).
14. I. Jovanovic, B. J. Comaskey, and D. M. Pennington, *J. Appl. Phys.* **90**, 4328(2001).
15. H. Li, S. Li, X. Ma, X. Zhu, X. Tu, and Y. Zheng, *Laser Phys. Lett.* **10**, 055403 (2013).
16. T. Schröder, C. Lemmerz, O. Reitebuch, M. Wirth, C. Wührer, and R. Treichel, *Appl. Phys. B* **87**, 437 (2007).