Optics & Laser Technology 92 (2017) 1–4

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

CdSe optical parametric oscillator operating at 12.07 μm with 170 mW output

Jinhe Yuan, Yi Chen, Xiaoming Duan, Baoquan Yao*, Tongyu Dai, Youlun Ju

National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Keywords:
Parametric oscillators and amplifiers
Nonlinear optical crystals
Far infrared

ABSTRACT

A CdSe optical parametric oscillator (OPO) was demonstrated to operate at 12.07 μm with a maximum output power of 170 mW at a pulse repetition frequency of 1.2 kHz pumped at 2.09 μm with 14.64 W from an acousto-optic Q-switched Ho:YAG laser. To the best of our knowledge, 12.07 μm is the longest wavelength obtained with a 2-μm laser-pumped CdSe OPO. Besides, the angular tuning curve for type II CdSe was also investigated, and the idler wavelength from the OPO could be tuned from 10.24 to 12.07 μm.

1. Introduction

Long wave laser sources in the 8–12 μm atmospheric transmission window are of great importance in a range of applications including remote sensing, infrared (IR) countermeasures, spectroscopy, and chemical monitoring [1,2]. However, only a few gain media have the potential to directly obtain the laser radiation in this region. Stimulated emission in CO_2 is a frequently used approach to get the spectrum in 9–11 μm, but this method cannot cover the 8–9 μm and 11–12 μm bands. And the large volume of such a gas laser also greatly limits its applications [3]. Quantum cascade lasers are an alternative, but the limited brightness and power scalability may limit their use in some applications [4,5]. By contrast, frequency down-conversion technology based on nonlinear optical (NLO) crystals offers an effective solution and could avoid those disadvantages simultaneously. Among the parametric down-conversion technologies, an optical parametric oscillator (OPO) is an attractive approach especially for the purpose of generating high power and high energy output [6,7]. In particular, pumping middle infrared OPOs with 2-μm laser sources (Tm-doped, Ho-doped and Tm,Ho co-doped) would have more advantages due to the available sources with high average output power/or output energy [8] and relatively higher conversion efficiency which is proportional to the ratio λ_3/λ_1 where λ_1 is the idler wavelength and λ_3 is the pump wavelength. Hitherto, quite a few high quality NLO crystals, such as $AgGaSe_2$ (AGSe), $ZnGeP_2$ (ZGP), GaAs, and CdSe have been reported to access the long wave coherent light with 2-μm laser-pumped OPOs. And the longest wavelength of 12.6 μm was demonstrated with a type-II AGSe crystal, which was pumped at 2.088 μm by a LD-pumped Tm:YLF/Q-switched Ho:YAG laser system operating at a pulse repetition frequency (PRF) of 100 Hz. The idler energy reached 360 μJ (36 mW) at 8.18 μm but dropped to 50 μJ (5 mW) at 12.21 μm [7,9]. On the other hand, ZGP based OPOs could produce high output power/energy, especially in the 3–5 μm region due to its' excellent nonlinear conversion properties [8]. However, the transmittance of ZGP decreases significantly when the wavelength reaches ~10 μm. The longest idler wavelength obtained with 2-μm laser-pumped ZGP OPO was 9.8 μm, but the average output power was limited to be ~0.2 W [5]. In addition, an quasi-phase matched orientation-patterned gallium arsenide (OPGaAs) based OPO directly pumped by a Q-switched 2.054 μm Tm,Ho:YLF laser was demonstrated in 2013 [10]. The idler wavelength of this OPO can be tuned from 8.8 to 11.5 μm. Nevertheless, the output energy obtained at 11.5 μm was only ~8 μJ, corresponding to an output power of ~4 mW. To sum up, the output power of the idler beam of current 2-μm laser-pumped OPOs remains to be improved, especially for the 10–12 μm wavelength region.

Compared with the above mentioned materials, CdSe owns a wide transparency range from 2 to 24 μm. Also, it has a reasonably large nonlinearity (d_{31}=18 pm/V), and making long CdSe crystals with high optical quality is possible [11,12]. However, there have been few studies on the employment of CdSe to obtain long wave radiation. In 1997, a CdSe OPO pumped by a 2.79 μm Cr,Er:YSGG laser was reported [13]. Average output power of 12–24 mW between 8.5 and 12.3 μm was obtained. In 2003, a CdSe OPO in the 9–10 μm region was reported, and the pump source was a PPLN OPO [12]. An idler power of 70 mW generated internal to the CdSe was inferred with the Manley-Rowe relation under the pump power of 800 mW. In 2004, CdSe difference-frequency generation pumped by a KTP OPO was demonstrated [14]. The output wavelength was tuned from 10 to 21 μm.

* Corresponding author.
E-mail address: yaobq08@hit.edu.cn (B. Yao).

http://dx.doi.org/10.1016/j.optlastec.2016.12.037
Received 21 June 2016; Received in revised form 28 December 2016; Accepted 30 December 2016
Available online 07 January 2017

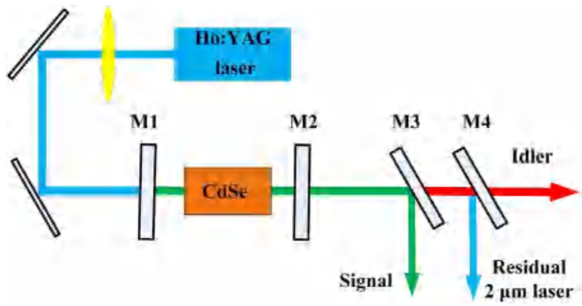

Fig. 1. Schematic diagram of the experiment setup.

However, the maximum output power was only 7 mW. Another CdSe difference-frequency generation experiment was reported in the same year, and the wavelength can be tuned from 9 to 24.1 μm with pulse energies between 21 μJ at 11 μm and 0.3 μJ at 24.1 μm [15]. In 2012, a CdSe OPO operating at 8.9 μm pumped by a 2.05 μm Tm,Ho:$GdVO_4$ laser was demonstrated [16]. The maximum output power of 64 mW was obtained at 7.6 W incident pump power, corresponding to an optical-to-optical efficiency of 0.84%.

In this paper, a CdSe OPO pumped by a 2.09 μm acousto-optic Q-switched Ho:YAG laser is presented. To the best of our knowledge, we obtained a record idler output power of 170 mW at 12.07 μm for a CdSe OPO. The tuning range of the idler was from 10.24 to 12.07 μm.

2. Experimental setup

Fig. 1 shows the schematic diagram of the experiment setup. The pump source was a homemade 2.09 μm acousto-optic Q-switched Ho:YAG laser which was dual-end-pumped by two orthogonally polarized and continuous wave Tm:YLF lasers at 1.908 μm. The maximum average output power of the Ho:YAG laser could reach 33 W. After passing a lens transformation system, the pump beam from the Ho:YAG laser was shaped to 0.55 mm ($1/e^2$ radius) on the CdSe crystal. The CdSe we used was cut at θ=71°, φ=0° and its dimensions were 10×12×40 mm^3. The cut angle enables the CdSe crystal to meet the requirement for type II phase matching (o→e+o). Both surfaces of the CdSe were antireflection (AR) coated for pump (R < 1%), signal (R < 0.5%), and idler (R < 0.5%) wavelengths. The surface damage threshold of this CdSe was also studied. Under the abovementioned experimental condition, the measured surface damage threshold was ~3.33 J/cm^2 of incident on-axis fluence. The CdSe crystal was maintained at room temperature with the aid of cooling water. The CdSe OPO was designed to resonate the signal wavelength, and the physical length of the cavity was 50 mm. Input mirror M1 was highly reflectively (HR) coated in the range of 2.5–2.8 μm and AR coated at 10–12 μm and 2 μm. Output coupler M2 had a transmission of 20% in the range of 2.5–2.8 μm, and it was also AR coated at 10–12 μm and 2 μm. In order to reduce the feedback to the pump laser, the optical axis of the OPO was slightly tilted compared with the pump beam direction. M3 (HR@ signal) and M4 (AR@ idler and HR@ pump) were beam splitter mirrors, with which we could separate idler from signal as well as residual pump.

3. Results and discussion

The output characteristics of the 1 kHz Ho:YAG laser are shown in Fig. 2. From Fig. 2, we could see that average output power increased linearly with the increase in pump power, and the maximum output power obtained was 33 W (33 mJ per pulse). In contrast, the pulse width decreased as the pump power increased, and a minimum pulse width of 31 ns was achieved under the maximum pump power. The M^2 factor of the Ho:YAG laser was less than 1.2 for both vertical and horizontal directions. With a 50-μm-thick uncoated YAG etalon utilized as a Brewster plate, we achieved *s*-polarized output laser.

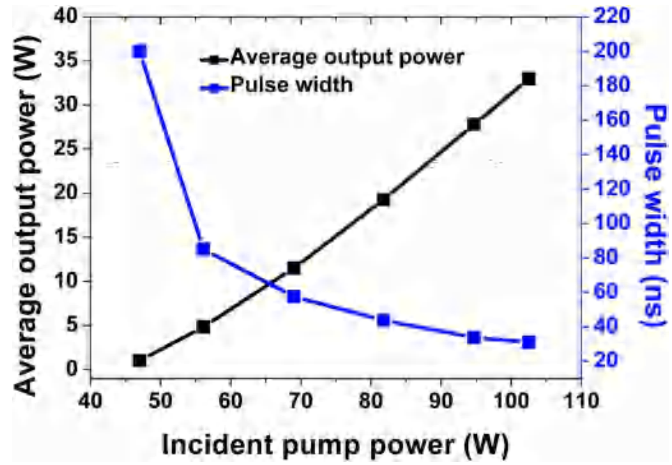

Fig. 2. Output characteristics of the Ho:YAG laser (PRF,1 kHz).

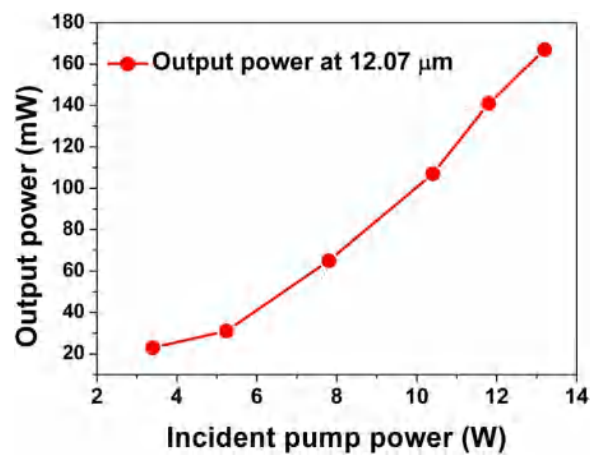

Fig. 3. Output power of the idler at 12.07 μm.

Fig. 3 shows the output power of the 12.07 μm idler from the CdSe OPO, which was obtained at the phase-matched angle of 67.4°. The threshold of the CdSe OPO was about 3.4 W, corresponding to a pulse energy of 3.4 mJ and a pump intensity of 0.36 J/cm^2. With the increase in pump power, the output power increased monotonically. We obtained an output power of 167 mW (~167 μJ pulse energy) with a pump power of 13.2 W (13.2 mJ pulse energy). At the same time, a pump pulse with pulse width of 53 ns generated an idler pulse with pulse width of 40 ns. It should be noted that the output power was limited by the surface damage threshold of the CdSe. Under the pump power of 13.2 W, the incident pump influence was calculated to be 2.9 J/cm^2, which approached the surface damage threshold of CdSe (3.33 J/cm^2).

Under the same pump energy of 12.2 mJ, the average output power at 12.07 μm was investigated at different PRFs (shown in Fig. 4). It is noted from Fig. 4 that the output power monotonically increased with the increase in PRF. The maximum output power of 170 mW (~141 μJ pulse energy) was obtained at a PRF of 1.2 kHz, under a pump power of 14.64 W. Meanwhile, a minimum output power of 42 mW (~105 μJ pulse energy) was obtained at 400 Hz under a pump power of 4.88 W. We can expect that higher output power could be possible if we use a pump source with higher pump power and higher PRF.

The idler spectrum was measured with a WDG30-Z grating monochromator and a liquid nitrogen refrigeration MCT-16-2.00 detector (InfraRed ASSOCIATES, Inc). As shown in Fig. 5, the central wavelength was 12.07 μm. With a 2.09 μm laser as the pump source, we further investigated the tuning characteristics of the CdSe crystal. Fig. 6

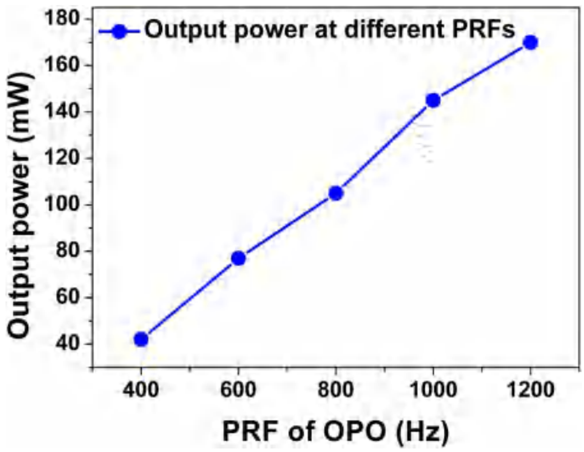

Fig. 4. Output power at different PRFs under the same pump energy of 12.2 mJ.

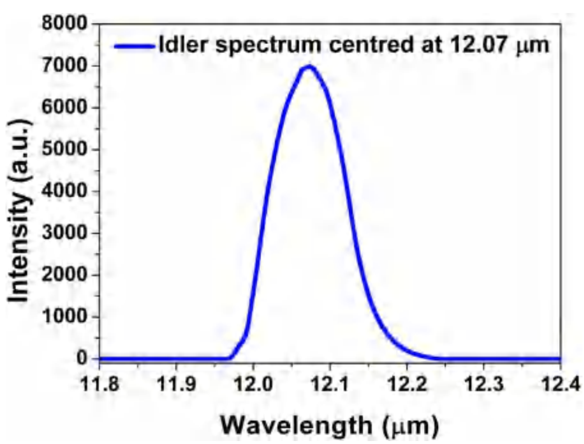

Fig. 5. The measured idler spectrum at 12.07 μm.

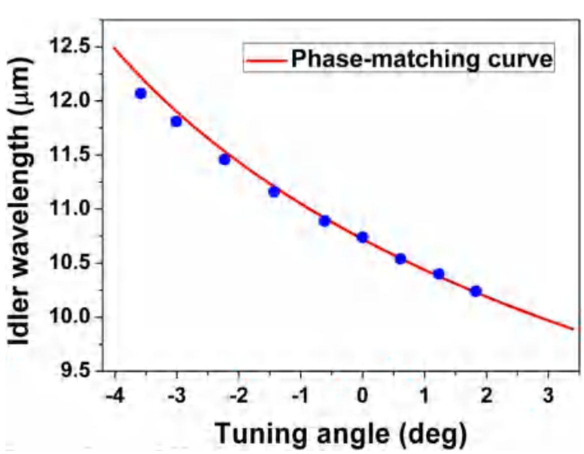

Fig. 6. Idler wavelength versus tuning angle of CdSe crystal (internal phase-matching angle).

shows the phase-matching curve, where the solid line is the theoretical curve of the rotation angle with respect to the normal front surface calculated based on the Sellmeier equations (S-E) in Ref. [17]. The solid points represent the experimental data obtained under a pump power of 9.1 W (9.1 mJ pulse energy). As the tuning angle changed from 1.83° to −3.58°, the idler wavelength varied from 10.24 to 12.07 μm. The smaller the incident angle is, the longer the idler wavelength is. It also can be seen from Fig. 6 that the measured data matched the theoretical calculated values well.

Fig. 7 shows the relationship between the output power and the

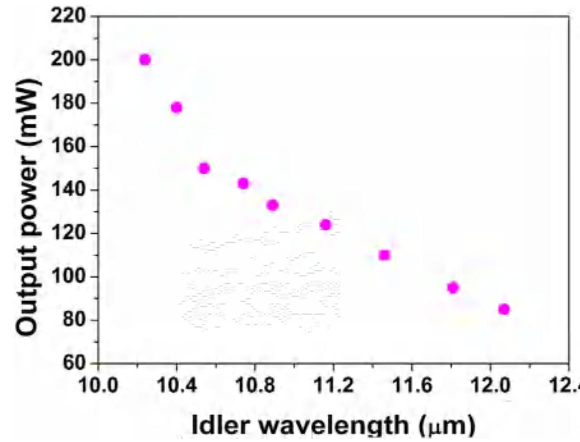

Fig. 7. Output power versus idler wavelength with 9.1 W pump power.

idler wavelength for the CdSe OPO. For all the measurements, we kept the pump power at 9.1 W, and the PRF at 1 kHz. The output power decreased as idler wavelength increased. Finally, we obtained an output power of 200 mW at 10.24 μm and an output power of 85 mW at 12.07 μm with a pump power of 9.1 W (9.1 mJ pulse energy).

4. Conclusion

In conclusion, we choose a CdSe crystal to generate the long-wave light in an OPO owing to the properties of its wide transparency range and reasonably large nonlinearity. As a result, a record idler output power of 170 mW was achieved at 12.07 μm with a 2.09 μm laser as the pump source. Meanwhile, 12.07 μm is the longest wavelength obtained with a 2-μm laser-pumped CdSe OPO. Under the pump power of 9.1 W (9.1 mJ pulse energy), the tuning range of the CdSe OPO was 10.24–12.07 μm. In addition, at the same pump energy, the output power monotonically increased with the pulse repetition frequency. Our results indicate that CdSe is a promising NLO crystal for generating high-power long-wave light in an OPO regime.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Nos. 61308009, 61405047, 50990301), China Postdoctoral Science Foundation funded project (No. 2015T80339), Fundamental Research funds for the Central Universities (Grant No. HIT. NSRIF. 2014044, Grant No. HIT. NSRIF. 2015042), and Science Fund for Outstanding Youths of Heilongjiang Province (JQ201310).

References

[1] S. Das, Broadly tunable multi-output coherent source based on optical parametric oscillator, Opt. Laser Technol. 71 (2015) 63–67.
[2] Z.G. Figen, O. Aytür, O. Arikan, Idler-efficiency-enhanced long-wave infrared beam generation using aperiodic orientation-patterned GaAs gratings, Appl. Opt. 55 (2016) 2404–2412.
[3] F. Yang, J.Y. Yao, H.Y. Xu, F.F. Zhang, N.X. Zhai, Z.H. Lin, N. Zong, Q.J. Peng, J.Y. Zhang, D.F. Cui, Y.C. Wu, C.T. Chen, Z.Y. Xu, Midinfrared optical parametric amplifier with 6.4-11.1 μm range based on $BaGa_4Se_7$ crystal, IEEE Photonics Technol. Lett. 27 (2015) 1100–1103.
[4] M. Troccoli, A. Lyakh, J. Fan, X. Wang, R. Maulini, A.G. Tsekoun, R. Go, C. Kumar, N. Patel, Long-wave IR quantum cascade lasers for emission in the λ=8-12 μm spectral region, Opt. Mater. Express 3 (2013) 1546–1560.
[5] E. Lippert, G. Rustad, G. Arisholm, K. Stenersen, High power and efficient long wave IR $ZnGeP_2$ parametric oscillator, Opt. Express 16 (2008) 13878–13884.
[6] A. Hildenbrand, C. Kieleck, A. Tyazhev, G. Marchev, G. Stöppler, M. Eichhorn, P.G. Schunemann, V.L. Panyutin, V. Petrov, Laser damage of the nonlinear crystals $CdSiP_2$ and $ZnGeP_2$ studied with nanosecond pulses at 1064 and 2090 nm, Opt. Eng. 53 (2014) 122511.
[7] V. Petrov, Frequency down-conversion of solid-state laser sources to the mid-infrared spectral range using non-oxide nonlinear crystals, Prog. Quantum Electron. 42 (2015) 1–106.
[8] B.Q. Yao, Y.J. Shen, X.M. Duan, T.Y. Dai, Y.L. Ju, Y.Z. Wang, A 41-W $ZnGeP_2$

optical parametric oscillator pumped by a Q-switched Ho:YAG laser, Opt. Lett. 39 (2014) 6589–6592.
[9] S. Chandra, M. Wager, B. Clayton, A. Geiser, T.H. Allik, J.L. Ahl, C. Miller, P. Budni, P. Ketteridge, K. Lanier, E. Chicklis, J.A. Hutchinson, W.W. Hovis, 2-micron pumped 8-12 μm OPO source for remote chemical sensing, Proc. SPIE 4036 (2000) 200–208.
[10] R.K. Feaver, R.D. Peterson, P.E. Powers, Longwave-IR optical parametric oscillator in orientation-patterned GaAs pumped by a 2 μm Tm,Ho:YLF laser, Opt. Express 21 (2013) 16104–16110.
[11] T. Zeng, B. Zhao, S. Zhu, Z. He, B. Chen, Z. Tan, Optimizing the growth procedures for CdSe crystal by thermal analysis techniques, J. Cryst. Growth 316 (2011) 15–19.
[12] M.A. Watson, M.V. O'Connor, D.P. Shepherd, D.C. Hanna, Synchronously pumped CdSe optical parametric oscillator in the 9–10 μm region, Opt. Lett. 28 (2003) 1957–1959.
[13] T.H. Allik, S. Chandra, D.M. Rines, P.G. Schunemann, J.A. Hutchinson, R. Utano, Tunable 7–12-μm optical parametric oscillator using a Cr,Er:YSGG laser to pump CdSe and $ZnGeP_2$ crystals, Opt. Lett. 22 (1997) 597–599.
[14] A.A. Mani, Z.D. Schultz, A.A. Gewirth, J.O. White, Y. Caudano, C. Humbert, L. Dreesen, P.A. Thiry, A. Peremans, Picosecond laser for performance of efficient nonlinear spectroscopy from 10 to 21 μm, Opt. Lett. 29 (2004) 274–276.
[15] K. Finsterbusch, A. Bayer, H. Zacharias, Tunable, narrow-band picosecond radiation in the mid-infrared by difference frequency mixing in GaSe and CdSe, Appl. Phys. B. 79 (2004) 457–462.
[16] B.Q. Yao, G. Li, G.L. Zhu, P.B. Meng, Y.L. Ju, Y.Z. Wang, Comparative investigation of long-wave infrared generation based on $ZnGeP_2$ and CdSe optical parametric oscillators, Chin. Phys. B 21 (2012) 034213.
[17] G.C. Bhar, Effective quantum efficiency of photodetectors for photon energies much larger than threshold, Appl. Opt. 15 (1976) 305–307.