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2015 Laser Phys. 25 035403

(http://iopscience.iop.org/1555-6611/25/3/035403)

IOP Publishing | Astro Ltd Laser Physics

Laser Phys. **25** (2015) 035403 (5pp) doi:10.1088/1054-660X/25/3/035403

Efficient high-peak-power and high-repetition-rate eye-safe laser using an intracavity KTP OPO

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Received 4 December 2014, revised 12 January 2015
Accepted for publication 19 January 2015
Published 12 February 2015

Abstract

An efficient high-peak-power and high-repetition-rate intracavity KTP optical parametric oscillator pumped by a Q-switched Nd:YVO_4 laser is demonstrated. We achieved 1.5 W output power of 1.5 μm at 10 kHz repetition rate with the pulse duration of 6 ns. The maximum peak power of 25 kW and the maximum pulse energy of 150 μJ have been obtained. The maximum conversion efficiency of 9.5% is achieved with respect to a laser diode power of 10.5 W.

Keywords: efficient, intracavity OPO, high-peak-power, high-repetition-rate

(Some figures may appear in colour only in the online journal)

1. Introduction

High-peak-power and high-repetition-rate 1.5 μm laser sources attract great interest in eye-safe applications such as laser radar and ranging, pollution detection, remote sensing and optical communications. They can be obtained by Er lasers and Raman shifted lasers [1, 2]. Moreover, to achieve high stability, the optical parametric oscillator (OPO) based on $KTiOPO_4$ (KTP) crystal is developed as an alternative way to obtain such wavelengths [3, 4]. The conventional intracavity OPOs with flash lamps or quasi-continuous diodes used as the pump sources restrict operations to low repetition rates (less than 1 kHz) [5, 6]. In high-repetition-rate operation of Nd lasers, the requirement for continuous wave (CW) laser diode (LD) pumping results in relatively low energy per pulse. This may lead to the high threshold of external KTP OPO since the KTP crystal has a low effective nonlinear coefficient [7, 8]. An approach to overcome this problem is to use a crystal with high nonlinear coefficient, such as periodically poled $LiNbO_3$ (PPLN) and periodically poled KTP (PPKTP) [9, 10], or to place the OPO cavity inside the laser cavity, which can take advantage of the intense fluence inside the laser cavity and increase the effective nonlinear interaction length due to the multiple passes of the pump beam through the OPO [11].

Intracavity KTP OPOs for eye-safe wavelength have been reported by several research groups [12–17]. Chen *et al* achieved average power of 1.33 W at 1573 nm with a peak power of 2 kW from an intracavity KTP OPO pumped by a Q-switched Nd:YVO_4 laser at 80 kHz repetition rate [12]. In a later experiment with an optimized cavity length and higher LD pump power, they improved the peak power to higher than 5 kW at 60 kHz repetition rate [13]. Zendzian *et al* obtained more than 8 kW-peak-power pulses at 40 kHz repetition rate from an intracavity KTP OPO [14]. An intracavity KTP OPO pumped by a Q-switched Nd:YAG laser has been reported by Wang *et al* [15], they achieved average power of 1.15 W at 1.57 μm at 4.3 kHz repetition rate with 8 ns duration and the peak power of the pulses up to 33.4 kW. Liu *et al* reported an intracavity KTP OPO pumped by an end-pumped acousto-optically Q-switched Nd:$LuVO_4$ laser [16]. They achieved peak power of 4.8 kW at 1.57 μm at 5 kHz. Huang *et al* demonstrated an intracavity Nd:YLF/KTP OPO [17], under an incident pump power of 12.7 W and a pulse repetition rate of 5 kHz, the pulse energy and peak power of 1.55 μm output are 306 μJ and 4 kW, respectively.

In this paper, we demonstrate a compact intracavity OPO based on a type II phased matched KTP crystal with an end-pumped acousto-optically Q-switched Nd:YVO_4 laser. We

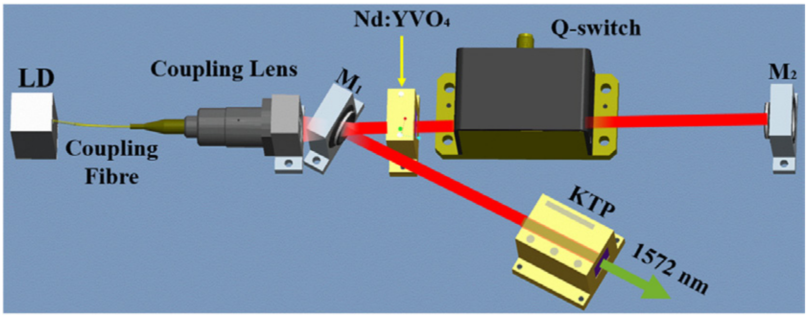

Figure 1. Experimental setup of intracavity KTP OPO.

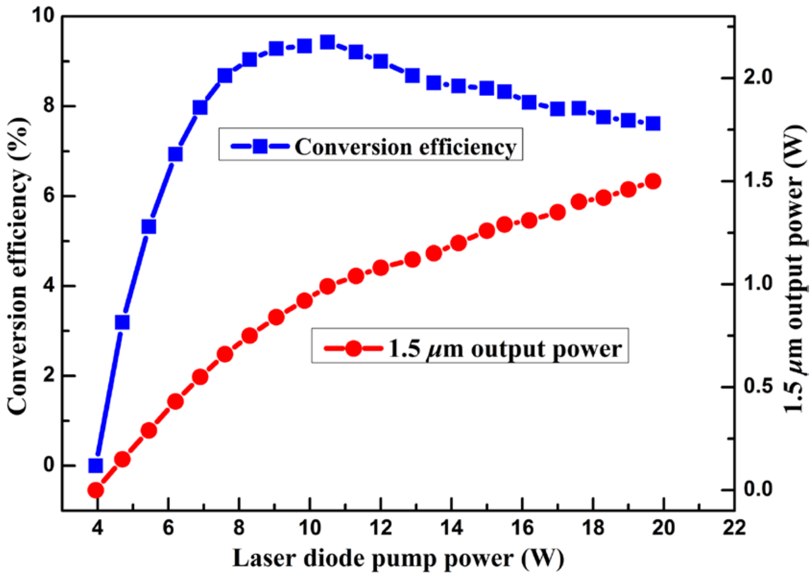

Figure 2. 1.5 μm average output power and conversion efficiency as a function of LD power.

have achieved average output power of 1.5 W at 1.5 μm with a pulse width of 6 ns at 10 kHz repetition rate. A maximum peak power of 25 kW and maximum pulse energy of 150 μJ have been obtained. The maximum conversion efficiency is 9.5% with respect to LD pump power. The M^2 values of the OPO output at the maximum power are 1.68 and 1.78 in the horizontal and vertical directions, respectively.

2. Experimental setup

The experimental setup of the intracavity KTP OPO is depicted in figure 1. A 20 W fiber-coupled laser diode array at 808 nm was used as the pump source, the output fiber pigtail has a core diameter of 400 μm and a numerical aperture of 0.22. The output beam from the optical fiber is imaged with 1:1 magnification into a 0.3 at.% doped a-cut Nd:YVO_4 crystal by a pair of aspherical plane-convex lenses with coupling losses of about 2%. The 10 mm long Nd:YVO_4 crystal with a 4 × 4 mm aperture is wrapped with indium foil and mounted in a copper holder whose temperature is stabilized at 25 °C by a thermoelectric unit. Both ends of the crystal are flat and antireflection-coated at 1064 and 808 nm with the reflectivity at 1064 nm less than 0.1%.

The fundamental cavity is formed by two flat mirrors M_1, M_2 and the coated KTP crystal. The pump-induced thermal lens in the Nd:YVO_4 crystal brings the flat–flat resonator into geometric stability. The cavity length is 280 mm. Mirror M_1 is highly reflective (>99%) at 1064 nm and highly transmissive (>98%) at 808 nm for light at the incidence angle of 15 degree. Mirror M_2 is highly reflective (>99.5%) at 1064 nm. One of the KTP crystal surfaces is coated with high reflectivity at 1064 nm (>99.5%) and 50% reflectivity at 1.5 μm and used as the fundamental cavity rear mirror and output coupler of the OPO cavity. Another surface is antireflection-coated at 1064 nm (>99%) and is coated with high reflectivity at the signal wavelength of 1.5 μm (>99.5%). The OPO cavity is formed by a coated KTP crystal only and its cavity length of 30 mm is equal to the KTP crystal length. The KTP crystal is cut for type II non-critical phase-matching (θ = 90°and ϕ = 0°), in order to have a maximum effective nonlinear coefficient and to eliminate the walk-off effect between the pump, signal and idler beams. The crystal is mounted in a copper holder and the temperature is stabilized at 25 °C by a thermoelectric unit. Because of the high absorption of the idler wave in the KTP crystal and the low reflectivity of the OPO cavity at the idler wavelength, the OPO is resonant on the signal frequency only.

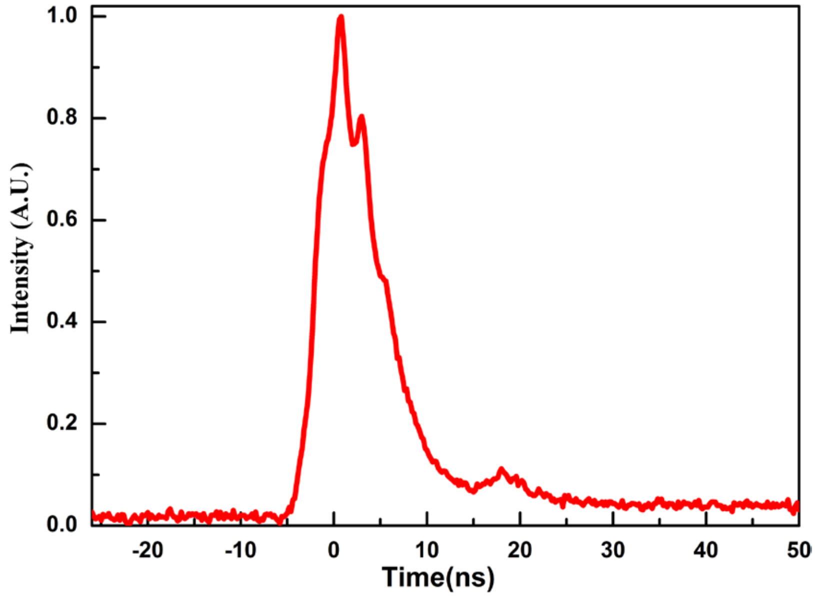

Figure 3. Pulse shape of 1.5 μm at maximum power.

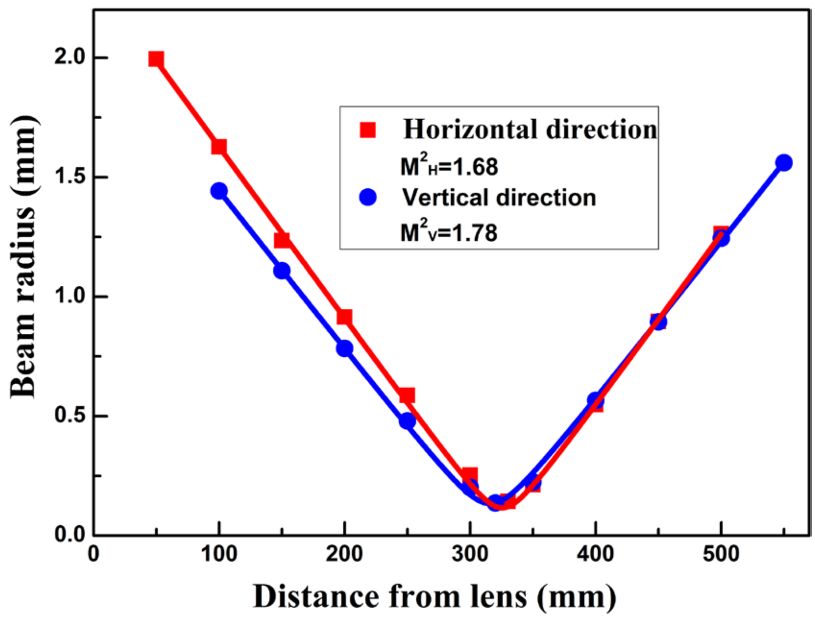

Figure 4. M^2 measurements of the maximum 1.5 μm output by using an f = 250 mm focusing lens.

A 32 mm long acousto-optic Q-switch is used for intracavity Q-switching operation.

3. Results and discussions

Without the intracavity OPO, the Nd:YVO$_4$ laser can produce 6 W output power at 1064 nm at 10 kHz repetition rate with a 20% output coupler. The 1064 nm laser is in stable operation with its M^2 values less than 1.5 in both the horizontal and vertical directions. The pulse duration of 1064 nm laser output is measured to be 20 ns with a Si transimpedance amplified detector (Thorlabs, PDA10A) and a digital phosphor oscilloscope (Tektronix, TDS 3032). With the KTP OPO placed in the laser cavity, a maximum output power of 1.5 W at 1.5 μm is achieved at 10 kHz. The maximum pulse energy is 150 μJ. Figure 2 depicts the average output power of 1.5 μm and the conversion efficiency as a function of the LD pump power. The maximum conversion efficiency of 9.5% is obtained at the LD power of 10.5 W. With the LD power increasing from 10.5 to 20 W, the conversion efficiency drops to 7.5%. This conversion efficiency reduction is mainly attributed to the increased thermal effect of the Nd:YVO$_4$ crystal. With an increased LD power, the increased thermal effect of the Nd:YVO$_4$ crystal will lead to the changing of distribution of the pump beam in KTP crystal, which results in poor mode matching and reduced conversion efficiency.

The 1.5 μm pulse duration is measured with an InGaAs detector (Thorlabs, DET08CFC). Figure 3 shows the pulse

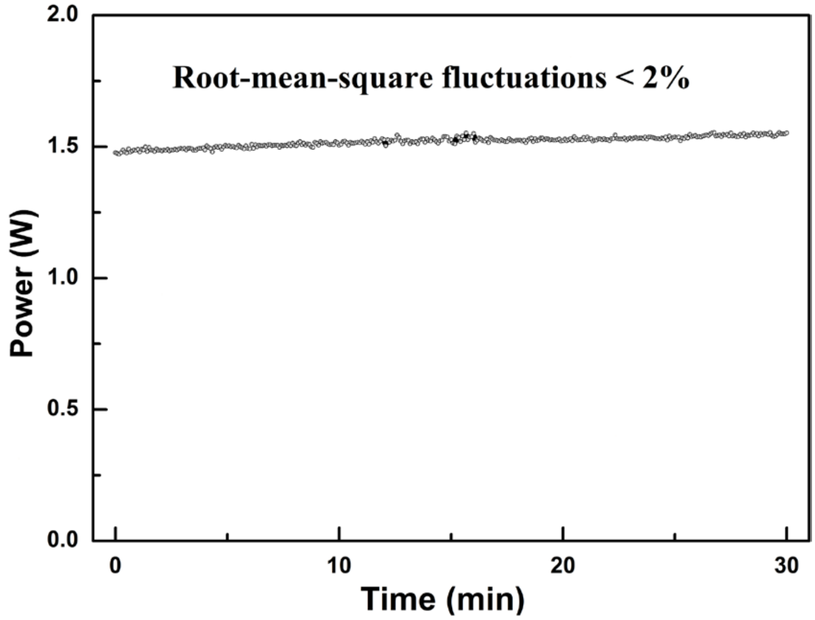

Figure 5. Stability of the maximum 1.5 μm output power as a function of time.

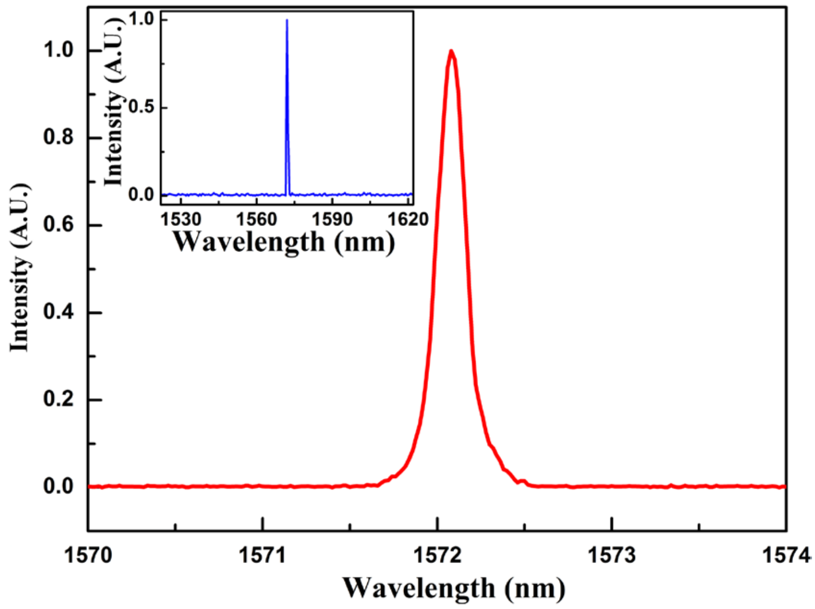

Figure 6. Output spectrum of 1.5 μm output. Inset graph shows the large scale scanning spectrum.

shape of 1.5 μm at the maximum power. The pulse duration of 1.5 μm is 6 ns, which is much shorter than that of 1064 nm. Such a short pulse duration is a result of the effective cavity dump of the intracavity OPO. A small additional pulse is observed after the main pulse because the stored energy once again reaches the threshold of the OPO. As a result of the relatively short pulse, the peak power at 1.5 μm is 25 kW at the repetition rate of 10 kHz.

The measured M^2 values of 1.5 μm output are shown in figure 4. The parameter M^2 of the horizontal and vertical directions are 1.68 and 1.78, respectively. Such a good beam quality at 1.5 μm is a result of the approximately TEM_{00} Gaussian profile of the 1064 nm beam and the good mode matching between 1064 nm and 1.5 μm. In our experiments, the single resonance resulted in a stable operation at the maximum power of 1.5 μm. Figure 5 shows the stability of the maximum 1.5 μm output power as a function of time. The standard deviation of the power fluctuations is less than 2% in half an hour.

The output spectrum at 1.5 μm, measured by an imaging spectrometer (HJY, iHR550), is shown in figure 6. The inset graph shows the large scale scanning spectrum. Apart from the signal peak of 1572 nm, no other peaks can be observed in the output spectrum. The bandwidth (FWHM) of the spectrum is 0.2 nm.

4. Conclusion

In conclusion, we have achieved 1.5 W output at 1.5 μm at 10 kHz repetition from an intracavity KTP OPO, which is pumped by an end-pumped Q-switched Nd:YVO_4 laser. The maximum peak power is 25 kW with respect to a 6 ns pulse duration. The maximum conversion efficiency is 9.5% with respect to the LD power of 10.5 W. Due to the approximately TEM_{00} Gaussian profile of the 1064 nm, the M^2 values of the 1.5 μm output are 1.68 and 1.78 in the horizontal and vertical directions at the maximum power. This high efficiency and high peak power of eye-safe lasers can attract many practical applications, such as laser ranging and pollution detection. Our future work will focus on 1.5 μm laser operation with higher peak power and repetition rate.

Acknowledgments

This work was partially supported by the National Natural Science Foundation of China under grants 61308056, 11204044, 11232015 and 11072271, the Research Fund for the Doctoral Program of Higher Education of China under grants 20120171110005 and 20130171130003, the Fundamental Research Funds for the Central Universities of China under grant 14lgpy07 and the Opening Project of Science and Technology on Reliability Physics and Application Technology of Electronic Component Laboratory under grant ZHD201203.

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