Optics & Laser Technology 43 (2011) 636–641

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Comparison of eye-safe KTA OPOs pumped by $Nd:YVO_4$ and Nd:YLF lasers

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ARTICLE INFO

Article history:
Received 25 May 2010
Received in revised form
22 August 2010
Accepted 1 September 2010
Available online 22 September 2010

Keywords:
Eye-safe
Optical parametric oscillator
KTA

ABSTRACT

An eye-safe KTA OPO pumped by a Nd:YLF laser is demonstrated and a comparison with that pumped by a $Nd:YVO_4$ laser is performed. Although the slope efficiency of the continuous-wave free-running Nd:YLF laser is lower than that of the $Nd:YVO_4$ laser, the performance of KTA OPOs pumped by the Q-switched Nd:YLF laser is better, especially at lower repetition rates. The slope efficiency of KTA OPO pumped by a Nd:YLF laser is 14.6% at 30 kHz and 11.04% at 10 kHz. The better energy storage ability of Nd:YLF makes it an excellent laser medium in IOPOs.

1. Introduction

High-peak-power nanosecond eye-safe lasers within the 1.5–1.6 μm range are of great interest for various applications such as laser radar, active imaging, remote sensing, etc. Besides lasers based on bulk solid-state crystals and glasses doped with rare earth ions [1], erbium-doped fiber amplifiers (EDFAs) [2], crystals doped with transition metal ions [3] and Raman lasers [4] and eye-safe optical parametric oscillators (OPOs) pumped by all-solid-state lasers offer us better methods for their high efficiency, high reliability, low threshold and compactness in size for the generation of eye-safe radiation. A large number of commercial nonlinear crystals are available for such devices. OPOs based on periodically poled crystals can realize low-threshold, high-repetition rate or even CW operation, but some of their uses are limited by the disadvantages of small aperture and complicated growing process. OPOs based on $KTiOPO_4$ (KTP) and its isomorphs under non-critically phase-matched (NCPM) configuration ($\theta=90^\circ$, $\varphi=0^\circ$) are the most favorable methods with the advantages of large acceptance angle, large effective nonlinear coefficient, no walk-off and being applicable for multimode pumping.

Compared with extracavity pumped OPOs (EOPOs), intracavity pumped OPO (IOPOs) takes advantage of the intense power inside the laser cavity, resulting higher conversion efficiency and lower threshold. Most of the pump lasers for IOPOs are Nd-doped lasers using gain media such as Nd:YAG [5–10], $Nd:YVO_4$ [11–15], $Nd:GdVO_4$ [16], etc. The Nd:YAG laser is the most commonly used type of solid-state laser because of its high gain, low threshold and the excellent physical properties of the laser crystal, but the severe thermally induced birefringence in Nd:YAG significantly decreases the efficiency of a linearly polarized output under CW pumping condition. Therefore, natural birefringent crystals are more favorable. Owing to a large emission cross section five times higher than Nd:YAG and a high absorption coefficient over a broad band around 809 nm, which is particularly relevant to laser diode pumping, $Nd:YVO_4$ has established its important value as the gain medium of pumping lasers for IOPOs. However, the excited state lifetime of $Nd:YVO_4$ is too short and the thermal conductivity is about only half compared with Nd:YAG, resulting in the main drawbacks of Q-switched operation. To overcome these disadvantages, the Nd:YLF crystal can be used as the laser gain medium, which has longer fluorescence lifetime and smaller emission cross section than $Nd:YVO_4$. The dn/dT coefficient of Nd:YLF is negative, which greatly decreases the thermal lensing effects [17]. The better storage capability and weaker thermal lensing in Nd:YLF coupled with its natural birefringence provide additional advantages in high-power and large-pulse-energy operation. The main material properties of $Nd:YVO_4$ and Nd:YLF [18–20] are shown in Table 1.

In this paper we compare the performance of two KTA IOPOs pumped by $Nd:YVO_4$ and Nd:YLF lasers. Although the efficiency of CW $Nd:YVO_4$ laser is higher than that of Nd:YLF, the performance of Nd:YLF under Q-switched regime is better, and also the slope efficiency of KTA IOPO pumped by Q-switched Nd:YLF laser is higher than that of $Nd:YVO_4$. The experimental results show that Nd:YLF is a kind of promising gain material used for pumping lasers for IOPOs.

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doi:10.1016/j.optlastec.2010.09.004

Table 1
Main properties of $Nd:YVO_4$ and Nd:YLF.

Parameters	$Nd:YVO_4$	Nd:YLF
Laser wavelength (nm)	1064.3	1047 (π) 1053 (σ)
Emission cross section (cm^2)	15.6×10^{-19}	$1.8\times10^{-19}(\pi)$ $1.2\times10^{-19}(\sigma)$
Fluorescence lifetime (μs)	100	480
Refractive index	$n_o=1.96$ $n_e=2.166$	$n_o=1.4481$ $n_e=1.4704$
Thermal conductivity (W/cm K)	0.051	0.06
dn/dT (10^{-6}/K)	8.5 (100) and (010) 3 (001)	−3
Peak absorption wavelength (nm)	809	793, 797, 806

2. Theoretical analysis

For IOPO, the main cavity is the pump-laser cavity formed by the two mirrors both with high reflectivity for the pump field, one of which can also be used as the output coupler of the OPO cavity. Two processes should be considered during the generation of a signal pulse: one is the foundation of the pump field and the other is the parametric interaction process, generating the signal and idler waves. According to the IOPO theories by Debuisschert et al. [21], for a singly resonant IOPO (SR-IOPO), the time evolutions of the population inversion, the pump and signal intensities are given by

$$\frac{dI_s}{dt}=I_s(I_p-1) \tag{1}$$

$$\frac{\tau_p}{\tau_s}\frac{dI_p}{dt}=I_p(N-1)-FI_sI_p \tag{2}$$

$$\frac{2\tau_a}{\tau_s}\frac{dN}{dt}=\sigma-N(1+xI_p) \tag{3}$$

where

$$\tau_p=\frac{2n_pL_{laser}}{c}\frac{1}{1-r_p} \tag{4}$$

$$\tau_s=\frac{2n_sL_{OPO}}{c}\frac{1}{1-r_s} \tag{5}$$

$$F=\frac{1-r_s}{1-r_p} \tag{6}$$

In the equations above, the population inversion $N(t)$ is normalized by its value at the threshold of the pump laser, $I_p(t)$ and $I_s(t)$ are normalized by the pump intensity at the threshold of the OPO, τ_a is the lifetime of the upper level of the laser transition, n_p and n_s are the refractive indices for pump and signal wave of the media, respectively, L_{laser} and L_{OPO} are the cavity lengths of the pump laser and OPO, respectively, c is the light velocity, r_p and r_s are the reflectivities of the output mirror at the pump and signal wavelengths, respectively, σ is the pumping level of the laser medium relative to the laser threshold and x is the ratio between the OPO threshold flow and the laser-medium saturation flow, and its expression is given in [21].

We perform the numerical simulation of KTA IOPO pumped by $Nd:YVO_4$ and Nd:YLF lasers each. The signal reflectivity of the output coupler is set to be 70%, and the relevant parameters are

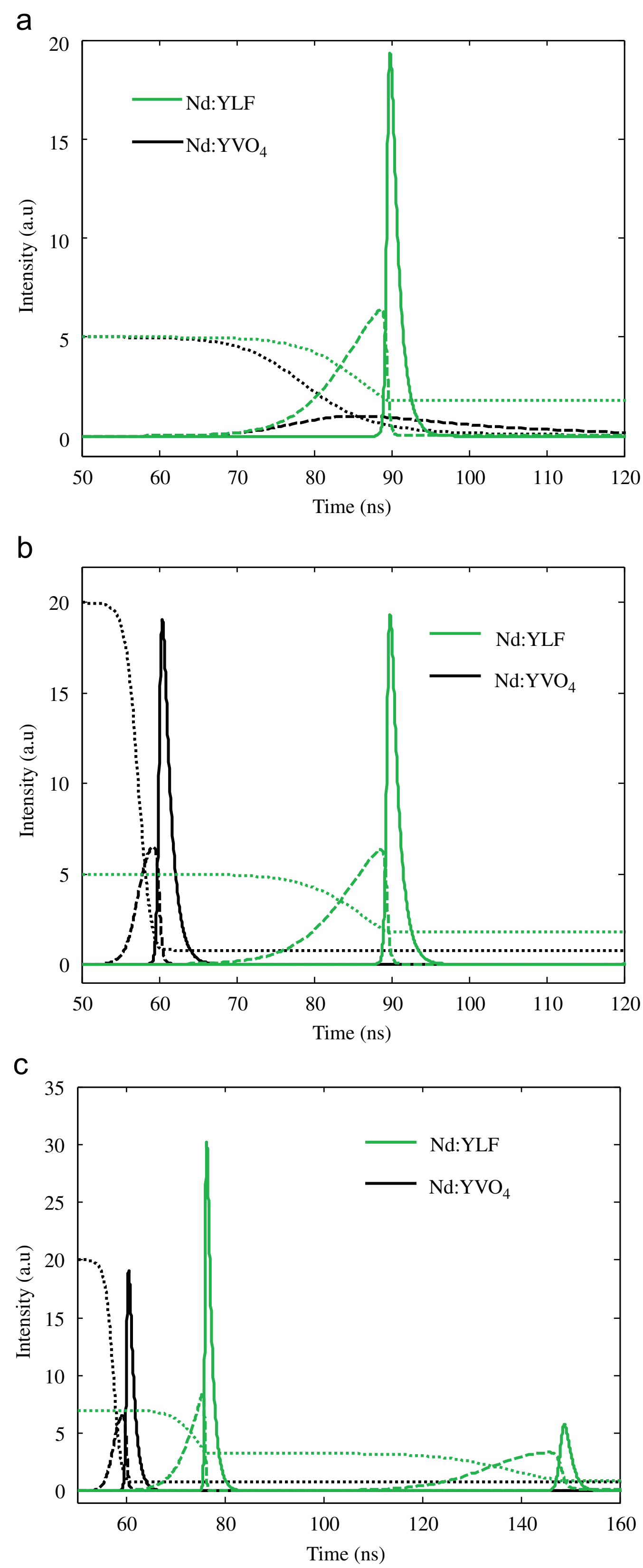

Fig. 1. Temporal characteristics of the KTA IOPO pumped by $Nd:YVO_4$ and Nd:YLF lasers. Inversion population—dotted curve; pump pulse—dashed curve; signal pulse—solid curve.

demonstrated in Table 1. Fig. 1(a) shows the case that the pumping intensity of the two laser media is the same: $\sigma=5$. When the peak power of the Nd:YLF laser pulse exceeds the OPO

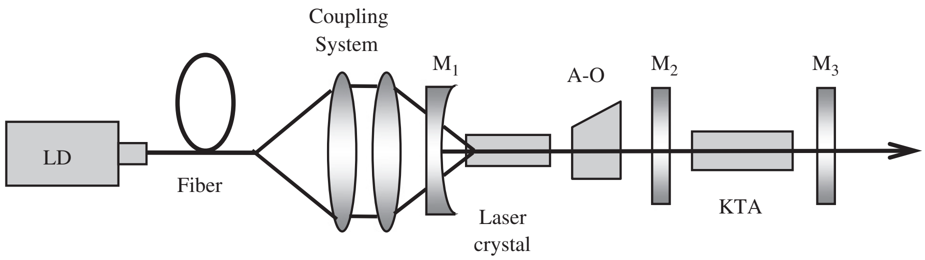

Fig. 2. Experimental setup of KTA IOPO.

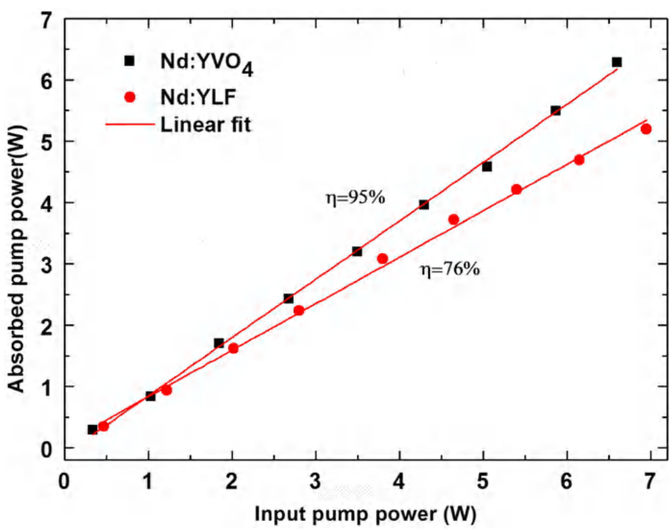

Fig. 3. Absorbed pump power for Nd:YVO_4 (a) and Nd:YLF (b).

threshold and a signal pulse is released, the peak power of the Nd:YVO_4 laser remains at a low level, which is below the OPO threshold. If the pumping intensity for Nd:YVO_4 laser is increased to $\sigma=20$, which is 4 times higher than that of the Nd:YLF laser, the OPO threshold is overcome and the signal peak power increases to almost the same amplitude with that pumped by a Nd:YLF laser, as shown in Fig. 1(b). Fig. 1(c) shows the generation of a second signal pulse if the pump intensity of the Nd:YLF laser is increased to $\sigma=7$, when the final inversion population after the first signal pulse still holds higher than the OPO threshold.

It is obviously seen in Fig. 1 that the emission cross section and fluorescence lifetime τ_a of laser media greatly affected the pump threshold and signal peak power of the OPO, and the behaviors using Nd:YVO_4 and Nd:YLF as the pump laser differ a lot. Owing to the good energy storage ability, Nd:YLF shows a better performance as the pump laser in IOPOs, which will be experimentally investigated in the next part.

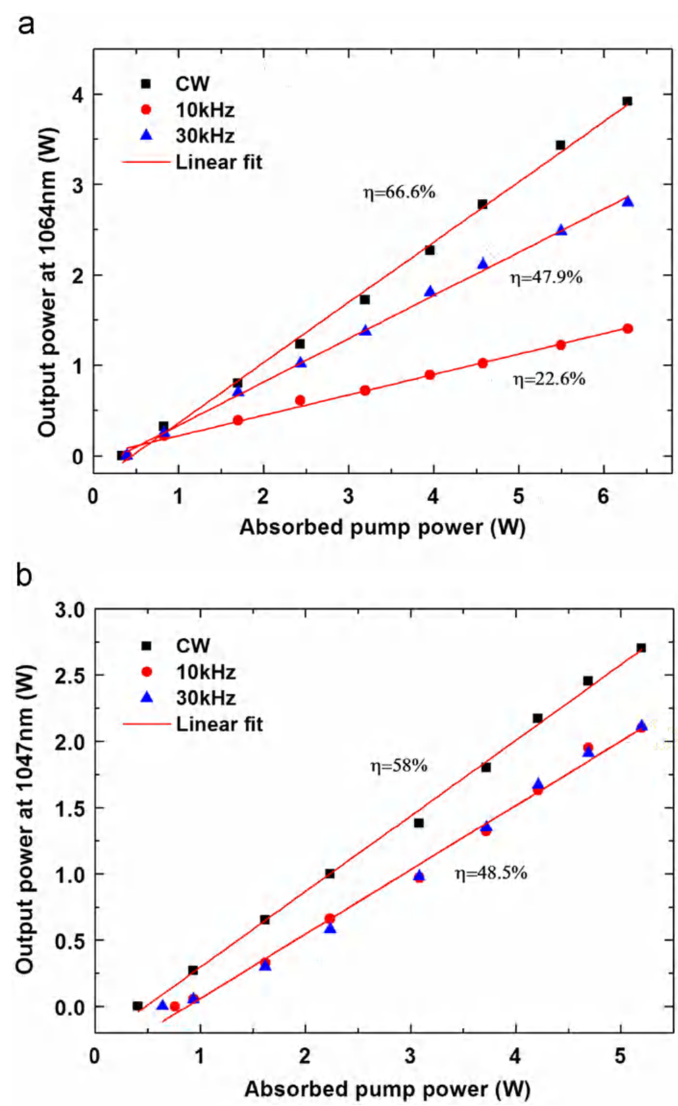

Fig. 4. Performance of Nd:YVO_4 (a) and Nd:YLF (b) lasers.

3. Experimental setup

The experimental setup is shown in Fig. 2. A fiber coupled diode laser (LIMO Inc.) with a central wavelength of 808 nm at room temperature is used as the pump source. It has a maximum output power of 30 W, a numerical aperture of 0.22 and a core diameter of 400 μm. The pump wave is focused onto the laser gain medium by the coupling system at a spot radius of about 160 μm. Both the laser crystals Nd:YVO_4 and Nd:YLF used in the experiment are commercial $3\times3\times5$ mm^3 in size, a-cut and antireflective (AR) coated around 800 nm and 1.06 μm, but their doping concentrations are 0.5 and 1 at%, respectively. A simple concave-plane cavity is used for the fundamental laser. The rear mirror (M_1) is plane-concave with its both faces AR coated at 808 nm and the concave face also highly reflective (HR) coated at 1064 nm. The 45 mm-long A-O Q-switch (Gooch and Housego) has AR coatings around 1.06 μm and is driven at 27.12 MHz with the maximum RF power up to 100 W. The KTA crystal is $7\times7\times20$ mm^3, cut along the *x*-axis ($\theta=90^\circ$, $\varphi=0^\circ$) to work at type II non-critically phase-matching (NCPM) configuration. It is AR coated on both faces for pump (1.04–1.07 μm), signal (1.5–1.6 μm) and idler (3–3.6 μm) waves. M_2 and M_3 form the cavities of a singly resonant OPO. M_2 is coated for AR at 1.04–1.07 μm and HR at 1.5–1.6 μm, and M_3 is coated for HR at 1.04–1.07 μm, with partly reflection at 1.5–1.6 μm. The OPO mirrors M_2 and M_3 are made of BK7 glass with a cut-off wavelength around 2.1 μm in its transparent range; therefore only the signal wave in the eye-safe band can be coupled out of the cavity. The laser diode, laser crystals, A-O Q-switch and the KTA crystal are all cooled by water. The cavity length of the fundamental laser is 130 mm and the OPO cavity length is 26 mm.

The peak absorption wavelength for $Nd:YVO_4$ is around 809 nm; however, Nd:YLF has two major absorption peaks at 793 and 797 nm, and also a minor one at 806 nm. In order to use the available pump source in the experiment, the output wavelength of the laser diode is tuned by controlling the LD temperature. The optimal operating temperatures for the diode lasers were experimentally determined to be 15 and 8 °C for $Nd:YVO_4$ and Nd:YLF lasers, respectively.

4. Experimental results and discussions

The absorbed pump power is firstly measured because the laser crystals are not sufficiently long especially for Nd:YLF with a much lower absorption coefficient. The comparison is shown in Fig. 3. The incident power is limited to 7 W to avoid optical damage to the laser crystals in the comparison. The absorptivity of the Nd:YLF is 76%, much lower than that of the $Nd:YVO_4$ with a absorptivity of 95%. The absorption coefficient for a 0.5 at%-doped $Nd:YVO_4$ is calculated to be 1.1 times higher than a 1 at%-doped Nd:YLF.

The output powers of the free-running $Nd:YVO_4$ and Nd:YLF lasers are shown in Fig. 4(a) and (b). The cavity configuration is the same as that in Fig. 2, without the OPO elements and with an output coupler transmission of 20% at 1.04–1.07 μm. The slope efficiency for $Nd:YVO_4$ laser under CW operation is 66.6%, higher than 58% for the Nd:YLF laser. With respect to Q-switching operation, the performance of Nd:YLF seems to be better, especially at lower repetition rates, because the long lifetime of the excited state allows better energy storage ability. The slope efficiency of the Nd:YLF laser at 10 kHz was 48.5%, more than twice of the $Nd:YVO_4$ laser. Their temporal behaviors of the output pulses at 10 kHz under relatively high pump powers are shown in Fig. 5(a) and (b), respectively. The pulse shape is distorted and a parasitic pulse is generated for the $Nd:YVO_4$ laser,

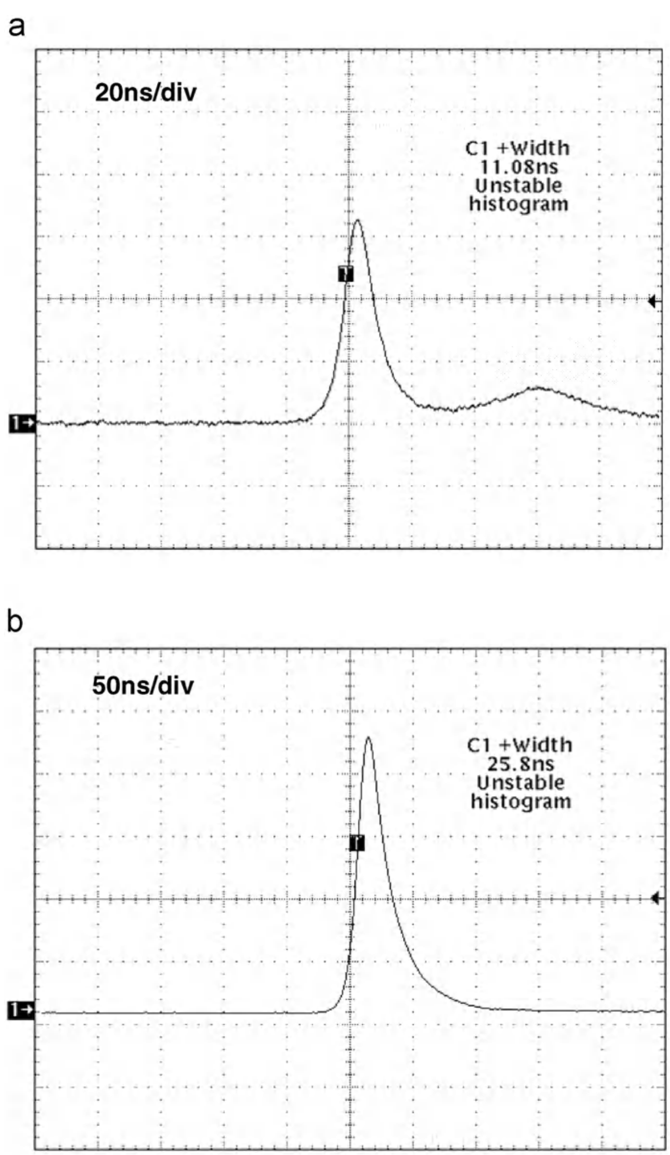

Fig. 5. Temporal behavior of $Nd:YVO_4$ (a) and Nd:YLF (b) laser pulses.

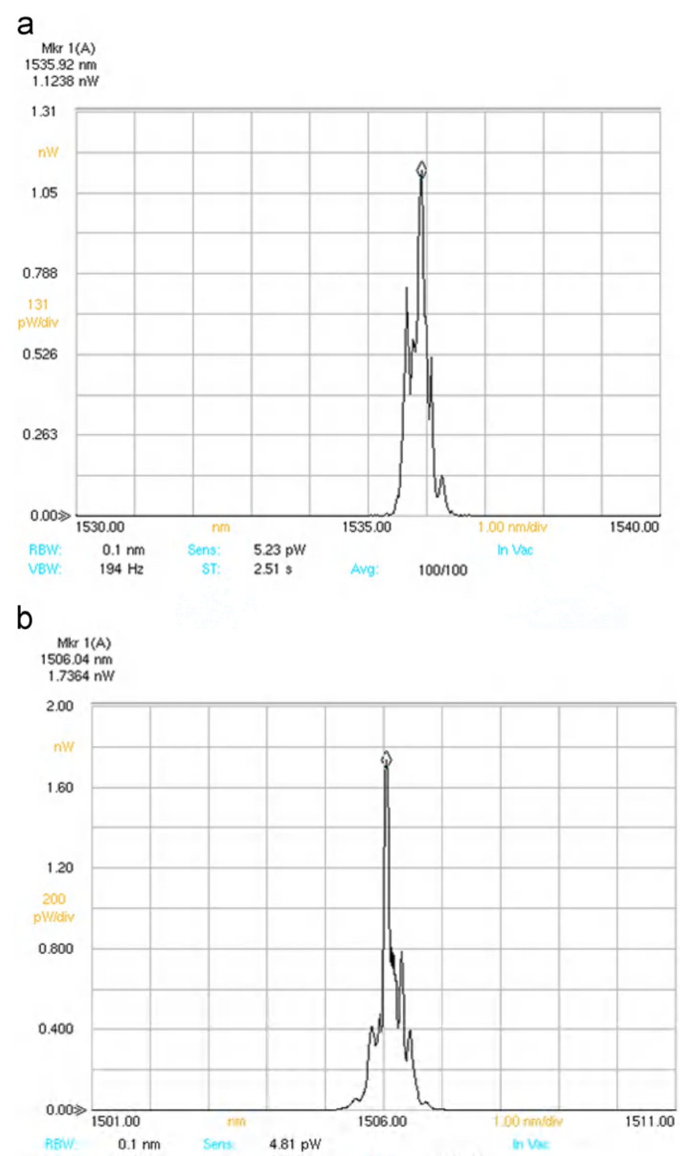

Fig. 6. Output spectrum of KTA OPO pumped by $Nd:YVO_4$ (a) and Nd:YLF (b) lasers.

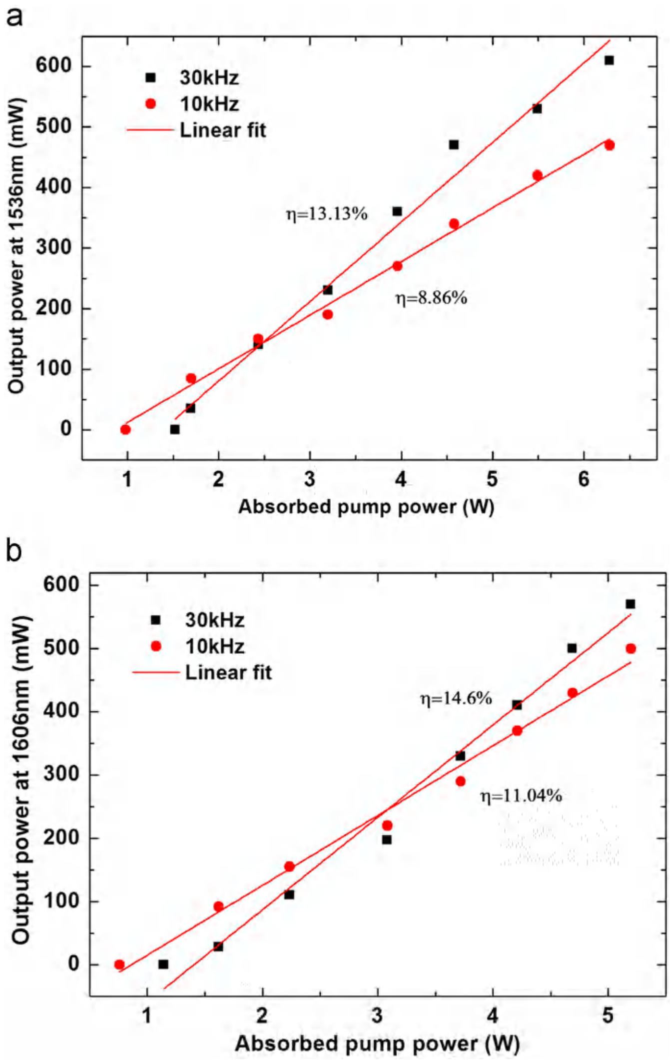

Fig. 7. Output signal power of KTA OPO pumped by Nd:YVO_4 (a) and Nd:YLF (b) lasers.

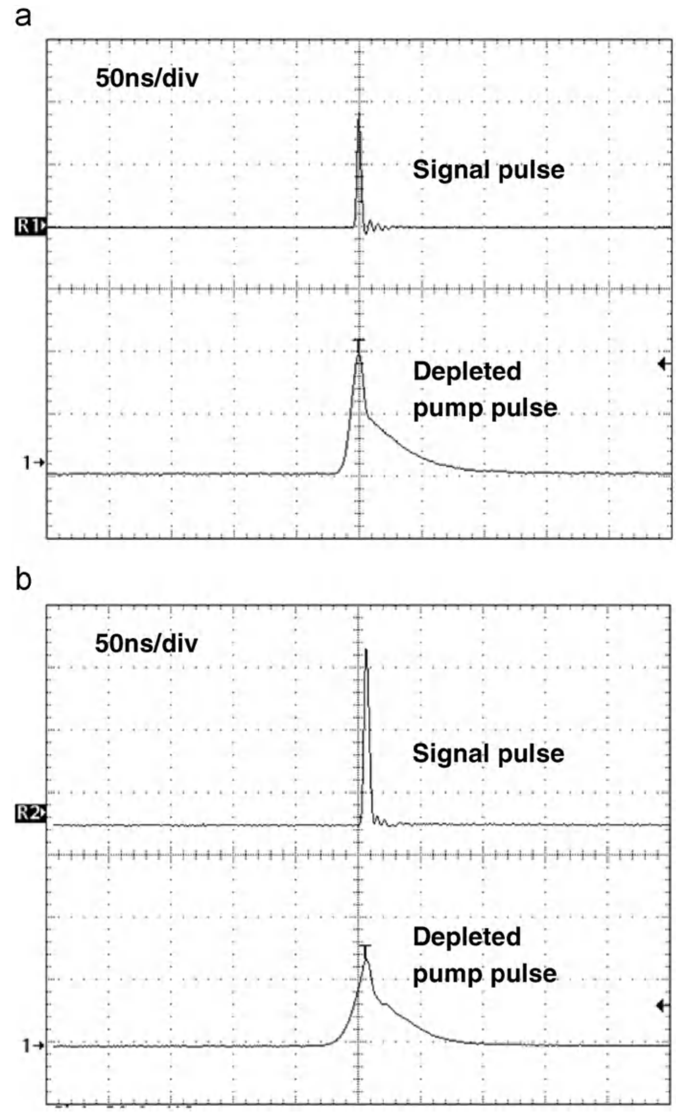

Fig. 8. Temporal behavior of the signal and depleted pump pulses pumped by Nd:YVO_4 (a) and Nd:YLF (b) lasers.

because it is difficult to shut off the laser oscillation inside the cavity owing to its large emission cross section and short lifetime at excited state.

Inserting the OPO elements into the laser cavity, the generated signal wavelengths of the KTA OPOs pumped by a Nd:YVO_4 and a Nd:YLF laser are 1536 and 1506 nm, respectively, measured with an Agilent 86142B spectrometer, and are shown in Fig. 6(a) and (b). The signal linewidths are about 0.6 nm.

A dichroic mirror coated for HR at 1.04–1.06 μm and AR at 1.5–1.6 μm is placed in front of the power meter to filter out the fundamental wave. The output signal power is measured with a Molectron PM10 power meter, as shown in Fig. 7(a) and (b). Pumped by a Nd:YVO_4 laser, the maximum output powers of the KTA OPO are 610 and 470 mW at 30 and 10 kHz, respectively, corresponding to the slope efficiencies of 13.13% and 8.86%. As to the KTA OPO pumped by a Nd:YLF laser, the maximum output powers are 570 and 500 mW, and their corresponding slope efficiencies were 14.6% and 11.04%, respectively. Apparently the slope efficiency of the OPO pumped by a Nd:YLF laser is higher than that pumped by a Nd:YVO_4 laser, and it is more evident at a lower repetition rate. Moreover, the threshold of the OPO pumped by a Nd:YLF laser is lower. The optical-to-optical conversion efficiencies reach 11% and 9.62% at 30 and 10 kHz when the absorbed pump power is 5.2 W. It should also be noted that the cavity is designed specially for the case that the pump laser gain medium is Nd:YVO_4, which has a serious thermal lens effect in the gain medium. The performance of the KTA OPO pumped by a Nd:YLF laser can be better if the cavity is optimized.

The output laser pulse shapes are detected by a fast response InGaAs photodiode and recorded on a Tektronix TDS620B 500 MHz oscilloscope. The temporal pulses for the signal and depleted pump waves using different pump lasers are shown in Fig. 8(a) and (b). Obvious pump depletion can be observed compared with Fig. 5(a) and (b). Although the pulse width of the free-running Nd:YVO_4 laser is much narrower than that of the Nd:YLF laser, there is no much difference between the durations of the signal pulses, which are determined by the lifetime of the signal photon in the OPO cavity expressed by Eq. (5) [21]. The signal pulse widths are about 2.5–4 ns at 1506 and 1536 nm. The phenomenon of signal pulse series is not observed because the pump power is not high enough. A typical temporal signal pulse behavior is shown in Fig. 9. The signal pulse width is about 3 ns, indicating that the signal pulses are 3.7 and 8.7 times shorter than the fundamental pulse widths of the Nd:YVO_4 and Nd:YLF lasers. When the output signal power is 500 mW at 10 kHz, the signal pulse energy is 50 μJ and the peak power is 17 kW, more

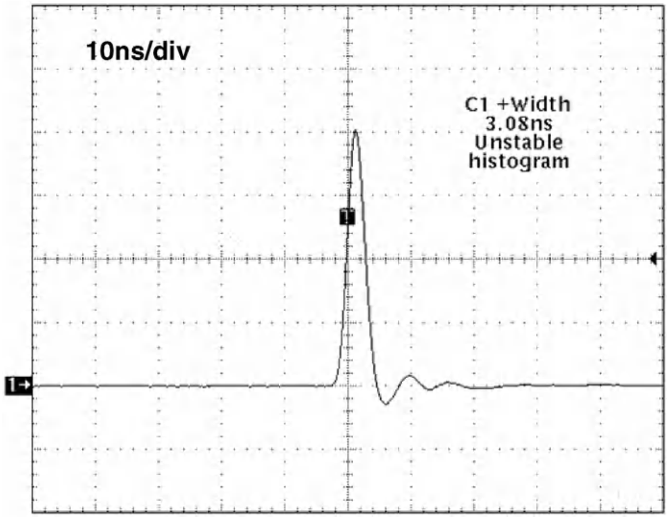

Fig. 9. Temporal behavior of a typical signal pulse.

than twice of the corresponding peak power of fundamental pulses at 1047 nm. Using the root mean square (rms) method $(\Delta\overline{P})/\overline{P}=(1/\overline{P})\sqrt{\Sigma_{i=1}^{n}(P_i-\overline{P})^2/n}$, the instabilities of the output signal powers are 2.57% and 2.85%, pumped by Nd:YVO_4 and Nd:YLF lasers, respectively.

5. Conclusion

In conclusion, we present an eye-safe KTA OPO pumped by a Nd:YLF laser and perform comparisons with that pumped by a Nd:YVO_4 laser theoretically and experimentally. Owing to the higher energy storage ability and better performance at Q-switching operation, Nd:YLF laser is proved to be a good pump source for IOPOs, especially at lower repetition rates. The signal peak power exceeds twice of the fundamental pulses at 10 kHz. The slope efficiency of KTA OPO pumped by a Nd:YLF laser is 14.6% at 30 kHz and 11.04% at 10 kHz, both are apparently higher than that using Nd:YVO_4 laser as the pump laser gain medium. It is believed a Nd:YLF crystal long enough to enhance the pump absorption is an excellent laser crystal in pumping IOPOs.

Acknowledgements

This work is supported by National Basic Research Program of China (Grant no. 2007CB310403) and National Natural Science Foundation of China (Grant nos. 60801017 and 10874128).

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