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Low threshold narrow pulse width eye-safe intracavity optical parametric oscillator at 1573 nm

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Abstract

We demonstrate a low threshold operation of a KTP-based intracavity optical parametric oscillator, emitting at 1573 nm, driven by a cw diode-end-pumped actively Q-switched Nd:YVO_4 laser. Diode-pump threshold around 0.86 W is achieved, which, to the best of our knowledge, is the lowest one under the similar experimental conditions. Owning to the efficient cavity-dumping effect, a signal pulse width as short as 1.4 ns and peak power higher than 3 kW is obtained, at the incident diode-pump power of 1.3 W and A-O modulating frequency of 9 kHz. Moreover, threshold characteristic for the IOPO is also studied, which is in well agreement with the experimental results.

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Keywords: Optical parametric oscillator; Eye-safe laser; Diode-end-pump; Q-switched

1. Introduction

The current research interest in eye-safe laser sources has been focused on optical parametric oscillators (OPOs), pumped by pulsed Nd-doped laser systems. Owing to their high efficiency and simplicity, the OPOs are considered to be an alternative to erbium and Raman shifted lasers emitting directly at 1.54 μm [1].

OPOs known to us usually refer to the external optical parametric oscillators (EOPOs), in which the OPO and the pump source are separate elements. However, EOPOs usually exhibit relatively high threshold, typically over 100 MW/cm^2 (single resonated) [2], which sets stringent requirement to the pump source. Diode-end-pumped pulsed lasers, with the advantage of high efficiency and single-transverse-mode outputs, seem to be the ideal pump sources for EOPOs. Unfortunately, this type of lasers often result in low energy per pulse (typically less than half mJ) and pulse width of several tens of nanoseconds [3], which cannot exceed the EOPO threshold. Low threshold operation can be achieved by using period poled crystals (e.g., PPLN and PPKTP) with high effective nonlinear coefficient as the nonlinear element. However, this kind of crystals is very expensive and cannot be commercially widespread. To overcome the issues mentioned above, another approach with low threshold operation is to put the OPO inside the Nd-doped lasers, namely intracavity optical parametric oscillator (IOPO).

Taking advantage of the intense intracavity power in the pump laser, IOPO reduces the pump level necessary to exceed the oscillation threshold and increases the overall efficiency. In fact, IOPO serves as a nonlinear cavity dumper to extract the energy stored in the intracavity optical field [4]. Since the early 1990s [5], IOPO has gained a renaissance after about 20 years dreariness. Studies in this field are focused on KTP-based noncritically phase matched (NCPM) IOPO, emitting in the eye-safe range.

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Nevertheless, the pump sources mainly are flash-lamp side-pumped [6] or quasi-cw diode end-pumped [7], Nd-doped, Q-switched lasers with low repetition rate and low overall efficiency. The first KTP-based IOPO driven by a cw diode end-pumped Q-switched $Nd:YVO_4$ laser was realized by Conroy et al. [8]. Recently, Chen has demonstrated several IOPOs with cw diode end-pumped Q-switched $Nd:YVO_4$ lasers [9–11]. But, the diode-pump threshold of the devices we refer to above is higher than 1.1 W.

In this work, we demonstrate a compact low threshold KTP-based IOPO with a cw diode end-pumped acousto-optically (A-O) Q-switched $Nd:YVO_4$ laser. The diode-pump threshold is as low as 0.86 W, to the best of our knowledge, this is the lowest one under the similar experimental conditions. With an incident pump power of 1.3 W and a repetition rate of 10 kHz, we get 48 mW average power output at 1573 nm and a signal pulse duration of 1.4 ns. At the 9 kHz repetition rate, we also obtain a peak power higher than 3 kW.

2. Experimental setup

The elaborate design of the IOPO system is schematically shown in Fig. 1. A plane-concave cavity configuration was employed, and the KTP crystal was placed near the output coupler, where the pump spot size was small enough to give the highest parametric gain and the lowest pump threshold. The pump laser was driven by a 2 W cw diode, emitting at 809.1 nm (under the room temperature) which can well match the peak absorption spectra of the $Nd:YVO_4$ crystal to fully extract the pump energy. For the divergent and unsymmetrical emitting property of the diode, a well designed coupling optics was used here, with a coupling efficiency of 95%. Taking advantage of high gain and linear polarization emitting characteristic, a $3\,mm \times 3\,mm \times 2\,mm$, a-cut, 1.0 at.% doped $Nd:YVO_4$ was used as the active medium instead of the usually used Nd:YAG. Besides, both sides of the crystal were antireflection (AR) coated at 1064 nm. The 18 mm long A-O Q-switcher, with a 40 MHz center frequency, was AR coated at 1064 nm on both sides and its modulating frequency can be successively changed from 2 to 40 kHz. The KTP crystal, with a length of 20 mm and cut for type-II non-critical phase-matching ($\theta = 90°$, $\phi = 0°$), was coated high transmission at 1064 nm ($T > 95\%$) and high reflection (HR) at 1573 nm ($R > 99.8\%$) on one side, serving as a cavity mirror for the OPO, and was AR coated at both 1064 nm and 1573 nm on the other side. The pump laser cavity, formed by M1 and M3, was approximately 64 mm long. As the input mirror, M1 was high transmission at 808 nm on both sides and high reflection at 1064 nm on the concave side, with a radius of curvature of 50 mm. Playing the part of cavity mirror for both the fundamental and OPO cavity, M3 was HR coated at 1064 nm ($R > 99.8\%$) and partly reflection at 1573 ($R = 86\%$) on one side, and high transmission at the two waves on the other side. For the KTP was placed very close to M3, the OPO cavity, formed by M2 and M3, was as long as the nonlinear crystal. In addition, several thermo-electric coolers were used in this setup to cool the laser rod, A-O modulator and KTP crystal.

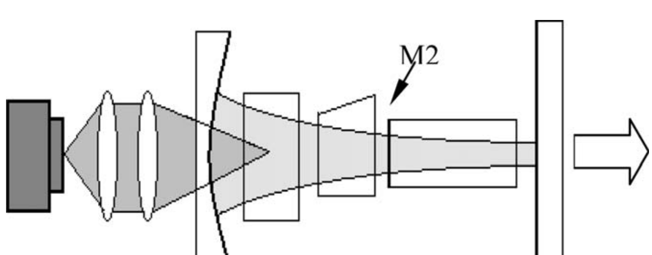

Fig. 1. Schematic configuration of the IOPO: LD, laser diode; CO, coupling optics; M1, input mirror; LC, $Nd:YVO_4$ crystal; AO, acousto-optical modulator; NLC, KTP crystal; M3, output coupler.

3. Threshold study

Low threshold property of the IOPO is attractive in compactness and commercialization of the OPO devices. Three reasons are attributed to the relatively low threshold operation of the KTP-based IOPO:

- non-critical phase-matching with the largest effective nonlinear coefficient and parametric gain, moreover, without walk off;
- high intense intracavity pump power which reduces the pump level and increases the conversion efficiency;
- high finesse cavity which increases the overlap between the pump and signal fields, and provides double-pass parametric gain.

The threshold pump intensity for the IOPO with high finesse cavity can be described as [12]:

$$I_{\text{th}} = \frac{2.25}{\kappa g_s l^2 (1+\gamma)^2}\left[\frac{33\,L}{2\tau_p c} + 2\alpha l + \ln\frac{1}{\sqrt{R}} + \ln 4\right]^2, \tag{1}$$

where

$$\kappa = \frac{8\pi^2 d_{\text{eff}}^2}{\lambda_s \lambda_i n_p n_s n_i \varepsilon_o c} \tag{2}$$

here $d_{\text{eff}} = 3.2$ pm/V is the effective nonlinear coefficient. $\lambda_s = 1.573$ μm, $\lambda_i = 3.288$ μm are the signal and idler wavelength, respectively. n_p, n_s, n_i are refractive indices for the pump, signal and idler wave, respectively; and g_s is the signal spatial mode coupling coefficient defined by:

$$g_s = \frac{1}{1 + (w_s/w_p)^2} \tag{3}$$

here w_s, w_p are signal and pump beam waist, respectively; L is the optical cavity length for the OPO defined by:

$$L = L' + (n-1)l \tag{4}$$

here l is the length of the KTP crystal, L' is the physical length of the OPO cavity, n is the refractive index of the KTP; $\gamma = 0.9$ is the ratio of back to forward pump field amplitude inside the nonlinear crystal; $2\alpha l = 0.01$ is the estimated round trip loss for the pump wave; $\tau_p = 20$ ns is the pump pulse width; and $R = 0.86$ is the reflectivity of the out coupler at signal wave.

From Eq. (1) one can get that the pump beam waist w_p is a vital factor which determines the IOPO threshold. And not only can it impact the overlap between the pump and signal but also determines the intracavity pump intensity. Furthermore, the steady-state signal spot size w_s is also associated with w_p as follows [12]:

$$\left(\frac{\pi}{2L\lambda_s}\right)^2 w_s^6 + w_s^2 - \frac{w_p^2}{2} = 0. \quad (5)$$

Solving Eqs. (1), (3), and (5), we obtained the relationship between I_{th} and w_p as shown in Fig. 2. As a comparison, we also give out the expression, in terms of w_p, for the intracavity pump intensity (I_{in}). As we know, the relation between internal and external power intensity of the laser cavity can be described as:

$$\frac{I_{in}}{I_{ex}} = \frac{1}{2}\left(\frac{1+R_p}{1-R_p}\right), \quad (6)$$

where R_p is the reflectivity of the output coupler at 1064 nm. Assume that the pump spot in the KTP crystal is round and homogeneous, and then the extracavity intensity can be defined by $I_{ex} = \frac{P_{pe}}{\pi w_p^2}$. Here $P_{pe} = \frac{P_{av}}{f\tau_p}$ is the output peak power of 1064 nm, and P_{av}, f are the average power and pulse repetition rate of the pump, respectively. Hence, we finally obtained the expression of I_{in} as:

$$I_{in} = \frac{P_{av}(1+R_p)}{2\pi f \tau_p w_p^2 (1-R_p)}. \quad (7)$$

The evolutive curve, calculated from Eq. (7), with w_p for I_{in} is also plotted in Fig. 2.

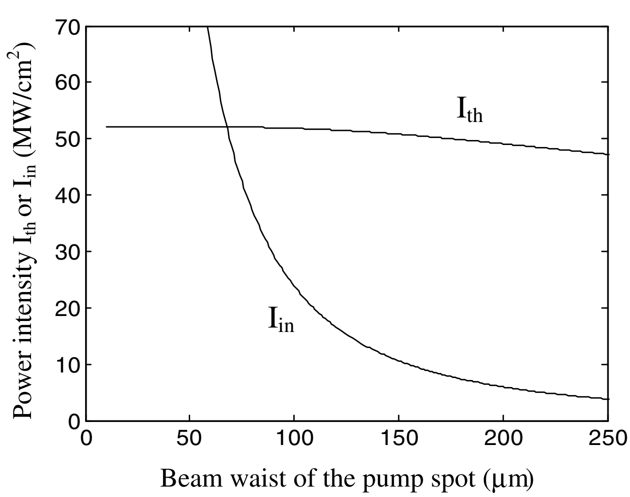

Fig. 2. Simulated curves for the IOPO threshold and intracavity power intensity, with respect to the pump beam waist.

As shown in Fig. 2, the degenerate point divides the curves into two parts. In the left part, the I_{in}-curve is above the I_{th}-curve, whereas, in the other part, it is in the reverse condition. That means, under the existing experimental configuration, the value of w_p can not be higher than 68 μm, corresponding the lowest threshold of 52 MW/cm^2 (degenerate point). According to this theory, in our experiment, we used an overall physical cavity length of 64 mm, and the measured experimental $I_{th} \approx 49$ MW/cm^2, which is in well agreement with the theoretical value mentioned above. Moreover, we can find that the theoretical threshold is somewhat higher than the experimental one. The difference should mainly be attributed to the discrepancy between the accurate value of d_{eff} for the KTP and well accepted one we used in this work. More details about the value of d_{eff} for the KTP crystal can be available in [13–15].

4. Results and discussion

The horizontal linear polarized cw-diode pump light was focused on the laser rod with a beam waist of around 100 μm. And in order to obtain an efficient parametric interaction, y-axis of the KTP was placed to be exactly parallel to the polarization direction of the pump light. Moreover, our OPO is designed to be single-resonated at 1573 nm by means of being highly attenuated in the idler wave ($\lambda_i = 3.288$ μm): on the one hand, the output coupler was coated to be only high-reflected at the signal wave; on the other, absorption in the KTP crystal, for the wavelength longer than 3.1 μm, is significantly high, and transmission at the idler wave is only around 30% [16,17]. Fig. 3 shows the spectrum for the signal, recorded by AQ 6317B Spectrum Analyzer, with a center wavelength of 1573.7 nm.

The average output power of 1573 nm, in the function of incident pump power, is depicted in Fig. 4. The detected diode-pump threshold is approximately 0.86 W, and the maximum average output signal power is 48 mW at the

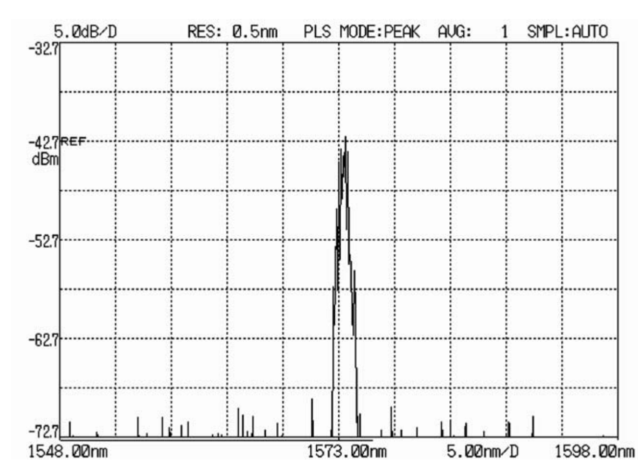

Fig. 3. Typical spectrum for the signal wave which emitted from the single-resonated IOPO system, and with a center wavelength of 1573.7 nm.

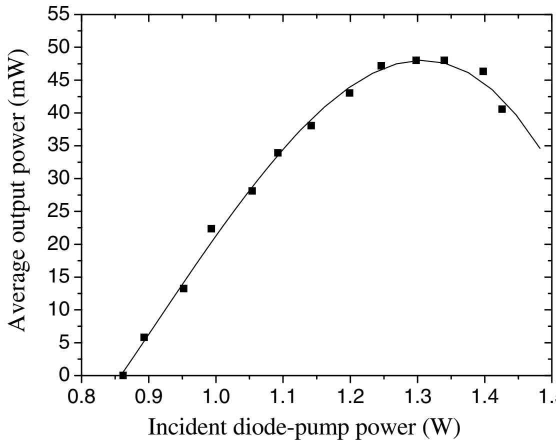

Fig. 4. Average output power for 1573 nm at the A-O modulating frequency of 10 kHz, with respect to the absorbed diode-pump power.

incident pump power of 1.3 W and pulse repetition rate of 10 kHz. When the pump power beyond 1.3 W, the conjunct impact of the thermal lens in the laser rod, A-O modulator and KTP crystal become serious, resulting in the falloff of the output signal power, as shown in Fig. 4. Fig. 5 gives the average power and peak power at 1573 nm, with respect to A-O modulating frequency.

The pulse temporal behavior for the pump and signal wave were recorded by a LeCroy 9361C Dual 300 MHz oscilloscope and an InGaAs photodiode. Owing to the too high reflectivity (99.8%) of the output coupler at 1064 nm, and also to the depletion of the pump field, we cannot detect the temporal behavior of the pump pulse after the OPO begin to oscillate. Fig. 6(a) depicts the temporal shape of the pump pulse, recorded before the OPO oscillation, with a pulse width of around 20 ns. Temporal behavior for the typical signal pulse is pictured in Fig. 6(b). As it shows, the pulse duration is as short as 1.4 ns, which is 14 times shorter than that of the fundamental pulse. This evidently exhibits a significant pulse shortening mechanism of the IOPO. Because of the relatively too

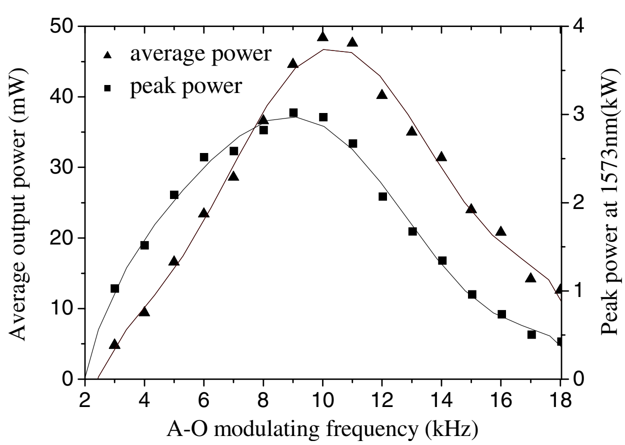

Fig. 5. Average output power and the corresponding peak power for 1573 nm, with respect to the A-O modulating frequency.

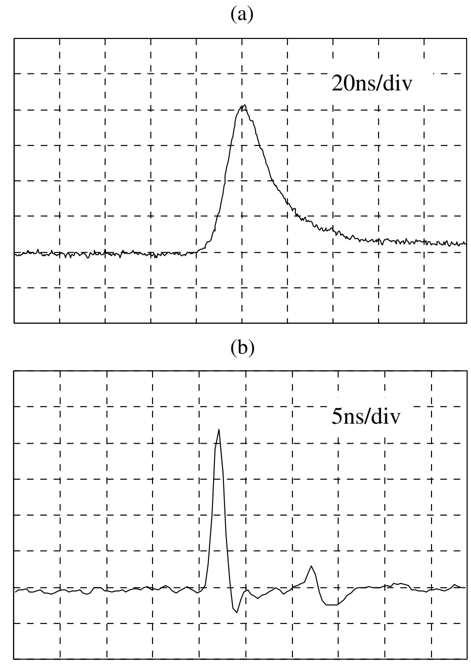

Fig. 6. (a) Temporal shape of the pump pulse recorded before the OPO oscillation, with a pulse duration of 20 ns. (b) Temporal profile of the signal pulse at the incident diode-pump power of 1.3 W and A-O modulating frequency of 9 kHz, with a pulse width as short as 1.4 ns.

high reflectivity of the output coupler at 1573 nm, a satellite pulse is emerged, with an interval of 16 ns to the main pulse, indicating the IOPO's cavity-dumping characteristic. Single-pulse performance can be realized by choosing ideal output coupler with appropriate reflectivity at the signal wave [4,18].

Finally, in our experiment, we also investigated some faint green light (532 nm), owning to the second harmonic generation of 1064 nm in the KTP crystal. In order to observe the signal spot, a prism was employed to disperse the green and signal light. However, the beam quality is not ideal, which was mainly caused by the plane-parallel cavity configuration of the OPO. More better beam quality can be obtained by using an unstable cavity configuration. In addition, we observed that the divergence angle of the signal wave is much bigger than that of the fundamental wave. From the calculation of Eq. (5) we can get that it is mainly because the beam waist of the signal is about 1.4 times smaller than that of the fundamental wave.

5. Conclusions

In summary, we have accomplished a low threshold operation of a KTP-based intracavity optical parametric oscillator, driven by a diode-end-pumped Q-switched $Nd:YVO_4$ laser. Cavity-dumping characteristic of the IOPO leads to the fast buildup of signal pulses, with pulse width as narrow as 1.4 ns, resulting in the high peak power output. We expect higher average and peak power output at 1573 nm by using more efficient cooling technique to reduce the thermal-lens effect. Threshold property of the IOPO was also studied, which can match well to the experimental results. In the future work, our interest should be diverted on the more compact and efficient IOPO, driven by the Cr:YAG passively Q-switched Nd-doped laser system.

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