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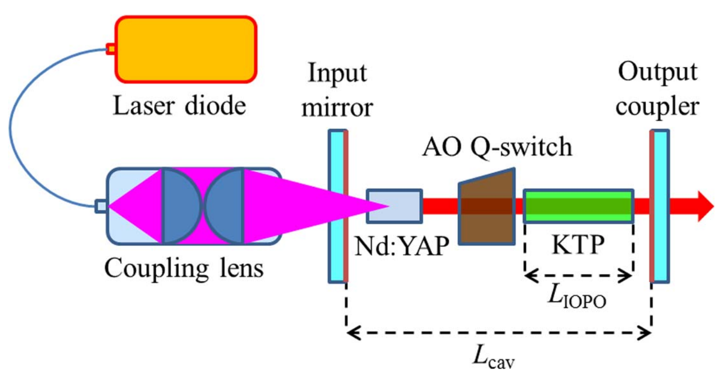

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Diode-Pumped Nd:YAP Intracavity Optical Parametric Oscillator Emitting at 1603 nm: Influence of Energy-Transfer Upconversion

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Abstract: A diode-end-pumped actively *Q*-switched Nd:YAP laser at 1080 nm is originally designed to intracavity pump a Potassium Titanyl Phosphate KTiOPO4 (KTP)-based optical parametric oscillator for obtaining the signal wavelength at 1603 nm. Under an absorbed pump power value of 11 W, the maximum average output power at the eye-safe radiation is efficiently generated to be 1.11 W at a pulse repetition rate of 10 kHz. At a pulse repetition rate of 5 kHz, the shortest pulse duration, the largest pulse energy, and the highest peak power are found to be 2.4 ns, 190 μJ, and 67.3 kW, respectively. In addition, the influence of energy-transfer upconversion effect on the capability of power scaling of the developed Nd:YAP fundamental laser is experimentally investigated and theoretically analyzed.

Index Terms: Infrared lasers, diode-pumped lasers, *Q*-switched lasers, solid-state lasers, coherent sources modeling and theory.

1. Introduction

The eye-safe coherent radiation emitting in the range of 1.4–1.7 μm can be used for a large number of scientific and industrial fields, including active imaging, medical surgery, photochemistry, range-finding, environmental sensing, and so on. The spectral emission at 1603 nm is one of the suitable wavelengths for detecting the traces of CO_2 in the atmosphere [1]–[3]. Although the 1.6-μm pulsed laser can be achieved by directly exploiting the Er-doped crystal as the gain medium, the wider pulse duration is the main hindrance for such a light source to be used in the practical applications [4]–[6]. Alternatively, constructing an optical parametric oscillator (OPO) pumped by a well-developed Nd-doped crystal laser offers a promising approach to generate the light radiation near 1.6 μm. In comparison with the extracavity configuration, the intracavity OPO attracts much attention thanks to the more compact architecture of laser cavity as well as the lower pump threshold and higher conversion efficiency benefitted from the multi-pass of highly intense fundamental beam through the nonlinear crystal.

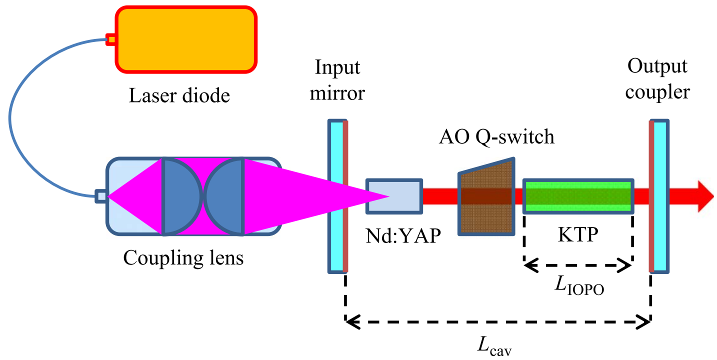

Fig. 1. Experimental setup of the diode-end-pumped actively *Q*-switched Nd:YAP/KTP eye-safe laser.

Moreover, the intracavity OPOs based on the non-critically phase-matched KTP and Potassium Titanyle Arsenate KTiOAsO4 (KTA) crystals, due to the advantages of maximizing the effective nonlinear coefficient and eliminating the walk-off effect among the pump, signal, and idler beams, have been widely developed over the past few years [7]–[14]. Nevertheless, to the best of our knowledge, the longest signal wavelength obtained from the non-critically phase-matched KTP- and KTA-based intracavity OPOs pumped by the Nd-doped crystal lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition band only reached 1573 nm [10]. Although it is a relatively new RTP nonlinear material, as well as an isomorph of the KTP crystal, was recently developed to produce the signal emission longer than 1.6 μm [15], [16], at least one shared optical components usually make their laser output rather sensitive when one attempts to individually align the fundamental and OPO cavities for optimizing the conversion efficiency with high stability.

The Nd:YAP material, also known as Nd:YAlO or Nd:YAlO$_3$, has been identified as a favorable active element for constructing a high-power solid-state laser owing to the similar physical, optical, and mechanical properties to the Nd:YAG crystal [17]–[19]. Moreover, the linearly polarized emission resulted from the orthorhombic lattice structure of the crystalline host makes the Nd:YAP laser essentially suitable for realizing efficient nonlinear wavelength conversion [20]–[22]. In this work, the high-gain emission line at 1080 nm of the *b*-cut Nd:YAP crystal is exploited to develop a compact KTP-based intracavity OPO for generating the eye-safe signal wavelength longer than 1.6 μm for the first time. We first systematically explore the acousto-optically *Q*-switched performance of the diode-end-pumped Nd:YAP laser, and the pulse-repetition-rate dependent fractional thermal loading is experimentally observed and theoretically analyzed with considering the effect of energy-transfer upconversion (ETU). We then design a monolithic KTP crystal to construct an efficient reliable intracavity OPO for extending the spectral emission from 1080 to 1603 nm. Under an absorbed pump power of 11 W, the maximum average output power of 1.11 W is efficiently generated at a pulse repetition rate of 10 kHz, corresponding to the diode-to-signal optical conversion efficiency of up to 10%. The shortest pulse duration of 2.4 ns, largest pulse energy of 190 μJ, and highest peak power of 67.3 kW are respectively achieved at a pulse repetition rate of 5 kHz. As far as we know, the spectral emission at 1603 nm is the longest signal wavelength ever reported among the diode-end-pumped Nd-doped crystal/KTP intracavity OPO eye-safe lasers. Moreover, the developed laser here can be expected to be practically useful for detecting the traces of greenhouse gases (CO_2) in the atmosphere.

2. Experimental Setup

The experimental arrangement of the diode-end-pumped actively *Q*-switched Nd:YAP/KTP eye-safe laser is schematically depicted in Fig. 1. A fiber-coupled laser diode with a core

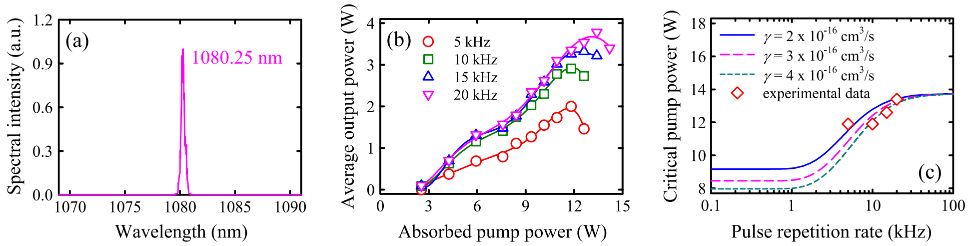

Fig. 2. (a) Optical spectrum and (b) average output power versus absorbed pump power for the fundamental operation at 1080 nm. (c) Theoretical calculation and experimental data for the critical pump power as a function of the pulse repetition rate.

diameter of 600 μm and a numerical aperture of 0.16 was employed as the pump source. Its emission wavelength was temperature-tuned to the strongest absorption around 803 nm of the Nd:YAP material. A pair of plano-convex lenses was used to reimage the fiber end into the laser crystal with the pump radius of 240 μm. The fundamental resonator was composed of the input mirror and the output coupler. The flat input mirror was coated for antireflection (AR) at 803 nm on the entrance side, and coated for high reflection (HR) at 1080 nm as well as high transmission (HT) at 803 nm on the other side. The flat output coupler was HR coated at 1080 nm and HT coated at 1603 nm. The gain medium was a 1% *b*-cut Nd:YAP crystal with the dimension of 3.7 mm in diameter and 5.85 mm in length. Both facets of the active element were AR coated at the pump and lasing wavelengths. We utilized a 20-mm-long acousto-optical (AO) Q-switch (Gooch & Housego) to realize the pulsed operation in the range of 5–20 kHz, and it was driven at a center frequency of 41 MHz with a RF power of 25 W. The AO Q-switch was AR coated at the lasing wavelength on both faces. The KTP crystal with the dimension of 3 mm $\times$ 3 mm $\times$ 20 mm was *x*-cut along $\theta = 90^\circ$, $\phi = 0^\circ$ for the type-II non-critically phase-matched OPO operation. The cavity mirrors for the OPO resonator were directly deposited on both sides of the KTP crystal to form a so-called monolithic cavity, which has proven its usefulness in improving the stability and efficiency of the eye-safe laser [23]. Referring to Fig. 1, the left face of the KTP crystal was HT coated at 1080 nm as well as HR coated at 1603 nm, and the right side was AR coated at 1080 nm, as well as coated to have the reflectivity of 50% at 1603 nm. Both laser and nonlinear crystals were wrapped with indium foil and mounted in water-cooled copper holders at the temperature of 16 °C to ensure stable laser output. The cavity lengths L_{cav} and L_{IOPO} for the fundamental and intracavity OPO resonators were 100 and 20 mm, respectively.

The spectral information at the laser output was analyzed by an optical spectrum analyzer (Advantest, Q8381A) that employs a diffraction grating monochromator for high-speed measurement of pulsed light with the resolution of 0.1 nm. A digital oscilloscope (LeCroy, WavePro 7100, 10 G samples/s, 1 GHz bandwidth) together with a fast InGaAs photodiode, were employed to record the pulse temporal behaviors.

3. Experimental Results and Discussion

First of all, we studied the output characteristic of the AO *Q*-switched Nd:YAP fundamental laser, where a flat output coupler with the reflectivity of 90% at 1080 nm was adopted instead of the aforementioned one. As shown in Fig. 2(a), the oscillating wavelength is found to locate at 1080.25 nm, corresponding to the highest gain of the Nd:YAP crystal operating on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition band. The dependence of the average output power on the absorbed pump power is illustrated in Fig. 2(b) for the pulse repetition rate of 5, 10, 15, and 20 kHz. It can be seen clearly that there exists a critical pump power beyond which the thermal-lensing effect would lead the laser cavity to be unstable, thus causing the roll-over phenomenon of the average output power with increasing the absorbed pump power. Moreover, the critical pump power is found to increase with increasing the pulse repetition rate. For the plane parallel cavity with a thin thermal lens located near the input mirror, the focal length of thermal lens should be larger than the cavity length, i.e., $f_{\text{th}} \geq L_{\text{cav}}$, to satisfy the cavity stability criterion. Meanwhile, the effective focal length of the thermal lens can be evaluated by [24], [25]

$$\frac{1}{f_{\text{th}}} = \frac{\xi P_{\text{abs}}}{\pi K_c} \int_0^{l_{\text{cry}}} \frac{\alpha e^{-\alpha z}}{1 - e^{-\alpha l_{\text{cry}}}} \frac{1}{\omega_p^2(z)} \left[\frac{1}{2}\frac{dn_o}{dT} + (n_o - 1)\alpha_T \frac{\omega_p(z)}{l_{\text{cry}}} \right] dz \tag{1}$$

$$\omega_p(z) = \omega_{p0} \sqrt{1 + \left[\frac{M^2 \lambda_p}{n_o \pi \omega_{p0}^2} (z - z_0) \right]^2} \tag{2}$$

where ξ is the fractional thermal loading, which is normally given by $(1 - \lambda_p/\lambda_l)$ under the lasing condition, λ_l is the lasing wavelength, P_{abs} is the absorbed pump power, K_c and l_{cry} are the thermal conductivity and the length of the laser crystal, α is the absorption coefficient at the pump wavelength λ_p, dn_o/dT is the temperature dependence of the refractive index n_o, α_T is the coefficient of the thermal expansion, M^2 is the pump beam quality factor, and $\omega_p(z)$ is the variation of the pump radius, where the pump beam waist ω_{p0} is assumed a distance z_0 from the entrance of the laser crystal. For our 1080-nm Nd:YAP laser pumped by the 803-nm laser diode, the thermal focal length can be evaluated to decrease from 470 to 100 mm when the absorbed pump power increases from 3 to 15 W under the continuous-wave operation. On the other hand, combining (1) with the cavity stability criterion, the critical pump power $P_{\text{abs,cri}}$ can be expressed as

$$\xi P_{\text{abs,cri}} = \frac{\pi K_c}{L_{\text{cav}}} \left\{ \int_0^{l_{\text{cry}}} \frac{\alpha e^{-\alpha z}}{1 - e^{-\alpha l_{\text{cry}}}} \frac{1}{\omega_p^2(z)} \left[\frac{1}{2}\frac{dn_o}{dT} + (n_o - 1)\alpha_T \frac{\omega_p(z)}{l_{\text{cry}}} \right] dz \right\}^{-1} \tag{3}$$

Since the right-hand side of (3) is nearly invariable, it can be concluded that the increase of the critical pump power with increasing the pulse repetition rate means that the fractional thermal loading is a decreasing function with the pulse repetition rate. Previously, many studies have demonstrated that the ETU process has a considerable influence on the population mechanism of the Nd-doped crystals at high excitation densities [26]–[28]. Generally speaking, the ETU effect would cause the reductions of the effective lifetime as well as the available population inversion of the $^4F_{3/2}$ level and, thus, increase the fractional thermal loading in the laser material. Considering the ETU effect and following the same analyses presented in [29], the fractional thermal loading can be expressed as a function of the pulse repetition rate and the absorbed pump power. Therefore, the critical pump power with respect to the pulse repetition rate can be theoretically determined by solving the following equation:

$$P_{\text{abs,cry}} = \frac{1}{\xi(f, P_{\text{abs,cri}})} \frac{\pi K_c}{L_{\text{cav}}} \left\{ \int_0^{l_{\text{cry}}} \frac{\alpha e^{-\alpha z}}{1 - e^{-\alpha l_{\text{cry}}}} \frac{1}{\omega_p^2(z)} \left[\frac{1}{2}\frac{dn_o}{dT} + (n_o - 1)\alpha_T \frac{\omega_p(z)}{l_{\text{cry}}} \right] dz \right\}^{-1}. \tag{4}$$

With the parameters [30] $K_c = 11$ W/(m $\cdot$ K), $l_{\text{cry}} = 5.85$ mm, $\alpha = 0.48$ mm^{-1}, $\lambda_p = 803$ nm, $dn_o/dT = 14.5 \times 10^{-6}$ K^{-1}, $n_o = 1.95$, $\alpha_T = 4.3 \times 10^{-6}$ K^{-1}, $M^2 = 190$, $\omega_{p0} = 240$ μm, $z_0 = 1$ mm, $L_{\text{cav}} = 100$ mm, $\sigma = 2.4 \times 10^{-19}$ cm^2 (the stimulated emission cross section of the Nd:YAP material), $R_{\text{OC}} = 0.9$ (the reflectivity of the output coupler), $L = 0.01$ (roundtrip dissipative loss of the resonator), $\tau = 180$ μs (the upper-state lifetime of the Nd:YAP material), and $\lambda_f = 1061$ nm (the average fluorescence wavelength), the calculated results are plotted in Fig. 2(c) together with the experimentally measured data deduced from Fig. 2(b). Since the upconversion rate γ for the Nd:YAP crystal has never been reported, three values are used for the calculation,

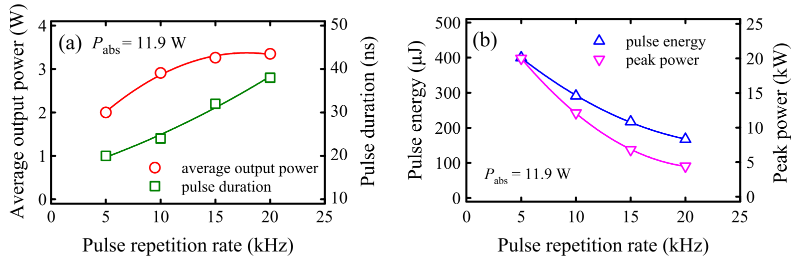

Fig. 3. Dependence of (a) average output power, pulse duration, (b) pulse energy, and peak power at 1080 nm on the pulse repetition rate.

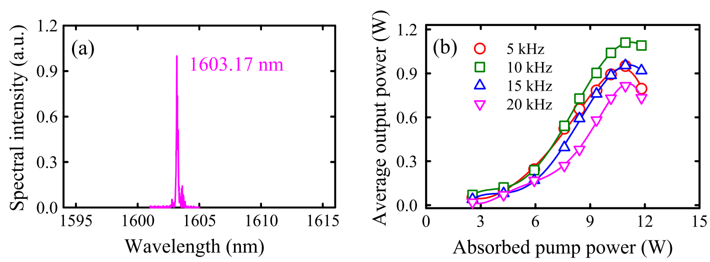

Fig. 4. (a) Optical spectrum and (b) average output power versus absorbed pump power for the intracavity OPO operation at 1603 nm.

i.e., $\gamma = 2 \times 10^{-16}$ cm^3/s, $\gamma = 3 \times 10^{-16}$ cm^3/s, and $\gamma = 4 \times 10^{-16}$ cm^3/s. The theoretical analysis with taking the ETU effect into account can be found to show similar trend with the experimental measurement. It, thus, can be concluded that the ETU effect has to be carefully considered in scaling the output power of the *Q*-switched Nd:YAP laser, especially at the low pulse repetition rate.

Then, the absorbed pump power is fixed as 11.9 W to systematically investigate the dependence of the average output power, pulse width, pulse energy, and peak power on the pulse repetition rate for the actively *Q*-switched Nd:YAP laser at 1080 nm. As shown in Fig. 3(a), by increasing the pulse repetition rate from 5 to 20 kHz, the average output power changes from 2 to 3.35 W and the pulse width monotonically raises from 20 to 38 ns. Consequently, the pulse energy and the peak power can be evaluated to decrease from 400 to 168 μJ and from 20 to 4.4 kW when the pulse repetition rate is varied in the range of 5–20 kHz, as illustrated in Fig. 3(b).

Next, we perform the wavelength extension to the eye-safe region via the intracavity OPO based on a monolithic KTP crystal. Fig. 4(a) depicts the optical spectrum, showing the signal wavelength to be 1603.17 nm. To the best of our knowledge, this is the longest signal wavelength obtained with the non-critically phase-matched KTP- or KTA-based intracavity OPO driven by the Nd-doped crystal lasers. The dependence of the average output power at 1603 nm on the absorbed pump power at 803 nm is illustrated in Fig. 4(b) for the pulse repetition rate of 5, 10, 15, and 20 kHz. The critical pump powers for the intracavity OPO operation are lower than those for the fundamental operation, implying that the fractional thermal loading is more significant during the generation of 1603-nm line, as compared with the production of 1080-nm emission. Functionally, the KTP crystal serves as a nonlinear output coupler in a manner analogous to the transmitting mirror of the fundamental Nd:YAP laser. Its effective output coupling is not a fixed value but shows a strong dependence for different pulse repetition rate. Maybe this is the reason why the critical pump power does not display an observable relationship with the pulse repetition rate during the intracavity OPO process. The theoretical model with considering this effect along with the ETU effect is under development.

Fig. 5(a) and (b) describe the average output power, pulse duration, pulse energy, and peak power at the signal wavelength versus the pulse repetition rate under an absorbed pump power

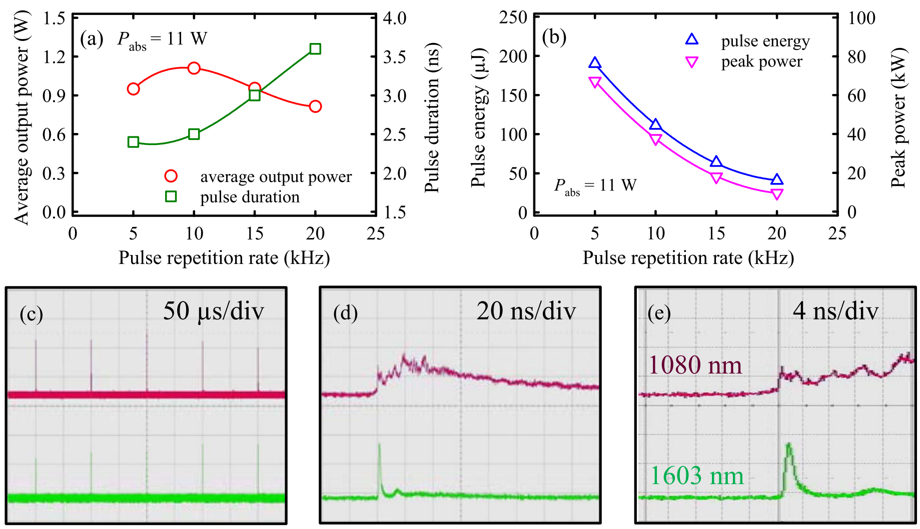

Fig. 5. Dependence of (a) average output power, pulse duration, (b) pulse energy, and peak power at 1603 nm on the pulse repetition rate. Oscilloscope traces at 10 kHz with the time spans of (c) 500 μs, (d) 200 ns, and (e) 40 ns.

of 11 W. Although the average output power at 1080 nm rises with the increase of the pulse repetition rate, the conversion efficiency of the intracavity OPO with respect to the fundamental power, which is proportional to the peak power at 1080 nm, decreases with the pulse repetition rate. As a consequence, the maximum average output power at 1603 nm is achieved at a pulse repetition rate of 10 kHz with the value to be 1.11 W, corresponding to the signal-to-diode and signal-to-fundamental optical conversion efficiencies of 10% and 38%, respectively. The nonlinear frequency conversion of the intracavity OPO process results in the pulse shortening at 1603 nm. When the pulse repetition rate is increased from 5 to 20 kHz, the duration of the major signal pulse slightly changes from 2.4 to 3.6 ns, while the pulse energy is estimated to vary from 190 to 41 μJ. Typical temporal behaviors of the residual fundamental and OPO output pulses at a pulse repetition rate of 10 kHz are recorded. The pulse-to-pulse amplitude stability at 1603 nm is experimentally found to be within ±5%, as shown in Fig. 5(c). Fig. 5(d) and (e) depict the detailed dynamical interaction between 1080 and 1603 nm with the time span of 200 and 40 ns. The satellite pulse after the main temporal peak at 1603 nm is due to the fact that the OPO threshold is reached again, and it may be avoided by increasing the output coupling for the signal wave. The ratio of the energy of the main to entire pulses is calculated to be around 85%. Therefore, the peak power is evaluated to decrease from 67.3 to 9.6 kW as the pulse repetition rate is increased from 5 to 20 kHz. The beam quality factors for both orthogonal directions are found to be generally better than 1.8. The obtained optical conversion efficiency as well as the laser performance at 1603 nm are comparable with the previously developed Nd-doped crystal/KTP intracavity OPOs operating around 1.57 μm.

4. Conclusion

In summary, we have successfully developed a compact reliable diode-end-pumped actively *Q*-switched Nd:YAP/KTP laser at 1603 nm based on a monolithic intracavity OPO cavity. The ETU effect has been theoretically analyzed and experimentally verified to be the main limiting factor for power scaling of the fundamental as well as intracavity OPO operations. Under an absorbed pump power of 11 W, the maximum average output power of up to 1.11 W at the eye-safe radiation was efficiently generated at a pulse repetition rate of 10 kHz. At a pulse repetition rate of 5 kHz, the shortest pulse duration, largest pulse energy, and highest peak power were achieved to be 2.4 ns, 190 μJ, and 67.3 kW, respectively.

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