

Article

Diode-Pumped Actively Q-Switched Nd:YVO₄/RTP Intracavity Raman Laser at 1.49 μm

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Abstract: For the first time, a diode-pumped actively Q-switched Nd:YVO₄/RbTiOPO₄ (RTP) intracavity Raman laser at 1.49 μm was demonstrated to the best of our knowledge. Experimentally, a dual-end diffusion-bonded YVO₄-Nd:YVO₄-YVO₄ crystal was employed as the laser medium to generate 1.34 μm laser radiation, and an RTP crystal as the Raman medium to enable the frequency conversion, by which radiation at 1.49 μm was achieved successfully. With an incident pump power of 10.4 W, an average output power of 502 mW was obtained at a pulse repetition rate of 15 kHz, corresponding to a conversion efficiency of 4.8%.

Keywords: diode-pumped lasers; stimulated Raman scattering; Raman lasers; RbTiOPO₄ crystal

1. Introduction

The eye-safe lasers around 1.5 μm are of great importance for such kinds of potential applications, such as optical communications, optical sensing, lidar, and medicine [1–3]. Usually, only limited wavelengths can be generated directly by the gain media due to their fixed energy-level structures. To generate the wavelengths that cannot be addressed directly, one has to resort to nonlinear frequency conversion technique. Stimulated Raman scattering, as an efficient method for laser frequency conversion, is quite promising for generating radiation in the eye-safe spectral region, because of the availability of suitable pumping laser and Raman crystal with required Raman frequency shift. Thus far, many different wavelengths have been successfully generated by using different Raman crystals, such as nitrates (Ba(NO₃)₂) [4–6], vanadates (YVO₄, GaVO₄) [7–9], and tungstates (KLu(WO₄)₂, BaWO₄, SrWO₄) [10–12].

RTP crystal is isomorphic with KTiOPO₄ (KTP) crystal, which belongs to orthorhombic system, mm2 point group, and Pna2₁ space group [13–15]. It shows high resistivity, high second-order nonlinear coefficient, and high damage threshold. Therefore, it has been widely used in optical parametric oscillators [16,17], and high repetition rate electro-optically Q-switched lasers [18,19]. Until recently, it was found that RTP crystal is Raman active and could be used for high efficiency Raman conversion. In 2006, Pearce S. reported an RTP-based Raman laser, which delivered a pulsed laser at 1096 nm with a pulse duration of less than 1 ns [20]. In 2016, Duan et al. demonstrated an intracavity RTP-based cascaded Raman laser with multi-wavelength output [21]. In 2018, they reported a compact passively Q-switched RTP-based cascaded Raman laser with multi-Stokes laser output at 1.1 μm [22]. Actually, there are many Raman vibration frequencies for RTP crystal, such as 269 cm⁻¹, 689 cm⁻¹, and 765 cm⁻¹, because of the distortion of TiO₆, the combination of mode vibration frequencies, and the splitting of some three degenerate modules [13–15,23]. Hence multi-wavelength Stokes output is

easy to be obtained, which, however, has influence on the laser stability. To the best of our knowledge, almost all the researches were focused on the wavelength range of 1.1 μm , and there is still no report on the generation of 1.5 μm source based on RTP Raman laser.

In this contribution, we report an LD end-pumped actively Q-switched Nd:YVO₄/RTP intracavity Raman laser at 1.49 μm for the first time. A single-wavelength Raman laser at 1495 nm was obtained by optimizing the laser resonator. With an incident pump power of 10.4 W, an average power of 502 mW was achieved with a repetition rate of 15 kHz. The corresponding conversion efficiency was 4.8%.

2. Experimental Setup

Figure 1 shows the schematic diagram of the experimental setup of the diode-pumped actively Q-switched Nd:YVO₄/RTP intracavity Raman laser. The pump source was a fiber-coupled 808 nm laser diode. The core diameter of the fiber is 400 μm and the numerical aperture is 0.22. A focusing lens system with a focal length of 100 mm and a coupling efficiency of 95% was used to couple the pump beam into the laser crystal. A concave-plane cavity was used in the experiment. The concave mirror M₁ with a curvature radius of 3000 mm is high reflection (HR) coated at 1342 nm and 1495 nm ($R > 99.8\%$) and anti-reflection (AR) coated at 808 nm ($T > 95\%$). The output coupler M₂ (plane mirror) is HR coated at 1342 nm ($R > 99.8\%$) and partial reflection (PR) coated at 1495 nm ($R = 92\%$). An a-cut dual-end diffusion-bonded Nd:YVO₄ crystal was used as the gain medium with dimensions of 3 mm \times 3 mm \times 12 mm. It consists of one 2-mm-long undoped YVO₄ crystal at the pump facet, one 8-mm-long 0.3 at.% Nd³⁺-doped YVO₄ crystal at the middle and one 2-mm long undoped YVO₄ crystal at the other facet. The diffusion bonded crystal can alleviate thermal lensing effect considerably. An X-cut RTP crystal was adopted as the Raman medium with dimensions of 4 mm \times 4 mm \times 30 mm. The diffusion-bonded Nd:YVO₄ and RTP crystals were both wrapped with indium foil and mounted in water-cooled copper blocks, and the temperature was maintained at 19 $^{\circ}\text{C}$. An acousto-optic (AO) Q-switch (Gooch and Housego, QS041-H/J) was placed between the bonded Nd:YVO₄ crystal and the RTP crystal. Both sides of the diffusion-bonded Nd:YVO₄ crystal the RTP crystal and the AO Q-switch are AR coated at 1342 nm and 1495 nm ($R < 0.2\%$). All the elements are placed as close as possible to form a compact cavity, with a cavity length of 88 mm. A dichroic mirror M₃, which is AR coated at 1495 nm ($T > 98\%$) and HR coated at 1342 nm ($R > 99\%$) was employed to extract the 1495 nm Stokes radiation from the residual fundamental radiation.

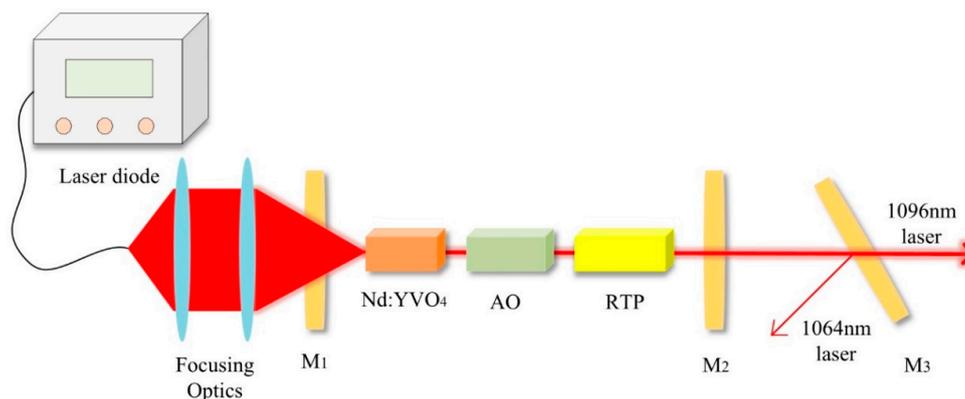


Figure 1. Schematic diagram of the diode-pumped actively Q-switched Nd:YVO₄/RTP intracavity Raman laser.

The average output power was measured by a power meter (Moletron PM10) connected to Moletron EPM2000. The spectrum was recorded by an optical spectrum analyzer (Yokogawa AQ 6315A, 350–1750 nm). The pulse temporal behavior was monitored by a Tektronix digital phosphor oscilloscope (TDS 5052B, 5 G Samples/s, 500 MHz bandwidth) with a fast PIN photodiode.

3. Experimental Results and Discussion

Firstly, the fundamental laser performances were characterized at 1342 nm experimentally. To this end, the mirror M_2 shown in Figure 1 was replaced with a plane mirror PR coated at 1342 nm ($T = 16\%$). Figure 2 shows the output power of the 1342 nm laser with respect to the incident pump power. A maximum continuous wave (CW) output power of 2.60 W was obtained with a pump power of 15 W. The laser slope efficiency was 17.2%. For Q-switched operation, average powers of 1.72 W, 1.83 W and 1.99 W were obtained at pulse repetition rates (PRRs) of 5 kHz, 10 kHz and 15 kHz. The pulse duration was about 42 ns when the pump power was 15 W.

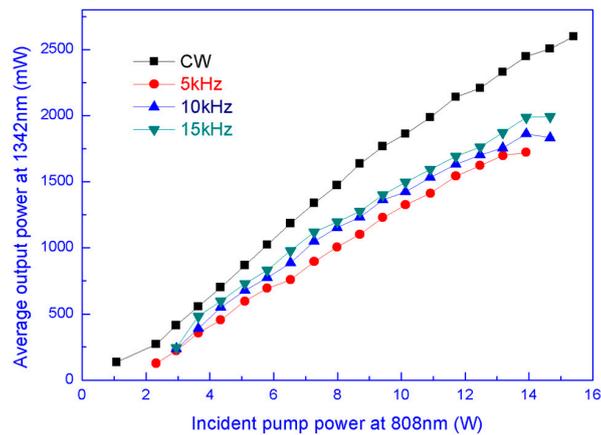


Figure 2. Average output power at 1342 nm with respect to the incident pump power at the PRRs of 5 kHz, 10 kHz, and 15 kHz.

Stokes radiation was easily obtained when M_2 was used as the output mirror. Figure 3 shows the spectrum. It can be seen that the frequency shifts between the Stokes and the laser line is 765 cm^{-1} , which is in good agreement with the Raman vibration frequency of RTP crystal. A dichroic mirror M_3 was used to separate the Raman laser from the residual fundamental radiation. Figure 4 shows the average output power of the 1495 nm laser with respect to the incident 808 nm pump power at the PRRs of 5 kHz, 10 kHz, and 15 kHz. SRS is a third order nonlinear process, so decreasing the PRR is beneficial for lowering the threshold for the Raman laser. As shown in Figure 4, the threshold pump powers were 5.05 W, 6.29 W, and 7.07 W at 5 kHz, 10 kHz, and 15 kHz PRRs, respectively. With increasing pump power, the average output power reached 388 mW, 450 mW, and 502 mW at the PRRs of 5 kHz, 10 kHz, and 15 kHz, respectively. And the corresponding optical-optical conversion efficiencies from the diode laser to the 1495 nm laser were 4.23%, 4.33% and 4.82%.

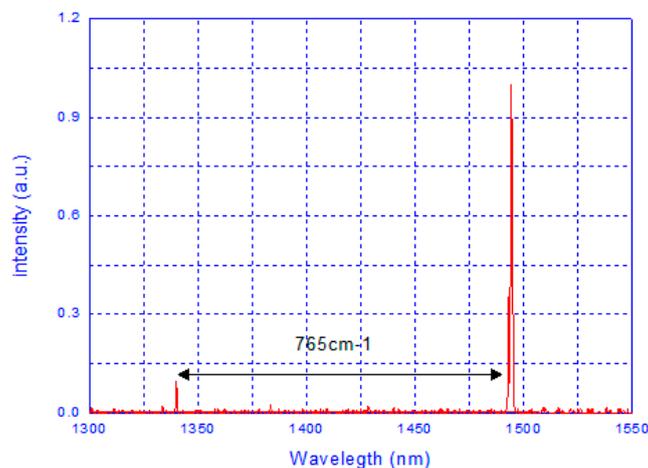


Figure 3. Optical spectrum of the actively Q-switched Nd:YVO₄/RTP intracavity Raman laser.

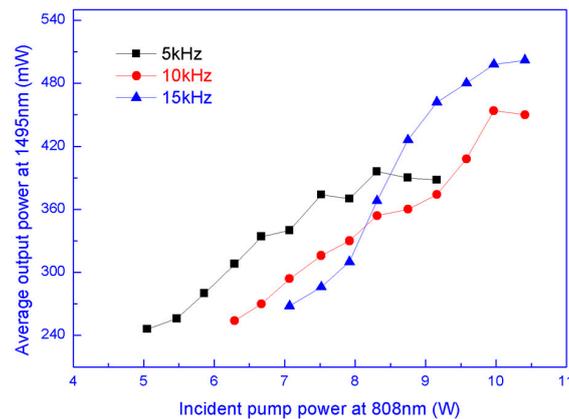


Figure 4. Average output power of 1495 nm laser with respect to the incident pump power for the PRRs of 5 kHz, 10 kHz, and 15 kHz.

The pulse's temporal behavior was recorded by a digital phosphor oscilloscope. Figure 5 gives the relationship between the pulse duration of the Raman laser with respect to the incident pump power at the PRRs of 5 kHz, 10 kHz, and 15 kHz, respectively. It can be seen that the pulse duration gets narrowed with increasing pump power. For a given pump power, it also gets narrowed with increasing PRR. Figure 6 gives the typical pulse shape of the Raman laser which was recorded at the pump power of 10.4 W and the PRR of 15 kHz. The Raman laser pulse duration was 34 ns. The corresponding single pulse energy was 33.5 μ J, and the peak power was 0.98 kW.

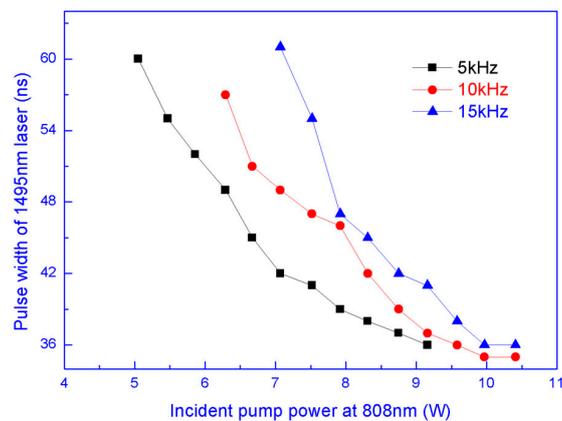


Figure 5. Pulse durations at the Stokes wavelength with respect to the incident pump power for the PRRs of 5 kHz, 10 kHz, 15 kHz.

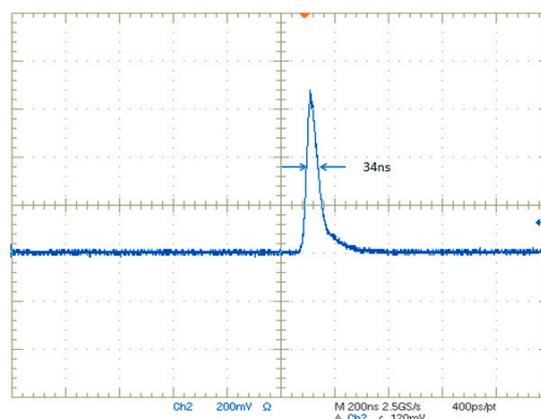


Figure 6. Typical pulse trace for the Raman pulse.

4. Conclusions

In summary, the characteristics of a diode-pumped actively Q-switched Nd:YVO₄/RTP Raman laser at 1495 nm have been investigated for the first time. The laser characteristics were obtained under different PRRs and pump powers. When the incident pump power was 10.4 W and the PRR was 15 kHz, the average output power of the Raman laser was 502 mW. The corresponding single pulse energy was 33.5 μJ, and the peak power was 0.98 kW.

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