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Power scale-up of the diode-pumped actively Q-switched Nd:YVO_4 Raman laser with an undoped YVO_4 crystal as a Raman shifter

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ABSTRACT With an undoped YVO_4 crystal as a Raman shifter, we substantially improved the reliability and the output performance of an actively Q-switched 1176-nm Nd:YVO_4 Raman laser. With an incident pump power of 18.7 W, the average power is greater than 2.6 W at 80 kHz. The pulse width of the pulse envelope is shorter then 5 ns with mode-locked modulation. With an incident pump power of 12.7 W, the pulse energy and peak power is higher than 43 μJ and 14 kW at 40 kHz.

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1 Introduction

Since the development of new Raman crystals in the last decade [1–12], the stimulated Raman scattering (SRS) in crystal [13] has provided solid-state lasers with an important way of operating in different wavelengths. The most commonly known materials for SRS are $Ba(NO_3)_2$ [14], $LiIO_3$ [15], $KGd(WO_4)_2$ [16], $PbWO_4$ [17], and $BaWO_4$ [5, 6, 18–22]. Moreover, for self-Raman lasers, the materials such as Yb:$KGd(WO_4)_2$ [23], Nd:$KGd(WO_4)_2$ [24–31], Nd:$PbWO_4$ [32], Nd:$Gd_xY_{1-x}VO_4$ [33, 34], Nd:$PbMoO_4$ and Nd:$SrMoO_4$ [11, 12] have been reported. A combination of their laser-emission and SRS properties made these crystals appealing self-Raman media. Nevertheless, the Raman scattering was generated by host material. Lasers could offer a number of advantages if the SRS could be transferred from self-Raman media to additional undoped crystals.

Nd-doped YVO_4 and $GdVO_4$ crystals, the acknowledged useful gain media, were used in passively Q-switched (PQS) and actively Q-switched (AQS) self-Raman lasers [34–39]. For instance, an AQS Nd:YVO_4 self-Raman laser demonstrated the average power, pulse width and peak power of 1.5 W, 18 ns and 4.2 kW for the Stokes wavelength of 1176 nm [36]. However, the issue of the filed-induced crystal damage usually restricted the output powers in self-Raman Q-switched lasers [39].

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In this work, to our knowledge, we report a new design of a diode-pumped AQS 1176-nm Nd:YVO_4 Raman laser to increase the average power, repetition rate, peak power, and damage threshold comprehensively. An undoped YVO_4 crystal is employed to be an intracavity Raman shifter in a Nd:YVO_4 AQS laser. At an incident pump power of 18.7 W, the AQS Raman laser produces an average power greater than 2.6 W with a pulse repetition rate of 80 kHz. The output pulses noticeably display a mode-locking phenomenon that leads to the maximum peak power to be higher than 14 kW.

2 Experimental setup

Figure 1 shows the experiment configuration for AQS Nd:YVO_4 1176-nm Raman laser which differs from self-Raman laser. The pump source was an 808-nm fiber-coupled laser diode with the core diameter of 800 μm, the numerical aperture of 0.16, and the maximum output power of 25 W. A focusing lens unit with a 85% coupling efficiency was used to reimage the pump beam into the gain medium with a pump spot radius of 400 μm. The gain medium, a 9-mm-long a-cut Nd:YVO_4 crystal with low concentrations, 0.25 at. %, was used to reduce thermally induced fracture [36]. Both sides of this laser crystal were coated for antireflection (AR) at 1.06 μm ($R < 0.2\%$). The Raman crystal was a 9.6-mm-long a-cut undoped YVO_4 crystal. These two crystals were both wrapped with indium foil and mounted in water-cooled copper blocks individually. The 30-mm-long acousto-optic (AO) Q switch (NEOS Technologies) had AR coating at 1064 nm on both faces and was driven at a 27.12-MHz center frequency by 15 W of RF power. The resonator was a plano-concave configuration. Front mirror, a 500-mm radius-of-curvature concave mirror, was coated with AR coating at 808 nm ($R < 0.2\%$) on the entrance face, and with high-reflection (HR) coating at 1064 nm ($R > 99.8\%$) and high-transmission (HT) coating at 808 nm ($T > 90\%$) on the other face. The coating of front mirror at 1176 nm was high-reflection, too. The output coupler (OC) was a flat mirror with HR coating at 1064 nm ($R > 99.8\%$) and partial-reflection (PR) coating at 1176 nm ($R = 51\%$). The cavity length was around 115 mm and depended on pumping power. The spectrum of laser output was monitored by an optical spectrum analyzer (Advantest Q8381A, includ-

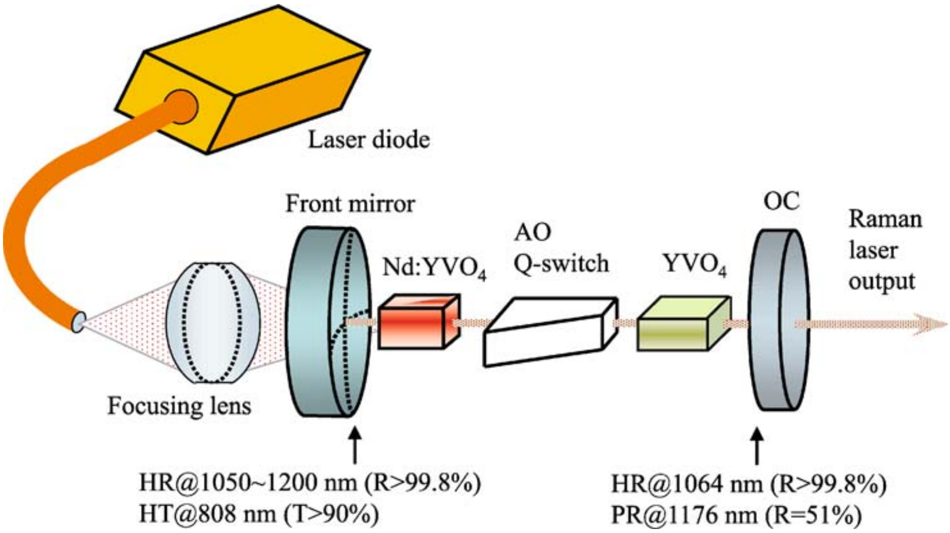

FIGURE 1 Schematic of a diode-pumped actively Q-switched Nd:YVO_4 Raman laser at 1176 nm

ing a diffraction lattice monochromator) with a resolution of 0.1 nm. The temporal behaviors for fundamental and Raman pulses were recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gs/s, 1-GHz bandwidth) with two fast p-i-n photodiode and an interference filter allowing transmission only at 1064 nm.

3 Experimental results and discussion

As a stimulated Raman material, taking the place of Nd:YVO_4 by undoped YVO_4 has advantages on robustness and output properties. Figure 2 displays the experimental result for optical spectrum of the laser output and Raman scattering spectrum of the YVO_4. The first Stokes wavelength near 1176 nm was conversed from the fundamental wavelength near 1064 nm by Raman peak at 890 cm^{-1}. The Raman shift of Nd:YVO_4 and undoped YVO_4 were almost the same, came from the same periodic YVO_4 lattice. But crystals without dopant had more perfect lattice, which brought on higher damage threshold and more stable frequency conversion. So, we can put the pure YVO_4 as a Raman crystal in the position where the intensity is highest in the cavity, and still increase the pumping power. Further, the reflectance of OC can be lower (from 93% to 51%) to scale up average output power due to lower lasing threshold at Raman wavelength. By using lower reflection coating, we can narrow the pulse width. At the same time, when we over drove current during the experiment, the damage never happened in Nd:YVO_4, but in Raman crystal. That means the SRS was generated mainly in pure YVO_4, a more reliable and replaceable component in practical laser.

Figures 3 and 4 illustrate the output performance of AQS 1176-nm Nd:YVO_4 Raman laser. The average output power at the Stokes wavelength of 1176 nm with respect to the inci-

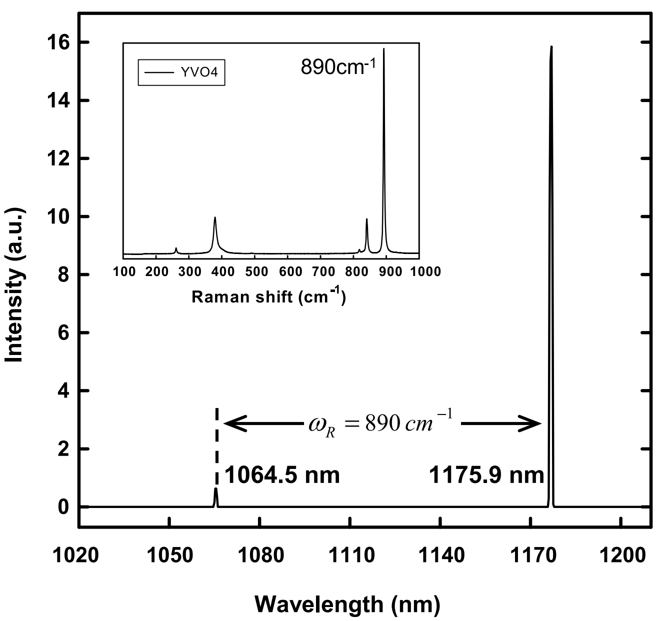

FIGURE 2 Optical spectrum of the actively Q-switched Raman output. The Raman scattering spectrum of an YVO_4 crystal showed in *inset*, which is almost the same as it of Nd:YVO_4 crystal

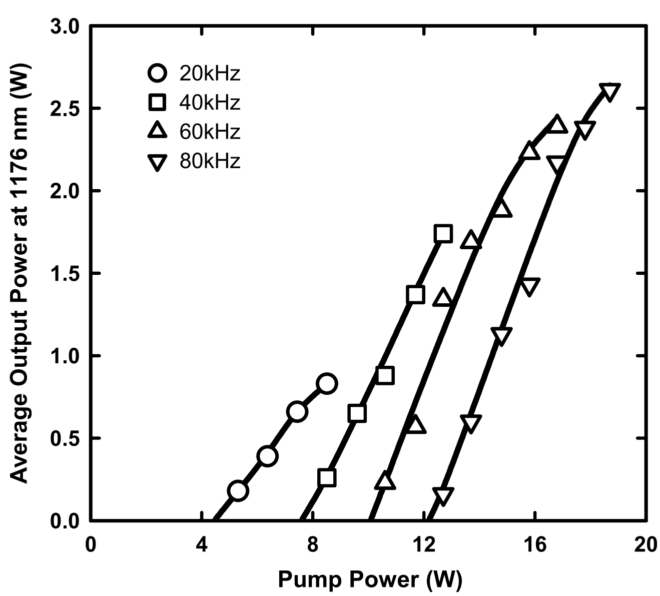

FIGURE 3 The average output power at the Stokes wavelength of 1176 nm with respect to the incident pump power at different pulse repetition rate from 20 kHz to 80 kHz

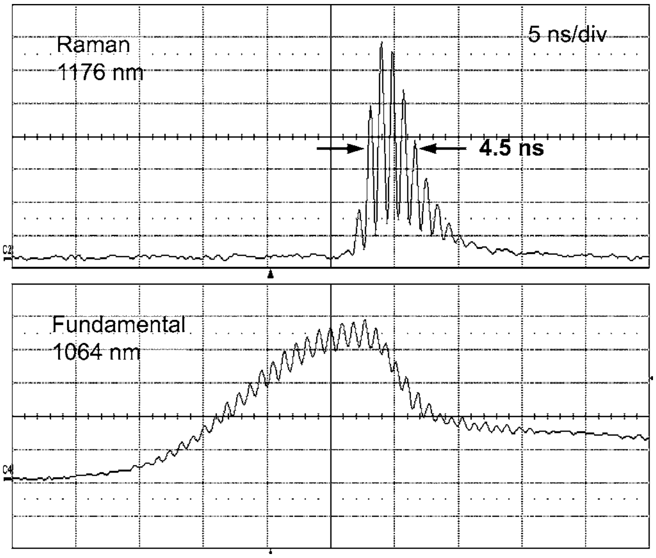

FIGURE 4 An oscilloscope trace with mode-locking effect for fundamental and Raman pulses

dent pump power for different pulse repetition rate of 20, 40, 60, and 80 kHz shown in Fig. 3. Because the thermal loading of the end-pumped Q-switched Nd-doped laser increases with decreasing repetition rate [24, 25], it can be seen that although the pumping threshold is higher, increasing the pulse repetition rate can efficiently increase the maximum average output power at 1176 nm and its maximum pump power ($P_{\mathrm{p,max}}$). And for a certain repetition rate, to pump over $P_{\mathrm{p,max}}$ will get the unstable Raman conversion and fall the output power. The average output power is up to 2.61 W with an incident pump power of 18.7 W at a repetition rate of 80 kHz, corresponding to the conversion efficiency of 14% and slope efficiency of 40%. Comparing to results of 1176-nm self-Raman laser by use of Nd:YVO_4 with lower dopant concentration of 0.2 at. % [36], this Raman laser still has the increase of ratio in average power of 74% and in conversion efficiency of 0.7%. It could be better if we were able to use 0.2 at. % Nd:YVO_4 and correctly AR-coated c-cut [41] YVO_4 in this Raman laser. On the other hand, the maximum pulse energy is generally greater then 40 μJ at repetition rate from 20 to 60 kHz, and up to 43.5 μJ at 40 kHz with an incident pump power of 12.7 W. The maximum pulse energy at repetition rate of 80 kHz is 32.6 μJ.

The typical time traces for fundamental and Raman pulses are shown in Fig. 4. The pulse width is always shorter then 5 ns, but the effective pulse width is much shorter due to mode-locked shape. With the pulse energy of 43.5 μJ, the pulse width of the pulse envelop in Fig. 4 is 4.5 ns, and the peak power of the pulse seen as a Gaussian shape should be 9.7 kW. However, after curve fitting for the mode-locked shape, the peak power is enhanced to 14 kW, 1.45 times the 9.7 kW. In other words, the effective pulse width is around 3.1 ns which is much shorter than 18 ns of self-Raman laser [36]. Comparing to 1176-nm Nd:YVO_4 AQS self-Raman laser of 4.2 kW [36], the output peak power was enhanced to be more than two times. The present peak-power level was close to the results of the PQS Nd:$GdVO_4$ self-Raman lasers in which the average power, pulse width and peak power were found to be 83 mW, 500 ps, and 9.2 kW at 1174 nm in [37], or 140 mW, 750 ps, and 8.4 kW at 1176 nm in [38].

4 Conclusions

In conclusion, with an undoped YVO_4 as a stimulated Raman crystal, we substantially improve the damage threshold, repetition rate, average output power, pulse width, and the peak power of AQS Nd:YVO_4 Raman lasers at 1176 nm. With an incident pump power of 18.7 W, the average power is 2.6 W at 80 kHz correspond to the optical-to-optical conversion efficiency of 14%. Coming with the mode-locked pulse shape, the effective cavity dump of intracavity SRS leads to peak power at 1176 nm that is generally greater than 10.5 kW at repetition rate from 20 to 80 kHz. With an incident pump power of 12.7 W, the pulse energy and peak power is higher than 43.5 μJ and 14 kW at 40 kHz.

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