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3.1 W laser-diode-end-pumped composite Nd : YVO_4 self-Raman laser at 1176 nm

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Abstract We report a laser-diode-end-pumped acousto-optical Q-switched double-end diffusion-bonded Nd : YVO_4 self-Raman laser at 1176 nm. The maximum average output power at the first-Stokes wavelength of 1176 nm was obtained to be 3.1 W at the incident pump power of 25 W and the repetition rate of 90 kHz, with the corresponding optical conversion efficiency of 12.4%. The shortest pulse width, the maximum pulse energy and the highest peak power were measured to be 5 ns, 42 μJ and 7.5 kW, respectively.

1 Introduction

In the past few years, Raman lasers which are based on stimulated Raman scattering (SRS) have attracted much attention because they can achieve wavelength regions not directly available with traditional solid-state lasers. There are many advantages which distinguish solid-state Raman media from traditional liquid-state and gas-state Raman media, such as high mechanical quality, chemical inertness, high gain, good thermal conductivity and long lifetime. Conventional Nd : YVO_4 crystals have been identified as efficient laser materials. YVO_4 crystals have the Raman shift of 890 cm^{-1} and a moderately high Raman gain coefficient of around 4.5 cm/GW at 1000 nm, which were discussed by Kaminskii et al. [1]. Thus, a single Nd : YVO_4 crystal can be employed as a self-Raman laser material which performs the dual functions of laser material and Raman medium to generate the first-Stokes output. The laser radiation at 1176 nm and 1525 nm based on self-Raman conversion of 1064 nm and 1342 nm in an actively Q-switched Nd : YVO_4 laser have been reported, respectively [2–5]. Frequency doubling of solid-state self-Raman lasers at 1.17 μm has been proved to be a feasible approach to obtain radiation in yellow–orange regions. In 2004, the average output power of 125 mW at 1178.6 nm was achieved from a diode-pumped passively Q-switched Nd : YVO_4 self-Raman laser by Chen [2], corresponding to an optical conversion efficiency of 6.3%. In the same year, the average output power of 1.5 W at 1176 nm was achieved from a diode-pumped actively Q-switched Nd : YVO_4 self-Raman laser [3], with the corresponding optical conversion efficiency of 13.9%. However, the conventional Nd : YVO_4 laser crystals simultaneously acting as a Raman medium have stronger thermal effects because the thermal load is generated not only from the absorption of pump light but also from the Raman conversion. Therefore, how to mitigate the thermal effects is identified as a major factor for scaling up self-Raman lasers. Recently, employing a composite crystal with a nonabsorbing undoped end has been proved to be a promising way of mitigating thermal effects to improve the performance of diode-pumped solid-state lasers [6, 7]. Especially, the composite crystal was successfully applied to the Q-switched self-Raman eye-safe laser at 1525 nm recently [8].

In this work, we report a diode-end-pumped acousto-optical (AO) Q-switched laser at 1176 nm, with a double-end diffusion-bonded Nd : YVO_4 crystal as the self-Raman medium. The first-Stokes radiation at 1176 nm was efficiently generated by self-Raman frequency conversion of 1064-nm radiation. The maximum average output power at

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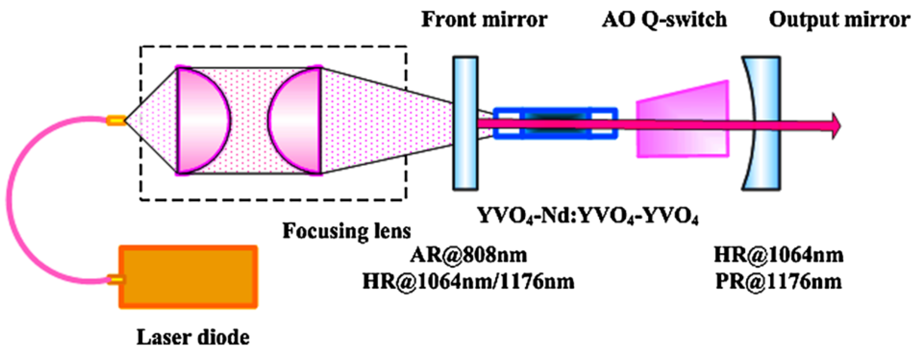

Fig. 1 Schematic diagram of the experimental composite Nd : YVO_4 self-Raman laser setup

1176 nm was obtained to be 3.1 W, with the corresponding optical conversion efficiency of 12.4%. The excellent laser performance demonstrates that composite vanadate crystals are promising self-Raman laser materials for generating high-power Raman radiation with high efficiency.

2 Experimental setup

The diode-pumped self-Raman conversion laser experiments were carried out in a plano–concave resonator, as shown schematically in Fig. 1. The pump source was a commercially available high-power fiber-coupled diode-laser array. The core diameter and numerical aperture (N.A.) of the fiber were 0.4 mm and 0.22, respectively. The pump beam from the fiber at the wavelength of 808 nm was focused into the laser crystal with the spot size of 320 µm in diameter by an optical imaging system with the imaging ratio of 1 : 0.8. The front mirror was a flat mirror anti-reflection (AR) coated at 808 nm on the entrance face, and high-reflection (HR) coated at 1000–1200 nm and high-transmittance (HT) coated at 808 nm on the other face. The output mirror was a concave mirror with a radius of curvature of 250 mm, HR coated at 1064 nm and partial-transmission coated at 1176 nm. The $4 \times 4 \times 14$ mm^3, *a*-cut YVO_4–Nd : YVO_4–YVO_4 crystal with two 2-mm-long undoped YVO_4 ends bonded to both facets of 0.3 at.% Nd^{3+}-doped YVO_4 crystal was AR coated at 808 nm and 1000–1200 nm on both of its faces. To remove the heat generated in the laser crystal, the composite Nd : YVO_4 crystal was wrapped with indium foil and mounted in a water-cooled copper block. The temperature of the water was kept to be about 20°C during the experiments. An AO Q-switch AR coated at 1064 nm on both of its faces was inserted into the cavity. Its repetition rate could be tuned continuously from 1 kHz to 100 kHz. The total cavity length was experimentally optimized to be about 104 mm.

The laser performance was investigated with several output mirrors with different transmissions at 1176 nm of 4.4%, 17.6%, 35% and 50%. The transmission of the output mirror at 1176 nm was experimentally optimized to be 17.6%.

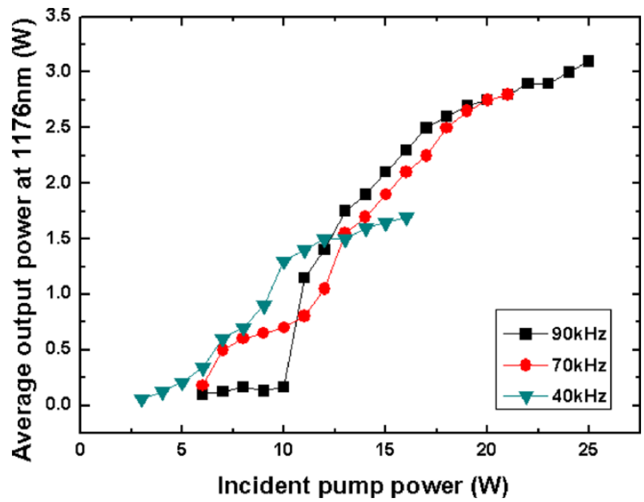

Fig. 2 Average output power at 1176 nm versus the incident pump power for different pulse repetition rates

So, only the experimental results obtained with the 17.6% transmission output mirror are given in this paper.

3 Results and discussion

The average output power at 1176 nm versus the incident pump power was measured at different pulse repetition frequencies (PRFs) of 40 kHz, 70 kHz and 90 kHz, as shown in Fig. 2. At the PRF of 90 kHz and an incident pump power of 25 W, the maximum average output power was obtained to be 3.1 W with the corresponding optical conversion efficiency of 12.4%. The threshold pump power was measured to be 6 W. At the other PRFs of 70 kHz and 40 kHz, the maximum average output powers were obtained to be 2.8 W and 1.7 W, with the corresponding optical conversion efficiencies of 12.7% and 9.4%, respectively. The threshold pump power increased with the increase of PRF. Compared with our previous experimental results obtained with a conventional $3 \times 3 \times 15$ mm^3, 0.3 at.% Nd^{3+}-doped Nd : YVO_4 crystal [9, 10], the self-Raman laser performance of the composite Nd : YVO_4 crystal was better than that of the conventional Nd : YVO_4 crystal. It is mainly because employ-

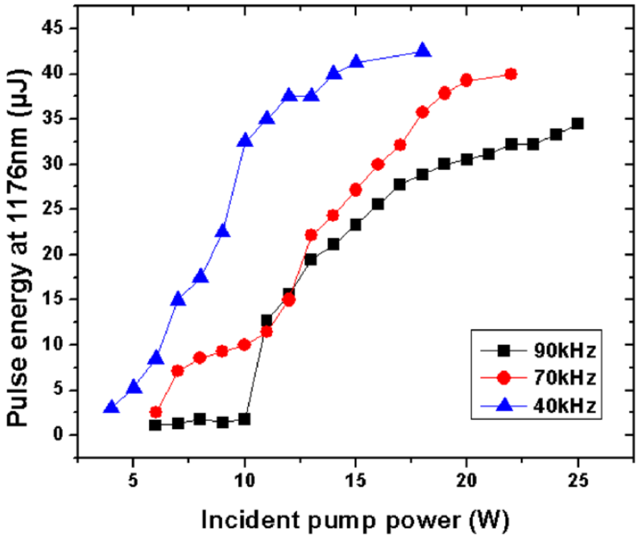

Fig. 3 Pulse energy of the self-Raman laser versus the incident pump power at different PRFs

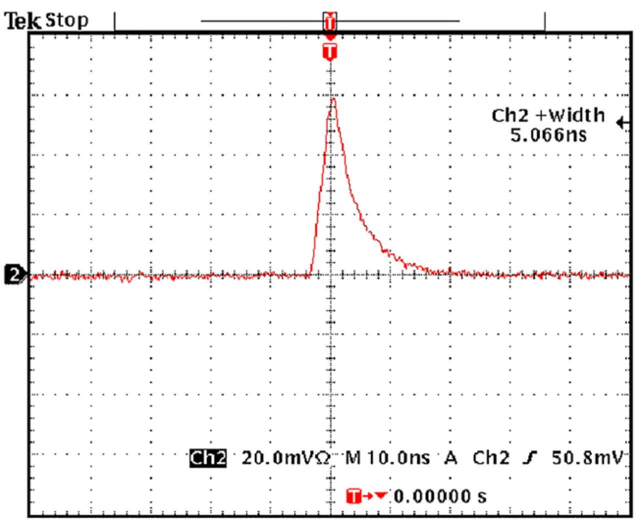

Fig. 4 The temporal pulse profile with the shortest pulse width of 5 ns

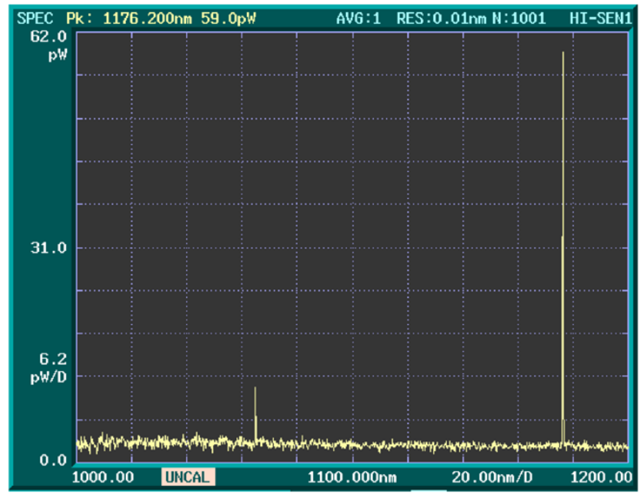

Fig. 5 Optical spectrum of the actively Q-switched composite Nd : YVO_4 crystal self-Raman laser

ing composite crystals can not only increase the interaction length for the Raman conversion, but also reduce the thermal effect through reducing the absorption of the pump power in the undoped pump end.

The laser pulse signal was detected by using a fast photodiode detector (EOT ET-3500), and was observed and measured with a 300 MHz oscilloscope (Tektronix TDS 3032B). The pulse energy at 1176 nm versus the incident pump power is shown in Fig. 3. The highest pulse energy was obtained to be 42 μJ at the incident pump power of 18 W and the PRF of 40 kHz. From the figure, we can see that the pulse energy increased with the incident pump power.

The shortest pulse width at 1176 nm was measured to be about 5 ns at the pump power of 18 W and the PRF of 70 kHz. Its temporal pulse profile is shown in Fig. 4. The highest peak power was obtained to be 7.5 kW when the incident pump power was increased to 20 W.

The spectral information of the self-Raman laser was measured by an optical spectrum analyzer (Advantest Q8384). The optical spectrum of the actively Q-switched double-end diffusion-bonded Nd : YVO_4 crystal self-Raman laser output is shown in Fig. 5. From the figure, it can be seen that the frequency shift between the fundamental wavelength of 1064 nm and the first-Stokes wavelength of 1176 nm is about 890 cm^{-1}, which corresponds to the optical vibration modes of the tetrahedral VO_4^{3-} ionic groups.

4 Conclusions

An efficient acousto-optical Q-switched double-end diffusion-bonded Nd : YVO_4 self-Raman laser at 1176 nm was demonstrated. As much as 3.1 W of average output power at the first-Stokes wavelength was achieved at the PRF of 90 kHz and the incident pump power of 25 W, with the corresponding optical conversion efficiency of 12.4%. The highest pulse energy of 42 μJ, the shortest pulse width of 5 ns and the highest peak power of 7.5 kW were obtained, respectively. The excellent laser performance indicates that the composite vanadate crystals are promising in the application field of high-power self-Raman lasers.

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