Compact efficient Q-switched eye-safe laser at 1525 nm with a double-end diffusion-bonded Nd:YVO$_4$ crystal as a self-Raman medium

Y. T. Chang, K. W. Su*, H. L. Chang, and Y. F. Chen*

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan
**Corresponding author: sukuanwei@mail.nctu.edu.tw, yfchen@cc.nctu.edu.tw*

Abstract: We report on an efficient Q-switched eye-safe laser at 1525 nm with a double-end diffusion-bonded Nd:YVO$_4$ crystal as a self-Raman gain medium. A diffusion-bonded crystal not only reduces the thermal effects but also increase the interaction length for the stimulated Raman scattering. With an input pump power of 17.2 W, average power of 2.23 W at the first-Stokes wavelength of 1525 nm is generated at a pulse repetition rate of 40 kHz, corresponding to a conversion efficiency of 13%.

OCIS codes: (140.3550) Lasers, Raman; (140.3380) Laser Materials; (140.3480) Lasers, diode-pumped.

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1. Introduction

Since water absorption in eye tissue and the intraocular fluid prevents light in the spectral range of 1.4-1.8 μm from reaching the retina, there is a considerable interest in compact laser sources with wavelengths in this eye-safe regime. The methods of generating eye-safe laser include optical parametric oscillators [1-4], Er^{3+}, Cr^{4+}, and Yb^{3+} doped solid-state laser [5-7], and stimulated Raman scattering (SRS) [8-15]. SRS has been convinced to be a promising method for wavelength conversion in solid-state lasers [16-18]. The discovery of new Raman materials gives birth to the laser sources at new wavelengths. In the recent years, eye-safe lasers from SRS frequency conversion have been successfully demonstrated in several Raman materials such as $Ba(NO_3)_2$, Nd:YVO_4, Nd:$GdVO_4$, Nd:$SrWO_4$, Nd:$KGWO_4$, $BaWO_4$, and $PbWO_4$ [8-15]. The laser crystal simultaneously serving as a Raman crystal can provide the advantage of compactness and simplicity for an intracavity SRS laser [19,20]. The laser emission at wavelengths of 1176 and 1525 nm based on self-SRS action in 1064- and 1342-nm actively Q-switched Nd:YVO_4 laser have been reported, respectively [9, 21-22]. However, the overall performance is hindered by the thermal effects because the Raman gain coefficient decreases substantially with increasing temperature above room temperature [21]. Therefore, to improve the thermal effects in the gain medium is critically important for developing self-Raman solid-state lasers.

In the past few years, the thermal effects have been verified to be efficiently improved by using the so-called composite crystal as a gain medium. The composite crystal is fabricated by the diffusion bonding of a doped crystal to an undoped crystal with the same cross section [23-29]. To the best of our knowledge, the composite crystal has not been applied to the self-Raman laser systems. In this work, we employ a double-end diffusion-bonded Nd:YVO_4 crystal to investigate the output performance of the self-Raman laser at 1525 nm. With an input pump power of 17.2 W, the maximum average power at 1525 nm is 2.23 W at a pulse repetition rate of 40 kHz, corresponding to conversion efficiency of 13%. The maximum average output power with the composite crystal is found to be nearly 40% higher than that with a conventional Nd:YVO_4 crystal at the same pulse repetition rate.

2. Experimental setup

The experimental setup of a diode-pumped actively Q-switched eye-safe Raman laser employing a composite Nd:YVO_4 crystal is shown in Fig. 1. The laser crystal is an *a*-cut 4 mm × 4 mm × 20 mm double-end diffusion-bonded Nd:YVO_4 crystal bounded with one 2-mm-long undoped YVO_4 end at the pumped facet of 0.3-at.% Nd^{3+}-doped Nd:YVO_4 crystal and one 8-mm-long undoped YVO_4 end at the other facet. The laser crystal is supplied by Witcore Co., Ltd. With the 1342-nm fundamental pump wavelength, the wavelength of the first-Stokes component for the YVO_4 Stokes shift at 890-cm^{-1} can be calculated to be around 1525 nm. The front and output coupler are designed for the first-Stokes generation. Both sides of the laser crystal are coated for antireflection at 1330-1530 nm (R<0.2%). In addition, the laser crystal is wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 22°C. The front mirror is a 500-mm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face (R<0.2%), high-transmission (HT) coating at 808 nm (T>90%), and high-reflection (HR) coating at 1342 and 1525 nm on the other face (R>99.8%). The output coupler is a flat mirror with high-reflection coating at 1342 nm and partial-reflection (PR) coating at 1525 nm (R=65%). The pump source is an 808-nm fiber-coupled laser diode with a core diameter of 600 µm, a numerical aperture of 0.16, and a maximum power of 17.2 W. The pump beam is reimaged at the laser active medium and the waist radius is nearly 250 µm. The 30-mm-long acousto-optic Q-switcher (NEOS Technologies) had antireflectance coatings at 1342 nm on both faces and was driven at a 27.12-MHz center frequency with 15.0 W of rf power. The overall laser cavity length is 75 mm.

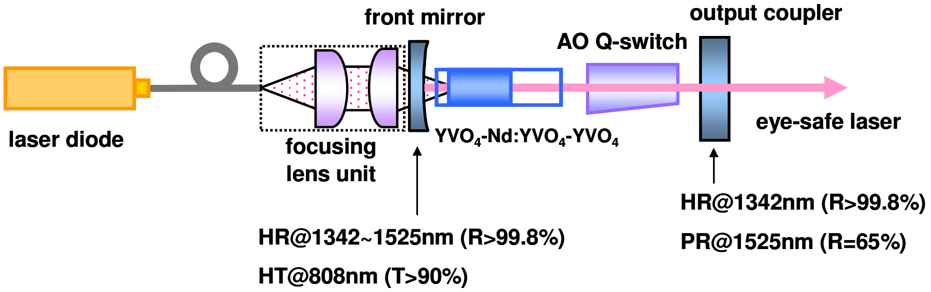

Fig. 1. Experimental setup of a diode-end-pumped actively Q-switched Nd:YVO_4 Raman laser.

3. Experimental results and discussions

We firstly used a simple laser setup for CW operation at 1342 nm to investigate the improvement of the thermal lensing effect in a double-end diffusion-bonded Nd:YVO_4 crystal [30]. For this investigation an output coupler with partial reflection at 1342 nm was used instead of the above-mentioned Raman cavity output coupler. The optimum reflectivity of the output coupler was found to be approximately 92–94%. The effective focal lengths of the thermal lens were estimated based on the fact that the laser system would start unstable for a cavity length longer than the critical length related to the thermal lensing. Even though the absolute accuracy is not easily achieved, this method is confirmed to provide the high relative accuracy for the effective focal lengths of the thermal lens [30]. Figure 2 shows the experimental data and fitted lines of thermal lensing power in a conventional crystal and a double-end diffusion-bonded crystal with the same dopant concentration. It can be seen that the effective focal length in a double-end diffusion-bonded crystal is nearly 1.6 times that in a conventional Nd:YVO_4 crystal. As a result, the thermal effects can be substantiated to be significantly reduced in a double-end diffusion-bonded crystal.

#106396 - $15.00 USD Received 15 Jan 2009; revised 28 Feb 2009; accepted 28 Feb 2009; published 3 Mar 2009

When the Raman cavity output coupler was used in the laser cavity, the pumping threshold for the Raman laser output was found to be 2–3 W for the pulse repetition rates within 20-40 kHz. The beam quality factor was found to be better than 1.5 over the entire operating region. The spectrum of laser output is measured by an optical spectrum analyzer (Advantest Q8381A) employing a diffraction lattice monochromator with a resolution of 0.1 nm. As shown in Fig. 3, the optical spectrum for the actively Q-switched self-Raman output displayed that the fundamental laser emission was at 1342 nm and the Stokes component was at 1525 nm. The frequency shift between Stokes and laser lines is in good agreement with the optical vibration modes of tetrahedral VO_4^{-3} ionic groups (890 cm^{-1}) [19].

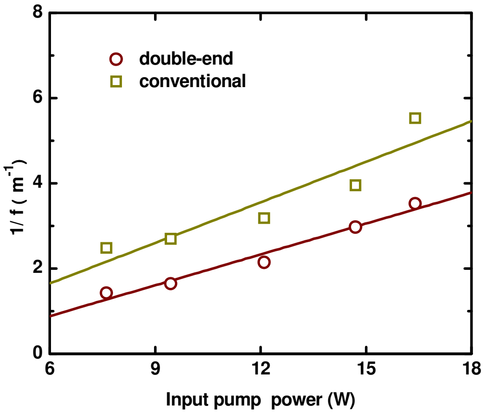

Fig. 2. Dependences of thermal lensing power on input pump power for conventional and double-end diffusion-bonded Nd:YVO_4 CW laser at 1342 nm.

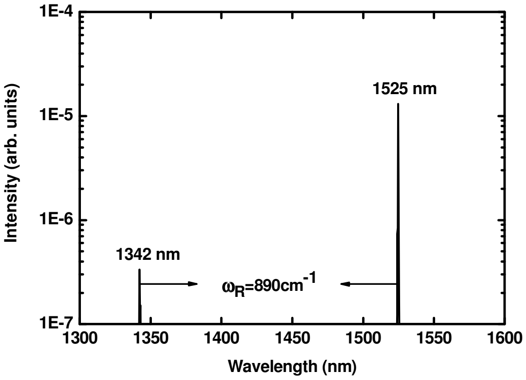

Fig. 3. Optical spectrum of the diode-pumped actively Q-switch Nd:YVO_4 self-Raman laser.

Figure 4 shows the experimental results of the average output power at 1525 nm with respect to the input pump power for the present self-Raman laser at pulse repetition rates of 20 and 40 kHz. For comparison, the previous results obtained by Chen [9] with a conventional 0.2%-doped Nd:YVO_4 crystal at a repetition rate of 20 kHz is also depicted in the same figure. Note that there were no experimental data for a conventional 0.2%-doped Nd:YVO_4 crystal at a pulse repetition rate of 40 kHz because of the high lasing threshold. It can be seen that the Raman lasing threshold for a double-end diffusion-bonded Nd:YVO_4 crystal is approximately 2.0 W that is substantially lower than the lasing threshold of 8.5 W for a conventional Nd:YVO_4 crystal at the repetition rate of 20 kHz. Moreover, the lasing threshold at a pulse

#106396 - $15.00 USD Received 15 Jan 2009; revised 28 Feb 2009; accepted 28 Feb 2009; published 3 Mar 2009

repetition rate of 40 kHz for present self-Raman laser is below 3.0 W. A rather low lasing threshold for high pulse repetition rates comes from the fact that the undoped part of the composite crystal increases the interaction length and then enhances the Raman gain.

It has been experimentally evidenced that the maximum output power for a conventional self-Raman laser is limited by the critical pump power that induces a large temperature gradient in the gain medium to lead to the Raman gain lower than the cavity losses [21]. Consequently, the output power begins to saturate when the pump power exceeds the critical pump power. As shown in Fig. 4, the critical pump power for the self-Raman laser with a double-end diffusion-bonded Nd:YVO_4 crystal can exceed 17.2 W that is limited by the available pump power and is considerably greater than the critical pump power of 13.5 W with a conventional Nd:YVO_4 crystal. As a result, the self-Raman laser with a double-end diffusion-bonded Nd:YVO_4 crystal can generate the maximum average output power up to 1.72 W that is approximately 43% higher than the result with a conventional 0.2 %-doped Nd:YVO_4 crystal [9]. At a repetition rate of 40 kHz, the maximum power at 1525 nm is even up to 2.23 W with an input pump power of 17.2 W, corresponding to a conversion efficiency of 13%. To the best of our knowledge, this is the highest average power for diode-pumped eye-safe self-Raman laser.

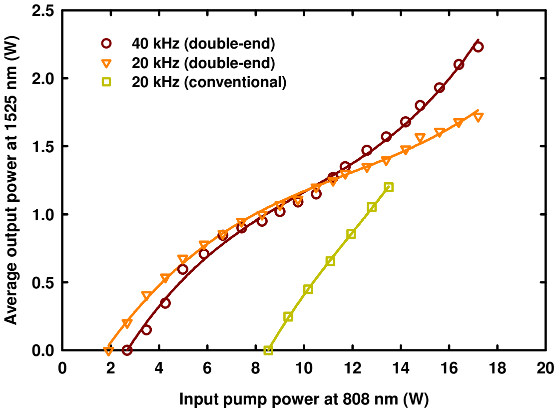

Fig. 4. The average output power at 1525 nm with respect to the input pump power at pulse repetition rates of 20 and 40 kHz shown as the down-triangle and circle symbols respectively for the double-end diffusion-bonded Nd:YVO_4 crystal and that at 20 kHz shown as the square symbol for a conventional Nd:YVO_4 crystal reported by Chen [9].

The temporal traces for the fundamental and Raman pulses are recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gsamples/s, 1-GHz bandwidth) with two fast p-i-n photodiodes. At a repetition rate of 40 kHz the pulse energy is up to 56 μJ with an input pump power of 17.2 W and the pulse width is measured to be approximately 3.2 ns, as shown in Fig. 5. The corresponding peak power is higher than 17 kW. At the pulse repetition rate of 20 kHz, the maximum pulse energy is up to 86 μJ. Figure 6 shows the pulse width at a pulse repetition rate of 20 kHz with a pump power of 17.2 W. It can be seen that although a second tiny Raman pulse usually follows the main first peak, its contribution is rather limited. Consequently the peak power can be generally higher than 22 kW. Since the fundamental energy is remained after first Raman pulse, the sub-pulse of fundamental wave is formed shown as Fig. 5 and Fig. 6. At a pulse repetition rate of 20 kHz, the remaining energy is sufficient to reach Raman gain and a second tiny Raman pulse is produced shown as Fig. 6. The sub-pulse would not be generated if the reflectivity of output coupler was lowered.

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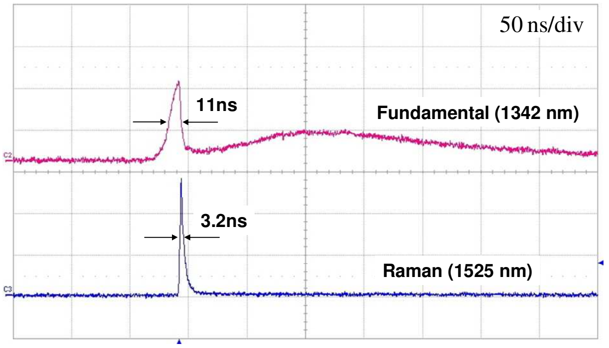

Fig. 5. Temporal characteristics of the fundamental and Raman pulses at a pulse repetition rate of 40 kHz with a pump power of 17.2 W.

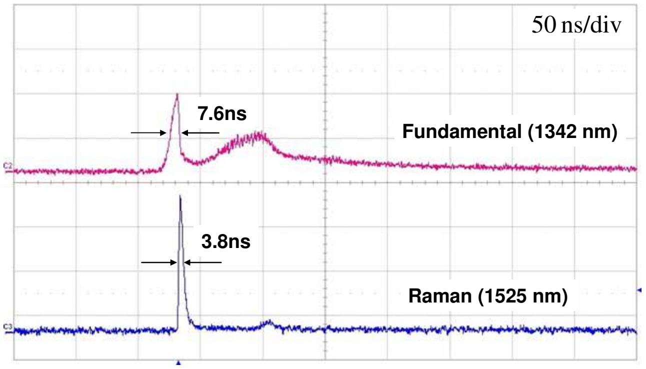

Fig. 6. Temporal characteristics of the fundamental and Raman pulses at a pulse repetition rate of 20 kHz with a pump power of 17.2 W.

4. Conclusion

A compact efficient high-power diode-pumped actively Q-switched self-Raman laser at 1525 nm is demonstrated by employing a double-end diffusion-bonded Nd:YVO$_4$ crystal. Experimental results reveal that the composite crystal can reduce the thermal effects to reach a higher critical pump power. More importantly, the undoped part plays a critical role in lowering the lasing threshold at high pulse repletion rates because of the increase of the Raman interaction length. The maximum average output power of 2.23 W at first-Stokes wavelength of 1525 nm is generated at a pulse repetition rate of 40 kHz, and the pulse width of Raman pulse is about 3.2 ns with an input pump power of 17.2 W. The corresponding conversion efficiency and peak power are approximately 13% and 17.4 kW, respectively.

Acknowledgments

The authors thank the National Science Council for their financial support of this research under Contract No. NSC-95-2112-M-009-041-MY2.