An efficient continuous-wave YVO_4/Nd:YVO_4/YVO_4 self-Raman laser pumped by a wavelength-locked 878.9 nm laser diode*

Li Fan(樊莉)[1,2,†], Weiqian Zhao(赵伟倩)[1], Xin Qiao(乔鑫)[1], Changquan Xia(夏长权)[1], Lichun Wang(汪丽春)[1], Huibo Fan(范会博)[1], and Mingya Shen(沈明亚)[1]

[1] *College of Physics Science and Technology, Institute of Applied Photonic Technology, Yangzhou University, Yangzhou* 225002, *China*
[2] *National Laboratory of Solid State Microstructures, Nanjing University, Nanjing* 210093, *China*

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We report an efficient continuous-wave self-Raman laser at 1176 nm based on a 20-mm-long composite YVO_4/Nd:YVO_4/YVO_4 crystal and pumped by a wavelength-locked 878.9 nm diode laser. A maximum output power of 5.3 W is achieved at a pump power of 26 W, corresponding to an optical conversion efficiency of 20% and a slope efficiency of 21%. The Raman threshold for the diode pump power was only 0.92 W. The results reveal that in-band pumping by a wavelength-locked diode laser significantly enhances output power and efficiency of self-Raman lasers by virtue of improved pump absorption and relieved thermal loading.

Keywords: continuous-wave self-Raman laser, in-band pumping, composite crystal

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1. Introduction

Simulated Raman scattering (SRS) is a famous third-order nonlinear optical effect that has been widely used for frequency conversion to generate new laser wavelengths in the visible and infrared region. In recent years, continuous-wave (cw) operation of diode-pumped solid-state Raman lasers have gained extensive attention due to their potential applications in many areas such as biomedicine, spectroscopy, optical communication, and environmental control.[1–4] Compared with the intracavity Raman conversion, self-Raman conversion is a more promising scheme for cw Raman operation, in which only one crystal is used for the fundamental laser generation and Raman conversion. By reducing the number of optical elements in the laser cavity, self-Raman lasers have the benefits of compactness, lower cavity losses, shorter resonators, and enhanced efficiency. The cw diode-pumped self-Raman laser was first demonstrated with Nd:KGW crystal in 2005.[5] Later, a variety of crystals such as Nd:YVO_4,[6,7] Nd:$GdVO_4$,[8,9] Nd:$LuVO_4$,[10] and Yb:KGW[11] were employed for efficient cw self-Raman conversion.

In spite of the above-mentioned advantages, thermal loading of cw self-Raman lasers is more severe, which limits the improvement of cw self-stimulate Raman laser performance due to the following two reasons: (i) strong thermal lensing effect induces resonator instability and limits the use of higher pump power; (ii) Raman gain coefficient decreases as crystal temperature increases. Therefore, alleviation of thermal effects in self-Raman medium is especially important for cw self-Raman lasers. Over the past twenty years, it has been demonstrated that thermal effects can be efficiently reduced by using composite laser crystals[12–14] and in-band pumping.[15–18] In 2010, we realized an efficient cw self-frequency Raman generation in a composite YVO_4/Nd:YVO_4/YVO_4 crystal. The Raman threshold was measured at 2.2 W of the traditional 808 nm diode laser (LD) pump. Under the incident diode pump of 25.5 W, the highest cw Raman output power obtained at 1175 nm was 2.8 W for an optical conversion efficiency of 11%.[19] In the same year, Lu *et al.* reported a cw frequency-doubled, self-Raman laser with a composite $LuVO_4$/Nd:$LuVO_4$/$LuVO_4$ crystal pumped by an 880 nm laser diode.[10] The results demonstrated that significant reduction in thermal load can be obtained by in-band pumping. However, due to the narrow linewidth of the absorption band under 880 nm in-band pumping, the emission spectrum (of common 880 nm in-band pumping LD) is difficult to match accurately to the absorption peak of crystal's in-band pumping band. Thus, pump absorption is relatively low, restraining the overall optical efficiency of Raman lasers. In 2014, a wavelength-locked in-band pumping LD is introduced to actively *Q*-switched self-Raman lasers by Sheng *et al.*[20] and Ding *et al.*[21] The pump absorption fraction of 0.3-at.% doped Nd:YVO_4 crystal with a length of 10 mm increases from 77% to 86% by wavelength-locked LD pumping.[21]

In this paper, we report a cw efficient self-Raman laser operation at 1176 nm based on a composite YVO_4/Nd:YVO_4/YVO_4 crystal. For the first time, a 878.9-nm wavelength-locked laser diode is introduced as the in-band pump source of continuous-wave self-Raman laser. Since

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†Corresponding author. E-mail: fanli@yzu.edu.cn

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the narrow and stable emission is accurately matched to the absorption peak of the Nd:YVO_4 crystal's 880-nm in-band pumping band, pump absorption is improved and simultaneously thermal loading is mitigated. Finally, 5.3 W of cw 1176-nm first-Stokes output was generated at the incident pump power of 26 W, corresponding to an optical (diode-to-Stokes) conversion efficiency of 20%. The threshold for SRS was only 0.92 W of diode pump power at 878.9 nm. The Raman output power and efficiency are obviously increased as opposed to 808-nm traditional pumping.

2. Experimental setup

The experimental configuration is illustrated in Fig. 1. The pump source was a 30 W, 878.9 nm, wavelength-locked fiber-coupled laser diode (nLIGHT, Inc.). The emission spectrum of the LD is narrowed and stabilized at 878.9 nm (operating cw at 30 °C) based on external locking with volumetric Bragg grating (VBG). The spectral width is reduced to $\sim$ 0.3 nm (FWHM) and the wavelength temperature coefficient is $\sim$ 0.01 nm/°C. As a reference, typical unlocked 880 nm LD (nLIGHT, Inc.) spectral width is $\sim$ 3.5 nm, with the wavelength temperature coefficient of $\sim$ 0.31 nm/°C. It should be noted that the absorption peak of Nd:YVO_4 in-band pumping band appears around 879 nm with a narrow absorption linewidth of 3.8 nm in Ref. [22]. Thus, the emission spectrum of VBG-locked LD is accurately locked to the absorption peak of Nd:YVO_4 crystal's 880-nm direct pumping band, thereby avoiding temperature-induced peak wavelength shifting, which should improve the pump absorption and temperature stability. The core diameter and the numerical aperture of the pump fiber were 200 μm and 0.22, respectively. The beam emerging from the fiber was imaged with a commercial 1:2 coupler onto the facet of laser crystal (to a spot diameter of about 400 μm). For comparison, three a-cut Nd:YVO_4 crystals (Crystech, Inc.) were employed in this experiment. Two samples were $4\times4\times14$ mm^3 and $4\times4\times20$ mm^3 double-end diffusion-bond Nd:YVO_4 composite crystals (YVO_4/Nd:YVO_4/YVO_4), in which each facet of a 0.3-at.% Nd:YVO_4 crystal was diffusion-bonded to a 2-mm-long pure YVO_4 end. The other was a $4\times4\times10$ mm^3, 0.3-at.% conventional Nd:YVO_4 crystal. All light-passing faces of crystals were AR coated at 1064/1176 nm to reduce the insertion loss. The crystals were mounted in water-cooled copper blocks which were kept at a temperature of 15 °C.

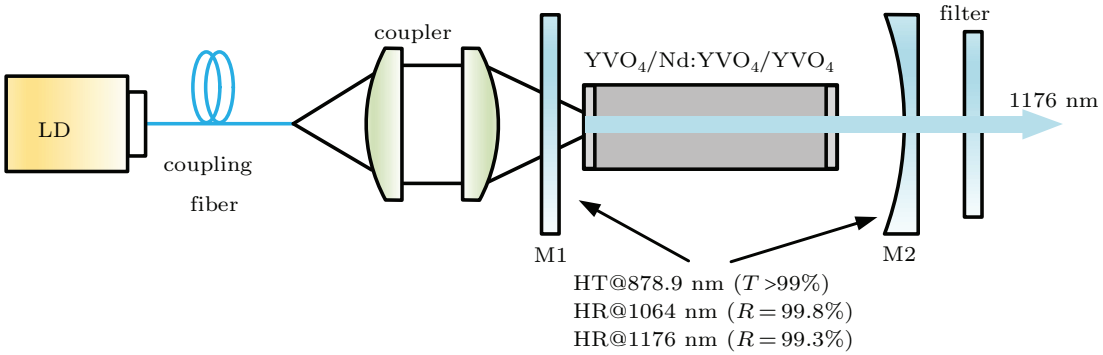


Fig. 1. (color online) Arrangement of a cw diode-end-pumped composite YVO_4/Nd:YVO_4/YVO_4 self-Raman laser.

The resonator was formed by a flat input mirror and a concave output coupler, which were both coated with high transmission ($T > 99\%$) at 878.9 nm and high reflectivity at both 1064 nm ($R = 99.8\%$) and 1176 nm ($R = 99.3\%$). To optimize the cavity, a variety of output couplers with different radii of curvature (50, 100, 200, 300, 500, and 800 mm) were employed. In the experiment, all the elements in the resonator were placed in close proximity to each other to minimize the resonator length. The shortest resonator length was 17 mm for the 10 mm and 14 mm long crystals and extended to 23 mm to accommodate the 20-mm-long crystal. A longpass filter (FEL1100 Thorlabs) and a bandpass filter (FLH1064-8 Thorlabs) were used to measure output powers of the Raman and the fundamental laser, respectively, which were recorded by a laser power meter (LP-3B).

3. Results and discussion

The output spectral characteristics of the laser system were investigated using an optical spectrum analyzer with 0.02 nm resolution (Yokogawa, AQ-6370C). As shown in Fig. 2, the first-Stokes line was observed at 1176 nm with a shift of 890 cm^{-1} towards the fundamental line at 1064 nm. No more Stokes lines were found in the experiment. An increase in both linewidths of the fundamental and Stokes spectra was observed with the pump power increasing. Thus, the linewidth of the fundamental line was approximately 0.13 nm at the generation threshold and increased to 1.04 nm at the

maximum pump power. Synchronously, for the Raman line, the linewidth was 0.037 nm at the threshold and 0.71 nm at the maximum pump power. As studied by Bonner *et al.*,[23] such a spectral broadening of the fundamental line is likely to be due to spatial hole burning and SRS-induced broadening, which results in a reduction of the effective Raman gain.

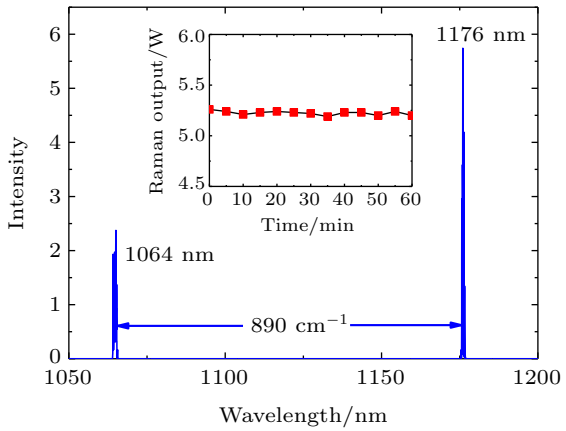


Fig. 2. (color online) Output spectrum of the cw YVO_4/Nd:YVO_4/YVO_4 self-Raman laser. Inset: temporal stability of the cw self-Raman laser under the incident pump of 26 W.

The performance of the cw Raman laser is evaluated using three different length crystals and output couplers with several radii of curvature (50, 100, 200, 300, 500, and 800 mm). For three different length crystals, the highest output powers of Stokes radiation were all obtained using a 100 mm concave output coupler. Cw Raman output power at 1176 nm is shown in Fig. 3 as a function of the incident pump power with different length crystals. For comparison, the cw Raman output powers obtained in our previous work[19] when pumping an almost identical system at 808 nm are also depicted in Fig. 3. When pumped by 878.9 nm wavelength-locked LD, for the 10-mm-long Nd:YVO_4 crystal, a maximum output power of 3.2 W at 1176 nm was obtained for 26 W of pump power incident on the laser medium. The threshold for SRS was 1.7 W of incident pump power. For the 14-mm-long composite YVO_4/Nd:YVO_4/YVO_4 crystal, a peak Raman output of 4.3 W was achieved and the threshold was 1.33 W, corresponding to an optical conversion efficiency of 16.5%. It can be seen that the Raman output power and efficiency are obviously higher than those under traditional 808 nm pumping (we obtained 2.8 W Raman output at an incident pump power of 25.5 W when using the 14-mm-long composite YVO_4/Nd:YVO_4/YVO_4 crystal). The Raman thresholds are also lower than the threshold of 2.2 W reported in Ref. [19]. The employment of an 878.9-nm wavelength-locked LD is undoubtedly the primary factor responsible for the improvement in performance. When the 20-mm-long composite crystal was adopted, the maximum output power of Stokes radiation at 1176 nm increased to 5.3 W for the incident pump power of 26 W and the threshold decreased to 0.92 W. This corresponded to a diode-to-Stokes conversion efficiency of 20% and a slope efficiency of 21%. As shown in the inset in Fig. 2, the Raman laser with the 20-mm-long composite crystal has excellent long term stability and exhibits a fluctuation of $\sim$ 1.3% in Stokes output power, recorded every 5 min over a period of 60 min at the maximum pump power of 26 W.

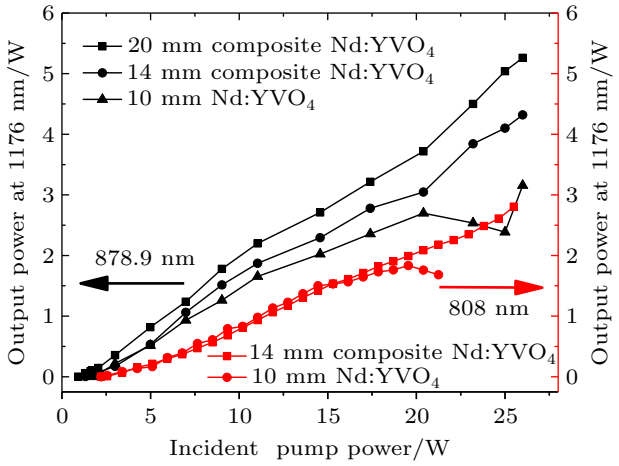


Fig. 3. (color online) Output power at 1176 nm as a function of incident pump power with different length crystals under different pump wavelengths. Black lines denotes the Raman output powers under 878.9 nm wavelength-locked pumping, while red lines are the Raman output powers under traditional 808 nm pumping.

Pump absorptions of three different length crystals were also investigated under a pump power of 26 W. For the 10-mm-long Nd:YVO_4 crystal, the residual output power of the pump laser at 878.9 nm from the output coupler was 4.3 W, corresponding to an absorption fraction of 83.5%. For the 14-mm-long and 20-mm-long composite YVO_4/Nd:YVO_4/YVO_4 crystals, the residual output pump powers were measured to be 3.64 W and 1.0 W, corresponding to the absorption fractions of 86% and 96%, respectively. As a reference, a 10-mm-long, a-cut Nd:YVO_4 crystal with 0.3-at.% doping concentration can absorb only $\sim$ 77% of the non-polarized common 880-nm incident pump power.[24] This reveals that improved pump absorption is achieved by introducing a wavelength-locked LD as pump source and by increasing the length of the crystal. It should be noted that output power did not show any saturation behavior under the maximum pump power for the two composite crystals, whereas for the conventional Nd:YVO_4 crystal, Raman output power rolls over as the incident pump power goes beyond 20 W, caused by cavity instability. These results indicate that the application of a wavelength-locked LD at 878.9 nm and a long composite crystal significantly reduces thermal load and at the same time enhances pump absorption, thus achieving a more efficient Raman conversion. Because no saturation phenomenon in the Raman output and no optical damage were observed at the maximum pump power, it is expected that higher Raman output power can be obtained as

pump power increases. In addition, we notice that the residual fundamental (1064 nm) output power from the output mirror is much higher than that in Ref. [19], with both cavity mirrors of high reflectivity ($R = 99.8\%$) at 1060–1180 nm. Given that the cw Raman laser is sensitive to the cavity mirror coating, we can speculate that the actual reflectivity of cavity mirrors in this work were lower than 99.8%. Therefore, considerable increases in Raman power can be anticipated by increasing the cavity-Q for the fundamental optical field.

When the output mirror was replaced by a flat output coupler with 10% transmission at 1064 nm (optimum transmission for maximum output power), we also investigated the performance of cw 1064 nm fundamental laser with the 20-mm-long composite YVO_4/Nd:YVO_4/YVO_4. For the shortest cavity length of 23 mm, maximum output power obtained at the fundamental line was 17.6 W at 26 W incident pump power. The onset of thermal fracture of crystal and resonator instability were not observed at the highest pump power. Based on this observation we estimate the thermal lens in the composite YVO_4/Nd:YVO_4/YVO_4 crystal should be longer than 23 mm at the maximum pump power of 26 W. It should be noted that when the length of cavity was increased to 100 mm, cavity instability was observed at the incident pump power of 18 W.

4. Conclusion

In conclusion, we have demonstrated an efficient cw self-Raman laser at 1176 nm with a composite YVO_4/Nd:YVO_4/YVO_4 crystal. The combination of in-band pumping by a wavelength-locked LD and the use of a long (20 mm) self-Raman composite crystal has reduced thermal effects and simultaneously improved pump absorption. With a 20-mm-long composite crystal, 5.3 W maximum output power at 1176 nm was obtained for diode pump power of 26 W, corresponding to an optical diode-to-Stokes conversion efficiency of 20%. The measured Raman threshold for the incident pump power was only 0.92 W. Both output power and efficiency are obviously higher than those under traditional 808 nm pumping and common 880 nm pumping. The experimental results demonstrate that the employment of a wavelength-locked in-band pumping LD can efficiently improve self-Raman laser performance in continuous wave regime because of the reduction in thermal effects and the improvement of pump absorption.

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