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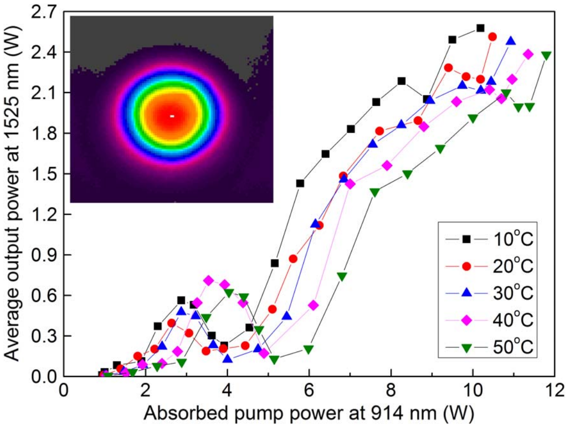

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Efficient Eye-Safe Nd:YVO$_4$ Self-Raman Laser In-Band Pumped at 914 nm

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Abstract: An efficient Q-switched eye-safe Nd:YVO$_4$ self-Raman laser, which we believe to be the first one in-band pumped at 914 nm, is presented, and 2.58 W of 1525-nm Stokes output was generated under the absorbed pump power of 10.2 W with a high repetition rate of 100 kHz, corresponding to a conversion efficiency of 25.3%. The optical efficiency with respect to incident pump also reached 16.4%. Influences of crystal temperature and dopant concentration on the performance of the eye-safe self-Raman laser were experimentally investigated.

Index Terms: Eye-safe, in-band pumping, stimulated Raman scattering, vanadate laser.

1. Introduction

Frequency conversion based on stimulated Raman scattering (SRS) has long been an economical and practical method to generate important 1.5-μm eye-safe laser, by shifting the 1.3-μm emission of Nd-doped lasers to the required wavelength range efficiently [1]–[3]. After crystalline laser hosts of YVO$_4$ and GdVO$_4$ were predicted and subsequently proved to be reliable Raman media [4]–[6], self-Raman lasers, where fundamental laser generation and SRS conversion can be achieved simultaneously employing just one crystal, flowered rapidly and played an significant role in increasing the spectral coverage of solid state lasers. However, despite the advantageous properties of self-Raman lasers such as diminished intracavity loss as well as compact resonator, the combined laser and Raman process severely exacerbate the thermal effects within the crystal. Furthermore, the Raman scattering cross section decreases when crystal temperature rises, which exerts a huge impact on output power scaling under heavy thermal load and hinders high conversion efficiency as a consequence. Reducing the heat deposited in crystals, therefore, is imperative but also effective to improve the performance of self-Raman lasers. In 2014, Ding *et al.* reported an eye-safe Raman laser based upon Nd:YVO$_4$-YVO$_4$ and in-band pumped by 878.6-nm wavelength-locked laser diode array to help relieve the thermal

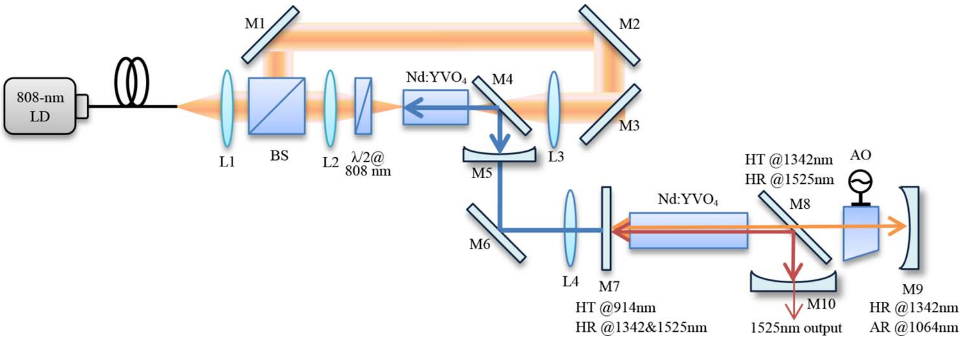

Fig. 1. Schematic diagram of the experimental configuration.

effects, eventually obtaining 5.2 W of 1525-nm Stokes emission, which is the highest output power of eye-safe Raman lasers ever reported [7].

By means of diminishing the energy difference between pump and laser photon, in-band pumping turns out to be one of the most fundamental ways to reduce the thermal load within self-Raman lasers and to ameliorate the laser efficiency. In 2008, Lee *et al.* developed a Nd:$GdVO_4$ intracavity frequency-doubled self-Raman laser pumped at 880 nm $(\mathrm{Nd}^{3+}: {}^4I_{9/2} \rightarrow {}^4F_{3/2})$, achieving a higher yellow output power together with better conversion efficiency as compared to 808-nm traditional pumping $(\mathrm{Nd}^{3+}: {}^4I_{9/2} \rightarrow {}^4F_{5/2})$ [8]. Afterwards, many Nd-doped YVO_4 and $GdVO_4$ self-Raman lasers were reported to be operating with rather high efficiency under 880-nm in-band pumping [9], [10]. Since 880 nm is not the longest wavelength in the absorption bands of Nd-doped vanadates, further reduction of quantum defect induced thermal load can be realized by pumping Nd^{3+} ions from the higher Stark sublevel of the ground state (Z_5) to upper-laser-level (R_1). So far, these kinds of in-band pumped Nd:YVO_4 lasers operating at 1.06- and 1.34-μm fundamental wavelength have already been demonstrated by using 914-nm pumping source, which exhibited noticeably low thermal fraction and high efficiency [11], [12]. Thus, even better performance of Nd:YVO_4 self-Raman laser could be expected with 914-nm in-band pumping adopted.

In this paper, we report for what we believe to be the first time a highly efficient vanadate self-Raman laser in-band pumped from high stark sublevel of the ground state. We used 914-nm laser emission as the pumping source of the acousto-optic Q-switched Nd:YVO_4 self-Raman laser operating at the first-Stokes wavelength of 1525 nm. Investigations concerning different pulse repetition frequencies (PRFs), crystal temperatures and dopant concentrations were conducted to explore the best power performance for the eye-safe Nd:YVO_4 self-Raman laser. By virtue of low quantum defect, a conversion efficiency of 25.3% from absorbed pump power to Stokes output was achieved in the experiment. Besides, the optical efficiency with respect to incident pump reached 16.4% by optimizing the crystal parameters and thereby improving the pump absorption.

2. Experimental Arrangement and Analysis

Our experimental layout is depicted schematically in Fig. 1. We employed a home-made double-end-pumped Nd:YVO_4 laser emitting at 914-nm wavelength to pump the follow-up self-Raman laser. The pump source of the 914-nm Nd:YVO_4 laser was an 808-nm fiber-coupled laser diode (LD) array with a fiber core diameter of 400 μm and a numerical aperture of 0.22. A polarizing beam splitter was used here to divide the pump light into two beams with nearly equal power but orthogonal polarizations. Both beams, one of which was rotated 90° by a half-wave plate to be polarized along the *c* axis of the crystal, were reimaged into the Nd:YVO_4 crystal from either end of it by two 100-mm focus lens. With this double-end pumping scheme applied, the pump power was almost fully absorbed by the gain medium. The $3 \times 3 \times 5\ \mathrm{mm}^3$ *a*-cut laser material was 0.15-at.% doped. The crystal entrance face near the half-wave plate was coated for anti-reflective (AR, $R < 5\%$) at 808 nm and highly reflective (HR, $R > 99.5\%$) at 914 nm, while the other face had AR ($\mathrm{R} < 0.5\%$) coating at 914 nm. The crystal wrapped in indium foil was mounted in an aluminum holder cooled by refrigerant water maintained at 8.8 °C. M4 was coated for HR ($R > 99.5\%$) at 914 nm as well as highly transmissive (HT, $T > 95\%$) at 1064 and 1342 nm. A concave mirror M5 with 100-mm radius of curvature (ROC) and 4.1% transmittance at 914 nm was used as the output coupler. The 914-nm Nd:YVO$_4$ laser whose cavity length was 40 mm could provide 17.0 W of maximum output power under 53-W incident LD pump power. The powermeter we used was Molectron EPM1000.

A focus lens L4, with the focal length of 100 mm, was used to focus the 914-nm pump beam into the self-Raman gain medium. Given in-band pumping scheme suffers comparatively poor pump absorption but which could be improved by means of high dopant concentration, we chose three Nd:YVO$_4$ crystals with relatively high Nd-dopant concentration of 1.0-, 1.5- and 2.0-at.%, respectively, in the experiment. Moreover, the pump light was polarized parallel to the *c* axis of the Raman-active crystals, in order to access a higher absorption cross section [11]. A 20-mm length was chosen for the crystals considering the fact that longer crystal can increase not only the pump absorption but the Raman interaction length effectively as well. The Nd:YVO$_4$ samples were coated for HT at 914-, 1342- and 1525-nm ($T > 97\%$@914 nm, $T > 99.8\%$@1342 & 1525 nm) wavelength range altogether. Wrapped in indium foil, the samples were clamped in an aluminum block whose temperature was controlled by circulating water so that we could investigate the influence of temperatures. We also selected a 20-mm-long acousto-optic Q-switch driven at 80-MHz ultrasonic frequency by 15 W of radio-frequency power, with AR ($R < 0.2\%$) coating at 1.06–1.5 μm on both sides.

A composite cavity was adopted here instead of the shared cavity often used in self-Raman lasers. M7 is a plane mirror coated for HT ($T > 95\%$) at 914 nm and HR ($R > 99.5\%$) at 1300–1600 nm. It made up the 1342-nm fundamental laser cavity along with M9, a concave mirror with ROC of 200 mm and the same coating. The Stokes resonator consisted of M7, a plane mirror M8 which was coated for HT ($T > 99.5\%$) at 1342 nm on both sides and HR ($R > 99.5\%$) at 1525 nm on one side, and a concave Stokes wave output coupler M10 ($\mathrm{ROC} = 200$ mm) with transmittance of 6.5% at 1525 nm. All the elements which make up the self-Raman laser cavity were also coated for AR at 914 nm to avoid the coupling of 914-nm pump laser between the two laser cavities and ensure the accuracy of pump absorption measurement. With this composite cavity, we could control the lengths of the two cavities separately to achieve better mode matching between the pump, fundamental laser and Stokes wave. Furthermore, the composite cavity allowed us to optimize the aligning of the two cavities simultaneously. When using the shared cavity instead, we have often observed deviation between the fundamental laser and the Stokes wave as studying Nd:YVO$_4$ self-Raman laser at 1176 nm. (1176-nm Stokes wave with blue fluorescence deviated from the bright pump spot, which could be observed clearly by eyes.) This means that by aligning one shared cavity, it is hard for the fundamental and the Stokes to operate in their optimal state at the same time, which, nevertheless, would be overcome by employing composite cavity arrangement. The thermal lens effect in the Nd:YVO$_4$ crystal is estimated following the work of Innocenzi *et al.* and Pask [13], [14] so that the cavity parameters can be determined for mode matching under the maximum pumping. According to [13, eq. (13)], 16 W of 914-nm incident pumping with 200-μm pump spot radius, provided a 20-mm-long, 1.0-at.% doped Nd:YVO$_4$ as the gain medium (absorption coefficient of 0.52 cm^{-1} at 10 °C), would rouse 14.6 diopters of thermal focal power on account of lasing. When the 1525-nm Stokes cavity length was set to 65 mm, the heat generated in SRS process with ~ 210 μm beam radius in the crystal would results in another ~1.4 diopters using [14, eq. (30)] and the cumulative thermal focal length is ~62.5 mm. The 1342-nm laser cavity was therefore determined to be 80 mm, and the resultant beam radius of fundamental was $\sim$210 μm, which realized good overlap with both 914-nm pump and 1525-nm Stokes. For the mature 880-nm in-band pumping with a typical crystal doping concentration of 0.5 at.% and fixed crystal length of 20 mm, the thermal focal length would be shorter than 50 mm with the same pump power and spot size, bringing great difficulty in cavity design. Although the decrease of quantum defect by using 914-nm pumping is less than 10% due to the long laser wavelength of 1342 nm, considering the relatively small stimulated emission cross

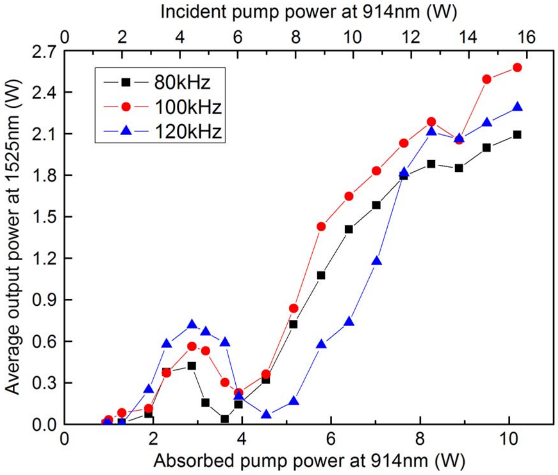

Fig. 2. Average output power at 1525 nm as functions of absorbed 914-nm pump power with the 1.0-at.% Nd:YVO$_4$ crystal under different PRFs.

section and the enormous influence of temperature on Raman gain [5], the reduction in thermal load can be important for promoting the conversion efficiency.

3. Results and Discussion

We measured the pump absorption of each Raman-active medium in the first place. The aluminum block was heated from 10 °C to 50 °C, with intervals of ten degrees centigrade. As crystal temperature increased, the measured absorption coefficients of 1.0-, 1.5-, and 2.0-at% doped samples rose from 0.52, 0.93, and 1.12 cm^{-1} (with corresponding absorption fraction of 65.0%, 84.5%, and 89.3%, respectively) to 0.67, 1.03, and 1.26 cm^{-1} (with corresponding absorption fraction of 73.9%, 87.1%, and 92.0%, respectively). Higher crystal temperature indeed improves the pump absorption under in-band pumping scheme [11], [15]. However, the increments in absorption fraction are limited since the absorption has already reached a relatively good level at 10 °C for the three long and highly doped crystals.

Fig. 2 gives the Stokes average output power versus absorbed pump power with the 1.0-at.% Nd:YVO$_4$ crystal at 10 °C. The PRF was arranged as 80, 100, and 120 kHz where the duty cycle was optimized to be 5%. When the absorbed pump power reached the highest of 10.2 W, the maximum Stokes average output power of 2.58 W was achieved at 100 kHz, with conversion efficiency up to 25.3%, which is the highest amongst eye-safe self-Raman lasers based on Nd-doped vanadates reported to date. Meanwhile, the corresponding optical efficiency with respect to 15.7-W incident pump reached 16.4%. Undoubtedly, the reduction in quantum defect under 914-nm in-band pumping is the major factor responsible for the improvement in efficiency. It should be mentioned that the pump source we used here, the 914-nm Nd:YVO$_4$ laser, has a linewidth much narrower than that of the common InGaAs LDs [11] and, therefore, guarantees adequate pump absorption and favorable optical efficiency. For practical applications, one could adopt commercial wavelength-locked LD, whose emission linewidth is locked to less than 0.3 nm by volume Bragg grating, and realize efficient direct diode in-band pumped self-Raman laser. Compared to 100 kHz, the maximum Stokes average output dropped to 2.29 W at 120 kHz and 2.09 W at 80 kHz. Eye-safe self-Raman lasers reported before often operated with relatively low PRF to overcome the Raman threshold and the maximum conversion efficiency declined as PRF increased [16]. The result here shows that the 1.5-μm self-Raman laser is also capable of operating efficiently with high PRFs.

It is worthwhile noticing that there are obvious dips on the output curves at 3–4 W of absorbed pump power in Fig. 2. Since Raman gain is relatively low and self-Raman lasers highly rely on the overlap between fundamental and Stokes beam, the Stokes output power is quite sensitive

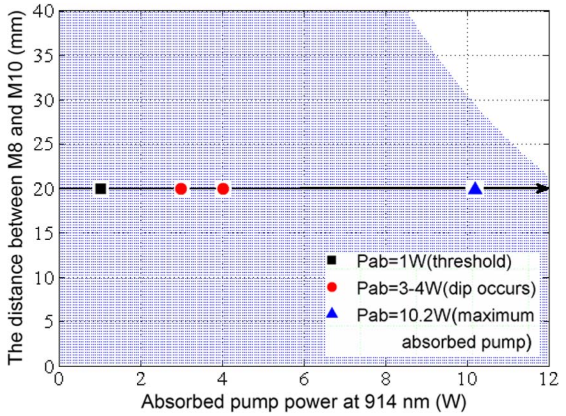

Fig. 3. Stable region (shadowed) of the Stokes resonator. The horizontal axis represents absorbed pump power, while the vertical axis represents the distance between M8 and M10.

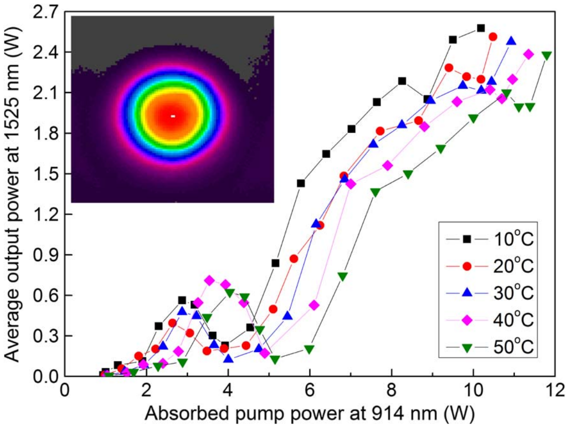

Fig. 4. Average output power as functions of absorbed pump power with the 1.0-at.% doped crystal under different temperatures.

to cavity alignment. Therefore, even tiny change in cavity mode resulting from thermal load variation could make the cavity deviate from its optimal alignment and, thus, affect the output obviously. Similar dips have also been observed by other authors and were explained as the consequence of cavity instability [17]. However, the several watts of pump was too low to interrupt the cavity stability. The calculated stable region of the Stokes resonator as absorbed pump changed with different cavity length is shown in Fig. 3. Clearly the cavity was stable all along when absorbed pump increased from threshold to the maximum with the fixed distance of 20 mm between M8 and M10 employed in the experiment. Besides, the average power of the 1525-nm Stokes output would go back to a reasonable level if we realigned the resonator when the dip occurred, which also proved that the dips were not caused by instability of the cavity.

The power performance for the 1.0-at.% doped crystal at different temperatures is plotted in Fig. 4, under the PRF of 100 kHz. Due to different absorption coefficients under temperatures from 10 °C to 50 °C, the maximum absorbed pump power increased from 10.2 W to 11.7 W under the same incident pump power of ~15.7 W. Although higher temperature helps promote the pump absorption, the Stokes average output powers at the maximum incident pump power exhibited unexpected decline from 2.58 W to 2.38 W as temperature increased. We attribute such decreases to the reason that the Raman scattering cross section, together with the laser stimulated emission cross section, is a decreasing function of crystal temperature [18]. On the other hand, the improvement of pump absorption through temperature rising is limited with these long

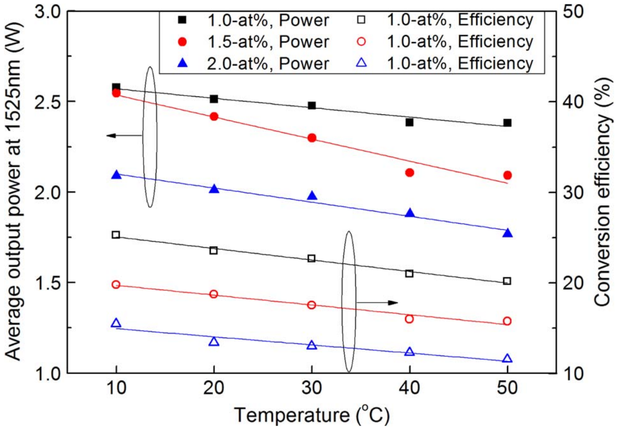

Fig. 5. Average output powers and corresponding conversion efficiencies at the maximum incident pump power of ~15.7 W with 1.0-, 1.5-, and 2.0-at% doped crystals versus different temperatures.

and highly doped crystals whose absorption fractions have already reached an acceptable level. Therefore, the influence of heating induced decay in both Raman scattering and stimulated emission cross section affects more than the contribution of absorption improvement, resulting in the near-linear decrease of output power. The inset is the beam profile recorded by Ophir PYIII at the maximum output power of 2.58 W, where the M^2 factor was measured to be 1.92 in the horizontal plane. The Stokes pulse duration was ~40 ns at the threshold and shortened to ~18 ns at the maximum pump.

Fig. 5 shows the average output powers of 1525-nm Stokes and corresponding conversion efficiencies of each crystal with different holder temperatures under 15.7 W of incident pump. With the 1.5- and 2.0-at.% doped crystals used, the Stokes output power also decreased with increasing temperature. Moreover, the Stokes output power showed a trend of decline with higher dopant concentration. The maximum Stokes output power with 1.0-at.% doped crystal was 2.58 W, which dropped to 2.55 and 2.09 W, respectively, with the 1.5- and 2.0-at.% doped crystals used, though the absorbed pump power increased significantly from 10.2 W to 13.3 and 14.0 W. The reason should be the declining upper-laser-level lifetime induced by higher dopant concentration. The lifetime of $^4F_{3/2}$ of 1.0-at.% doped Nd:YVO$_4$ is $\sim$100 μs and decays to $\sim$60 μs or shorter with the dopant concentration of 2.0-at.% [19]. In addition, better pump absorption results in heavier thermal load, which would reduce the Raman gain [5]. As a result, the conversion efficiency from absorbed pump power to 1525-nm Stokes output degenerate from 25.3% to 19.2% and 14.9% in succession with the 1.0-, 1.5-, and 2.0-at.% doped samples.

4. Conclusion

In summary, an efficient 1525-nm Nd:YVO$_4$ self-Raman laser in-band pumped at 914 nm is demonstrated for the first time. The conversion efficiency of 25.3% with respect to absorbed pump power, which is higher than those of ever-reported 1.5-μm self-Raman lasers, is achieved by virtue of reduction in quantum defect. Moreover, the optical efficiency from incident pump to Stokes output reached 16.4%, with the 1.0-at.% doped, 20-mm-long crystal ensured the pump absorption and, meanwhile, avoided the concentration-related performance decay.

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