High efficiency actively Q-switched Nd:YVO_4 self-Raman laser under 914 nm in-band pumping

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Abstract: An high efficient actively Q-switched Nd:YVO_4 self-Raman laser based on in-band pumped at 914 nm was reported. Particles from thermally excited Stark leveled in the ground-state were pumped to the upper lasing level directly, the Stokes factor loss was reduced to a minimum and the quantum efficiency loss was eliminated. This alleviated the thermal effect of the laser and consequently realized better performance. The effect of pump absorption on conversion efficiency was investigated experimentally in detail with the in-band pumping. Using two Nd:YVO_4 crystals with different doping concentration, 1.51 W (1.0-at.%, 20 ℃) and 2.11 W (2.0-at.%, 20 ℃) output power were obtained respectively, corresponding to the conversion efficiency of 42.7%(1.0-at.%) and 39.0%(2.0-at.%) and the optical efficiency of 28.5%(1.0-at.%) and 35.2%(2.0-at.%).

Key words: self-Raman; in-band pumping; Nd:YVO_4 laser

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914 nm 共振泵浦高效率主动调 Q Nd:YVO_4 自拉曼激光器

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摘 要: 报道了一种基于 914 nm 共振泵浦技术的高效主动调 Q Nd:YVO_4 自拉曼激光器。将处于基态低斯塔克能级粒子直接泵浦到激光上能级,可以减小斯托克斯因子损耗、降低量子亏损,从而实现了高效的 1 176 nm 拉曼光输出。在共振泵浦条件下,对泵浦吸收对转换效率的影响进行了详细的实验研究。使用两块掺杂浓度不同的 Nd:YVO_4 晶体,分别获得了 1.51 W(1.0-at.%, 20 ℃)和 2.11 W(2.0-at.%, 20 ℃)的平均输出功率,对应的光光转换效率分别为 28.5%(1.0-at.%)和 35.2%(2.0-at.%),相对于吸收泵浦光的转换效率分别为 42.7%(1.0-at.%) 和 39.0%(2.0-at.%)。

关键词: 自拉曼; 共振泵浦; Nd:YVO_4 激光器

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0 Introduction

Stimulated Raman scattering (SRS) is an economical and practical approach to generate laser sources operating at some significant wavelengths. Q-switched and CW self-Raman lasers based on Nd-doped laser crystals provide the first Stokes line between 1 100 and 1 200 nm. Through frequency doubling, these lasers can generate radiation at wavelength in the yellow-orange spectral region which is difficult to generate in other ways and is of great use for sodium guide star laser, medical screening, etc. For self-Raman lasers, fundamental laser emission and SRS conversion can be achieved in the same materials such as Nd:KGd$(WO_4)_2$, Nd:$PbWO_4$ and Nd:YVO_4, etc. Since self-Raman lasers diminish the intra-cavity loss as well as achieve a compact resonator design, it has been widely studied and developed over the past decades[1-6]. Some commonly used Raman crystals doped trivalent laser ions such as Nd:YVO_4 and Nd:$GdVO_4$[7] attract much attention because of their capability for excellent third-order nonlinear optical performance. In 2004, Y. F. Chen reported diode-pumped passively Q-switched Nd:YVO_4 self-stimulated Raman laser first[8]. In the same year, he reported a high-power diode-pumped actively Q-switched Nd:YVO_4 self-Raman laser and obtained the highest efficiency[9]. However, as mentioned yet in Ref.[10], thermal load of the combined laser and Raman process was exacerbated severely at high average power and the pump power was largely restricted because of the thermal lens effect and resultant resonator instability. Moreover, the Raman gain is a decreasing function of crystal temperature. Therefore, thermal load becomes the main limitation for high output power and conversion efficiency of self-Raman laser[11]. In order to overcome this problem, many methods have been proposed such as using composite laser crystals[10] and in-band pumping[12].

The in-band pumping is a method to pump the ions from the ground state($^4I_{9/2}$) directly to the upper-laser-level($^4F_{3/2}$) instead of the excited state($^4F_{5/2}$) and thus diminish the quantum defect between pumping and laser photons, which was represented and experimentally proved by R. Lavi et al[13]. In 2008, the first in-band pumped vanadate self-Raman laser pumped at 880 nm was demonstrated by A. J. Lee et al[12]. Compared with the traditional 808 nm pump source, heat generation decreased significantly, before long, this method was also successfully derived with a large number of configurations[14-15]. For all this, the thermal effect with 880 nm in-band pumping was still serious.

In our previous work[16-17], the results demonstrated that further reduction of quantum defect can be realized by pumping ions from the higher Stark sublevel of the ground state (Z_5) to upper-laser-level (R_1) with longer wavelength than 880 nm. In comparison with pumping at 880 nm, the quantum defect can be reduced by 18.5%[18], which was confirmed in a series of experiments[16-20]. Thus, a better performance of Nd:YVO_4 self-Raman laser could be expected with 914-nm pumping source adopted. However, the absorption coefficient at 914 nm of Nd:YVO_4 crystal is not sufficiently satisfying. As a result, improving pump absorption is the key to improve the performance of self-Raman laser. Usually, the absorption coefficient varies with the crystal parameters such as crystal length, doping concentration and temperature. Investigating the effects of crystal parameters on laser performance experimentally, therefore, is meaningful for 914 nm pumping.

In this paper, three samples are employed to investigate the influences of doping concentration and temperature of the Nd:YVO_4 crystals on pump absorption and optical efficiency of 914 nm in-band pumped Nd:YVO_4 self-Raman laser, with the purpose of finding an efficient method to improve the pump absorption of this pumping scheme and then obtain high optical efficiency. With the optimal conditions, 1.51 W(1.0-at.%, 20 ℃) and 2.11 W(2.0-at.%, 20 ℃)

output power were obtained respectively, corresponding to the conversion efficiency of 42.7%(1.0–at.%) and 39.0%(2.0–at.%) and the optical efficiency of 28.5% (1.0–at.%) and 35.2%(2.0–at.%).

1 Experimental setup

The experimental setup of the end-pumped actively Q –switched Nd:YVO$_4$ laser with self-frequency Raman conversion is shown in Fig.1. A 914 nm Nd:YVO$_4$ laser with a maximum output power of 8 W, which was used as the pump source of the in-band pumped self-Raman laser here, was made by ourselves. The pump source of the 914 nm Nd:YVO$_4$ laser was an 808 nm fiber-coupled laser diode array with a fiber core diameter of 400 μm and a numerical aperture of 0.22. The 3 mm×3 mm× 5 mm gain medium was a 0.15–at.% and *a*–cut Nd:YVO$_4$ crystal and the entrance face of which was antireflection (AR) coated at 808 nm and was coated for highly reflective (HR, R>99.5%) at 914 nm. It was wrapped in indium foil and was mounted in an aluminum heat sink cooled with refrigerant water at 10 ℃. The output mirror M1 of 914 nm laser was a concave mirror with a 100 mm radius of curvature and was coated for partially transmissive at 914 nm (T=4.1%) and AR (R<20%) at 1 064 & 1 342 nm to suppress parasitic oscillations on lines in these region. The output beam from M1 was reimaged by a focusing lens with focal length of 50 mm into the second Nd:YVO$_4$ crystal which was used as the self-Raman gain medium. A compact plano-concave resonator with a length of 50 mm was designed for efficient conversion at the first Stokes of 1 176 nm. The *a*–cut Nd:YVO$_4$ crystal was wrapped in indium foil and mounted in the aluminum heat sink. Three crystals with different Nd^{3+} concentrations of 1.0, 1.5 and 2.0–at.%, were adopted in the experiment for comparison. It is worth noting that it may bring difficulty on realizing good overlapping between the fundamental and Raman beams, thereby reducing the efficiency if the crystal length is too long. For this reason, we adopted a crystal length of 20 mm (3 mm× 3 mm× 20 mm) that can guarantee interaction length and also meet a relatively good overlapping between the fundamental and Raman beams. Both sides of the each crystal were AR coated at 914 nm pump wavelength and were coated for highly transmissive (HT, T>99.5%) at 1 000–1 200 nm. A 20–mm–long acousto-optic Q –switch (AOS) has AR coating at 1 000–1 200 nm on both faces and was driven by an 80 MHz center frequency with 15 W of radio frequency power. The input mirror M2 was a plane mirror HT (T>95%) coated at the pumping wavelength of 914 nm and HR coated at 1 064 & 1 176 nm. The output mirror M3 was a concave mirror with a 100 mm radius of curvature and was coated for partially transmissive (T=6.5%) at 1 176 nm and HR at 1 064 nm. A dichroic mirror with HR coating at 1 176 nm and HT coating at 914 & 1 064 nm was adopted to separate the leakage at 1 064 and 914 nm from the output at 1 176 nm. The pump power and the average power of the first-Stokes output were measured by a power meter Molectron EPM1000.

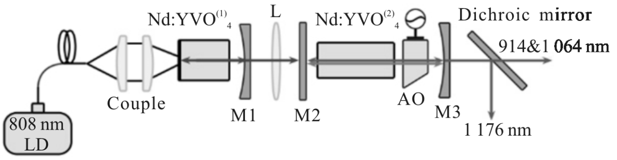

Fig.1 Experimental arrangement of the actively Q–switched Nd:YVO$_4$ self-Raman laser in-band pumped at 914 nm

2 Results and discussion

After propagating through L and M2, there was at most 6.0 W pump power at 914 nm that could incident into the self-Raman gain medium. The pump light was polarized parallel to the *c* axis of the Nd:YVO$_4$ crystal, so as to access a higher absorption cross section. Given 914 nm pumping suffers comparatively low pump absorption, we first investigated the pumping process with regard to the absorption coefficients versus different temperatures and doped concentration.

Since the population on Stark sublevels of the ground state obeys Boltzmann distribution, heating the crystal can be expected as an effective method to elevate the population from lower Stark sublevel to higher Stark sublevel and consequently promote the absorption. As shown in Fig.2, the pump absorption increased when the crystals were altered from 20 to 50 ℃ by virtue of the increasing population in high Stark sublevel of the ground state. The absorption coefficient of the 1.0, 1.5 and 2.0-at.% crystals rose from 0.53, 0.93 and 1.12 cm^{-1} to 0.67, 1.02 and 1.26 cm^{-1}, respectively. Indeed, higher crystal temperature improves the pump absorption under in-band pumping scheme. However, the increments in absorption fraction are limited since the absorption has already reached a relatively good level at 20 ℃ for the long and highly doped crystals. It is promising to let the self-Raman laser operate effectively where the absorption fraction is over 60% with low-Nd-dopant crystal.

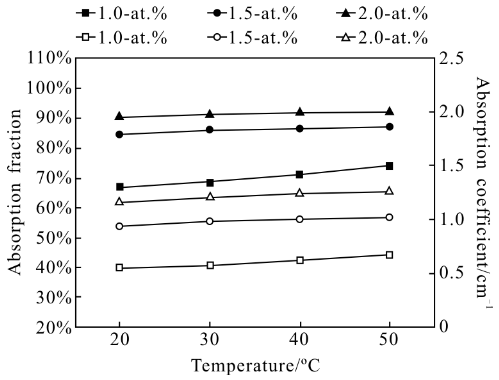

Fig.2 Absorption fractions of each crystal under different temperature and corresponding absorption coefficients (without lasing)

The output performance of the self-Raman laser with different samples was studied under different temperatures. The average output power at the first-Stokes wavelength of 1 176 nm as a function of the incident and absorbed pump power at different temperatures (1.0-at.% sample) is shown in Fig.3.

The average output power roughly increased along with the increasing of the pump power. Nevertheless, the growth of the average output power has a slower trend after the pump power reaching ~3 W and even has a downside afterwards. We consider that it result from 914 nm pump beam quality deterioration. The output power almost all reached the highest point at different temperature, when the incident pump power was above ~5.2 W. The maximum output powers were 1.51, 1.56, 1.61 and 1.65 W, respectively, under roughly the same pump power. It, apparently, increased with the temperature rising from 20 to 50 ℃ (shown in the inset of Fig.3 (a)) because of the better pump absorption brought by higher temperature. As shown in Fig.3 (b), the conversion efficiency (the ration between the output power and the absorbed pump power) decreased when the crystal was heated under temperature from 20 to 50 ℃. High temperature induced the decreasing of stimulated emission cross section and Raman gain, thereby reducing the efficiency.

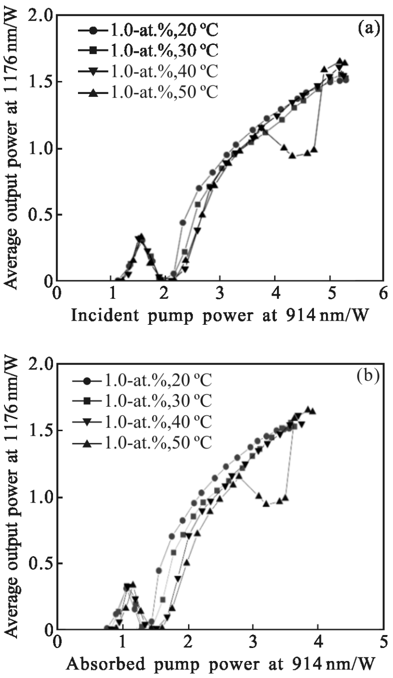

Fig.3 Average output power of the 1 176 nm Raman laser versus the incident and absorbed pump power at 914 nm (1.0-at.% Nd:YVO_4)

Figure 3 shows that there are obvious dips on the output power curves at 3.76-4.91 W when the temperature was 50 ℃. The weak overlapping of fundamental and Raman beams induced by thermal lens effect is to blame for the dip. The nonuniform pumping of the diode-end-pumped system and the touching between the holder and the four surfaces of the crystal are the two factors together result in asymmetrical thermal gradient inside the laser material. The consequent faulty thermal lens formed in the Raman-active medium, thereby, performed an uncertain affection on cavity mode, especially for self-Raman laser which is extremely sensitive to the overlap between fundamental emission beam and Raman output beam. In fact, we have observed such phenomenon several times in our experiment occasionally. In addition, we found another apparent dip on the incident pump power curves at 2 W in Fig.3. The same phenomenon was mentioned yet in Ref.[21] and the author interpreted that it was arouse by instability of resonator because of the thermal effect. Nevertheless, the pump power (1.5–2.6 W) of the dip was so low that cannot influence the stability of cavity significantly. We found that just one stable region was contained in our resonator through our calculations and the resonator became instability only when the thermal focal length was less than 30 mm. However, the thermal focal length versus the maximum pump power of our experiment was ~300 mm (far greater than 30 mm), so the phenomenon was unlikely caused by instability of the resonator.

We repeated the experiment after replacing the 1.0–at% sample with the 2.0–at.% sample and the results were given by Fig.4. The highest optical efficiency was 35.4% versus incident pump power of 5.46 W. There are similar dips in Fig.4, and we can reasonably speculate that the trend of the curves matches with our deduction. For the 1.5–at.% sample with the same length, we obtained the highest optical efficiency of 36.6% at 20 ℃ and its relation curves were similar to other two samples mentioned above. Therefore, the images of the 1.5–at.% sample are not given for conciseness.

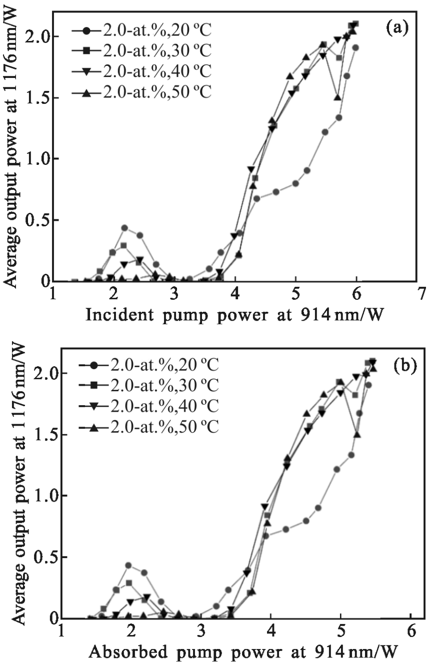

Fig.4 Average output power of the 1 176 nm Raman laser versus the incident and absorbed pump power at 914 nm (2.0–at.% Nd:YVO$_4$)

Figire 5(a) gives the optical efficiency versus the maximum incident pump power at different temperature, and the highest optical efficiency of different samples are approximately 31.0% (50 ℃, 1.0–at.%), 35.0% (20 ℃, 1.5–at.%) and 35.4% (20 ℃, 2.0–at.%), respectively. We can learn that the optical efficiency is an increasing function of crystal temperature for 1.0–at.% sample. This is because that increased absorption coefficient generated by high temperature plays a primary role compared with smaller stimulated emission cross section induced by the same reason. Moreover, the absorption fraction rose from 66.8% to 73.9% when the 1.0–at.% sample was heated from 20 to 50°C and the growth of ~7% was higher than ~2% (the growth of the other two samples), thus significantly increased the optical efficiency. This provides an effective method, heating the medium, for low–dopant crystal to achieve high optical efficiency. Conversely, the optical efficiency of 1.5 and 2.0–at.% samples is roughly a decreasing function of temperature. The result is also reasonable and it is mainly because of decreasing of stimulated emission cross section with the increasing of temperature.

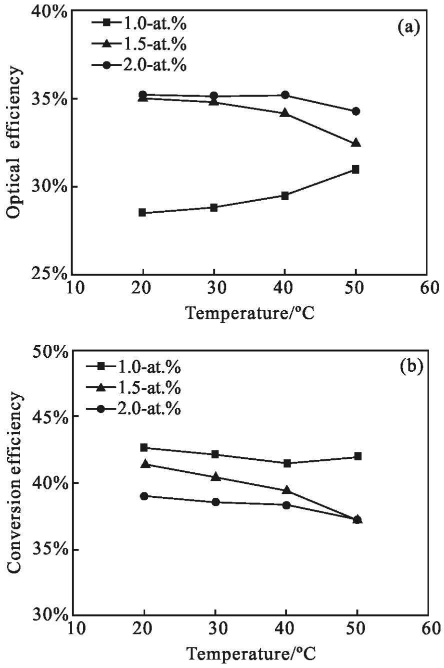

Fig.5 Optical efficiency and conversion efficiency versus the maximum pump power at different temperatures

Therefore, it is an unfavorable method to heat the crystal once the pump absorption reaches to a certain degree which is enough to let laser operate efficiently. It is obviously that high doping concentration and low temperature are conducive to high optical efficiency.

The conversion efficiency versus maximum absorbed pump power for different samples are approximately 42.7%(20 ℃, 1.0-at.%), 41.4%(20 ℃, 1.5-at.%) and 39.0%(20 ℃, 2.0-at.%), respectively (as shown in Fig.5(b)). The conversion efficiency reduced significantly when the high doping concentration crystals were used as self-Raman medium, though the pump absorption was much better than that of the 1.0-at.% doped crystal. This is due to the short upper lasing level lifetime and significant cross relaxation caused by high doping concentration. Moreover, higher pump absorption accompanied with high doping concentration also brought stronger Auger upconversion under the same incident pump power[22-23]. The population inversion is consumed in these processes and these all influence the laser gain, thus reducing the conversion efficiency. Therefore, it is a testament to the low doping concentration crystal being superiority for high conversion efficiency.

The relationship between absorbed 914 nm pump power and corresponding 1 176 nm output power as well as the relevant conversion efficiency at the holder temperature of 20 ℃ is depicted in Fig.6. To the best of our knowledge, the conversion efficiency of 42.7% under the 3.54 W maximum absorbed pump power is the highest among 1 176 nm Nd:YVO_4 self-Raman lasers reported to date. An even higher conversion efficiency up to 47.6% was achieved when absorbed pump power was 2.58 W with average output power of 1.23 W. After the conversion efficiency reached the maximum at ~2.6 W absorbed pump power, it began to decrease gently along with the increasing of pump power, which is an indicative of the beam quality deterioration of the pump source at 914 nm.

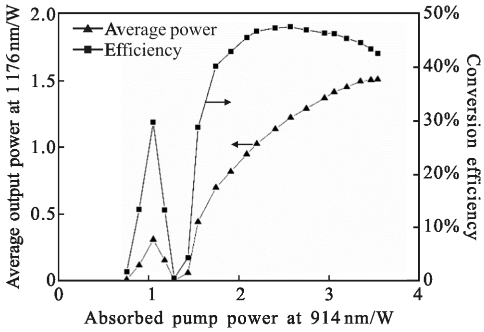

Fig.6 1 176 nm average output power and corresponding conversion efficiency as functions of 914 nm absorbed pump power at 20 ℃ (1.0-at.% Nd:YVO_4)

3 Conclusion

A compact 914 nm end-pumped actively Q-switched self-Raman laser with the highest conversion efficiency at 1 176 nm was demonstrated in this paper. Three *a*-cut Nd:YVO_4 crystals with different Nd^{3+} concentrations were adopted and operated at different temperatures to investigate optimal parameters to gain high optical efficiency and conversion efficiency. The results of the experiment reveal that relatively high doping concentration and low temperature benefit the optical efficiency and low doping concentration and low temperature are positive for conversion efficiency.

The efficiency would be much higher if better coated lens were adopted. Using two Nd:YVO_4 crystals with different doping concentration, 1.51 W(1.0–at.%, 20 ℃) and 2.11 W (2.0–at.%, 20 ℃) output power were obtained respectively, corresponding to the conversion efficiency of 42.7%(1.0–at.%) and 39.0%(2.0–at.%) and the optical efficiency of 28.5%(1.0–at.%) and 35.2%(2.0–at.%). This confirms that 914 nm in-band pump source, adopted for Nd:YVO_4 self-Raman laser, own bright prospects and enormous potential for achieving higher optical and conversion efficiency.

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