High efficiency actively Q-switched Nd:YVO_4 self-Raman laser under 880 nm in-band pumping

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Abstract: An efficient acousto-optic Q-switched Nd:YVO_4 self-Raman laser in-band pumped at 880 nm was demonstrated. Using two 10-mm-long Nd:YVO_4 crystals as gain medium, 6.11 W of average output power at 1 176 nm Stokes wavelength was obtained under the incident pump power of 26.8 W and a high pulse repetition rate of 190 kHz, corresponding optical efficiency was 22.8%. The influence of Raman-gain-length on conversion efficiency was investigated in the experiment and the dips on Stokes output power was also discussed. Control experiment of the self-Raman laser under 808 nm traditional pumping shows that in-band pumping help improve the conversion efficiency and maximum output power greatly.

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

CLC number: TN248.1 **Document code:** A **DOI:** 10.3788/IRLA201645.0105002

880nm 同带泵浦的高效率 Nd:YVO_4 自拉曼激光器

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摘 要: 利用 880 nm 半导体激光器同带泵浦声光调 Q Nd:YVO_4 自拉曼激光器，以减轻热效应对泵浦功率的限制和对拉曼增益的影响,获得高效的 1 176 nm 一阶斯托克斯光输出。使用两块长度 10 mm 的 Nd:YVO_4 晶体作为增益介质,脉冲重复频率 190 kHz 时,在 26.8 W 入射泵浦功率下获得 6.11 W 的平均输出功率,光光转换效率 22.8%。实验研究了拉曼增益介质长度对输出功率和转换效率的影响,并对自拉曼激光器输出功率曲线中出现凹陷的原因进行分析,认为凹陷并非源自谐振腔稳定性,而是由于增益较弱的斯托克斯光对于谐振腔失调的敏感性所致。对照试验结果显示,与 808 nm 传统泵浦方式相比,880 nm 同带泵浦下自拉曼激光器的输出功率和转换效率得到明显提高。

关键词: 自拉曼激光器; 同带泵浦; Nd:YVO_4 激光器

收稿日期: 2015-10-05; **修订日期:** 2015-12-10

基金项目: 国家自然科学基金(61178028,61405141);天津市应用基础与前沿技术研究计划(15JCQNJC02500)

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0 Introduction

Frequency conversion by means of stimulated Raman scattering(SRS) in crystalline media have been used to obtain efficient all-solid-sate coherent radiation sources in multiple useful wavelengths from visible region to 1.5x μm eye-safe infrared[1-3]. Since the commonly used laser host materials of YVO_4 and $GdVO_4$ were predicted and soon proved reliable Raman-active mediums, lasers with self-frequency Raman conversion have attracted increasing interests[4-5]. By virtue of removing the necessity of an additional Raman crystal, the self-stimulated Raman lasers are compact in structure, easy to miniaturization and of course, economical[6]. However, accompanied with advantages above, the self-Raman lasers suffer thermal effects much more serious than common lasers because the energy difference between pump and Stokes photons becomes the lattice vibration, which is an extra heat source that increases the thermal load. On the other hand, the Raman gain is a decreasing function of crystal temperature. Therefore, the heat has been the major obstacle that limits the performance of high power self-Raman lasers[7-10]. Many methods have been tried to overcome this problem, such as quasi-continuous-wave pumping[11], using composite laser crystals[7,12], and in-band pumping[8].

The in-band pumping could decrease the quantum defect between pump and laser photons, thus reduces the heat generation and improves the laser efficiency. The reduction in thermal load could relief the temperature-induced Raman gain decay. It could also levels up the upper limit of the pump power determined by thermal lens effect, which hinders the power scaling of self-Raman laser. The application of in-band pumping in self-Raman lasers benefits from the combination of the two aspects. The first in-band pumped self-Raman laser is a continuous-wave Nd:$GdVO_4$ device pumped at 880 nm which demonstrated by Lee et al. [8], which proved the expectation of milder thermal load and increased the maximum output power. After that, in-band pumped vanadate self-Raman lasers are reported by different researchers and good results are obtained[13-14].

In this work, we describe an actively Q-switched Nd:YVO_4 self-Raman laser which is in-band pumped at 880 nm. 6.11 W average output power at 1 176 nm Stokes wavelength is obtained under 26.8 W incident laser diode pump power with a high pulse repetition rate (PRF) of 190 kHz, corresponding to an optical efficiency of 22.8% . The influences of pumping wavelength on thermal load and SRS conversion efficiency are investigated, by carrying out the control experiment of self-Raman laser under 808 nm pumping. The relationship between circulating fundamental laser power and Stokes power with different Raman gain length is also discussed.

1 Experimental arrangement

The Raman laser is depicted in Fig.1. The pump source is an 880-nm fiber-coupled laser diode with a core diameter of 400 μm, a numerical aperture of 0.22, and a maximum output power of 50 W. A multi-lens coupler reimages the pump beam into the laser crystal with a ratio of 1:1. M1 is a flat mirror with antireflection (AR) coating at 800-900 nm on both faces and high-reflection (HR) coating at 1 000-1200 nm on one face. It makes the resonator along with the output coupler M2, which is a concave mirror with 100 mm radius of curvature and coated for HR at 1 064 nm and partial-reflection (PR) at 1 176 nm. The laser crystal is a 3 mm×3 mm×10 mm a-cut Nd:YVO_4 crystal with AR coating at 800-1 200 nm on both faces. Since the Raman gain is proportional to the length of gain medium, another 3 mm×3 mm×10 mm Nd:YVO_4 crystal with the same coatings is inserted into the cavity to increase the Raman gain length to 20 mm. The doping concentrations of the two crystals are 0.3- and 0.5-at.%, respectively. To avoid the thermal fracture of crystal under high pump power, the 0.3-at.% doped crystal is arranged to absorb the pump power and the 0.5-at.% doped one is located behind it. The second Nd:YVO_4 crystal is 8 mm away from the first one and therefore the pump absorption and laser gain in it are very limited and negligible. The crystals are wrapped in indium foil and mounted in aluminum holders cooled at 10 ℃. A 30-mm-long acousto-optic Q-switch has AR coatings at 1 064 nm and 1176 nm on both faces and is driven at an 80-MHz center frequency by 15.0 W of RF power. The high ultrasonic frequency of 80-MHz is used to ensure the diffraction efficiency. Since the stimulated emission cross section of a-cut Nd:YVO_4 is rather large and a relatively short cavity length is adopted due to the serious thermal lens effect in the crystal, high diffraction efficiency is needed to make the effective Q-switch shut off. The overall cavity length is 72 mm. A flat filter which is 45° coated for AR at 1 064 nm and HR at 1 176 nm is used to separate the Stokes output and 1064 nm laser leakage. Two laser powermeters, a Molectron EPM1000 and a Newport 842-PE, are used to record them synchronously.

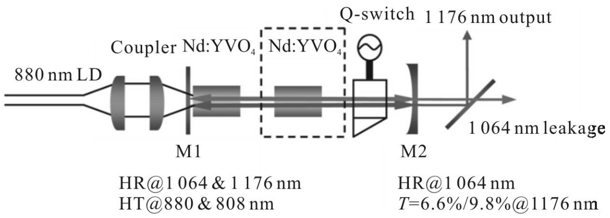

Fig.1 Schematic of the Nd:YVO_4 self-Raman laser

2 Results and discussion

Output couplers with different transmittances of 6.6% and 9.8% at the 1 176 nm Stokes wavelength are used in the experiment. The maximum output power is obtained with the T=9.8% output coupler and the results given bellow are all with this one used. With the cavities aligned for lowest threshold, the Stokes power often stops growing with increasing pump power after that reaches a certain level(typically more than ten watts), unless realigning the cavity, mostly because of the influence of serious thermal effect on the beam propagation. Therefore, the cavities are optimized for Stokes power under the maximum pump power used of 26.8 W instead of for lowest threshold. The duty-cycle is also optimized for maximum Stokes power. The optimal RF OFF time with the PRFs of 50, 100, and 190 kHz are found to be 290, 310, and 190 ns, respectively (corresponding duty-cycle of 5.8%, 3.1%, and 2.85%).

Figure 2 gives the average output power at the Stokes wavelength of 1 176 nm versus incident LD pump power at different PRFs when using both of the two Nd:YVO_4 crystals (total length of 20 mm) in the cavity. The Stokes power with 190 kHz PRF starts increasing once pumped beyond the Raman threshold of 5.97 W and exceeds 1.6 W under ~12 W pumping. However, it begins to drop after that and decreases to only several milliwatts under the pump power of ~15 W. When the pump power goes higher than 18 W, the Stokes power grows rapidly again and a maximum output power of 6.11 W is obtained under the incident LD power of 26.8 W, corresponding to an optical efficiency of 22.8% . Considering the 0.3-at.%-doped, 10-mm-long Nd:YVO_4 crystal absorbs only 77% of the incident non-polarized LD pump, the conversion efficiency with respect to absorbed pump power is 29.6%. Higher pump power is not applied in the experiment due to the risk of crystal damage. The maximum output powers with the PRFs of 50 and 100 kHz under the same pump power are 5.06 and 5.83 W, while the SRS thresholds are 3.28 and 5.2 W, respectively. As can be seen from Fig.2, when increasing the pump power, the Stokes powers with these two PRFs also dip to several milliwatts at a certain pump power range and then grow again, just like that observed with 190 kHz PRF. The difference between them is that the dip occurs later but is more obvious with higher PRF. Similar phenomenon has been observed in other authors′ work and was explained as cavity instability [12]. However, the dip could appear at the pump power below 10 watts (PRF=100 kHz), or even 5 watts (PRF=50 kHz). Such level of pumping is not strong enough to affect the cavity stability of this short linear cavity. Besides, the Stokes output power could go back to a reasonable level if we readjust the resonator when the dip occurs. Since the Raman gain is relatively low and is concerned in the overlap between the fundamental laser and Stokes beams, the Stokes output is much more sensitive to the cavity alignment compared with the fundamental laser. Therefore, any change in thermal lens effect under different pump power and resultant slight impact on intracavity beam propagation, could lead to serious Stokes power fluctuation, which however does not affect the fundamental wave much.

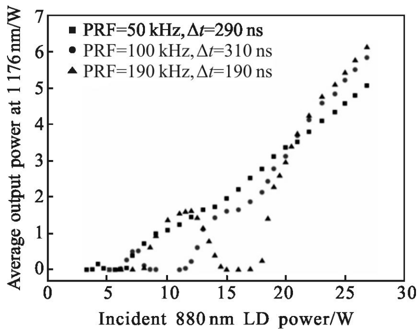

Fig.2 1 176 nm Stokes average output power versus incident pump power at different pulse repetitions of 50, 100 and 190 kHz

By using the ABCD matrix, we can know that the shortest thermal focal length allowed of this 72-mm-long cavity, which is limited by cavity stability, is ~80 mm. This indicates that the thermal focal length is larger than 80 mm even pumped at 26.8 W with the PRF of 50 kHz. In Ref.9, the thermal focal length of Nd:$GdVO_4$ is estimated to be ~70 mm when the incident 880 nm pump power is 20 W. The thermal lens effect here is much more modest, even the thermal conductivity of $GdVO_4$ crystal is larger than that of YVO_4.

The output waveform is measured by a fast photodiode and oscilloscope (Tektronix TDS5104). Figure 3 shows the 1 176 nm Stokes output pulse duration as function of incident 880 nm LD pump power. Higher pump power and lower PRF result in shorter pulse duration. The shortest pulse duration of 7.8 ns is obtained with the PRF of 50 kHz under 26.8 W pumping, while the average output power is 5.06 W. This corresponds to a single pulse energy of 0.1 mJ and a peak power of 13 kW, respectively.

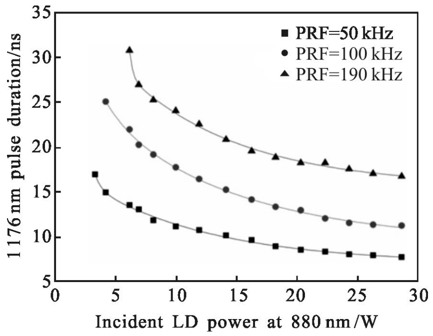

Fig.3 1 176 nm Stokes pulse duration versus 880 nm pump power with different PRFs

When only one 10-mm-long Nd:YVO_4 crystal is used with the same PRF, duty-cycle, and cavity length, the Raman threshold increases from that of 5.97 W with the two crystals to 10.5 W. Only 4.13 W Stokes power is obtained under the maximum incident pump power of 26.8 W, as shown in Fig.4. Increasing the length of Raman gain medium is indeed necessary for high conversion efficiency. To make it more clear,

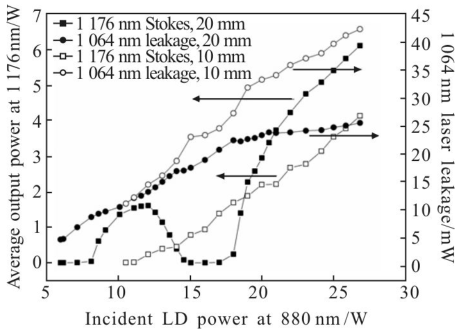

Fig.4 1 176 nm Stokes average output power and 1 064 nm laser leakage as functions of incident pump power with only one crystal/both of the two crystals in the cavity. The PRF is 190 kHz and the duty-cycle is 2.85%

the 1 064 nm laser leakage is recorded synchronously with the 1 176 nm Stokes output power. With only one Nd:YVO_4 crystal used, the leakages of 1 064 nm laser at the Raman threshold is 11.2 mW, 2.33 times higher than that of 4.8 mW when using the two crystals. The reason why it is 2.33 times instead of 2 times is that when pumped at 10.5 W, the crystal temperature is higher than that under 5.97 W pump power and is also much higher than that of the second $Nd:YVO_4$ crystal which absorbs little LD pump. The higher temperature decays the Raman scatting cross section thus affects the Raman gain.

With the two crystals used, the increasing of 1 064 nm laser power slows down when incident pump power is 8–12 W (solid circle), corresponding to the first rapid increasing of Stokes power(solid square), as shown in Fig.4. It can also be seen that when the Stokes power is decreasing (12–15 W LD pump power), the 1 064 nm power increasing is faster than when the Stokes power remains almost zero (15–18 W LD pump power). This is because the power of Stokes field goes back to fundamental laser field during its decreasing. The monotonically growing of fundamental laser power also indicates that the dip on Stokes power after its first peak is not due to the cavity instability because the 1 064 nm laser and the 1 176 nm Stokes share almost the same stable region. After the pump power exceeds 18 W, the increasing of 1 064 nm laser power becomes rather slow, accompanied with the fast growing of the Stokes power. When only one crystal is used, both the Stoke power and the laser power show near linear growing with the pump power. The laser leakage under the maximum pump power is 42.3 mW, much higher than the 25.6 mW with the two crystals used. The relatively short Raman gain medium length of 10 mm can not provide enough gain for efficient SRS conversion. The beam quality of the 1 176 nm Stokes output is measured by knife-edge method at the maximum output power of 6.11 W. The M^2 factors in x and y directions are 3.4 and 3.2, respectively.

The control experiment of the Raman laser pumped by an 808 nm fiber-coupled LD with the same fiber core diameter and NA is also carried out. The difference in pump wavelength results in different quantum efficiency and thermal load under the same absorbed pump power, and therefore influences the SRS efficiency. Figure 5 gives the comparison of Stokes average output power as functions of absorbed 808 nm and 880 nm pump power, respectively. 4.4 W Stokes average output power is obtained with 20.4 W absorbed 808 nm pump power, corresponding to a conversion efficiency of 22.2%, much lower than the efficiency of the 29.6% achieved with 20.6 W absorbed 880 nm pump power. Part of the efficiency decay is induced by the difference in quantum defect between the two pump wavelengths. The remaining part is due to the heavier thermal load under 808 nm traditional pumping compared to 880 nm pumping. Heavier thermal load results in higher crystal temperature, which decreases Raman gain, as well as the higher thermal diffractive loss. The depression on the output power curve is also observed under 808 nm pumping. The output power rolls over when the 808 nm pump power exceeds 20.4 W, which indicates that the thermal focal length is shorter than 80 mm by then.

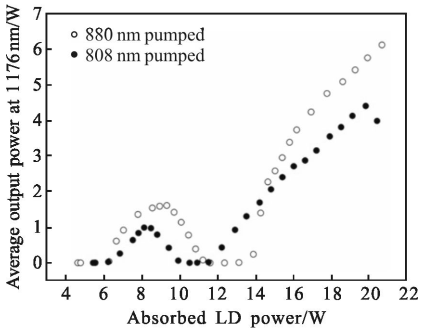

Fig.5 Comparison of Stokes average output power versus absorbed LD power under 880 nm and 808 nm pumping

3 Conclusion

In summary, an AO Q-switched $Nd:YVO_4$ self-Raman laser in-band pumped at 880 nm is demonstrated. A maximum output power of 6.11 W is achieved under the incident pump power of 26.8 W at the high PRF of 190 kHz. The optical efficiency is 22.8% and the conversion efficiency with respect to absorbed pump power reaches 29.6%. The influence of the Raman gain length on SRS efficiency is investigated by measuring the 1 064 nm laser leakage synchronously with the Stokes output. The results show that longer Raman gain length is necessary for high conversion efficiency and the depression on the Raman output power curve is not due to cavity instability. The control experiment of different pump wavelengths reveals that the in-band pumping could greatly improve the conversion efficiency of the self-Raman laser by virtue of lower quantum defect and resultant thermal load reduction.

References:

[1] Kores C C, Jakutis-Neto J, Geskus D, et al. Diode-side-pumped continuous wave $Nd^{3+}:YVO_4$ self-Raman laser at 1 176 nm[J]. ***Optics Letters***, 2015, 40(15): 3524-3527.

[2] Li Shutao, Dong Yuan, Jin Guangyong, et al. Normalized theoretical analysis of continuous-wave intracavity frequency-doubled Raman laser [J]. ***Infrared and Laser Engineering***, 2015, 44(1): 71-75. (in Chinese)

[3] Zhang Fang, Wang Zhengping, Xu Xinguang. Anisotropy of stimulated Raman scattering in $SrWO_4$ crystal[J]. ***Optics and Precision Engineering***, 2014, 22(1): 39-43. (in Chinese)

[4] Kaminskii A A, Ueda K, Eichler H J, et al. Tetragonal vanadates YVO_4 and $GdVO_4$-new efficient $\chi^{(3)}$-materials for Raman lasers [J]. ***Optics Communications***, 2001, 194(1): 201-206.

[5] Chen Y F. Efficient 1521-nm Nd:GdVO4 raman laser[J]. ***Optics Letters***, 2004, 29(22): 2632-2634.

[6] Yu H, Li Z, Lee A J, et al. A continuous wave $SrMoO_4$ Raman laser[J]. ***Optics Letters***, 2011, 36(4): 579-581.

[7] Li Long, Shi Peng, Liu Xiaofang, et al. Thermal effect of YVO_4-Nd:YVO_4 composite laser crystals [J]. ***Optics and Precision Engineering***, 2006, 14(5): 786-791. (in Chinese)

[8] Wang Yang, Duanmu Qingduo. Efficient cw Nd:$LuVO_4$-BiBO deep-bluelaser [J]. ***Infrared and Laser Engineering***, 2015, 44(3): 884-887. (in Chinese)

[9] Cui Li, Hu Wenghua, Zhang Hengli, et al. Nd:$GdVO_4$ laser with hybrid resonator at 1.34 μm [J]. ***Infrared and Laser Engineering***, 2014, 43(8): 2404-2406. (in Chinese)

[10] Shi Peng, Chen Wen, Li Long, et al. Influence of laser distribution on thermal effect of Nd:YVO_4 crystal [J]. ***Optics and Precision Engineering***, 2008, 16(2): 197-201. (in Chinese)

[11] Dekker P, Pask H M, Spence D J, et al. Continuous-wave, intracavity doubled, self-Raman laser operation in Nd:$GdVO_4$ at 586.5 nm [J]. ***Optics Express***, 2007, 15(11): 7038-7046.

[12] Zhu H, Duan Y, Zhang G, et al. Efficient second harmonic generation of double-end diffusion-bonded Nd:YVO_4 self-Raman laser producing 7.9 W yellow light [J]. ***Optics Express***, 2009, 17(24): 21544-21550.

[13] Ding X, Fan C, Sheng Q, et al. 5.2-W high-repetition-rate eye-safe laser at 1525 nm generated by Nd:YVO_4-YVO_4 stimulated Raman conversion [J]. ***Optics Express***, 2014, 22(23): 29111-29116.

[14] Jiang W, Zhu S, Chen X, et al. Compact passively Q-switched Raman laser at 1176nm and yellow laser at 588 nm using Nd^{3+}:YG/Cr^{4+}:YAG composite crystal [J]. ***Applied Optics***, 2014, 53(7): 1328-1332.