

High-power Simultaneously Q-switched and Kerr-lens Mode-locked Eye-safe Nd:YAP/YVO₄ Intracavity Raman Laser Based on Injection Locking

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Abstract: A multi-Watt, multi-GHz laser eye-safe laser was obtained by simultaneously Q-switched Kerr-lens mode-locking and stimulated Raman scattering. The high power fundamental laser at 1342 nm was generated efficiently with a side-pump Nd:YAP laser rod. The fundamental laser was captured by the intra-cavity Raman cavity, and the mode beating of the fundamental laser and the Raman laser was maximized by setting the suitable length relationship between the fundamental cavity and the Raman cavity. The output performance of the Raman lasers with different output coupler were measured and analyzed. The maximum average output power at 1526 nm was 3.5 W, the pulse duration was about 220 ps and the pulse repetition rate was 0.64 GHz.

1 INTRODUCTION

Water has a large absorption coefficient in this spectral region at the vicinity of 1.5 μ m, which can prevent the energy from reaching the retina. High power laser at eye-safe wavelength region are widely used in medical treatment, remote sensing, radar system and optoelectronic countermeasure. Optical parametric oscillator (OPO) is one of the most effective methods to generate high-power eye-safe pulse laser (Huang YP et al. 2009, Huang YJ et al. 2012, Chang HL et al. 2011, Huang JY et al. 2012). Raman laser also has become another promising way to explore laser at new wavelength region due to the rapid development of crystalline Raman medium in the recent several years. Generally, there are two approaches to achieve Raman laser within the eye-safe wavelength region, the laser operation on the 2nd or 3rd stokes pumped by laser at 1.064 μ m (Shpak et al. 2012, Sabella et al. 2011) from the $^4F_{3/2}-^4I_{11/2}$ transition of Nd³⁺ and the 1st stokes pumped by laser at 1.3 μ m (Chang YT et al. 2009, Chen XH et al. 2012) from the $^4F_{3/2}-^4I_{13/2}$ transition. However, it's relatively difficult to obtain a high-order stokes generation, because it has lower

conversion efficiency and strict requirements on both of the mirror coating and the working temperature control of the Raman crystals.

Kerr-lens mode-locking is a promising way to obtain laser pulse with picoseconds or femtosecond scale. Adding a Q-switch in the Kerr lens mode-locking laser has dual functions: to trigger the Kerr-lens effect (KLE) in the Raman crystal and to further modulate the mode-locking pulse train. Q-switched Kerr-lens mode locking (QML) is usually avoided in the laser experiment because the high peak power it generates may damage the elements in the resonate cavity. However, the stable QML laser can be achieved with critical resonator design. In 2013, Chenlin Du (Huang GX et al. 2013) reported a diode-end-pumped QML first-stokes laser operating at 1175.9 nm. But rare stable diode-side-pumped QML Raman laser publications were seen to the best of the authors' knowledge.

With regard to the high power Raman laser, in the recent two years, the diode side pumped modular was applied popularly in the Raman laser. Zhang X.Y. reported a diode-side-pumped nanosecond Q-switched Nd:YAG/BaWO₄ (Shen et al. 2012) in 2014 and Nd:Gd₃Ga₅O₁₂/BaWO₄ high-order stokes laser in 2013 (Shen et al. 2013). They also referred

to the Q-switched self-mode-locking phenomenon. Admittedly, diode-side-pump module may have lower combining efficiency, but it also has many irreplaceable advantages. Laser rod with big dimension can be employed and the side-pump module can provide higher pump power and better water cooler, which are beneficial for obtaining high power laser. Nd:YAP is an excellent side-pump laser material at 1.3 μm (Zhu et al. 2007, Zhu et al 2009). It possesses high thermal conductivity, excellent optomechanical coefficient, and large product value ($330 \times 10^{-19} \text{cm}^2 \mu\text{s}$) of stimulated emission cross section and fluorescence lifetime at 1342 nm (from R2-X1 intense overlapped stark transitions), which contribute to the low threshold and high power laser output. Cerny et al. (2004) referred to a passively Q-switched BaWO_4 first-stokes nanosecond laser pumped by Nd:YAP at 1.5 μm in 2004.

In this paper, a Q-switched Kerr-lens mode-locked Raman eye-safe laser was obtained. The Raman laser cavity and the fundamental cavity were separated, and the fundamental laser at 1342 nm was captured by the Raman cavity for efficient and stable mode-locked Raman laser generation when the frequency of two cavities matched. The maximum output power was 3.5 W, pulse duration was 220 ps, and pulse repetition rate was 0.64 GHz. The output performance of the QML laser was measured and analyzed.

2 EXPERIMENT DESIGN AND SETUP

A line-resonator is adopted and the experiment setup is sketched as Figure 1. The high pulse repetition rate laser can be generated in narrow cavity, so the separated Raman cavity is beneficial for obtaining high pulse repetition rate of the Raman laser. The side-pumped module (GT Optics, Beijing) consisting of three pump units arranged in a three-fold symmetry around the laser rod can provide a maximum pump power of 250 W at 808 nm. A c-cut Nd:YAP (grown by Fujian institute of research on the structure of matter, Chinese academy of sciences) with a dimension of $\varnothing 3 \times 65 \text{mm}^3$ and a Nd^{3+} doping concentration of 0.9 at. % is set in the side-pump system and cooled by water flow directly, with both facets AR ($R < 0.2\%$) coated at 1342 nm. The acousto-optical Q-switch (Gooch and Housego, QS-027) with anti-reflection coating on the both facets at 1342 nm provides a maximum modulation frequency of 50 kHz. A c-cut YVO_4 crystal with

dimension of $3 \times 3 \times 29 \text{mm}^3$ is applied as Raman gain media. It is wrapped with indium foil and mounted in water-cooled copper blocks. Both facets of the YVO_4 are coated with anti-reflection film at 1342 nm and 1525 nm. The Nd:YAP laser crystal, Q-switch and YVO_4 crystal are water cooled to be 23 $^\circ\text{C}$, 19 $^\circ\text{C}$, and 17 $^\circ\text{C}$, respectively.

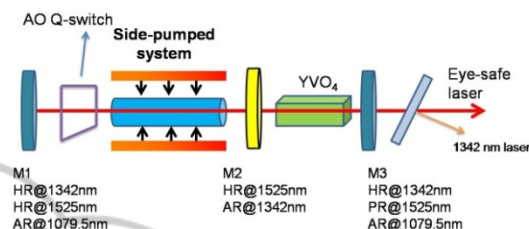


Figure 1: Actively Q-switched mode-locking 1525 nm laser setup.

The fundamental resonator is a plane-concave configuration, which consists of a plane mirror M_1 and a concave mirror M_3 with a curvature radius of 500 mm. The concave mirror M_3 is used to compensate the thermal lens effect of the laser rod. M_1 is directly coated with high-reflectivity dielectric film (HR@1342 nm, 1525 nm, $R > 99.8\%$), and anti-reflectivity (AR@1079.5 nm) to suppress the high-gain spectral line of Nd:YAP at 1079.5 nm. Output couple (OC) M_3 is coated with high-reflection (HR@1342 nm) for the fundamental wave, antireflection (AR@1079.5 nm), and part-reflection for the first-stokes wave (PR@1525 nm) output. Two OCs with different reflectivity are applied to carry out the experiment and the output performance is compared. The transmissivity of OC-1 and OC-2 is 5.1% and 2%, respectively. Another mirror M_2 which is coated for antireflection (AR@1342 nm) for the fundamental wave, but high reflectivity of the fundamental wave (HR@1525nm, $R > 99.9\%$) was set between side-pump module and the YVO_4 crystal to separate the two resonators. The distance between M_1 and M_3 is 37.35 cm and the length of the Raman cavity is 19.72 cm.

The average output power (AOP) was measured by a power meter (from Phycience Opto-Electronics, Beijing). The temporal pulse profile of lasers are received by a PIN photo detector with a rising time 25 ps (EOT ET-3500) and displayed by an oscilloscope with a bandwidth of 12 GHz and a sample rate of 40 GHz/s (Agilent DSA91304A). The emission spectra of the laser were monitored and measured by a grating spectrum meter (Zolix Omni- λ 300) of a spectra range from 300 to 1700 nm.

3 EXPERIMENT RESULT AND ANALYSIS

3.1 Kerr-lens Mode Locking and Injection Locking

The Q-switched mode-locked laser was generated by modulating the fundamental Nd:YAP laser with the Q-switch and the Kerr-lens effect of the Nd:YVO₄. The Raman laser was generated by capturing and converting the energy from the fundamental cavity to the Raman cavity and Raman laser. The Q-switched laser pulse transformed into QML at the suitable modulation frequency. In the generation of the Q-switched pulse, the lower modulation frequency leads to a narrower Q-switched pulse and higher peak power. The KLE of the crystals depended on the power intensity and the intensity-dependent nonlinear index of refraction (Huang et al. 1992) in the Gaussian field is given by

$$n(r) = n_0 + \frac{2n_2P}{\pi\omega^2} \exp\left[-2\left(\frac{r}{\omega}\right)^2\right] \quad (1)$$

where n_0 is the linear refractive index, n_2 is the nonlinear index, P is the power, ω is the 1/e amplitude beam radius. Nd:YVO₄ has a large nonlinear refraction index ($n_2=4.7 \times 10^{-18} \text{ m}^2/\text{W}$), and is able to introduce a stronger self focusing of the beam (Haus et al. 1992). The Kerr lens effect affected by the power intensity generates a soft aperture to modulate the Q-switched fundamental laser pulse. The soft aperture has the function to suppress the modes whose perturbation intensity is too low. Thus, when repetition rate of the pulse which is modulated by the KLE matches the frequency separation of the resonator, QML laser can be achieved. The QML Laser with OC-1 is obtained at the modulation frequency range within 4.5 kHz to 16 kHz. The mode locking modulation depth varies with the changing modulation frequency, and reaches maximum at the modulation frequency of 13.5 kHz. The laser with OC-2 transforms into QML with the modulation frequency within 9 kHz to 12 kHz.

According to the properties of the Fabry-Perot cavity, the frequency separation Δf of the longitudinal modes in the resonator is given by Haus (1978)

$$\Delta f = \frac{c}{2L_{opt}} \quad (2)$$

Where L_{opt} is the optical length of the resonator. And the oscillating waves in the cavity is a series of eigenmodes with specific frequencies $f = n\Delta f$, where n is natural number $n = 0,1,2,3 \dots$. The

Raman line width of YVO₄ is 2.6 cm^{-1} (Piper et al, 2007), so the frequency gain bandwidth is $7.8 \times 10^{10} \text{ Hz}$. The frequency separation of the Raman resonator is 0.64 GHz, which indicates that every fundamental longitudinal mode whose intensity is higher than the Raman threshold will generate 121 first-stokes laser longitudinal modes. The transmission peaks of the F-P resonator also has a gain bandwidth, and its full width at half-maximum (FWHM) is given by (Haus et al. 1992)

$$\delta f_{1/2} = \frac{(1-R)c}{2\pi\sqrt{RL_{opt}}} \quad (3)$$

The FWHM of the transmission peak of the Raman cavity at the output coupler ($R=95\%$) is $2.0 \times 10^8 \text{ Hz}$, which is two degrees lower than the Raman gain bandwidth. In this case, every longitudinal mode whose power is over threshold will generate a Raman sideband and the oscillating frequencies depends on the characteristic frequency of the Raman cavity. but the injection locking and pulling occur in the process when the Raman cavity captures the fundamental laser. The length relationship between the two cavities is a crucial parameter for the mode beating of the two cavities in the transient process. The optical length of the fundamental cavity is two times longer than the length of the Raman cavity and after small adjustment was added in the position of the mirror M2, the fundamental laser can be damped by the Raman cavity efficiently and the modulation depth increased.

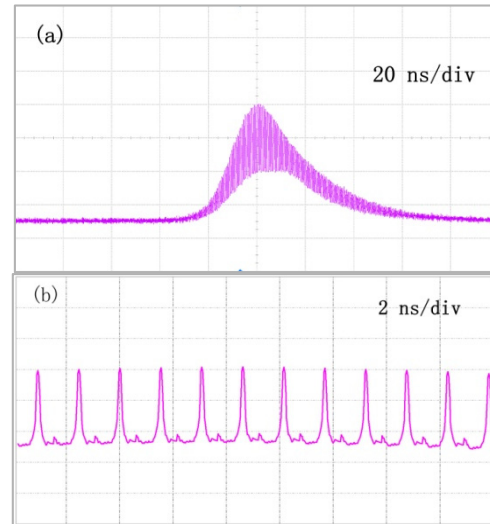


Figure 2: Oscilloscope traces of the performances of the fundamental laser and the first-stokes laser:(a) the first-stokes laser at 1525 nm at PRF of 13.5 kHz with the time span of 20 ns; (b) the first-stokes laser at 1525 nm at PRF of 13.5 kHz with the time span of 2ns.

The pulse of the QML Raman laser after adjustment at the modulation frequency of 13.5 kHz was shown in Figure 3. The repetition rate of the pulse beneath the Q-switch envelop is 0.64 GHz, which accords with the frequency separation of the Raman resonator. However, the modulation depth cannot reach 100% because there are some transverse modes in the side pump laser system and the soft aperture couldn't suppress all these modes. The pulse duration is 220 ps.

3.2 Output Power and Threshold Pump Power

The output power of lasers with OC-1 and OC-2 at different modulated frequency are measured and shown as figure 3. The output power increases with the increasing pump power and the slope efficiency decreased at high pump region. The threshold of the QML Raman laser with OC-1 and OC-2 is 78.3 W and 63 W at 13.5 kHz, respectively.

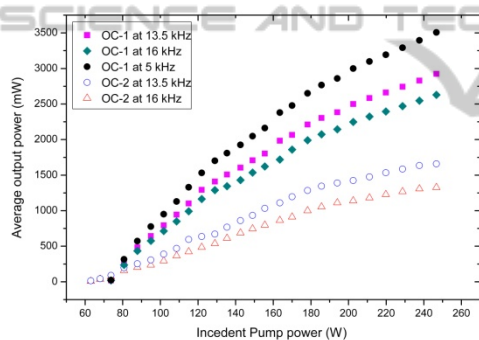


Figure 3: AOP for the QML laser at 1525 nm with OC-1 as a function of the incident pump power at 808 nm at 5 kHz, 13.5 kHz and 16 kHz, AOP for the QML laser at 1525 nm with OC-2 at 13.5 kHz and 16 kHz.

According to the Raman threshold given by Heuvel et al. (1992), The Raman threshold can be reduced by the higher Raman gain coefficient, higher pump laser beam quality, smaller effective action area and larger effective length of gain medium. The laser with OC-1 has higher power threshold than that of laser with OC-2 because the Raman laser cavity with OC-2 has lower loss than that of cavity with OC-1, the higher transmissivity is better for Raman laser intensity accumulation. Though the threshold pump power of the Raman crystal is the same, the laser with lower-reflectivity OC has higher a Raman laser threshold.

The output power of the QML Raman laser with OC-1 and OC-2 at 16 kHz, 13.5 kHz and laser with OC-1 at 5kHz is shown in figure 3. The laser with

OC-1 has higher output power than that of laser with OC-2. This is because the Raman conversion efficiency does not vary too much in these two cavities, but the transmissivity of OC-2 is too low and large part of the laser power is confined in the resonator after first-stokes generation. Thus, there is a suitable transmissivity for obtaining higher output power. The output power of laser with the same OC also differs from the modulation frequency of Q-switch. Under the same pump power, the output power of the QML laser increases with the decreasing modulation frequency because the envelop of the Q-switched laser pulse is shorten when the Q-switch modulation frequency decreases (Chen et al. 2013), which leads to a higher peak power of the fundamental laser and a higher Raman conversion efficiency. The maximum average output power of 3.5 W was obtained under the pump power of 245 W at the Q-switch modulated frequency of 5 kHz.

3.3 Spectrum and Beam Profile

The spectrum of the output laser under low pump power is shown in figure 4. The fundamental laser is at 1342 nm and the Raman laser is at 1525 nm, which reveals an 892 cm^{-1} Raman shift. The output laser at 1525 nm was received by a fluorescent screen, and the picture of the beam spot is also shown in figure 4.

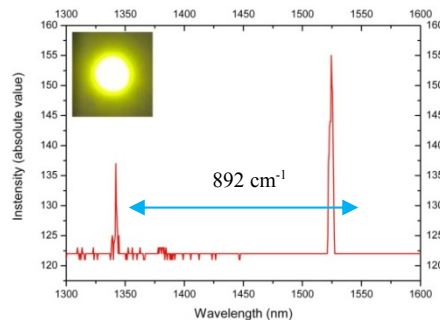


Figure 4: Optical spectrums for the fundamental laser at 1342 nm and the Raman laser at 1525 nm and the beam spot.

4 CONCLUSIONS

A stable LD side-pump narrow pulse laser modulated by Q-switch and Kerr-lens effect was achieved. A Nd:YAP laser rod is used to provide high power fundamental laser at 1342 nm. The fundamental resonator and the Raman resonator were separated. The transmissivity of OC has

significant effect on the average output power. The mode-locking modulation depth varies with Q-switch modulating frequency changing. With fixed Q-switch modulation frequency, the modulation depth of the Raman laser depends on the frequency beating of the two cavities.

In the further research, another mirror coated for high reflectivity of the fundamental laser and anti-reflectivity for the first Stokes laser can be inserted between the Raman crystal and the output coupler to construct a longer Raman cavity. With appropriate length relation between these two cavity, the conversion efficiency can be increased.

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