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Compact, Low Threshold Nd$^{3+}$:YVO$_4$ Self-Raman Laser at 1178 nm

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A compact low-threshold Raman laser at 1178 nm is experimentally realized by using a diode-end-pumped actively Q-switched Nd$^{3+}$:YVO$_4$ self-Raman laser. The threshold is 370 mW at a pulse repetition frequency of 5 kHz. The maximum Raman laser output is 182 mW with the pulse duration smaller than 20 ns at a pulse repetition frequency of 30 kHz with 1.8 W incident power. The optical efficiency from the incident power to the Raman laser is 10% and the slope efficiency is 13.5%.

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Raman lasers are a practical and efficient class of devices for the conversion of laser radiation using the technology of stimulated Raman scattering (SRS) in the Raman medium.$^{[1]}$ Although the study of SRS has been progressed steadily for over 40 years, there has been a surge of interest in this field due to the development of the efficient Raman crystals such as Ba(NO$_3$)$_2$$^{[2,3]}$ and KGW.$^{[4,5]}$ Combined with the diode pumped solid-state lasers, the all solid-state Raman lasers have been made quite compact, efficient and robust.

Some Raman crystals such as KGW and PbWO$_4$ can also be doped with Nd$^{3+}$ ions, and become laser active.$^{[6,7]}$ The laser radiation and Raman frequency conversion can be realized in only one crystal, which is called the self-stimulated Raman scattering. YVO$_4$ is also a kind of Raman active crystal.$^{[8]}$ The spontaneous Raman scattering in the YVO$_4$ crystal shows that the most intense Raman mode is at 890 cm$^{-1}$, and the Raman gain coefficient is higher than 5 cm/GW.$^{[8,9]}$ As is well known, the Nd$^{3+}$:YVO$_4$ crystal has been proven to be an excellent laser medium and has been used widely in the LD pumped all-solid-state lasers.$^{[10]}$ Thus the minimized Raman lasers both using Nd$^{3+}$:YVO$_4$ crystal as laser and Raman medium must be very interesting and useful. Recently, the self-Raman lasers in Nd$^{3+}$:YVO$_4$ crystals have been realized by Chen.$^{[11,12]}$

The SRS is a third-order nonlinear optical process and needs the fundamental laser with high power density and high coherence. As the Raman frequency conversion efficiency is deeply dependent on the power density of the fundamental laser, it is usually in Q-switched operation with high pulse-peak power. For a Q-switched laser operation, the smaller stimulated emission cross section in the laser activity is favourable for energy storage and high pulse peak power output.$^{[13]}$ YVO$_4$ belongs to the group of oxide compounds crystallizing in the zircon structure with a tetragonal space group. The uniaxial Nd$^{3+}$:YVO$_4$ crystal shows polarization-dependent fluorescence emission due to the strong crystal field. For the 1064-nm line of the spectrum in the Nd$^{3+}$:YVO$_4$ crystal, the stimulated emission cross section parallel to the c axis (a-cut), $\sigma_{//} = 25 \times 10^{-19}$ cm$^2$ is nearly four times the one orthogonal to the c axis (c-cut), $\sigma_{\perp} = 6.5 \times 10^{-19}$ cm$^2$.$^{[14]}$ Thus the higher pulse peak power can be achieved in a c-cut than the a-cut Nd$^{3+}$:YVO$_4$ crystal for Q-switched operation. Combined with the carefully designed output coupler, it can be expected that the low-threshold high-efficient self-Raman laser can be realized by using the c-cut Nd$^{3+}$:YVO$_4$ crystal.

In this Letter, we demonstrate a compact low-threshold high-efficient intracavity self-stimulated Raman laser using a c-cut Nd$^{3+}$:YVO$_4$ crystal. The threshold is as low as 370 mW at a pulse repetition frequency (PRF) of 5 kHz. The maximum Raman laser output is 182 mW with the pulse duration smaller than 20 ns at the PRF of 30 kHz with incident power 1.8 W. The optical conversion efficiency from the incident power to the Raman laser is 10% and the slope efficiency is 13.5%.

Figure 1 schematically shows the diode end-pumped actively Q-switched Nd$^{3+}$:YVO$_4$ self-stimulated Raman laser. A 2-W LD emitting at wavelength 808 nm at room temperature is employed. The multi-element lens has about 95% transmission at 808 nm, collimated and focused the pump radiation into the crystal with the spot size of 200 $\mu$m in diameter. The 7-mm-long c-cut Nd$^{3+}$:YVO$_4$ crystal with Nd$^{3+}$ doping concentration of 0.5 at. % was anti-reflection coated at 1064/1178 nm ($R < 0.2\%$) on both the facets. The resonator is composed of two mirrors.

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M1 and M2 with radius of 200 mm and 50 mm, respectively. For efficient Raman conversion, the input mirror M1 has a special dichroic coating. The concave facet was coated for high reflection at 1064/1178 nm ($R = 99.8\% @ 1064$ nm, $R = 99.5\% @ 1178$ nm), and the other facet was coated for high transmission at 808 nm. The output coupler M2 was coated for high reflection at 1064 nm ($R = 99.8\%$) and partial transmission at 1178 nm ($T = 2\%$). A 24-mm-long acousto-optical modulator with the central frequency 40 kHz is inserted the cavity. The overall cavity length is 40 mm. A LeCroy 9361C Dual 300 MHz oscilloscope and a fast InGaAs photodiode record the pulse temporal behaviour.

![Nd³⁺:YVO₄](image)

**Fig. 1.** Experimental setup of diode end-pumped self-stimulating actively Q-switched Nd³⁺:YVO₄ Raman laser. M1, input mirror; M2, coupling output mirror; C/O, coupling optics; A/O, acousto-optical modulator.

The Raman laser output with respect to incident pump power at PRFs is shown in Fig. 2. The maximum output power is 182 mW with the incident power of 1.8 W at the PRF of 30 kHz. The conversion efficiency from incident power to the Raman laser is 10%, and the slope efficiency is 13.5%. The conversion efficiency is higher relatively. The threshold for different PRFs is approximately from 370 mW to 450 mW. The lowest threshold is only 370 mW occurred at the PRF of 5 kHz. However, with the increase of the incident pump power, the Raman laser output increases slowly and even nearly keeps a constant when the pump power exceeds 1200 mW. The reason for this phenomenon may be related to the low transmission of the output coupler because the first Stokes is quite low at the PRF 5 kHz.

The threshold for the intracavity Raman laser can be calculated by using the condition: $R_1 R_2 \exp(2 I_p g_R l - L_i) = 1$, and $I_p = \frac{L_i - \ln(R_1 R_2)}{2 g_R l}$, where $R_1$ and $R_2$ are the reflection at the first stokes wavelength, $L_i$ is the internal cavity loss, $I_p$ is the power density of the fundamental laser. Assuming that the fundamental is a plane wave, the parameters we adopt are as follows: $R_1 = 99.8\%$, $R_2 = 98\%$, $L_i = 1.5\%$, $g_R \approx 5$ cm/GW, $l = 7$ mm, which lead to a value of $I_p = 5.5$ MW/cm² and result in the lower pump threshold. The small stimulated emission cross section of the $c$-cut Nd³⁺:YVO₄ crystal and the high reflection at the first Stokes wavelength of the output coupler both contribute to the low threshold.

![Fig. 2. Experimental Raman laser output as a function of incident pump.](image)

The experimental first Stokes pulse shape for maximum output is shown in Fig. 3. The pulse width is smaller than 20 ns (FWHM) with the peak power higher than about 300 W, using the equation $P_{peak} = P_a / \Delta t \cdot f$. Here $\Delta t$ is the pulse width, $f$ is the pulse repetition frequency. The pulse–pulse amplitude fluctuation is found to be within 10%.

![Time (20 ns/div)](image)

**Fig. 3.** Pulse shape of the first Stokes laser.

In summary, we have presented a compact low-threshold high-efficient diode end-pumped actively Q-switched intracavity self-stimulated Nd³⁺:YVO₄ Raman laser. With the incident pump power 1.8 W, we obtain a 182-mW Raman laser (1178 nm) generated at a PRF of 30 kHz. The conversion efficiency from incident power to the Raman laser is 10%, and the slope efficiency is 13.5%. The lowest threshold is only about 370 mW at the PRF 5 kHz. The small stimulated emission of the $c$-cut Nd³⁺:YVO₄ crystal and the high reflection at the first Stokes wavelength of the output coupler both contribute to the low threshold of the intracavity self-stimulated Raman laser.
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