

Compact efficient all-solid-state eye-safe laser with self-frequency Raman conversion in a Nd:YVO₄ crystal

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An efficient compact eye-safe laser at 1525 nm is presented by use of self-frequency Raman conversion in a diode-pumped actively *Q*-switched Nd:YVO₄ 1342-nm laser. At an incident pump power of 13.5 W, the self-stimulated Raman laser produces 1.2 W of 1525-nm average output power at a repetition rate of 20 kHz. The corresponding peak power at 1525 nm is generally greater than 10 kW for repetition rates from 5 to 20 kHz. © 2004 Optical Society of America

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The rapid discovery of new Raman-active media has made stimulated Raman scattering (SRS) in crystals a promising method for wavelength conversion of laser radiation.^{1,2} It is a practical advance to develop diode-pumped solid-state SRS lasers in view of the fact that diode-pumping technology has become an efficient and reliable technology. One especially interesting approach among SRS systems is the self-stimulated Raman laser that achieves laser generation and SRS action in one crystal.

In the past few years all-solid-state self-stimulated Raman lasers have been reported in materials such as Nd:KGd(WO₄)₂,^{3,4} Nd:PbWO₄,⁵ Yb:KGd(WO₄)₂,⁶ and Yb:KY(WO₄)₂.⁷ More recently, a diode-pumped passively *Q*-switched Nd:YVO₄ laser with self-frequency Raman shifting to 1178 nm was successfully demonstrated.⁸ This realization supported the possibility of developing a compact eye-safe laser at 1525 nm by means of the self-SRS of Nd:YVO₄ laser emission at 1342 nm.⁹

In this Letter, for the first time to my knowledge, a novel all-solid-state eye-safe laser at 1525 nm is demonstrated with self-SRS in a *Q*-switched Nd:YVO₄ laser at 1342 nm. At an incident pump power of 13.5 W the compact self-SRS cavity, operating at 20 kHz, produces average output powers at 1525 nm up to 1.2 W and peak power greater than 10 kW.

The experimental configuration for the diode-pumped actively *Q*-switched self-SRS laser at 1525 nm is depicted in Fig. 1. The cavity mirrors have a special dichroic coating for efficient conversion at the first Stokes component. The input mirror is a 500-mm radius-of-curvature concave mirror with antireflection coating at the pump wavelength (~808 nm) on the entrance face ($R < 0.2\%$), high-reflection coating at 1342 and 1525 nm ($R > 99.8\%$) and high-transmission coating at the pump wavelength on the other surface ($T > 90\%$). Note that the first Stokes wavelength is approximately 1525 nm for the fundamental wavelength of 1342 nm.⁹ The output coupler has high-reflection coating at 1342 nm ($R > 99.8\%$) and partial-reflection coating at 1525 nm ($R = 65\%$). Both mirrors have a transmission of 90%

at 1064 nm to suppress parasitic oscillations on lines in the 1064-nm region.

The pump source was an 808-nm fiber-coupled laser diode with a core diameter of 800 μm , a numerical aperture of 0.16, and a maximum output power of 16 W. A focusing lens with a 12.5-mm focal length and 90% coupling efficiency was used to reimage the pump beam into the laser crystal. The average radius of the pump beam was approximately 350 μm . The laser active medium was a 0.2-at. % Nd:YVO₄ crystal with a length of 9 mm. A Nd:YVO₄ crystal with a low dopant concentration was used to avoid thermally induced fracture.¹⁰ Both sides of the Nd:YVO₄ crystal were coated for antireflection at 1330–1530 nm ($R < 0.2\%$). The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. The 30-mm-long acousto-optic *Q*-switch (NEOS Technologies) had antireflection coating at 1342 nm on both faces and was driven at a 27.12-MHz center frequency with 15.0 W of rf power. The overall laser cavity length was 85 mm. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). A spectrum analyzer employing a diffraction lattice monochromator can be used for high-speed measurement of pulse light with

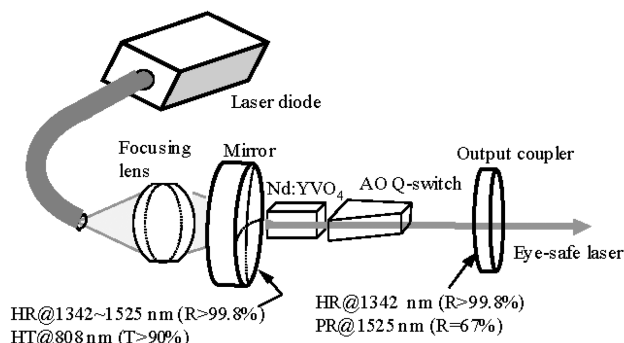


Fig. 1. Experimental configuration for the diode-pumped actively *Q*-switched self-SRS laser at 1525 nm. AO, acousto-optic; HR, high reflection; HT, high transmission; PR, partial reflection.

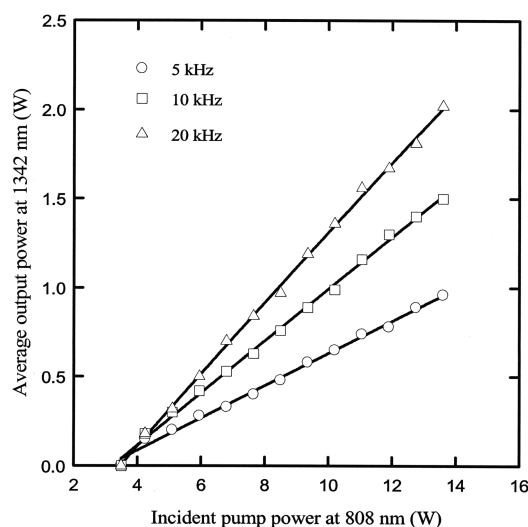


Fig. 2. Average output power at 1342 nm with respect to the incident pump power for pulse repetition rates of 5, 10, and 20 kHz.

a resolution of 0.1 nm. The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gsamples/s, 1-GHz bandwidth) with a fast p-i-n photodiode.

The diode-pumped *Q*-switched Nd:YVO₄ laser performance at 1342 nm was studied first. For this investigation an output coupler with partial reflection at 1342 nm was used instead of the above-mentioned Raman cavity output coupler. The optimum reflectivity of the output coupler was found to be approximately 92–94%. The optimum performance at 1342 nm provides the baseline for evaluating the optical-to-optical self-SRS conversion efficiency. Figure 2 depicts the average output power at 1342 nm with respect to the incident pump power for pulse repetition frequencies (PRFs) of 5, 10, and 20 kHz. The threshold for 1342-nm oscillation was approximately 3–4 W, and its dependence on different PRFs in the range 5–20 kHz was not significant. With an incident pump power of 13.5 W the average output power at 1342 nm was 2.0 W at a PRF of 20 kHz. Figure 3 shows the pulse width at 1342 nm with respect to the incident pump power for PRFs of 5, 10, and 20 kHz.

When the Raman cavity output coupler was used in the laser cavity, the pumping threshold for the Raman laser output was found to be 5–9 W, considerably dependent on the pulse repetition rate. The optical spectrum for the actively *Q*-switched self-Raman output displayed that the fundamental laser emission was at 1342 nm and the Stokes component was at 1525 nm, as shown in Fig. 4. The frequency shift between Stokes and laser lines is in good agreement with the optical vibration modes of tetrahedral VO₄³⁻ ionic groups (890 cm⁻¹).⁹ Figure 5 depicts the average output power at the Stokes wavelength of 1525 nm with respect to the incident pump power for pulse repetition rates of 5, 10, and 20 kHz. The beam quality factor was found to be better than 1.5 over the entire operating region. Since the Raman gain is highly dependent on the peak power of fundamental pulses, the Raman threshold strongly relies on the

PRF, as seen in Fig. 5. This substantial dependence leads to the result that the slope efficiency of the Raman output at a PRF of 20 kHz is three times higher than that at a PRF of 5 kHz. Even so, the maximum Raman output power at a PRF of 20 kHz is only twice that at a PRF of 5 kHz, as shown in Fig. 2 for fundamental output. In other words, the slope efficiency of the intracavity Raman operation with respect to the diode input power does not make physical sense because of the mechanism of nonlinear conversion. The present eye-safe laser-generated single pulses are of 0.12-mJ energy and 5–6-ns duration at 5 kHz. As a consequence, the highest peak power is up to 20 kW. On the other hand, a maximum power of 1.2 W at 1525 nm was obtained at 20 kHz, corresponding to a conversion efficiency of

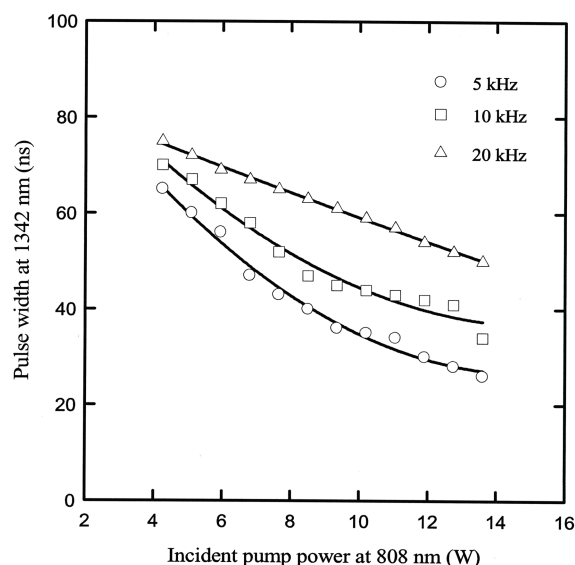


Fig. 3. Pulse width at 1342 nm with respect to the incident pump power for pulse repetition rates of 5, 10, and 20 kHz.

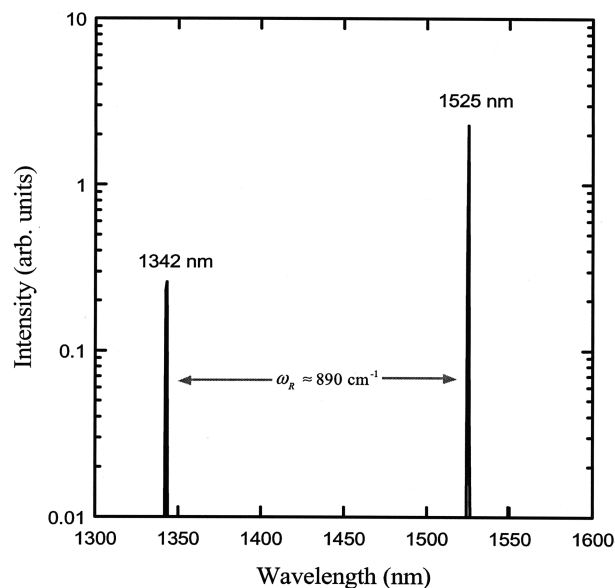


Fig. 4. Optical spectrum for the actively *Q*-switched self-Raman output.

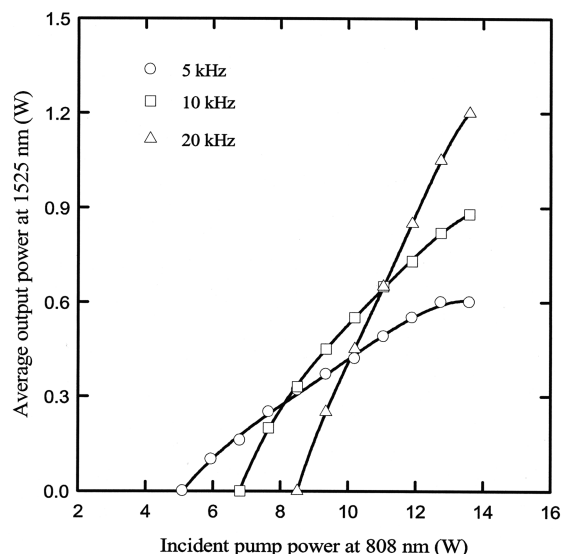


Fig. 5. Average output power at the Stokes wavelength of 1525 nm with respect to the incident pump power for pulse repetition rates of 5, 10, and 20 kHz.

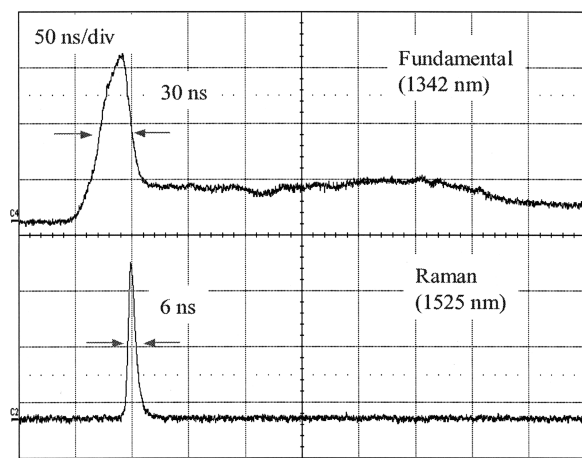


Fig. 6. Typical oscilloscope traces for the fundamental and Raman pulses.

60% with respect to the output power available from the fundamental laser of 1342 nm under optimum conditions. Alternatively, with respect to the diode laser input power, the Raman conversion efficiency was 8.9%. To my knowledge, this is the highest self-SRS efficiency for an eye-safe laser reported to date. The overall pulse width was shorter than 10 ns at a pulse repetition of 20 kHz. The typical time shapes for the fundamental and Raman pulses are shown in Fig. 6.

Finally, it is worthwhile to mention that the effective focal length of the thermal lensing in the Nd:YVO₄ crystal at the maximum pump power was estimated to

be approximately 10 cm. The effective thermal lens is deduced from the experimental critical pump power at which thermally induced lensing causes the laser cavity to be unstable.¹¹ Since the thermal lensing effect is close to the critical value, it is difficult to scale up the eye-safe output power with the present cavity configuration. For scaling to a higher output power it is suggested to reduce the thermal lensing effect by separating the gain medium and the Raman converter in the cavity with a low-Nd-dopant Nd:YVO₄ crystal and an undoped YVO₄ crystal.

In summary, an efficient compact eye-safe laser at 1525 nm has been developed based on a diode-pumped actively Q-switched Nd:YVO₄ self-SRS laser at 1342 nm. With a 13.5-W pump power, 1.2 W of 1525-nm average output power at a repetition rate of 20 kHz was obtained, corresponding to an optical-to-optical conversion efficiency of 8.9%. The effective cavity dump of intracavity SRS leads to a relatively short pulse width for repetition rates from 5 to 20 kHz. As a consequence, the peak power at 1525 nm was generally greater than 10 kW for the entire frequency range at a pump power of 13.5 W. The present eye-safe laser is believed to be an attractive source for practical applications.

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