

Y.F. CHEN

Compact efficient self-frequency Raman conversion in diode-pumped passively Q-switched Nd:GdVO₄ laser

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan

Received: 16 January 2004

Published online: 6 April 2004 • © Springer-Verlag 2004

ABSTRACT I report the first demonstration of the generation of efficient sub-nanosecond self-stimulated Raman pulses by a diode-pumped passively Q-switched Nd:GdVO₄/Cr⁴⁺:YAG laser. The conversion efficiency for the average power is 7% from pump diode input to self-Raman output and the slope efficiency is up to 14%. At an incident pump power of 2.0 W, the pulse duration, pulse energy, and peak power for the Stokes wavelength of 1175.6 nm were found to be 750 ps, 6.3 μJ, and 8.4 kW, respectively, with a pulse-repetition rate of 22 kHz.

PACS 42.55.Ye; 42.55.Xi; 42.60.Gd

As one of the most promising laser materials, neodymium-doped gadolinium orthovanadate (Nd:GdVO₄) has been receiving considerable attention due to its high absorption coefficient and large thermal conductivity [1–4]. In recent years, a GdVO₄ crystal was predicted [5] to be a promising material suitable for stimulated Raman scattering (SRS), which is a well-known method of frequency conversion based on a third-order nonlinear optical process [6–9]. Therefore, a GdVO₄ crystal is a very attractive self-SRS laser medium based on combinations of its stimulated emission and SRS properties. Even so, a self-Raman laser based on Nd:GdVO₄ has not been demonstrated in the available literature.

In this work I report, for the first time to my knowledge, the generation of efficient sub-nanosecond self-stimulated Raman pulses by a diode-pumped passively Q-switched Nd:GdVO₄ laser. At an incident pump power of 2.0 W, the pulse duration, pulse energy, and peak power for the Stokes wavelength of 1175.6 nm were found to be 750 ps,

6.3 μJ, and 8.4 kW, respectively, with a pulse-repetition rate of 22 kHz.

One important novelty in the present experiment is that a *c*-cut Nd:GdVO₄ crystal was used to enhance the performance of passive Q-switching for efficient Raman conversion. The GdVO₄ crystal belongs to the group of oxide compounds crystallizing in a zircon structure with tetragonal space group. The four-fold-symmetry axis is the crystallographic *c* axis. Perpendicular to this axis are the two indistinguishable *a* and *b* axes. The uniaxial Nd:GdVO₄ crystal shows strong polarization-dependent fluorescence emission due to the anisotropic crystal field. In a Nd:GdVO₄ crystal, the stimulated emission cross section parallel to the *c* axis, σ_{\parallel} , is several times higher than that orthogonal to the *c* axis, σ_{\perp} , for the emission wavelength at 1.06 μm. The conventional Nd:GdVO₄ crystal is cut along the *a* axis, i.e. *a*-cut, to use the stimulated emission cross section of σ_{\parallel} , due to the fact that a larger stimulated emission cross section leads to a lower pumping threshold for cw laser operation. For a passively Q-switched laser, a small stimulated

emission cross section is usually beneficial to the criterion that the saturation in the absorber must occur before the gain saturation in the laser crystal (the second threshold condition) [10–13]. When a Nd:GdVO₄ crystal is cut along the *c* axis, i.e. *c*-cut, the effective stimulated emission cross section is σ_{\perp} instead of σ_{\parallel} . Therefore, the *c*-cut Nd:GdVO₄ crystal is more appropriate than the *a*-cut one for the passive Q-switching operation, because σ_{\perp} is several times smaller than σ_{\parallel} .

It is of great importance to have a special dichromic coating on the cavity mirrors for efficient conversion in an intracavity Raman laser configuration. Figure 1 shows the experimental configuration for the passively Q-switched Nd:GdVO₄/Cr⁴⁺:YAG laser with self-frequency Raman conversion. The active medium was a 0.5 at.% Nd³⁺, 6-mm-long Nd:GdVO₄ crystal. Both sides of the laser crystal were coated for antireflection at 1.06 μm ($R < 0.2\%$). The pump source was a 2.5-W, 808-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.16. A focusing lens with 16.5-mm focal length and 90% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius, ω_p , was around 100 μm. The input mirror, M1, was a 15-mm radius-of-curvature concave mirror with an antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), a high-reflection coating at the lasing wavelength ($R > 99.8\%$), and a high-transmission coating at the diode wavelength on the other surface ($T > 90\%$). Note that the laser crystal was placed very near the input mirror. The

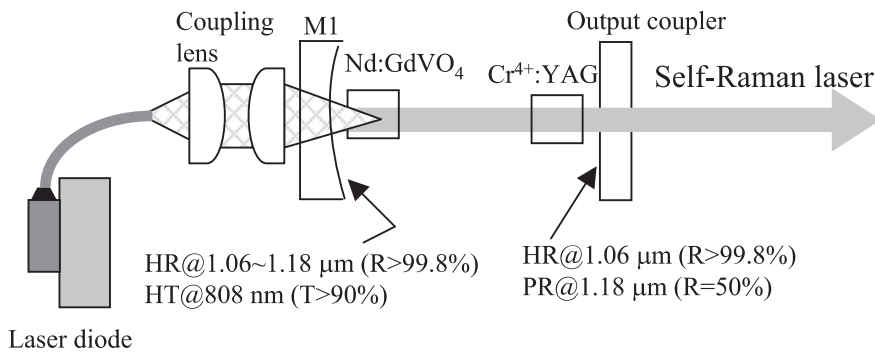


FIGURE 1 Schematic of a diode-pumped passively Q-switched Nd:GdVO₄/Cr⁴⁺:YAG self-Raman laser

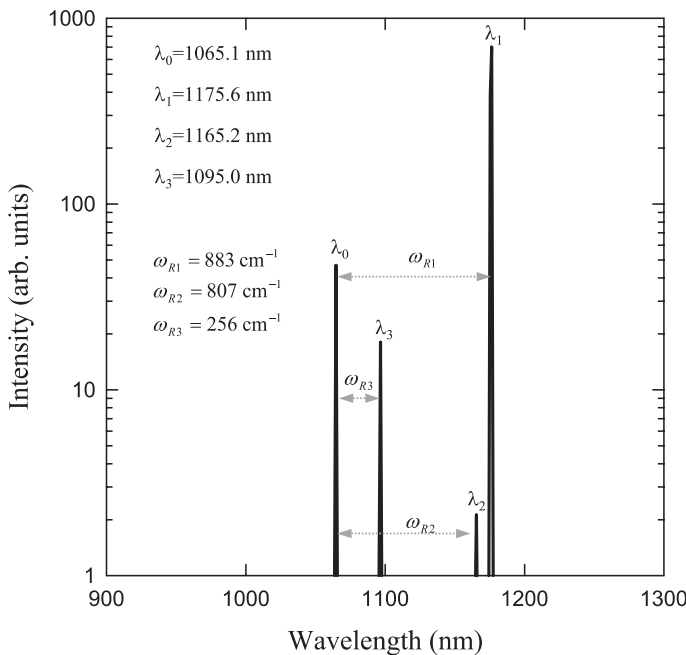


FIGURE 2 Optical spectrum for the passively Q-switched self-Raman output near the lasing threshold

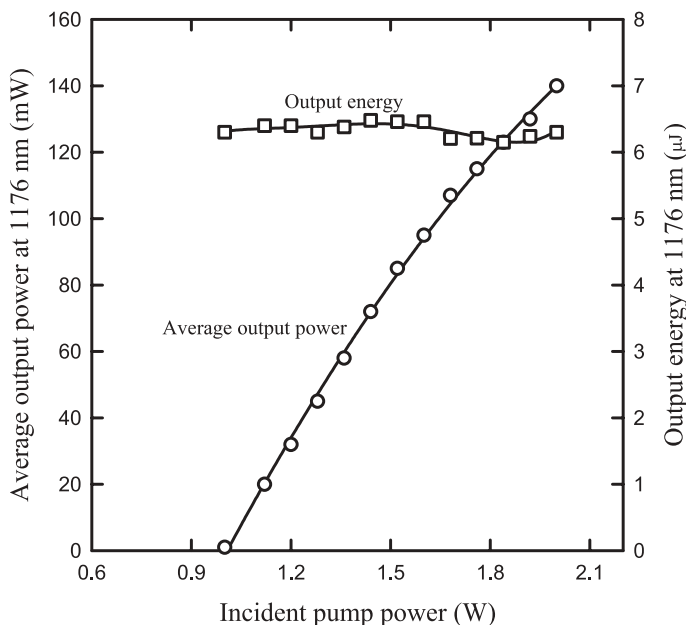


FIGURE 3 The average output power and the pulse energy at the Stokes wavelength of 1175.6 nm with respect to the incident pump power

Cr⁴⁺:YAG crystal has a thickness of 2 mm with 70% initial transmission at 1.06 μm. Both sides of the Cr⁴⁺:YAG crystal were antireflection coated at the fundamental wavelength ($R < 0.2\%$). The flat output coupler has a reflectivity $R > 99.8\%$ at 1.06 μm and $R = 50\%$ at 1.18 μm. The overall Nd:GdVO₄ laser cavity length was approximately 14 mm. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer employing a diffraction lattice monochromator can be used for high-speed measurement of pulse light with a resolution of 0.1 nm. The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gs/s, 1-GHz bandwidth) with a fast PIN photodiode.

Initially, an *a*-cut Nd:GdVO₄ crystal was used in the present cavity; however, the passive Q-switching process did not successfully operate. As a consequence, the intracavity fundamental power was not adequate to achieve Raman conversion. When a *c*-cut Nd:GdVO₄ crystal was used in the laser cavity, the lasing threshold for passive Q-switching was found to be about 1.0 W. Near the lasing threshold, the optical spectrum of the passively Q-switched self-Raman output displayed several lines, as shown in Fig. 2. Note that the strongest emission line of the Nd:GdVO₄ crystal for the σ polarization is close to 1065 nm. The frequency shifts between laser and Stokes lines consist of $\omega_{R1} = 883 \text{ cm}^{-1}$, $\omega_{R2} = 807 \text{ cm}^{-1}$, and $\omega_{R3} = 256 \text{ cm}^{-1}$, which agree very well with the optical vibration modes of tetrahedral VO₄³⁻ ionic groups in the GdVO₄ crystal [5].

For slightly far above threshold, the Stokes component of 1175.6 nm mostly predominated in the output power. Figure 3 shows the average output power and the pulse energy at the Stokes wavelength of 1175.6 nm with respect to the incident pump power from the laser diode. With increasing pump power, the average output power reached 140 mW and the Stokes pulse energy remained nearly constant and was found to be $6.3 \pm 0.2 \mu\text{J}$. The conversion efficiency from diode laser input power to Raman output power was approximately 7.0% and the slope efficiency was 14%. On the other hand, the pulse-repetition rate

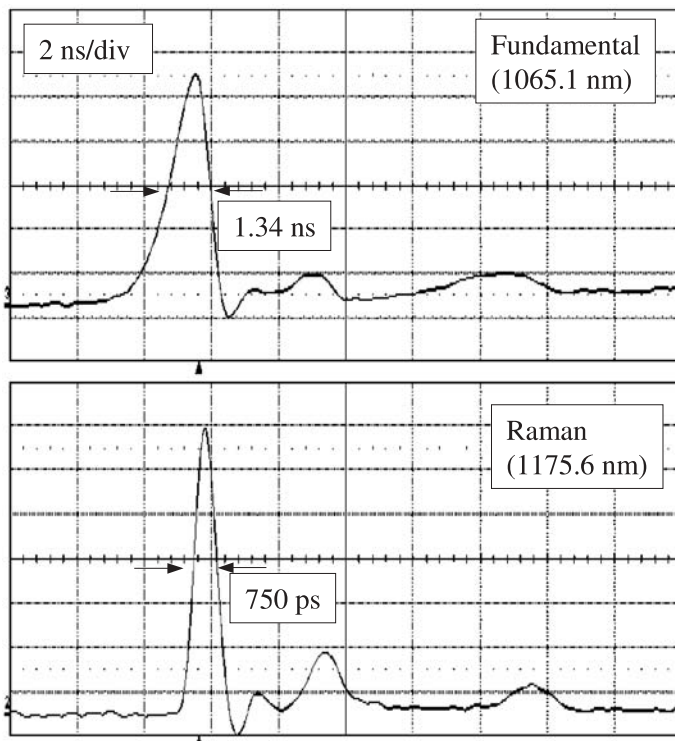


FIGURE 4 Typical oscilloscope traces for the fundamental and Raman pulses

changed from nearly 1 kHz at the threshold up to 22 kHz at a maximum pump power of 2.0 W.

The typical time shapes for the fundamental and Raman pulses are shown in Fig. 4. It can be seen that the nonlinear frequency-conversion process leads to the pulse reduction of the Stokes component, as mentioned in previous work [14, 15]. The pulse duration of the Raman output was about 750 ps. As a consequence, the peak power was found to be higher than 8.4 kW.

The pulse-to-pulse amplitude fluctuation was found to be within $\pm 8\%$.

In summary, sub-nanosecond self-Raman conversion has been efficiently demonstrated in a diode-pumped passively Q-switched Nd:GdVO₄ laser with Cr⁴⁺:YAG as a saturable absorber. Experimental results reveal that the self-frequency Raman conversion can be achieved with a *c*-cut Nd:GdVO₄ crystal in a nearly hemispherical cavity. The compact size and high efficiency of the present self-Raman laser make it an

attractive source for practical applications. At 2.0 W of incident pump power, the self-Raman laser produces stable 750-ps pulses at the Stokes wavelength of 1175.6 nm with 6.3 μ J of pulse energy at a 22-kHz repetition rate.

REFERENCES

- 1 T. Jensen, V.G. Ostroumov, J.P. Meyn, G. Huber, A.I. Zagumennyi, I.A. Shcherbakov: *Appl. Phys. B* **58**, 373 (1994)
- 2 V. Lupei, N. Pavel, Y. Sato, T. Taira: *Opt. Lett.* **28**, 2366 (2003)
- 3 T. Ogawa, Y. Urata, S. Wada, K. Onodera, H. Machida, H. Sagae, M. Higuchi, K. Kodaira: *Opt. Lett.* **28**, 2333 (2003)
- 4 C.P. Wyss, W. Luthy, H.P. Weber, V.I. Vlasov, Y.D. Zavartsev, P.A. Studenikin, A.I. Zagumennyi, I.A. Shcherbakov: *Appl. Phys. B* **68**, 659 (1999)
- 5 A.A. Kaminskii, K. Ueda, H.J. Eichler, Y. Kuwano, H. Kouta, S.N. Bagaev, T.H. Chyba, J.C. Barnes, G.M.A. Gad, T. Murai, J. Lu: *Opt. Commun.* **194**, 201 (2001)
- 6 G. Eckhardt, D.P. Bortfeld, M. Geller: *Appl. Phys. Lett.* **3**, 137 (1963)
- 7 W. Kaiser, M. Maier: in *Laser Handbook, Vol. II*, ed. by F.T. Arecchi, E.O. Schultz-Dubois (North-Holland, Amsterdam 1972) p. 1077
- 8 Y.R. Shen: *The Principles of Nonlinear Optics* (Wiley, New York 1984)
- 9 T.T. Basiev, R.C. Powell: *Opt. Mater.* **11**, 301 (1999)
- 10 A.E. Siegman: *Lasers* (University Science, Mill Valley, CA 1986) p. 1024
- 11 G. Xiao, M. Bass: *IEEE J. Quantum Electron.* **QE-33**, 41 (1997)
- 12 J.J. Degnan: *IEEE J. Quantum Electron.* **QE-31**, 1890 (1995)
- 13 Y.F. Chen, Y.P. Lan: *Appl. Phys. B* **74**, 415 (2002)
- 14 J. Findeisen, H.J. Eichler, P. Peuser: *Opt. Commun.* **181**, 129 (2000)
- 15 A.S. Grabtchikov, A.N. Kuzmin, V.A. Lisinetskii, V.A. Orlovich, G.I. Ryabtsev, A.A. Demidovich: *Appl. Phys. Lett.* **75**, 3742 (1999)