Available online at www.sciencedirect.com

ScienceDirect

Optics Communications 271 (2007) 555–558

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Low threshold, actively Q-switched Nd^{3+}:YVO_4 self-Raman laser and frequency doubled 588 nm yellow laser

Wang Baoshan [a,b,*], Tan Huiming [a], Peng Jiying [a,b], Miao Jieguang [a,b], Gao Lanlan [a,b]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Jilin 130033, China

[b] Graduate School of the Chinese Academy of Sciences, Beijing 100049, China

Received 20 January 2006; received in revised form 19 June 2006; accepted 23 October 2006

Abstract

We reported an actively Q-switched, intracavity Nd^{3+}:YVO_4 self-Raman laser at 1176 nm with low threshold and high efficiency. From the extracavity frequency doubling by use of LBO nonlinear crystal, over 3.5 mW, 588 nm yellow laser is achieved. The maximum Raman laser output at is 182 mW with 1.8 W incident pump power. The threshold is only 370 mW at a pulse repetition frequency of 5 kHz. The optical conversion efficiency from incident to the Raman laser is 10%, and 1.9% from Raman laser to the yellow.

PACS: 42.55.Xi; 42.55.Ye; 42.65.Dr; 42.65.Ky

Keywords: Raman laser; Self-stimulation; Actively Q-switched; Yellow laser

1. Introduction

Stimulated Raman scattering (SRS) in Raman medium has been proved to be an efficient method for wavelength conversion of laser radiation. Raman crystal such as $LiIO_3$ [1], KGW [2], and $Ba(NO_3)_2$ [3] combined with laser diode (LD) pumped solid-state lasers, the all solid-state Raman lasers have undergone a resurgence in recent years for the fact of compact, efficient and robust. By the technology of second harmonic generation (SHG) of the first stokes lasers using the nonlinear crystals, yellow or orange lasers which are used widely in spectroscopy, biomedical diagnostics and laser display system can be achieved efficiently [4].

A very interesting direction for the all solid-state Raman lasers is small-scale, efficient, and low-cost with the pump power of the order of 1–2 W. Of the Raman crystals, some tungstate crystals (such as KGW), can be doped with Nd^{3+} ions and become laser active. In this way, a single crystal can be used both to generate fundamental output and convert it through the SRS process, which is called self-stimulated Raman scattering (self-SRS). The Nd^{3+}:KGW self-Raman lasers have been studied for many years [5,6]. The YVO_4 and $GdVO_4$ crystals are also Raman active from Ref. [7]. And the Nd^{3+}:YVO_4 and Nd^{3+}:$GdVO_4$ self-Raman laser have been realized in actively or passively Q-switched configuration [8,9]. And the Raman conversion efficiency is higher than Nd^{3+}:KGW self-Raman lasers, for they have much higher Raman scattering cross-section compared with the KGW crystal [10]. For the comparison of the crystal Nd^{3+}:YVO_4 and Nd^{3+}:KGW, the laser and Raman properties of them were given in Table 1 [7,10,11].

For efficient Raman frequency conversion, the high power density and high coherence of the fundamental laser is needed. So the fundamental laser is usually Q-switched to receive high pulse peak power. The YVO_4 crystal belongs to the tetragonal space group I41/amd and crystallized in a zircon structure. The strong crystal field results in the polarized fluorescence spectra. For the 1.06 μm line of the spectrum in Nd^{3+}:YVO_4 crystal,

* Corresponding author. Address: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Jilin 130033, China. Tel.: +86 4315681789; fax: +86 4315261802.

E-mail address: baoshan002@126.com (B. Wang).

0030-4018/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2006.10.065

Table 1
The laser and Raman properties of Nd^{3+}:YVO_4 and Nd^{3+}:KGW [7,10,11]

	Nd^{3+}:YVO_4	Nd^{3+}:KGW
Space group	Tetragonal	Monoclinic
Lattice constants (nm)	$a = b = 0.7123$; $c = 0.6292$	$a = 0.8098$; $b = 1.0417$; $c = 0.7583$; $\beta = 94.43°$
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	5.1 [*a*]; 5.23 [*c*]	2.6 [1 0 0]; 3.8 [0 1 0]; 3.4 [0 0 1]
Thermal expansion ($10^{-6}\,K^{-1}$)	4.43 [*a*]; 11.37 [*c*]	4.0 [1 0 0]; 1.6 [0 1 0]; 8.5 [0 0 1]
Refractive index (300 K, 1 μm)	$n_o = 1.9573$; $n_e = 2.1625$	$n^g = 2.003$; $n^m = 1.986$; $n^p = 1.937$
Thermal-optic coefficient ($dn/dT\,10^{-7}\,K^{-1}$)	2.9 [*a*]; 8.5 [*c*]	−8 [K‖p, E‖m]; −55 [K‖p, E‖g]
Fluorescence lifetime (μs)	100	110
Emission cross-section σ_{em} ($10^{-19}\,cm^2$)@1 μm	25 [‖*c*]; 6.5 [⊥*c*]	4.3
Raman shift (cm^{-1})	890	901; 767
Raman line width $\Delta\nu$ (cm^{-1})	3	5.4 [901]; 5.4 [767]
Raman gain (cm/GW)	>5	3.3 [901]; 4.4 [767]

the stimulated emission cross-section parallel to *c*-axis (*a*-cut), $\sigma_{\parallel} = 25 \times 10^{-19}\,cm^{-2}$, which is nearly as four times as that orthogonal to the *c*-axis (*c*-cut), $\sigma_{\perp} = 6.5 \times 10^{-19}\,cm^{-2}$ [12]. For Q-switched operation, the smaller stimulated emission cross-section is favorable for store more energy in the active crystal and can easily achieve high pulse peak power output [13,14]. The peak power of the fundamental laser pulse in the *c*-cut Nd^{3+}:YVO_4/Cr^{4+}:YAG laser is much higher than the *a*-cut Nd^{3+}:YVO_4/Cr^{4+}:YAG laser [12]. Although the Raman gain coefficient is a little different between *a*- and *c*-cut Nd^{3+}:YVO_4 crystal [10], but we think it is not the important factor compared with the high fundamental power density received from the *c*-cut Nd^{3+}:YVO_4 crystal. So we can expect a low threshold, high efficient, intracavity self-Raman laser from the using of a *c*-cut Nd^{3+}:YVO_4 crystal.

In this report, we demonstrated a diode-pumped, actively Q-switched, intracavity Nd^{3+}:YVO_4 self-Raman laser. The maximum first stokes output is 182.2 mW and over 3.5 mW, 588 nm yellow laser is also realized from extracavity frequency doubling by use of LBO crystal at a pulse repetition frequency (PRF) of 30 kHz with 1.8 W incident power. The conversion efficiency from incident power to first stokes is about 10% and 1.9% from first stokes to the yellow laser.

2. Experiments

2.1. The experimental set-up and fundamental laser output

The schematic diagram of our experimental set-up is depicted in Fig. 1.

A 2-W LD that emitting wavelength at 808 nm in room temperature is employed. The multi-element lens has about 95% transmission at 808 nm collimated and focused the pump radiation into the laser crystal with the spot size of 200 μm in diameter. The 7-mm-long *c*-cut Nd^{3+}:YVO_4 crystal with Nd^{3+} ions concentration 0.5-at% was coated anti-reflection (AR) at 1064/1176 nm ($R < 0.2\%$) on both facets. The pump facet of the crystal was also coated high transmission at 808 nm. Note that the most intense Raman peak for YVO_4 crystal occurs at 890 cm^{-1} from Table 1, so the first stokes wavelength should be 1178 nm. The input concave mirror M1 with the radius of 200 mm was coated high reflection (HR) at 1064/1176 nm ($R = 99.8\%$@1064 nm, $R = 99.7\%$@1176 nm). Both the plane and the concave of M1 were coated high transition at 808 nm. The output coupler M2 with the radius of 50 mm was coated HR at 1064 nm ($R = 99.8\%$) and partial transmission at 1176 nm ($T = 2\%$). This cavity made a small beam waist in the Nd^{3+}:YVO_4 crystal and satisfied the condition of stability. A 24-mm-long acousto-optical modulator with AR at 1064 nm on both facets was inserted the cavity. The cavity length remains 40 mm-long. A 23-mm focal-length lens is employed to focus the Raman laser.

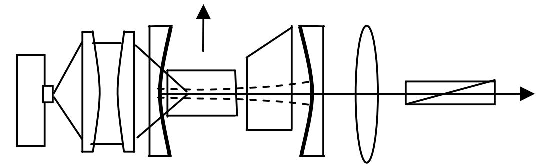

Fig. 1. Experimental setup of diode-pumped, actively Q-switched, self-stimulating Nd^{3+}:YVO_4 Raman laser and extracavity frequency doubling by use of LBO crystal. C/O is coupling optics; M1 and M2 are input and output mirror, respectively; A/O is acousto-optical modulator.

For the comparison of the conversion efficiency from fundamental to the Raman laser, the Q-switched fundamental laser operation at 1064 nm was studied first. The same radius output coupler with the transmission of 10% at 1064 nm was used instead of the Raman output coupler mentioned above.

Fig. 2 shows the average output of the fundamental with respect to the incident power at different PRFs (5, 10, 20, 30 kHz).

The maximum output is 213 mW at a PRF of 30 kHz with the incident power of 1.8 W. The conversion efficiency from incident to the fundamental is 11.8%, and the threshold for

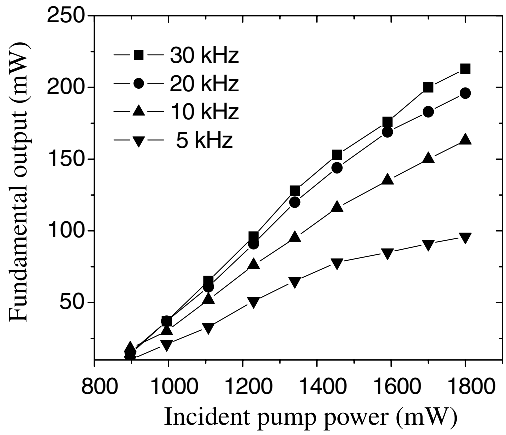

Fig. 2. Fundamental output with respect to the incident power at different PRFs.

Q-switched 1064 nm oscillation is approximately at 900 mW for different PRFs.

2.2. First stokes laser output

For the designing the intracavity Raman lasers, the thermal lensing due to quantum defect in the SRS process usually is identified as a major factor for affecting the cavity stability and Raman conversion efficiency [15]. Especially in the self-stimulated Raman lasers, the effect of thermal lensing is stronger for the fact of the heat deposition from not only the quantum defect in the SRS process but also the laser radiation.

The heat deposited in the Raman crystal in the SRS process is determined by $P_{heat} = P_{s1}\left(\frac{\lambda_{s1}}{\lambda_L} - 1\right)$, where P_{s1} is the average Raman power in the Raman crystal, and λ_{s1} and λ_L are the wavelengths of the first stokes and the pump laser (or the fundamental laser). Considering only the thermal-optic contribution of the thermal lens, the effective focal length can be expressed: $\frac{1}{f_R} = \left(\frac{dn}{dT}\right)\frac{1}{k_C}\frac{P_{s1}}{\pi\omega_{s1}^2}\left(\frac{\lambda_{s1}}{\lambda_p} - 1\right)$, where the dn/dT is the thermal-optic coefficient along c-axis, k_C is the conductivity of the crystal along a-axis, and ω_{s1} is the radius of the stokes beam waist. The heat deposited in the Raman crystal is deposited where the SRS happened, which is different from the conventional end-pumped lasers usually closed the surface of the crystal. For an end-pumped laser crystal, the thermal lens focal length f_{Laser} expressed: [16] $f_{Laser} = \frac{\pi k_C \omega_{pump}^2}{P_{dep}(dn/dT)_{Laser}}\left(\frac{1}{1-\exp(-\alpha L_{Laser})}\right)$, where the ω_{pump} is the beam radius of the diode beam in the laser crystal, P_{dep} is the amount of energy deposited as heat in the laser crystal (usually about 30% of the absorbed pump power), α is the absorption coefficient, and L_{Laser} is the length of the laser crystal.

Considering the interaction of the thermal lens and laser beam, for the maximum output the values we use as follows: $P_{s1} = 9$ W, $\omega_{s1} = 90$ μm, $\omega_{pump} = 100$ μm, $P_{dep} = 0.54$ W. We estimated the total focal length of the thermal lens in Nd^{3+}:YVO_4 crystal is about 300 mm. This is long enough for the stability of this cavity.

The first stokes laser output with respect to the incident power at different PFRs (5, 10, 30 kHz) are given in Fig. 3. Fig. 4 shows the pulse profile of the first stokes laser at the maximum output.

The maximum output is 182.2 mW with 1.8 W incident pump power at a PRF of 30 kHz and the threshold is about 450 mW. The conversion efficiency from incident pump to the first stokes is 10% and the slope efficiency is 13.5%. The lowest threshold is only 370 mW happened at a PRF of 5 kHz. The pulse duration is less than 20 ns (FWHM) for the maximum output. But the power of the first stokes increases slowly and even keeps a constant when the pump power exceeds 1200 mW. We think this phenomenon may be related to the relatively low transmission for the first stokes at 5 kHz [13].

The threshold for intracavity Raman laser can be calculated using the condition: [15] $R_1R_2\exp(2I_pg_Rl - L_i) = 1$, and $I_p = \frac{L_i - \ln(R_1R_2)}{2g_Rl}$. The R_1 and R_2 are the reflection at the first stokes wavelength of the resonator, respectively, L_i is the internal cavity loss, I_p is the power density of the fundamental. Assuming the fundamental is a plane wave, the values we use as follows: $R_1 = 99.8\%$; $R_2 = 98\%$; $L_i = 2.0\%$; $g_R \approx 5$ cm/GW; $l = 7$ mm. That led to a value

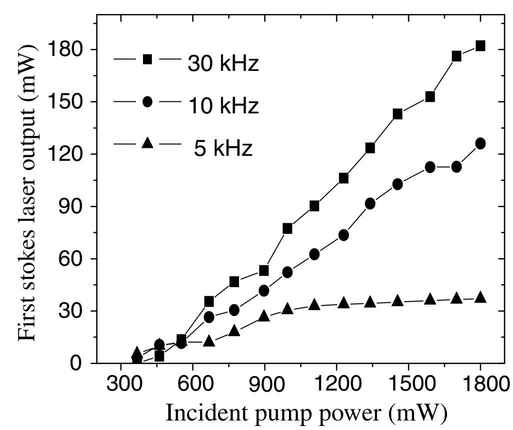

Fig. 3. First stokes laser output with respect to the incident power at different PRFs.

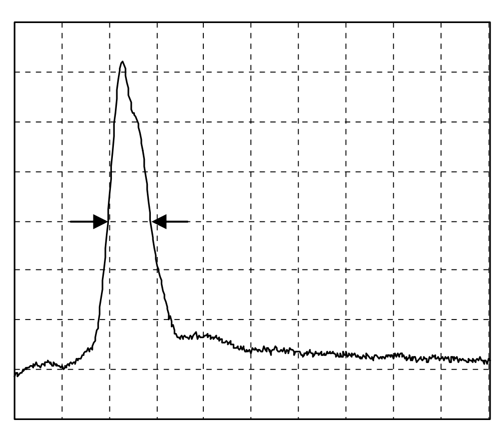

Fig. 4. Pulse shape of first stokes laser, 20 ns/div.

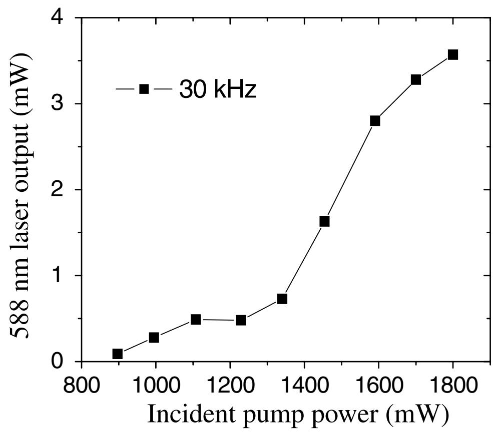

Fig. 5. Yellow laser output versus incident pump power at a PRF of 30 kHz.

Fig. 6. The far field beam profile of the 589 nm yellow laser.

of $I_p \approx 5.7$ MW/cm^2. We contributed this low threshold for the small emission cross-section of the *c*-cut Nd^{3+}:YVO_4 crystal and the high reflection at the first stokes wavelength of the output coupler.

2.3. Frequency-doubled yellow laser at 588 nm

LBO was chosen as the nonlinear SHG material for the reason of the high damage threshold, large acceptance angle and large nonlinear coefficient. The 10-mm-long LBO crystal was cut for type I critical phase matching and placed extracavity. Both the sides of LBO crystal were coated antireflection at 1176 nm. A 23-mm focal-length lens is employed to focus the first stokes into LBO crystal. Over 3.5 mW, 588 nm yellow laser was realized at a PFR of 30 kHz with 1.8 W incident pump power from Fig. 5.

The yellow laser has a good beam quality and the far field beam profile is also recorded by a CCD camera, Fig. 6.

3. Conclusion

In summary, a small-scale, low threshold, high efficient, intracavity Nd^{3+}:YVO_4 self-Raman laser at 1176 nm is demonstrated. Both the small emission cross-section of the *c*-cut Nd^{3+}:YVO_4 and the high reflection at the first stokes wavelength of the output coupler contribute the low threshold for the SRS process. From extracavity frequency doubling by use of a 10-mm-long LBO crystal, over 3.5 mW, 588 nm yellow laser is also achieved. In the next step, optimizing the experimental set-up or decreasing the thermal lensing in the crystal (such as reducing the Nd^{3+} doping, increasing the length of the Nd^{3+}:YVO_4 crystal) should increasing conversion efficiency and scaling output power of the first stokes laser. And intracavity frequency doubling also should increase the power of 589 nm yellow laser.

References

[1] H.M. Pask, J.A. Piper, Opt. Commun. 148 (1998) 285.
[2] H.M. Pask, Opt. Lett. 30 (2005) 2454.
[3] J.T. Murray, R.C. Powell, N. Peyghambarian, D. Smith, W. Austin, R.A. Stolzenberger, Opt. Lett. 20 (1995) 1017.
[4] Joshua Simons, Helen Pask, Peter Dekker, Jim Piper, Opt. Commun. 229 (2004) 305.
[5] J. Findeisen, H.J. Eichler, P. Peuser, Opt. Commun. 181 (2000) 129.
[6] Takashige Omatsu, Yasukuni Ojima, Helen. M. Pask, James A. Piper, Peter Dekker, Opt. Commun. 232 (2004) 327.
[7] Alexander A. Kaminskii, Ken-ichi Ueda, Hans J. Eichler, Yasuhiko Kuwano, Hikaru Kouta, Sergei N. Bagaev, Thomas H. Chyba, James C. Barnes, Gad M.A. Gad, Tomoyo Murai, Jianren Lu, Opt. Commun. 194 (2001) 201.
[8] Y.F. Chen, Opt. Lett. 29 (2004) 1915.
[9] T.T. Basiev, S.V. Vassiliev, V.A. Konjushkin, V.V. Osiko, A.I. Zagumennyi, Y.D. Zavartsev, S.A. Kutovoi, I.A. Shcherbakov, Laser Phys. Lett. 1 (2004) 237.
[10] Tasoltan T. Basiev, Peter G. Zverev, Alexander Ya. Karasik, Sergey V. Vassiliev, Alexander A. Sobol, Dmitri S. Chunaev, Vasily A. Konjushkin, Alexander I. Zagumennyi, Yuri D. Zavartsev, Sergey A. Kutovoi, Vyacheslav V. Osiko, Ivan A. Shcherbakov, Adv. Solid-State Photon. 94 (2004) 1.
[11] Igor V. Mochalov, Opt. Eng. 36 (1997) 1660.
[12] Y.F. Chen, Y.P. Lan, Appl. Phys. B 74 (2002) 415.
[13] John J. Degnan, IEEE J. Quantum Elect. 25 (1989) 214.
[14] Xingyu Zhang, Shengzhi Zhao, Qingpu Wang, B. Ozygus, H. Weber, IEEE J. Quantum Elect. 35 (1999) 1912.
[15] H.M. Pask, Prog. Quant. Electron. 27 (2003).
[16] W. Koechner, Solid-State Laser Engineering, Springer, Berlin, London, 1999.