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Low threshold, diode end-pumped Nd^{3+}:$GdVO_4$ self-Raman laser

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Abstract

Low threshold, high efficient Raman laser output has been realized from a compact, diode end-pumped, self-stimulating Nd^{3+}:$GdVO_4$ Raman laser. Maximum Raman output power of 100 mW was achieved at a pulse repetition frequency (PRF) of 10 kHz with 1.8 W pump power. The optical efficiency is 5.6% from diode to Raman laser and the slope efficiency is 8%. The lowest threshold for the SRS process is only 400 mW at a PRF of 5 kHz. By generating second harmonics using a LBO crystal, 3 mW 588 nm yellow laser was also produced. A strong blue emission was observed in the Nd^{3+}:$GdVO_4$ crystal when the Raman laser output, we contribute this for the upconversion of the Nd^{3+} in the crystal.

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Keywords: Raman laser; SRS; Actively Q-switched; Yellow laser

1. Introduction

All solid-state Raman lasers have been become a new device for frequency shifting in recent years using the stimulated Raman scattering (SRS) in Raman crystals. The Raman crystals used widely include $Ba(NO_3)_2$, $LiIO_3$ and KGW [1–3] and some new crystals with potential use in the Raman laser such as $SrWO_4$ [4]. Combined with diode pumped solid-state lasers, the Raman lasers have been made very compact, efficient and robust.

There are some special Raman crystals (such as KGW, $PbMoO_4$), which can be doped with Nd^{3+} ion and become laser active [5,6]. These crystals can be used both as laser and Raman medium and so the Raman laser device can be made quite compact using the process of self-stimulated Raman scattering (self-SRS) in only one crystal. The Nd^{3+}:KGW self-stimulated Raman lasers have been studied for many years. Since the $GdVO_4$ and YVO_4 crystals were found Raman active by Kaminskii [7], the self-stimulated Raman lasers using Nd^{3+}:$GdVO_4$ and Nd^{3+}:YVO4 crystals have been realized by Chen [8,9]. As all known, the Nd^{3+}:$GdVO_4$ crystal is a kind of good laser crystal and used widely in the diode-pumped solid-state lasers. So the Nd^{3+}:$GdVO_4$ self-Raman laser must be very interesting and useful compared with Nd^{3+}:KGW self-Raman laser. Table 1 shows the laser and Raman properties of the Nd^{3+}:GdVO4 [10] and Nd^{3+}:KGW [11] crystal.

In the uniaxial Nd^{3+}:$GdVO_4$ crystal, the luminescence shows strong polarization for the effect of the crystal field. There are different stimulated cross-section for *a*-cut and *c*-cut Nd^{3+}:$GdVO_4$ crystal, for example, the stimulated cross-section is $\sigma_{//} = 7.6 \times 10^{-19}$ cm^2 for *a*-cut and $\sigma_{\perp} = 1.2 \times 10^{-19}$ cm_2 for *c*-cut Nd^{3+}:$GdVO_4$ crystal for the line of 1.06 μm, respectively [12]. Smaller stimulated cross-section means large energy storage in laser medium and large pulse peak power output for the Q-switched operation [13]. Now that the Nd^{3+}:$GdVO_4$ crystal was used both

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Table 1
Properties of the Nd^{3+}:$GdVO_4$ and Nd^{3+}:KGW crystal [4,7,11]

Crystal	Nd^{3+}:$GdVO_4$	Nd^{3+}:KGW
Space group	Tetragonal	Monoclinic
Lattice constants (Å)	$a = b = 7.212$	$a = 8.098$;
		$b = 10.417$;
	$c = 6.350$	$c = 7.583$; $\beta = 94.43°$
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	10.1 [a];	2.6 [100]; 3.8 [010];
	11.7 [c]	3.4 [001]
Thermal expansion ($10^{-6} \cdot K^{-1}$)	1.5 [a]	4.0 [100]; 1.6 [010];
	7.3 [c]	8.5 [001]
Refractive index (300 K, 1 μm)	$n_o = 1.97$	$n^g = 2.003$;
		$n^m = 1.986$;
	$n_e = 2.19$	$n^p = 1.937$
Thermal-optic coefficient ($dn/dT \cdot 10^{-7} \cdot K^{-1}$)	0.93 [a]	−8 [K//p, E//m]
	1.36 [c]	−55 [K//p, E//g]
Fluorescence lifetime (μs)	100	110
Emission cross section σ_{em} ($10^{-19} \cdot cm^2$)	7.6 [//c];	4.3
	1.2 [⊥c]	
Raman shift (cm^{-1})	882	901.5 [K//p, E//m]
		767 [K//p, E//g]
Raman line width Δv (cm^{-1})		5.9 [901.5]; 7.8 [767]
Raman gain (cm/GW)	4.5	5.2 [901.5]; 5.2 [767]

as laser and Raman crystal, we cut it along *c*-axis to reduce the SRS threshold. Although there is a little difference in the Raman scattering cross section between a *a*-cut and *c*-cut Nd^{3+}:$GdVO_4$ crystal [14], we believe that it is not the critical aspect compared with the high pulse peak power especially for the low-level pump source.

The yellow lasers with powers about 1–10 mW have very important applications in guide-star, coastal bathymetry and laser display system. There are several ways to realized it include sum-frequency of the 1.06 and 1.3 μm outputs of Nd^{3+}:YVO_4 [15], frequency doubling of 1.129 μm transition in Nd^{3+}:SFAP. Second harmonic generation (SHG) of the Raman laser is also an efficient method for its high optical efficiency [16].

In this paper, we demonstrate low threshold, high efficient Raman laser output from using a *c*-cut Nd^{3+}:$GdVO_4$ crystal both as laser and Raman medium. Maximum Raman output power of 100 mW was achieved at a PRF of 10 kHz with 1.8 W pump power. The lowest threshold for the SRS process is only 400 mW at a PRF of 5 kHz. Yellow laser (588 nm) output of 3 mW was also obtained by use of a 10-mm long LBO crystal. The large heat deposition and strong blue emission were observed in the Nd^{3+}:$GdVO_4$ crystal in the process of Raman laser operation.

2. Experimental

2.1. Experimental set-up and fundamental laser output

The experimental configuration for the diode end-pumped, actively Q-switched Nd^{3+}:$GdVO_4$ self-Raman laser is depicted in Fig. 1.

A 2-W 808 nm LD was collimated and focused into the crystal with the spot size of 100 μm by multi-element lens with the transmission of 90% at 808 nm. The laser and Raman medium is a 0.5-at.%, *c*-cut Nd^{3+}:$GdVO_4$ crystal with the size of $3 \times 3 \times 5\ mm^3$. Both facets were coated anti-reflection (AR) coating at 1064/1176 nm. The cavity is composed of two mirrors, M1 and M2. The input mirror M1 is a 200 mm radius-of-curvature (ROC) concave mirror with high anti-reflection coating at pump wavelength (808 nm) on the entrance face ($R < 0.5\%$), high reflection coating at 1064/1176 nm ($R > 99.8\%$) on the other face surface. The output coupler M2 has a ROC of 50 mm with a special dichromic coating, high reflection at 1064 nm ($R > 99.8\%$) and partial transmission at 1176 nm ($T = 2\%$). A 24-mm long acousto-optical modulator was inserted into the cavity with both sides were coated AR at 1064 nm. The overall cavity length is 40 mm for the limitation of devices.

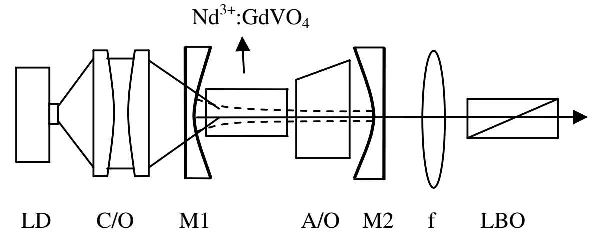

Fig. 1. Experimental set-up of diode pumped, actively Q-switched, self-stimulating Nd^{3+}:$GdVO_4$ Raman laser and extracavity frequency doubling by use of LBO crystal. C/O is coupling optics; M1 and M2 are input and output mirror, respectively; A/O is acousto-optical modulator.

The Q-switched operation of fundamental laser (1064 nm) was studied first for comparison of the conversion efficiency from the fundamental to Raman laser. The output coupler mentioned above was replaced by the same ROC output coupler with transmission of 10% at the fundamental. Fig. 2 shows the average output at different PRFs with respect to the incident pump power. The maximum output is 276 mW at a PRF of 30 kHz with the optical efficiency of 15.3% from incident power to the fundamental.

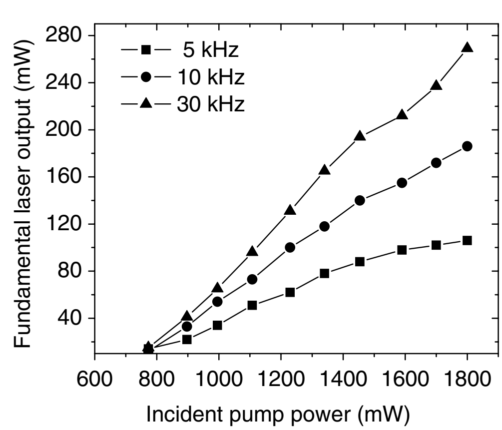

Fig. 2. Fundamental output with respect to incident power at different PRFs.

2.2. Raman laser output

The average output powers of the Raman laser for different PRFs (5, 10, 30 kHz) were depicted in Fig. 3. The maximum output power of the Raman laser is 100 mw at a PRF of 10 kHz. The conversion efficiency from incident power to first stokes laser is 5.6% and the slope efficiency is 8%. The output is decreased when the pump power is exceeded 1200 mW at a PRF of 30 kHz, we contribute this for the effect of thermal lens. The lowest threshold is only 400 mw happened at a PRF of 5 kHz. The threshold is quite low as we expected.

The threshold for intracavity Raman laser can be calculated using the condition [17]:$R_1R_2\ \exp(2I_pg_Rl - L_i) = 1$, 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 resonators, respectively; L_i is the internal cavity loss; I_p is the power density of the fundamental. Under a plane-wave approximation, the values we used as follows: $R_1 = 99.8\%$; $R_2 = 98\%$; $L_i = 1.5\%$; $g_R = 4.5$ cm/GW; $l = 5$ mm. That led to a value of $I_p \approx 8.5$ MW/cm^2. This is very low for the process of SRS. We contributed this low threshold for the small emission cross section of the *c*-cut Nd^{3+}:$GdVO_4$ crystal and low transmission at the first stokes wavelength of the output coupler.

The pulse width is about 19 ns for the maximum output, the pulse shape was shown in Fig. 4.

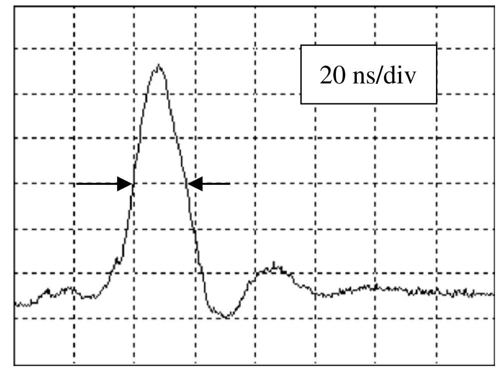

Fig. 4. Pulse shape of the first Stokes laser, 20 ns/div.

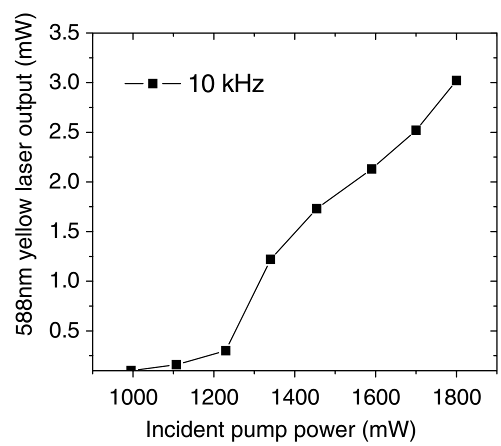

Fig. 5. Yellow laser output vs. incident pump power at a PRF of 10 kHz.

2.3. Frequency doubling

The LBO crystal was chosen for the SHG of the first stokes laser because of its high damage threshold and large acceptance angle. A 10-mm long LBO crystal with AR coating at 1176/588 nm on both facets was cut for type I critical phase matching and placed at extracavity. A focal lens ($f = 23$ mm) was used to focus the first stokes onto the LBO crystal. Fig.5 shows the average output of the 588 nm yellow laser at a PRF of 10 kHz with respect to the incident power. Maximum yellow laser output of 3 mW was obtained with the efficiency of 3% from the first stokes to yellow laser. The yellow laser has a good beam quality, and the far field beam profile was recorded by a digital camera, Fig. 6.

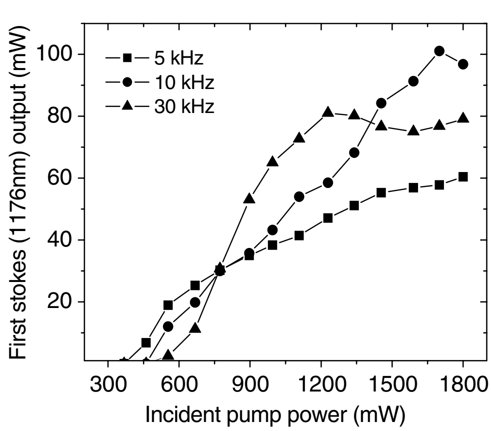

Fig. 3. First stokes laser output with respect to the incident power at different PRFs.

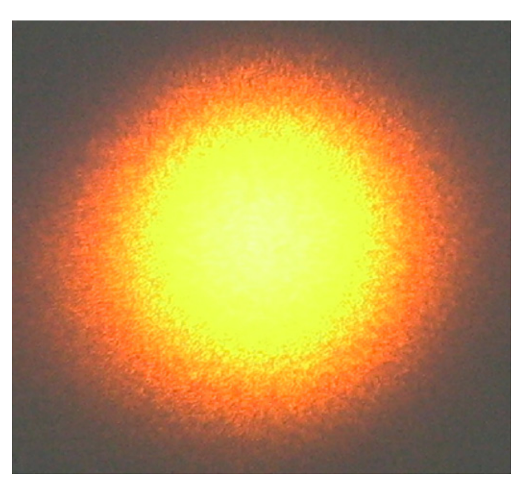

Fig. 6. Far field beam profile of the 588 nm yellow laser.

3. Discussion and conclusion

It was observed that the Nd^{3+}:$GdVO_4$ crystal became quite hot during the process of SRS. Obviously, the heat deposited in the Nd^{3+}:$GdVO_4$ crystal is much more than in only laser or Raman crystal for the fact that the quantum defect in it caused by both the laser radiation and SRS process. The effect of thermal lens caused by heat deposition in the crystal is the most important reason for affecting the stability of the cavity. It must be noted that the heat deposited in the Raman crystal where the SRS happened, which is different from the conversional end-pumped lasers usually closed to the surface of the crystal.

A strong blue emission not yellow–green emission was also observed in the process of Raman laser operation, but not observed in the process of fundamental laser operation. And it became brighter when the PRF changes from 30 kHz to 5 kHz. We couldn't record the spectrum of the blue emission for short of sensitive spectrometers, but we think that its spectrum may be located about 400 nm. From references [18,19], we speculated that the blue emission is due to the upconversion process of Nd^{3+} ions, the transition from the $^4D_{3/2}$, $^4D_{5/2}$ levels to the lower levels $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$. How this phenomenon affecting the thermal loading and the process of SRS needs further study in the next step.

In conclusion, we have achieved an output power of 100 mW Raman laser at 1176 nm in a small scale, diode end-pumped actively Q-switched Nd^{3+}:$GdVO_4$ self-Raman laser. The yellow laser (588 nm) was also obtained efficiently from SHG of the Raman laser. In the next step, the conversion efficiency should be further increased by optimizing the experimental set-up and using longer, low doping Nd^{3+} ions Nd^{3+}:$GdVO_4$ crystal. And intracavity frequency doubling can also increase the yellow laser output.

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