C-cut Nd-doped vanadate crystal self-Raman laser with narrow Q-switched envelope and high mode-locked repetition rate*

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In this paper, a passively Q-switched and mode-locked c-cut Nd-doped vanadate crystal self-Raman laser at 1.17 μm is firstly demonstrated by using Cr^{4+}:YAG. Two crystals of $Nd^{3+}:YVO_4$ and $Nd^{3+}:GdVO_4$ are adopted to generate laser, respectively. With the incident pump power of 13 W, the average output powers of 678 mW and 852 mW at 1.17 μm are obtained with the durations of Q-switched envelope of 1.8 ns and 2 ns, respectively. The mode-locked repetition rates are as high as 2.3 Hz and 2.2 GHz, respectively. As far as we know, the Q-switched envelope is the narrowest and the mode-locked repetition rate is the highest at present in this field. In addition, yellow laser output is also achieved by using the LiB_3O_5 frequency doubling crystal.

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Laser emission combined with stimulated Raman scattering frequency conversion in the same crystal is a research direction with high potential due to low intracavity losses and simple laser design. Q-switched and continuous wave (CW) self-Raman lasers based on Nd-doped and Yb-doped laser crystals have been demonstrated, which provide the first Stokes line in the near infrared region between 1 100 nm and 1 200 nm[1-4]. Combined with the frequency doubling, these lasers generate the radiation at wavelengths from yellow to orange spectral region. CW yellow-orange laser can be achieved by other methods, such as the sum frequency. But the pulse yellow-orange laser is difficult to achieve, which can be used as a potential light source in many fields, such as ecological monitoring and medical applications.

Especially, many Q-switched self-Raman lasers have been successfully demonstrated with the Cr^{4+}:YAG crystal as an efficient saturable absorber[5-7]. C-cut Nd-doped vanadate crystal is more suitable than the a-cut one for generating Q-switched laser[4-8]. Passively Q-switched and mode-locked Nd-doped vanadate crystal lasers with a Cr^{4+}:YAG saturable absorber have been demonstrated[9]. Actively Q-switched and mode-locked $Nd:YVO_4$ crystal self-Raman lasers were obtained with an acousto-optical Q-switch (AOS) in 2013[10].

In this paper, we report the multi-gigahertz picosecond c-cut Nd-doped vanadate crystal self-Raman laser for the first time. Besides, the operations of self-Raman lasers based on $Nd^{3+}:YVO_4$ and $Nd^{3+}:GdVO_4$ are both studied and compared. The output power of self-Raman laser based on $Nd^{3+}:GdVO_4$ is higher due to the smaller stimulated emission cross section. A compact and effective laser system is experimentally demonstrated, and picosecond self-Raman lasers with narrow Q-switched envelope and high mode-locked repetition rate are successfully observed. With the incident pump power of 13 W, the duration of the Q-switched envelope, the maximum average output power and the mode-locked pulse repetition rate for self-Raman lasers based on $Nd^{3+}:YVO_4$ and $Nd^{3+}:GdVO_4$ are 1.8 ns and 2 ns, 678 mW and 852 mW, 2.3 GHz and 2.2 GHz, respectively.

The experimental device is shown in Fig.1. The pump source used in the experiments is a fiber-coupled 808 nm laser diode (LD) with core diameter of 200 μm and numeric aperture of 0.22. The central wavelength of LD is 807.5 nm at 25 °C, and can be tuned by changing the working temperature of LD to match the best absorption of the laser crystal. A focusing lens system with focal length of 75 mm and coupling efficiency of 93% is used to reimage the pump beam into the laser crystal. The average pump size in the crystal is approximately 150 μm. The active media are c-cut $Nd^{3+}:YVO_4$ crystal with

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Nd atom percent of 2% and size of 3 mm×3 mm×10 mm and c-cut Nd^{3+}:$GdVO_4$ crystal with Nd atom percent of 2% and size of 3 mm×3 mm×12 mm. Crystal is high-transmission (HT) coated at 808 nm and 1 100–1 200 nm (>99.8%). The laser crystal is wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature is controlled to be 18 °C to ensure stable laser output. The resonator consists of M_1, output coupler (OC), a c-cut Nd-doped vanadate crystal and a Cr^{4+}:YAG absorber. The mirror M_1 is a spherical mirror with curvature radius of 100 mm, which is anti-reflection (AR) coated at 808 nm (>98%) and high-reflection (HR) coated at 1 064 nm and 1 100–1 200 nm (>99.8%). The OC is a flat mirror which is HR coated at 808 nm and 1 064 nm and partial-transmission (PT) coated at 1 100–1 200 nm (T=5%). The total optical-cavity length is about 60 mm. The mirror M_2 is a flat mirror with tilt angle of 45°, which is high-transmission (HT) coated at 1 064 nm and HR coated at 1 100–1 200 nm, and it is used as an optical filter to separate fundamental laser with Raman laser.

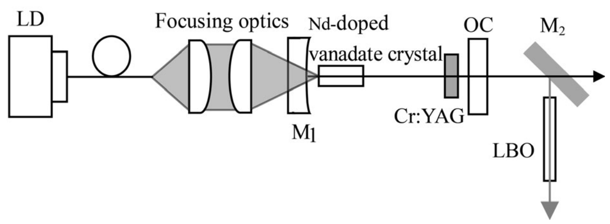

Fig.1 Schematic diagram of the Q-switched and mode-locked self-Raman Nd-doped vanadate crystal laser

In this experiment, a Cr^{4+}:YAG crystal with initial transmission at 1 064 nm of 75% is used, and both sides of the crystal are coated by AR layer for 1 064 nm. The ratio of the effective areas in the active medium and in the Cr^{4+}:YAG saturable absorber is needed to be as large as possible for realizing effective Raman scattering easily. Due to this reason, a mirror with curvature radius of 100 mm is designed, and the initial transmission of Cr^{4+}:YAG is optimized. Using the mirror with curvature radius of 100 mm, the ratio of the effective areas can be designed preferably, and the Raman output can be obtained easily. And Cr^{4+}:YAG is placed as close as possible to the OC, and the Nd-doped vanadate crystal is placed as close as possible to the input mirror M_1. With the ABCD matrix, the mode radii at the center of the active medium and Cr^{4+}:YAG can be calculated as 290 μm and 80 μm, respectively.

The mode-locked pulses are detected by a high-speed InGaAs photo detector with bandwidth of 10 GHz and a digital oscilloscope (LeCroy Wave pro 7300A) with electrical bandwidth of 3 GHz. The spectra of 588.7 nm and 587.0 nm yellow lasers are detected by an ocean spectrometer (HR 2000+).

The amplitude instability is minimized to obtain a relatively stable mode-locking operation by finely adjusting the cavity. Fig.2 shows the output power at 1 178 nm and 1 173 nm versus the incident pump power. From Fig.2, the output power of Nd^{3+}:$GdVO_4$ at 1 173 nm is higher than that at 1 178 nm, which can prove that the smaller stimulated emission cross section is more suitable for generating Q-switched mode-locked laser. Theoretically, the light intensity in the saturable absorber is proportional to initial population density in the gain medium. The initial population density is given as[11]

$$n_i = \frac{\ln(1/T_0^2) + \ln(1/R) + L}{2\sigma l}, \quad (1)$$

where T_0 is the initial transmission of the saturable absorber, R is the reflectivity of the output mirror, L is the non-saturable intracavity round-trip dissipative optical loss, σ is the stimulated emission cross section of the gain medium, and l is the length of the laser rod. Though c-cut Nd-doped vanadate crystal has a smaller gain cross section than a-cut Nd-doped vanadate crystal, it is still too large. The initial transmission of absorber (T_0) must be small enough to yield a large initial population density[12]. However, if the initial transmission of absorber is too small, the useless loss will be enhanced, and the efficiency will be decreased. For achieving the better mode locking, a Cr^{4+}:YAG initial transmission of 75% is adopted. However, it is smaller than the normal, and the loss is higher. The threshold of self-Raman laser is 7 W, which is higher than others[4-6]. With the c-cut Nd^{3+}:YVO_4 at the maximum incident pump power of 13 W, the average output power at 1 178 nm is about 678 mW. The first Stokes conversion efficiency is 5.2%, and the slope efficiency is 12.2%. With the same incident pump power of Nd^{3+}:$GdVO_4$, the average output power at 1 173 nm, the first Stokes conversion efficiency and the slope efficiency are 875 mW, 6.9% and 12.4%, respectively.

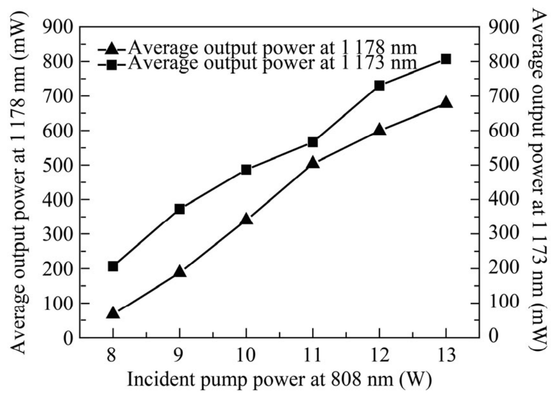

Fig.2 Output power at 1 178 nm and 1 173 nm versus the incident pump power

With an optical filter, the pulse train traces can be shown on the oscilloscope. Fig.3 shows the pulse trains of Nd:YVO_4 laser on different time scales at the incident pump power of 9 W, which prove that the duration of the

1 178 nm Q-switched and mode-locked pulse narrow envelope is about 2 ns, and the pulse repetition rate of the inside 1 178 nm mode-locked pulse train is about 2.3 GHz. The laser amplitude fluctuations are relatively small and stable. The mode-locked self-Raman optical-cavity length is 65 mm with the pulse period of 430 ps. It matches exactly with the cavity round trip transmit time and corresponds to the repetition rate of 2.3 GHz. For the 1 178 nm Raman laser, as the incident pump power is increased from 7 W to 13 W, the repetition rate of the Q-switched pulse envelope is changed from 5 kHz to 11 kHz, and the duration is changed from 2.5 ns to 1.8 ns. Laser pulse width shown on the oscilloscope is 130 ps, which approaches the limit of the instrument. The actual mode-locked pulse width is less than the estimated pulse duration.

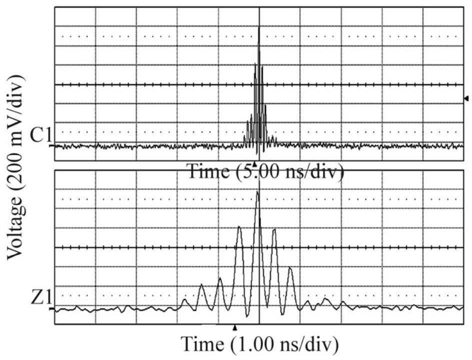

Fig.3 1 178 nm Q-switched mode-locked pulse train envelopes on two different time scales

With an optical filter, Fig.4 shows the $Nd:GdVO_4$ pulse trains on two different time scales of 5.00 ns/div and 1.00 ns/div at the incident pump power of 13 W. The duration of 1 173 nm Q-switched and mode-locked pulse envelope is about 2 ns, and the mode-locked repetition rate is about 2.2 GHz. For the 1 173 nm Raman laser, as the incident pump power is increased from 7.5 W to 13 W, the repetition rate of the Q-switched pulse envelope is changed from 4.5 kHz to 12.5 kHz, and the duration is changed from 2.6 ns to 2 ns. Laser pulse width shown on the oscilloscope is 135 ps. Comparing $Nd:YVO_4$ with $Nd:GdVO_4$, the waveforms and indices are similar.

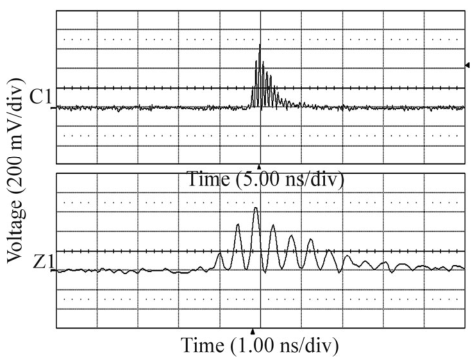

Fig.4 1 173 nm Q-switched mode-locked pulse train envelopes on two different time scales

LiB_3O_5 (LBO) is chosen as the frequency doubling crystal for its high damage threshold, large acceptance angle and large nonlinear coefficient. The 10 mm-long LBO crystal is cut for type I critical phase matching (θ=90°, φ=3.7°). Both sides of the LBO crystal are AR coated at 1 050–1 100 nm and 550–600 nm. The LBO is placed in external cavity, and no focal lens is used. The yellow laser output powers at 588.7 nm and 587.0 nm are achieved as 19 mW and 25 mW at pump power of 13 W, respectively. The spectra of yellow laser are shown in Fig.5. The far field beam profile of the yellow laser, which is recorded by a digital camera, is also indicated in the inset of Fig.5(a).

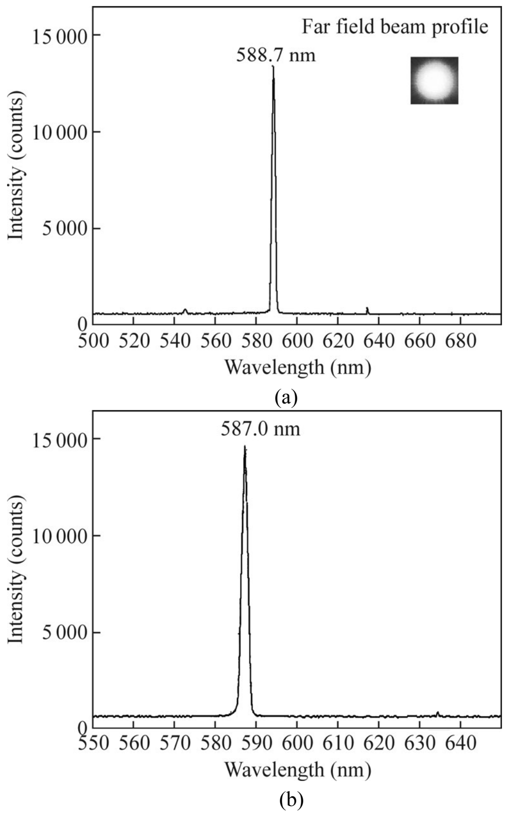

Fig.5 Spectra and far field beam profile of the yellow lasers at (a) 588.7 nm and (b) 587.0 nm

In conclusion, we demonstrate a compact passively Q-switched and mode-locked self-Raman laser with c-cut Nd-doped vanadate crystal for the first time. Cr^{4+}:YAG with 75% initial transmission is used as the mode-locked saturable absorber. Comparing $Nd:YVO_4$ with $Nd:GdVO_4$, the smaller stimulated emission cross section can generate the higher output power of Q-switched and mode-locked laser. Through the experiment, narrow Q-switched envelope and high mode-locked repetition rate are achieved. At the incident pump power of 13 W, for the lasers with $Nd:YVO_4$ and $Nd:GdVO_4$, the durations of Q-switched envelope, the maximum average output powers and the mode locked pulse repetition rates are 1.8 ns and 2 ns, 678 mW and 852 mW, 2.3 GHz and 2.2 GHz, respectively. Using a 10 mm-long LBO as the frequency doubling crystal, yellow laser outputs at 588.7 nm and 587.0 nm are obtained as 19 mW and 25 mW, respectively.

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