High-efficiency Q-switched dual-wavelength emission at 1176 and 559 nm with intracavity Raman and sum-frequency generation

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Abstract: An efficient Q-switched dual-wavelength laser with self-frequency Raman conversion in composite Nd:YVO_4 and intracavity sum-frequency generation in BBO is reported. With an input pump power of 17.5 W, average power of 0.53 W at the first-Stokes 1176 nm and average power of 1.67 W at the sum-frequency mixed 559 nm are simultaneously generated at a pulse repetition rate of 100 kHz, corresponding to a total conversion efficiency of 12.5%.

OCIS codes: (140.3550) Lasers, Raman; (140.7300) Visible lasers; (140.3480) Lasers, diode-pumped; (190.2620) Harmonic generation and mixing.

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1. Introduction

Stimulated Raman scattering (SRS) has been recognized as a promising and practical approach of wavelength conversion for infrared solid-sate laser [1]. In the recent years, new laser sources in the spectral range of visible and UV light have been successfully generated by combining SRS with second-Harmonic-generation (SHG) or sum-frequency-generation (SFG) [2]. More interestingly and importantly, yellow lights are useful for biomedicine, ophthalmology and dermatology. To date, the highest yellow average power of 3.14 W at 590 nm for a pulse repetition rate of 10 kHz was obtained by doubling diode-side-pumped Nd:YAG/$BaWO_4$ Raman laser [3]. In continuous-wave (CW) operation, the highest yellow average power of 2.51 W at 586.5 W was generated from intracavity frequency-doubling of a diode-end-pumped Nd:$GdVO_4$ self-Raman laser [4]. Recently, the yellow-green laser near 560 nm has been shown to give excellent excitation of phycoerythrins and low molecular weight fluorochromes [5]. The methods of generating yellow-green solid-state laser sources include external-cavity Raman laser pumped by frequency-doubled Nd^{3+} lasers, SHG in low-gain Nd^{3+} lasers, frequency-doubled optically pumped semiconductor laser, and SFG or SHG in infrared Raman lasers. Firstly, He et al. reported on a 532 nm-pumped multi-wavelength lasers comprising 25-mJ yellow-green emission at 563 nm based on cascade Raman generation in a $Ba(NO_3)_2$ crystal [6]. Kaminskii et al. reported on a greater than 1-mJ $PbWO_4$ Raman laser at 559 nm pumped by Q-switched frequency-doubled Nd:YAG laser at 532 nm [7]. Then, Jia et al. reported on a 1.67-W CW laser at 556 nm generated by frequency-doubling 1112-nm diode-pumped Nd:YAG laser [8]. Räikkönen et al. reported on a 55-mW yellow-green emission at 561 nm from frequency-doubling of a 1123-nm diode-pumped passively Q-switched Nd:YAG laser [9]. Hilbich et al. reported on diode-pumped frequency-doubled optically pumped semiconductor lasers comprising two higher than 100-mW CW yellow-green emissions at 554 and 565 nm [10]. In addition, selectable-wavelength Q-switched Nd:YAG/KGW Raman laser with intracavity SFG and SHG in angle-tuned BBO (β-BaB_2O_4) generated average power of 0.77 W at 559 nm presented by Pask et al. [11].

Recently, Nd:YVO_4 and Nd:$GdVO_4$ crystals have been identified as excellent laser gain media as well as SRS gain media for diode-pumped all-solid-state lasers [12,13]. Quite recently, the $\chi^{(3)}$-nonlinear generation effects in tetragonal $LuVO_4$ vanadates has been discovered [13,14]. The realization of Nd:YVO_4, Nd:$GdVO_4$, and Nd:$LuVO_4$ self-Raman lasers have been demonstrated [15–20]. In this work we employ a self-Raman Nd:YVO_4 laser to develop an efficient yellow-green laser at 559 nm based on intracavity sum-frequency-mixing of the 1064-nm fundamental wave and the 1176-nm first-Stokes component. With an input pump power of 17.5 W, the maximum average power at 559 nm is 1.67 W and the residual average power at 1176 nm is 0.53 W at a pulse repetition rate of 100 kHz, corresponding to conversion efficiency of 9.5% and 3%, respectively. To the best of our knowledge, it is the highest power at 559 nm obtained with intracavity SFG in a self-Raman laser.

2. Experimental setup

The experimental setup of a diode-end-pumped actively Q-switched Nd:YVO_4 self-Raman laser with intracavity SFG is shown in Fig. 1. The pump source is an 808-nm fiber-coupler laser diode with a core diameter of 600 μm, a numerical aperture of 0.16 and a maximum power of 18 W. The pump beam is focused at the active medium, and the waist radius is approximately 250 μm. An *a*-cut 20-mm-long composite 0.3-at.% Nd^{3+}-doped Nd:YVO_4

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crystal bounded with a 2-mm-long and an 8-mm-long undoped YVO_4 ends at its pumped facet and the other facet, respectively, is simultaneously used as a laser crystal and a self-Raman medium. With a fundamental pump wavelength of 1064 nm, the wavelength of the first-Stokes emission in accordance with the YVO_4 Stokes shift at 890 cm^{-1} is calculated to be around 1176 nm [12]. Both sides of the laser crystal is coated for antireflection at 1000-1200 nm (R<0.2%). The laser cavity is designed for the sum-frequency mixing of the fundamental wave and the first-Stokes laser. The 10-mm-long type-**I** BBO crystal with a phase-matching cutting angle ($\theta = 22.1°$ and $\psi = 0°$) is used as a sum-frequency mixer. Besides, the composite Nd:YVO_4 and BBO crystals are both wrapped with indium foil and mounted in water-cooled copper blocks. The water temperature is maintained at 20°C. The front mirror M1 is a 500-mm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face (R<0.2%), high-transmission coating at 808 nm (T>90%), and high-reflection coating at 1000-1200 nm on the other face (R>99.8%). The 30-mm-long acousto-optic Q-switcher (NEOS Technologies) had antireflectance coatings at 1064 nm on both faces and was driven at a 27.12-MHz center frequency with 15.0 W of rf power. The flat intracavity mirror M2 has high-transmission coating at 1064 nm and 1176 nm (T>95%) as well as high-reflection coating at 559 nm (R>99.7%). The output coupler M3 is a flat mirror with high-reflection coating at 1064 nm (R>99.8%), partial-reflection coating at 1176 nm (R = 98.1%), and high-transmission coating at 559 nm (T>85%). The overall laser cavity length is around 113 mm.

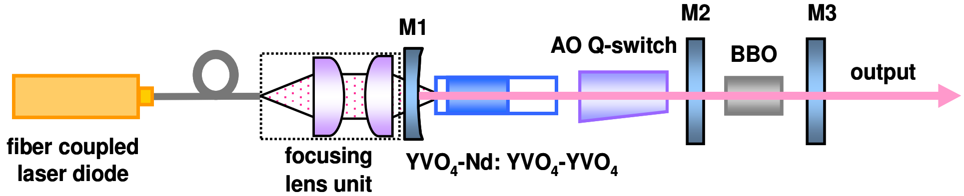

Fig. 1. Experimental setup of a diode-end-pumped actively Q-switched Nd:YVO_4/BBO laser with intracavity self-Raman frequency conversion and sum-frequency generation.

3. Experimental results and discussions

Since it has been verified that the enhancement of Raman gain is attributed from the significant reduced thermal effects and the increase of the Raman interaction length in a double-end diffusion-bonded Nd:YVO_4 crystal [21], we use a double-end diffusion-bonded Nd:YVO_4 crystal as a self-Raman gain medium in this work. The two two-mirror cavities are set up. The first two-mirror cavity with a output coupler having partial-reflection coating at 1064 nm (R = 85%) is used to set up a Q-switched Nd:YVO_4 laser at 1064 nm. With an input pump power of 17.5 W, average power of 8.7 W at 1064 nm is obtained at a pulse repetition rate of 100 kHz. The second two-mirror cavity with a output coupler having high-reflection coating at the 1064 nm and partial reflection coating at the first-Stokes component of 1176 nm (R = 56%) is used for the Q-switched Nd:YVO_4 self-Raman laser at 1176 nm. The laser cavity length is 7 cm and the pumping threshold for the Raman laser is 2.7 W to 3.5 W at the pulse repetition rates of 80 kHz to 120 kHz. With an input pump power of 12.1 W, the average output power of 3 W and the peak power of 7.6 kW at 1176 nm are achieved at a pulse repetition rate of 100 kHz, corresponding to a high conversion efficiency of 24.8%. The average power at 1176 nm and conversion efficiency are 2 times and 1.8 times that of the Nd:YVO_4 self-Raman laser with a conventional Nd:YVO_4 crystal without undoped endcaps, respectively [15].

After confirming the performance of the Q-switched Raman laser at 1176 nm, the laser cavity is designed for sum-frequency mixing of the fundamental wave and the first-Stokes component. The BBO crystal, the intracavity mirror M2, and the output coupler M3 are inserted in the laser cavity. The cavity alignment and the tilt of BBO crystal must be regulated to optimize the laser performance. As a result of the high-reflection coating at SFG

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wavelength on mirror M2, the present linear three-mirror-cavity takes the advantages of reduced loss of SFG emission transmitting through the front mirror M1 as well as reduced absorption of SFG emission in the Nd:YVO_4 which lowers the thermal load in the Nd:YVO_4 compared to the linear two-mirror-cavity [4]. Additionally, the present laser configuration is more compact than the three-mirror folded cavity. Note that the present output coupler M3 is non-optimal for SFG emission. Therefore, a higher output power at SFG wavelength can be obtained with the optimum output coupler having high-reflection coating at 1176 nm. The spectrum of laser output is measured by an optical spectrum analyzer (Advantest Q8381A) employing a diffraction lattice monochromator with a resolution of 0.1 nm. The experimental optical spectrum of the laser output is shown in Fig. 2, and it can be seen that the main laser output is the yellow-green laser at 559 nm from sum-frequency-mixing of 1176 and 1064 nm. The pumping threshold for oscillation at 559 nm is around 4.3 W to 6 W for the pulse repetition rates of 80 kHz to 120 kHz. The residual laser output is the first-Stokes laser at 1176 nm. The intensity of the fundamental wave at 1064 nm is weak and hard to measure due to the high-reflection coating at 1064 nm on the output coupler.

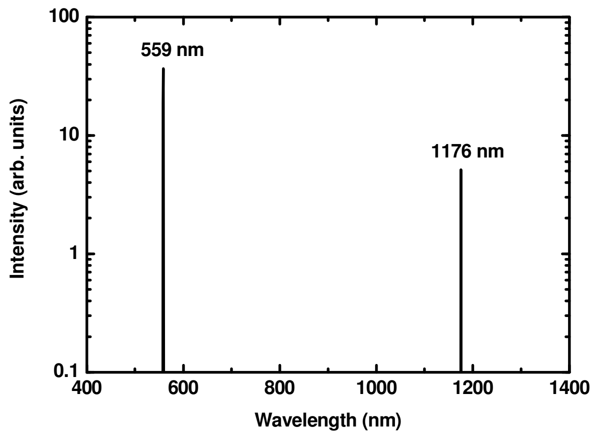

Fig. 2. Optical spectrum of the diode-end-pumped actively Q-switched Nd:YVO_4/BBO laser.

Figure 3 shows the total average power as well as individual average power at Stokes wavelength of 1176 nm and SFG wavelength of 559 nm with respect to the input pump power at a pulse repetition rate of 100 kHz. The M^2 beam quality factor is found to be less than 2.0 for all pump powers. The average power at 1176 nm is saturated at around 0.55 W with an input pump power above 12 W. With an input pump power of 12.9 W, the average power of 0.56 W at 1176 nm is obtained, corresponding to a conversion efficiency of 4.3%. However, increasing input pump power to higher than 12 W is beneficial for enhancing SFG average power. While the input pump power is increased to 17.5 W, the average power at 559 nm is up to 1.67 W corresponding to a conversion efficiency of 9.5%. The higher average output at 559 nm and the lower average output power at 1176 nm would be obtained if an output coupler with high-reflection coating at both 1064 and 1176 nm (R>99.8%) was used.

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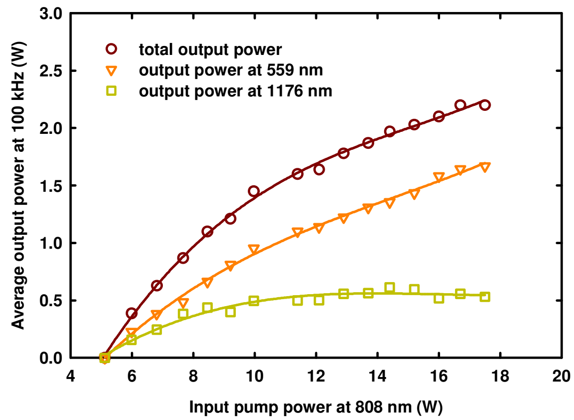

Fig. 3. The total average output power as well as individual average output power at 559 and 1176 nm with respect to the input pump power at a pulse repetition rate of 100 kHz.

The temporal traces for the laser emission comprising the fundamental, Raman, and SFG pulses are recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 Gsamples/s, 1-GHz bandwidth) with two fast p-i-n photodiodes. The oscilloscope trace of output pulse trains is shown in Fig. 4. It can be seen that the pulse-to-pulse amplitude fluctuation is within ± 15%. Note that the vertical scales for the pulses at 1064, 1176, and 559 nm are separate arbitrary units. The pulse widths of 1176 and 559 nm are measured to be shorter than 55 and 10 ns over the entire operation, respectively. As shown in Fig. 5, the pulse widths of 1176 and 559 nm pulses are approximately 32 and 5.4 ns with an input pump power of 17.5 W at a pulse repetition rate of 100 kHz, respectively. As shown in Fig. 5, the Raman pulse is generated after SFG pulse. It is because that when the intracavity power density of the fundamental pulse reaches the SRS threshold, the Raman and fundamental pulses are simultaneously rapidly converted to SFG pulse. Therefore, there exists a longer time shift of fundamental and Raman pulses than Raman laser without SFG. In summary, an efficient dual-wavelength Q-switched laser at 559 and 1176 nm based on self-Raman and intracavity SFG is demonstrated by using a double-end diffusion-bonded Nd:YVO_4 crystal and a BBO crystal. At a pulse repetition rate of 100 kHz, the main average output power of 1.67 W at 559 nm and the residual average output power of 0.53 W at 1176 nm is generated with an input pump power of 17.5 W, corresponding to conversion efficiency of 9.5% and 3% and peak power of 3.1 and 0.17 kW, respectively. The total conversion efficiency of SRS and SFG is 12.5%.

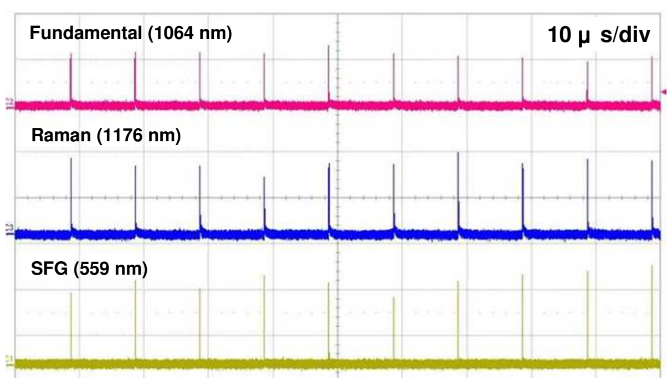

Fig. 4. Typical oscilloscope traces of pulse trains at 1064, 1176, and 559 nm.

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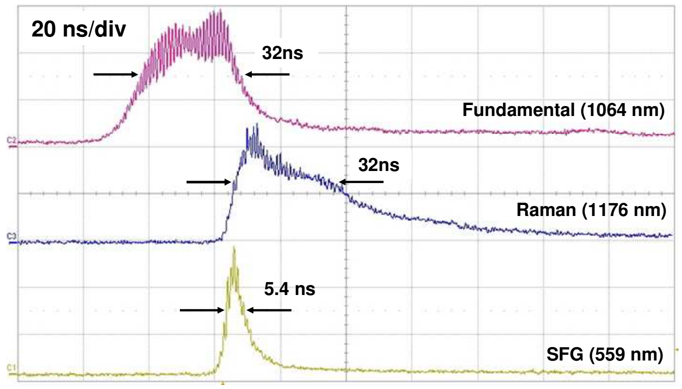

Fig. 5. Typical oscilloscope traces for output pulses at 1064, 1176, and 559 nm.

4. Conclusion

In conclusion, an efficient yellow-green laser at 559 nm with intracavity SFG in a diode-pumped Q-switched $Nd:YVO_4$ self-Raman laser is demonstrated. We utilize a double-bonded diffusion-bonded $Nd:YVO_4$ crystal as a self-Raman gain medium to improve thermal lensing effect and enhance the Raman gain. With input pump power of 17.5 W, the maximum average power at 559 nm is 1.67 W and the average power at 1176 nm is 0.53 W at a pulse repetition rate of 100 kHz, corresponding to conversion efficiency of 9.5% and 3%, respectively. The peak power of 559 nm pulse amounts to 3.1 kW.

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