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Actively Q-switched intracavity Nd:YVO_4/$GdVO_4$ Raman laser operating with multiple Raman shifts of 259, 882 and 890 cm^{-1}

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Abstract

A diode-pumped acousto-optic Q-switched crystal Raman laser operating at multi-wavelength is reported, in which a c-cut Nd:YVO_4 crystal was used as the self-Raman medium and a c-cut $GdVO_4$ crystal was used as the other Raman medium. Benefited from the overlapping gain at the Raman shift of 259 cm^{-1} in the two crystals, the corresponding cascade Stokes light efficiently oscillated, and the 1177, 1178 nm lights corresponding to the primary Raman-shifts of the two crystals oscillated with the 1097 nm laser. The laser configuration was investigated at pulse repetition frequencies (PRFs) of 10, 20, and 30 kHz. With an incident pump power of 8.62 W, the highest average Raman laser output of 1.31 W composed of 1097, 1129, 1177 and 1178 nm lights was obtained at the PRF of 20 kHz. The 1163 nm light corresponding to the third-Stokes light of the Raman shift of 259 cm^{-1} only arose at the PRF of 10 kHz when the incident pump power exceeded 6.37 W.

1 Introduction

Neodymium doped vanadates such as Nd:YVO_4 and Nd:$GdVO_4$ are excellent laser gain media and widely employed in solid state lasers [1, 2]. In 2001, YVO_4 and $GdVO_4$ were proved to be of good Raman-active performance, and were predicted to be excellent self-Raman materials by A. A. Kaminskii [3]. In 2004, efficient experimental investigations on Q-switched Nd:YVO_4 or Nd:$GdVO_4$ self-Raman lasers were reported by Y. F. Chen [4–6]. Since then, different experimental investigations on self-Raman laser based on Nd:YVO_4 or Nd:$GdVO_4$ have been reported, which included direct outputting Stokes light [7–9], intracavity frequency-doubling for yellow-orange laser generating [10, 11] and intracavity sum-frequency mixing for yellow-green laser generating [12, 13]. In 2012, integrating these two crystals in one resonator to obtain simultaneous dual-Raman-line outputting was experimentally investigated, an acousto-optic(AO) Q-Switched simultaneous dual-wavelength Raman laser was reported [14], in which an a-cut Nd:YVO_4 crystal was used as the self-Raman crystal and an a-cut Nd:$GdVO_4$ crystal was used as the other Raman medium, and efficient simultaneous pulse oscillations at 1522 and 1524 nm corresponding to the Raman shifts of 882 cm^{-1} in $GdVO_4$ and 890 cm^{-1} in YVO_4 was obtained. In 2013, with the same method, a simultaneous dual-wavelength pulse Raman laser at 1175 and 1176 nm was acquired [15].

Besides the experiments based on the primary Raman shifts in the two crystals mentioned above, the secondary Raman-shifts Stokes light oscillating in these two crystals were also experimentally investigated, in which c-cut Nd:YVO_4 self-Raman lasers on the Raman shift of 259 cm^{-1} were mostly concerned. In 2011, Fan et al. reported an AO Q-switched c-cut Nd:YVO_4 self-Raman laser outputting 1097 nm light [16]. In 2013, Wu et al. reported a Cr:YAG Q-switched 1097 nm c-cut Nd:YVO_4 self-Raman laser [17]. In 2017, Guo et al. reported an AO Q-switched cascade c-cut Nd:YVO_4 self-Raman laser corresponding to the Raman shift of 259 cm^{-1} [18], and Zhu et al. reported an AO Q-switched c-cut Nd:YVO_4 self-Raman laser outputting cascade Stokes light corresponding to the Raman shifts of 259 and 890 cm^{-1} [19]. In 2019, Bai et al. reported a diode-pumped passively Q-switched diffusion-bonded Nd:YVO_4/YVO_4 self-Raman laser [20], which outputted an average power of 0.66 W at 1097 nm with an incident diode power of 8.1 W. Besides the c-cut Nd:YVO_4 self-Raman laser on the Raman shift of 259 cm^{-1}, in 2012, Lin and Pask realized cascade Stokes light output corresponding to the Raman shift of

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382 cm^{-1} from an a-cut Nd:GdVO$_4$ self-Raman laser [21]; and in 2013, Li et al. realized cw cascade Stokes light output corresponding to the Raman shift of 379 cm^{-1} from an a-cut Nd:YVO$_4$ self-Raman laser [22]. In 2017, we investigated a diode-pumped actively Q-switched c-cut Nd:GdVO$_4$ self-Raman laser outputting two first-Stokes lights (1166 and 1176 nm) corresponding to the Raman shifts of 807 and 890 cm^{-1} with a limited pump power range of 1.5–4 W at a pulse repetition frequency(PRF) of 20 kHz [23].

Recently, we reported a diode-pumped Cr:YAG Q-switched Nd:GdVO$_4$/YVO$_4$ Raman laser in which a c-cut Nd:GdVO$_4$ was employed as the self-Raman medium and a c-cut Nd:YVO$_4$ crystal was used as the other Raman medium [24]. Benefited from the Raman gain coefficient of the Raman shift of 259 cm^{-1} amounting to about half of that corresponding to the primary Raman shift in each Raman crystal [25–27] and much lower cavity loss, the 1096 nm laser corresponding to the first-Stokes light of the Raman shift of 259 cm^{-1} arose ahead in competition with the 1176 and 1177 nm lights corresponding to the first-Stokes lights of the primary Raman shifts in the two Raman crystals and increased to a high intracavity density, thus the 1128 nm laser efficiently oscillated. The 1176 and 1177 nm laser pulse arose with 1096 nm laser in a Q-switch time and had comparable output powers with the 1096 nm laser.

Contrast to the passively Q-switched laser system, the actively Q-switched laser has the advantages of low intracavity loss, high efficiency and controllable PRF. In this paper, a diode-pumped AO Q-switched Raman laser in which a c-cut Nd:YVO$_4$ crystal was used as the self-Raman medium and a c-cut Nd:GdVO$_4$ crystal was used as the other Raman medium was experimentally investigated. There were five Raman lines appearing: 1097, 1129, 1163, 1177 and 1178 nm. The 1177 and 1178 nm lights were the first-Stokes lights corresponding to the primary Raman shifts of 882 cm^{-1} in GdVO$_4$ and 890 cm^{-1} in YVO$_4$, respectively. The 1097, 1129 and 1163 nm lights were the first-, second- and third-Stokes lines corresponding to the Raman shift of 259 cm^{-1}, which obtained gain in both the c-cut Nd:YVO$_4$ crystal and the c-cut Nd:GdVO$_4$ crystal. The highest average Raman laser output power of 1310 mW was obtained at the PRF of 20 kHz and the incident pump power of 8.62 W. The oscillating of the 1163 nm laser only arose at the PRF of 10 kHz while the incident pump power exceeded 6.37 W. To the best of our knowledge, this is the first actively Q-switched Raman laser in which three Raman shift effectively simultaneously oscillate.

2 Experimental setup

Figure 1 shows the experimental setup of the diode-pumped AO Q-switched Raman laser system. A 40 W fiber-coupled 808 nm laser diode system was used as the pump source, with a core diameter of 400 μm and a numerical aperture (NA) of 0.22. The pump beam was re-imaged onto the laser crystal with an 1:1 imaging-magnification and 97% coupling-efficiency focusing lens system. The laser cavity had a concave-plane structure. The input mirror M$_1$ ws a concave mirror with a curvature radius of 3000 mm, which was coated for high reflection (HR) at the range of 1060–1180 nm (R > 99.8%) and high transmission (HT) at 808 nm (T > 97%). The output mirror M$_2$ was a plane mirror coated for HR at 1066 nm (R > 99.8%) and partial reflection (PR) at 1097 nm (R = 99.4%), 1129 nm (R = 95.8%), 1163 nm (R = 91.7%), 1177 nm (R = 90.5%) and 1178 nm (R = 90.4%). A 3 × 3 × 20 mm^3 c-cut 0.3 at% doped Nd:YVO$_4$ crystal was used as the self-Raman medium and a 3 × 3 × 15 mm^3 c-cut 0.3 at% doped Nd:GdVO$_4$ crystal was used as the other Raman medium. Both sides of the two crystals were anti-reflection (AR) coated at 1066 nm (R < 0.2%) and 1097–1178 nm (R < 0.5%). The entrance surface of the Nd:YVO$_4$ was also HT coated at 808 nm (R < 3%). The crystals were wrapped with indium foils and mounted in water-cooled copper blocks with a water temperature maintained of 18 °C. An AO Q-switch (Gooch&Housego: I-QS041-1.5C10G-4-SO12) driven at 41 MHz center frequency with an rf power of 20 W was placed between the two Raman crystals, which was AR coated on each surface for 1064 nm (R < 0.2%). The overall laser cavity length was approximately 105 mm. The average output laser power was measured by an F150A power meter (OPHIR Company).

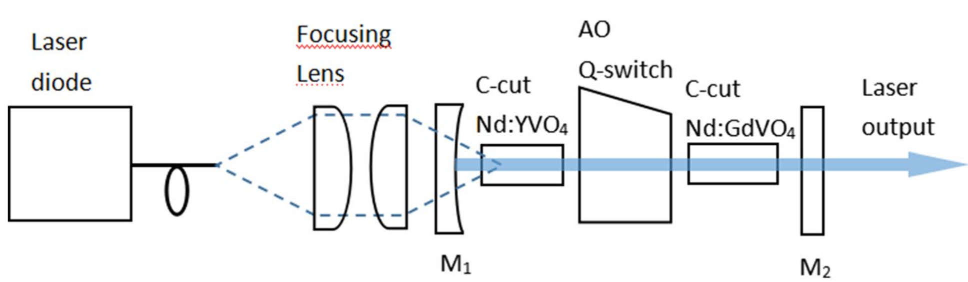

Fig.1 Experimental setup of the diode-pumped AO Q-switched c-cut Nd:YVO$_4$/GdVO$_4$ Raman laser

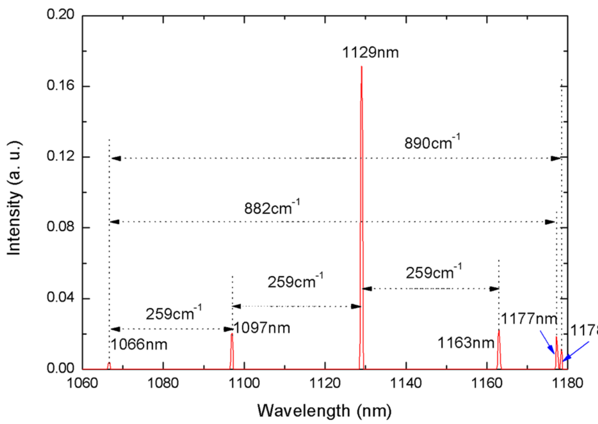

Fig. 2 Optical spectrum for the actively Q-switched c-cut Nd:YVO_4/$GdVO_4$ Raman laser at the PRF of 10 kHz with the incident pump power of 7.72 W

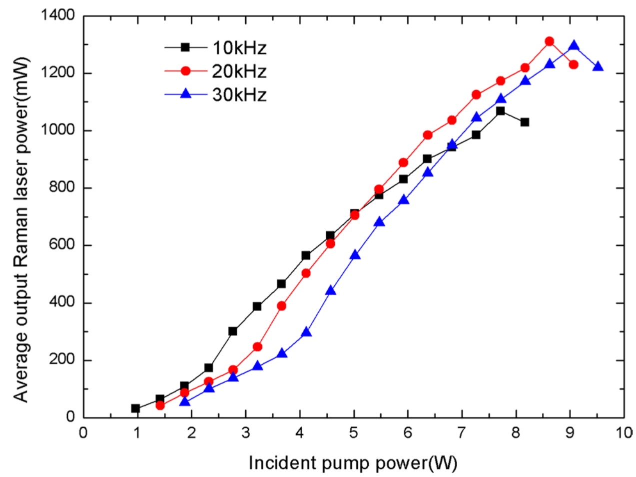

Fig. 3 Variation of the Raman laser output power with the incident pump power

3 Results and discussion

In this experiment, the Raman laser output at different Q-switch PRF was studied. The output spectrum for the actively Q-switched Raman laser was investigated with an optical spectrum analyzer (Yokogawa AQ 6373, 350–1200 nm). Figure 2 shows the output spectrum for the actively Q-switched c-cut Nd:YVO_4/$GdVO_4$ Raman laser at the PRF of 10 kHz with the incident pump power of 7.72 W. The output spectrum was composed of 1066, 1097, 1129, 1163, 1177 and 1178 nm laser lines, in which the 1066 nm laser was the fundamental light in c-cut Nd:YVO_4, the 1177 nm laser was the first-Stokes light of 882 cm^{-1} in the $GdVO_4$ crystal, and the 1178 nm laser was the first-Stokes light of 890 cm^{-1} in the Nd:YVO_4 crystal. The 1097, 1129 and 1163 nm lines were the first-, second- and third-Stokes light of 259 cm^{-1} Raman shift. In each Raman crystal, the Raman gain coefficient of 259 cm^{-1} is about half of that of the primary Raman shift(882 cm^{-1} in $GdVO_4$,890 cm^{-1} in YVO_4), so the overall gain of 1097 nm laser was close to that of 1177 and 1178 nm laser. Due to the much smaller transmission at 1097 nm than that at 1177 or 1178 nm, 1097 nm light had a much smaller oscillating threshold than those of the other two lights, the 1097 nm intracavity light intensity became strong enough and the 1129, 1163 nm lights oscillated in order with the pump power increasing at the PRF of 10 kHz. Benefited from the suitable output transmission, the1129 nm light occupied the majority of the output power.

The output power of each laser line could not be directly measured since we have no filters which is transmissive at one laser line and high reflective at the other five lines. By measuring the overall output power and the transmitted output power through filters with different transmittance curves with wavelength, the output powers at each Raman line were calculated [24]. Figure 3 gives the variation of the average output Raman laser powers at PRFs of 10, 20 and 30 kHz. The output power at 10 kHz was exceeded by those at PRFs of 20 and 30 kHz one after another and reached its highest value of 1070 mW with the incident pump power of 7.72 W. When the pump power continued to increase, it began to decline mainly due to the thermal effect in the self-Raman crystal. The output Raman laser powers at PRFs of 20 and 30 kHz reached the highest values with the incident pump powers of 8.62 and 9.07 W, respectively, and declined with the pump power increasing due to the thermal effect. The highest output power was 1310 mW at the PRF of 20 kHz, and the corresponding conversion efficiency from diode laser to Stokes light is 15.2%, which was not as high as that of the reported actively Q-switched self-Raman laser operating at the first Stokes light corresponding to the primary Raman shift [11] mainly due to the much more serious thermal effect in the laser gain medium and the much smaller Raman gain coefficients of 259 cm^{-1} shift in c-cut YVO_4 and $GdVO_4$: In YVO_4 or $GdVO_4$ crystal, the gain coefficient of the primary Raman shift along c-axis is about 60% of that along a-axis [7], and along c-axis the Raman gain coefficient of 259 cm^{-1} shift is about half of that of the primary Raman shift. The 1163 nm light was only observed when the incident pump power was large enough at the PRF of 10 kHz.

The 1097, 1177 and 1178 nm lasers were the first-Stokes lights corresponding to the Raman shifts of 259, 882 and 890 cm^{-1}, respectively. The gain rates of these three Stokes lights varied with the intracavity beam distribution determined by the cavity structure and the thermal effects in the crystals, which resulted in the variations of the output powers. Figure 4 shows the average output powers of 1097, 1177 and 1178 nm laser with respect to the incident pump power at the PRF of 10 kHz. It can be seen that 1097 nm laser arose ahead with the pump power increasing due to

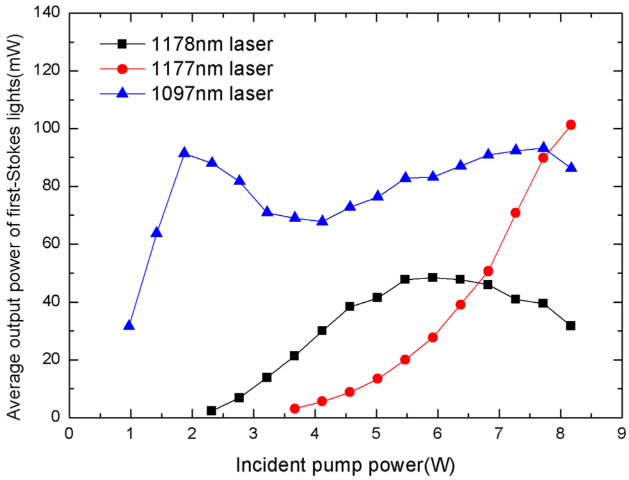

Fig. 4 Variation of the first-Stokes lights output power with the incident pump power at 10 kHz

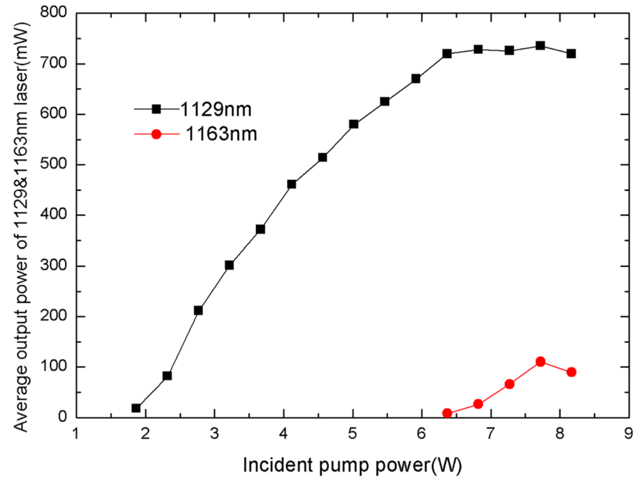

Fig. 5 Variation of the output power at 1129 and 1163 nm light output power with the incident pump power at 10 kHz

the much lower output transmission resulting in the much lower oscillating threshold. The output power of 1097 nm laser increased to 91 mW with the incident pump power of 1.87 W, and decreased to 68 mW with the incident pump power of 4.12 W due to the conversion into 1129 nm laser. Because of the stimulated Raman scattering arising in the second pulse in a Q-switch time, the 1097 nm laser increased to 93 mW with the incident pump power of 7.72 W and then decreased on account of the thermal effects. Due to the length difference between the two Raman crystals, the 1178 nm laser had a lower pump threshold than the 1177 nm laser. The pump threshold of the 1178 and 1177 nm laser were 2.32 W and 3.67 W, respectively. When the incident pump power exceeded 3.67 W, these three first-Stokes lights oscillate simultaneously. With the pump power increasing, thermal effects became strong which resulted in the beam cross section reduction in the $GdVO_4$ crystal, thus the gains of the 1177 and 1097 nm laser increased with the pump power and exceeded the 1178 nm laser, so the output power of 1178 nm decreased after increasing with the pump power and the 1177 nm laser had a more and more obvious increasing before becoming saturated due to the thermal effects in the Raman crystals. The highest output powers of 1178 and 1177 nm laser obtained at the PRF of 10 kHz were 48 and 101 mW at the incident pump power of 5.92 and 8.17 W, respectively.

The variation of the average output powers at 1129 and 1163 nm with the incident pump power at 10 kHz is showed in Fig. 5. The pump threshold of the 1129 nm laser was 1.87 W at which the output power at 1097 nm began to decrease after increasing. The growth of the output power at 1129 nm became slow with the pump power increasing while the output powers at 1177 and 1178 nm increasing, the thermal effects becoming serious and the intensity of the second pulse arising obviously. When the the output power at 1163 nm arose, the output power at 1129 nm nearly stopped increasing with the pump power. The acquired highest average output power at 1129 nm was 730 mW with the incident pump power of 7.72 W at the PRF of 10 kHz. The pump threshold for the 1163 nm laser at the PRF of 10 kHz was 6.37 W, and the average output power at 1163 nm was 115 mW with the incident pump power of 7.72 W at the PRF of 10 kHz. The highest overall average output power of the cascade Stokes light corresponding to the Raman shift of 259 cm^{-1} (1097, 1129 and 1163 nm) at the PRF of 10 kHz was 938mW with the incident pump power of 7.72 W, and the conversion efficiency from diode laser to the cascade Stokes lights corresponding to the Raman shift of 259 cm^{-1} was 12.1%. Though the relative large cavity length is a negative factor and the 1177 and 1178 nm laser competed with the 1097 nm laser, the conversion efficiency was much higher than that of the reported cascade c-cut $Nd:YVO_4$ self-Raman laser with a single 259 cm^{-1} shift [18] mainly due to the much larger active length for the SRS process of the Raman shift of 259 cm^{-1}.

The laser pulse profiles of the laser output was recorded with a digital phosphor oscilloscope (Tektronix MDO 3054, 500 MHz bandwidth, 5×10^9 samples/s) and a InGaAs Biased Detector (Thorlabs DET10 C/M, 700–1800 nm). The typical oscilloscope trace with the incident pump power of 7.72 W at the PRF of 10 kHz is shown in Fig. 6). An obvious second pulse was observed in a Q-switch time. Both the first pulse and the second pulse are composed of two pulse peak. The pulse width of the first pulse is 13.6 ns.

The beam profile was measured with a beam quality analyzer (M2-200 s-FW, Spiricon Corp.). Figure 7 shows the beam profile of the output laser with the incident pump

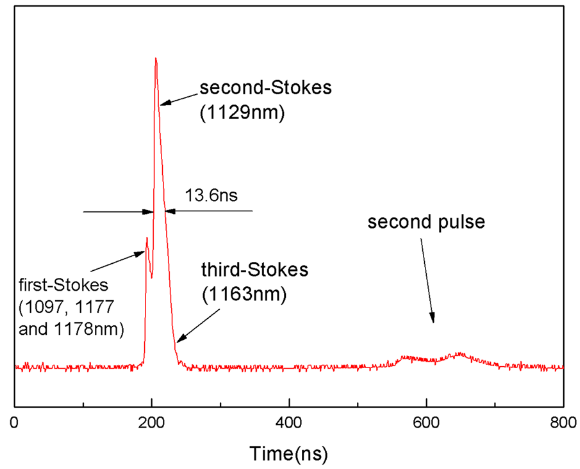

Fig. 6 The typical oscilloscope trace of the laser pulse with the incident pump power of 7.72 W at 10 kHz

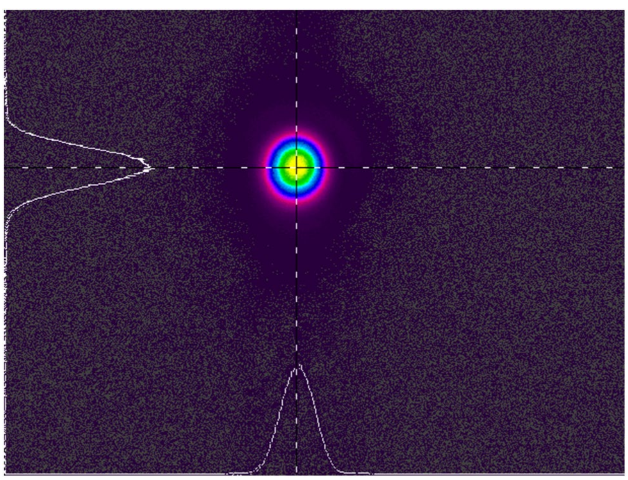

Fig. 7 The beam profile of the output laser at the incident pump power of 7.72 W and PRF of 10 kHz

power of 7.72 W at the PRF of 10 kHz. The M^2 factors of the two orthogonal directions were 1.52 and 1.36, respectively.

4 Conclusion

In summary, we demonstrated an acousto-optic Q-switched Nd:YVO_4 self-Raman and $GdVO_4$ Raman laser, in which three Raman shifts SRS took place: 890 cm^{-1} in the c-cut Nd:YVO_4 crystal, 882 cm^{-1} in the c-cut $GdVO_4$ crystal, and 259 cm^{-1} in both the two crystals. Benefited from the overall Raman gain at 259 cm^{-1} in both the c-cut $GdVO_4$ crystal and the c-cut YVO_4 crystal, simultaneous pulse oscillations of 1097, 1177 and 1178 nm have been acquired. Due to the low output transmission, the intracavity 1097 nm light density can increase high enough so that the 1129 nm laser corresponding to the second-Stokes light of the 259 cm^{-1} shift of 1066 nm laser can efficiently oscillate and occupied the majority of the laser output. The Raman laser is investigated at PRFs of 10, 20 and 30 kHz. The highest average Raman laser output of 1.31 W is obtained with the incident pump power of 8.62 W at the PRF of 20 kHz. The 1163 nm laser corresponding to the third-Stokes light of the Raman shift of 259 cm^{-1} only arose at the PRF of 10 kHz, and 115 mW average output power at 1163 nm is obtained with the incident pump power of 7.72 W.

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