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First-Stokes Wavelengths at 1175.8 and 1177.1 nm Generated in a Diode End-Pumped Nd:YVO_4/$LuVO_4$ Raman Laser *

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A diode end-pumped acousto-optic Q-switched Nd:YVO_4/$LuVO_4$ Raman laser is demonstrated. Both YVO_4 and $LuVO_4$ can work as Raman gain, and slightly different active vibration modes of both crystals can result in different first-Stokes wavelengths. The output characteristic as the Raman competition between YVO_4 and $LuVO_4$ crystals for the laser systems with both shared cavity and coupled cavity is experimentally investigated. For the shared cavity, simultaneous Raman conversion in both YVO_4 and $LuVO_4$ crystals is achieved with dual-wavelength emission at 1175.8 and 1177.1 nm. The maximum output power of 1.03 W and the conversion efficiency of 10.3% are obtained. The 0.84 W single first Stokes wavelength at 1177.1 nm with $LuVO_4$ Raman conversion is achieved with the coupled cavity. The results show that the coupled cavity with short Raman cavity can obtain a narrow pulse width. The separated laser crystal and Raman gain media with different vanadates in shared cavity have advantages in achieving dual-wavelength lasers with small frequency intervals.

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Stimulated Raman scattering has attracted much attention as an efficient frequency conversion technology.[1–4] Many kinds of crystals have been recognized as solid-state Raman gain materials.[5–8] Vanadate crystal is a typical Raman material with high Raman gain for its symmetric A1g optical vibration modes of tetrahedral VO_4^{3-} ionic groups. In 2001, the Raman properties of YVO_4 and $GdVO_4$ crystals were introduced by Kaminskii *et al.*[9] Chen realized the first self-Raman laser output in 2004.[10] Then, the Raman lasers based on vanadate crystals have been well studied.[11–16] In 2008, Kaminskii *et al.* also introduced the $\chi(3)$-nonlinear-laser manifestations of $LuVO_4$ crystal,[17] and reported its self-Raman laser output in the next year.[18] The 120 mW first-Stokes light has been obtained with the conversion efficiency of about 5%. Recently, the high quality $LuVO_4$ crystal growth and its Raman laser investigation has also attracted increasing attention.[19–22] Lu *et al.* and Tan *et al.* reported the intracavity frequency-doubled and sum-frequency mixing in a self-Raman Nd:$LuVO_4$ laser, separately.[23,24]

In addition to vanadate self-Raman laser, the Raman operation with separated laser crystal and Raman gain media also has advantage of simultaneously optimizing the fundamental laser generation and Raman operation.[25–29] Su *et al.* also reported a power scale-up Nd:YVO_4 Raman laser with a pure YVO_4 crystal as a Raman shifter by optimizing Raman crystal position.[30] Up to date, most $LuVO_4$ Raman laser reports were focused on Nd:$LuVO_4$ self-Raman operation. In this Letter, a pure $LuVO_4$ crystal Raman laser derived by an acousto-optic Q-switched Nd:YVO_4 crystal laser is investigated. The Raman competition between YVO_4 crystal and $LuVO_4$ crystal for both shared cavity and coupled cavity is studied. The slightly different active vibration modes of both crystals result in different first-Stokes wavelengths. Dual wavelengths at 1175.8 nm and 1177.1 nm are achieved in the shared cavity, and single wavelength at 1177.1 nm is obtained in the coupled cavity. The dual-wavelength laser with two closely spaced Stokes wavelengths may have potential applications in laser Doppler velocimeters[31,32] and terahertz generation.[33]

Both YVO_4 and $LuVO_4$ crystals are excellent vanadate Raman crystals with strong stimulated Raman scattering active vibration modes around 890 and 900 cm^{-1}. Therefore, their first-Stokes wavelength converted from the 1.06 μm fundamental wavelength of Nd^{3+} doped crystal laser will be located at 1.18 μm with slight difference on spectrum. Kaminskii *et al.* reported their Raman gain coefficient greater than 4.5 cm/GW[9] and 3.2 cm/GW.[17] The experimental setup of the Nd:YVO_4/$LuVO_4$ Raman laser with a linear cavity is schematically shown in Fig. 1.

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An a-cut pure $LuVO_4$ crystal with $3\times3\times15\,mm^3$ in size was used as Raman crystal and derived by an acousto-optic Q-switched Nd:YVO_4 crystal laser. A fiber-coupled laser diode with a fiber core diameter of 200 μm and a numerical aperture of 0.22 was employed to pump an a-cut Nd:YVO_4 crystal, and the pump beam was re-imaged into a spot size of 320 μm in diameter by a pair of lenses with focal lengths of 50 mm and 80 mm. The Nd:YVO_4 crystal with 0.3 at.% Nd^{3+} doped and $3\times3\times10\,mm^3$ in size was wrapped with indium foil and mounted tightly in a 18℃ water-cooled copper heat sink. Both end-faces of Nd:YVO_4 crystal and $LuVO_4$ crystal were anti-reflection (AR) coated for the pump wavelength at 808 nm, fundamental wavelength at 1.06 μm and Stokes wavelength at 1.18 μm. A 30-mm-long acousto-optic Q-switcher (AO, Gooch & Housego Co.) driven at a 40 MHz central frequency with 20 W of radio frequency power was seated after Nd:YVO_4 crystal for Q-switching operation.

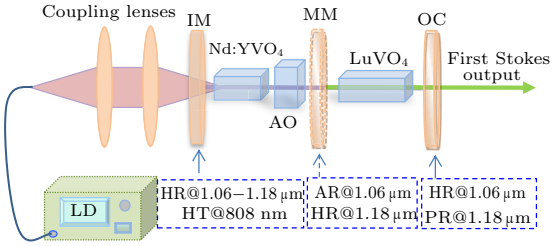

Fig. 1. Experimental arrangement of the diode end-pumped Q-switched Nd:YVO_4/$LuVO_4$ Raman laser. IM: pump input mirror; MM: additional middle mirror; OC: laser output coupler; AO: acousto-optic Q-switcher; LD: laser diode.

In our experiment, fundamental laser and Raman laser shared cavity (without additional middle mirror MM in Fig. 1), and coupled cavity (with MM included in Fig. 1) were designed for comparison. The pump input mirror IM was high-transmission (HT, $T > 95\%$) coated at 808 nm and high-reflection (HR, $R > 99.9\%$) coated from 1.06 to 1.18 μm. The laser output coupler OC was HR ($R > 99.9\%$) coated at 1.06 μm and partial-reflection (PR, $R = 97.5\%$) at 1.18 μm, and both plane and concave (radius of curvature 500 mm) mirrors were used for comparison. The fundamental and Raman oscillation could share the same cavity, consisting of an plane input mirror IM and an output coupler OC with a total cavity length of 75 mm for the shared cavity. For the coupled cavity, we only inserted an additional mirror MM (HT, $T > 98\%$ at 1.06 μm and HR, $R > 99.9\%$ at 1.18 μm) between the Q-switcher and the $LuVO_4$ crystal with the distance between MM and OC of about 30 mm. Therefore, the fundamental cavity formed by IM and OC, while the Raman cavity formed by MM and OC. The cavity length was kept the same as that for the shared cavity.

First, the laser output characteristics with the shared cavity were studied. Both plane and concave (radius of curvature 500 mm) mirrors were used as output coupler OC for comparison. Plane IM and plane OC formed a plane-plane cavity, while plane IM and concave OC formed a plane-concave cavity. The pulse frequency repetition of acousto-optic Q-switcher was optimized at 60 kHz. Figure 2 shows the average output power versus the incident pump power for both the plane-concave cavity and the plane-plane cavity. The Raman laser thresholds were around 6 W and 7 W for the plane-concave cavity and the plane-plane cavity, respectively. The maximum average output power up to 1.03 W for the plane-concave cavity was achieved under an incident pump power of 10 W, with the corresponding conversion efficiency of 10.3%. On the contrast, only 0.41 W average output power was obtained for plane-plane cavity at the same incident pump power. The output spectra were measured by a grating monochromater (model Omni-λ 500 with the resolution of 0.05 nm, ZOLIX). Dual-wavelength outputs with the central wavelengths 1175.8 nm and 1177.1 nm and line widths of about 0.35 nm were detected for both the cavities, as displayed in the inset of Fig. 2.

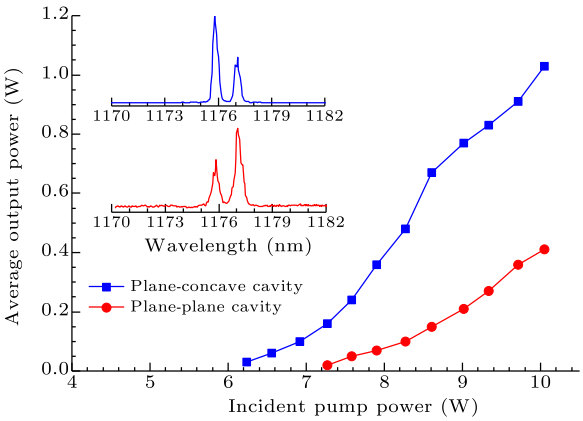

Fig. 2. Average output power versus incident pump power for both the plane-concave cavity and the plane-plane cavity with the shared cavity. The inset shows the output laser spectra.

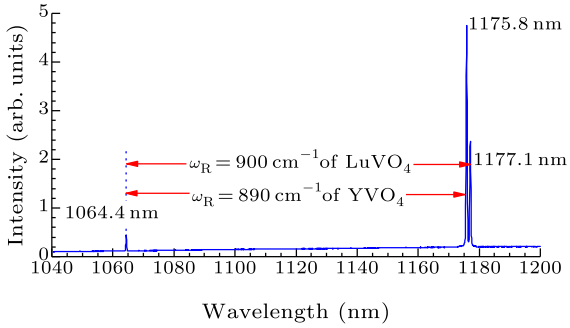

Fig. 3. Measured laser output spectra for the plane-concave cavity.

Figure 3 shows the measured laser output spectra

scanned from 1040 to 1200 nm for the plane-concave cavity. This indicates that Raman conversions in both the YVO_4 crystal and the $LuVO_4$ crystal with Raman shifts of 890 and 900 cm^{-1} were achieved at the same time, respectively. The relative intensity of 1175.8 nm line was higher than that of 1177.1 nm wavelength in the plane-concave cavity. However, the relative intensity of 1175.8 nm wavelength was lower than that of 1177.1 nm wavelength in the plane-plane cavity.

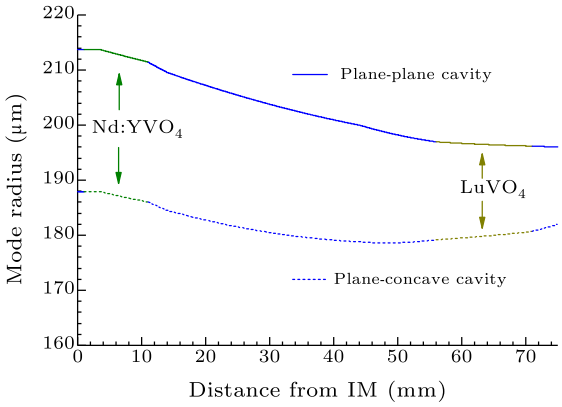

Fig. 4. Simulated cavity mode in the cavity between IM and OC with the thermal lens focal length 30 cm.

The relative intensity was mainly caused by the Raman gain of both the Raman crystals. The different relative intensities between two cavities may be caused by fundamental laser power density difference on the Nd:YVO_4 crystal and the $LuVO_4$ crystal for both the plane-concave cavity and the plane-plane cavity. According to the experimental setup, we simulated the fundamental cavity mode in the cavity between IM and OC when the thermal lens focal length was 30 cm, and the results are shown in Fig. 4. The plane-plane cavity owns larger cavity mode radius compared to the plane-concave cavity. The mode radius on the $LuVO_4$ crystal is smaller than that on the Nd:YVO_4 crystal, and the difference is much larger in the plane-plane cavity which resulted in the first-Stokes at 1177.1 nm converted by the $LuVO_4$ crystal with more intensity than 1175.8 nm line converted by the Nd:YVO_4 crystal. Therefore, the relative intensity between both Stokes lines depends not only on their Raman gain coefficient but also on the cavity mode on both crystals which can vary with the radius of curvature of cavity mirrors.

Then, the plane-concave cavity with the coupled cavity was also studied. A plane mirror MM with HT coated at 1.06 μm and HR coated at 1.18 μm was inserted between the Q-switcher and the $LuVO_4$ crystal. In this experiment, we also found the Raman competition between the YVO_4 crystal and the $LuVO_4$ crystal. MM and OC constructed a plane-concave Raman cavity for $LuVO_4$ Raman operation, however, IM and MM could also construct a plane-plane Raman cavity for Nd:YVO_4 self-Raman operation. The plane-concave cavity was much easier to realize the Raman operation as its lower sensitivity to misalignment compared to the plane-plane cavity. The first-Stokes wavelength at 1177.1 nm converted in the $LuVO_4$ crystal with its plane-concave cavity was achieved firstly when the additional middle mirror MM was slightly tilted relative to the input mirror IM. The $LuVO_4$ Raman operation in the cavity formed by MM and OC could transform into the Nd:YVO_4 self-Raman operation in the cavity formed by IM and MM while the additional middle mirror MM was well aligned and resulted in lower first Stokes loss of Nd:YVO_4 self-Raman. Because both Nd:YVO_4 self-Raman cavity mirrors IM and MM were HR coated at the first Stokes wavelength, the output power of the first-Stokes at 1177.1 nm has a sudden change from the maximum value into zero when the first Stokes wavelength at 1175.8 nm was generated in the Nd:YVO_4 crystal.

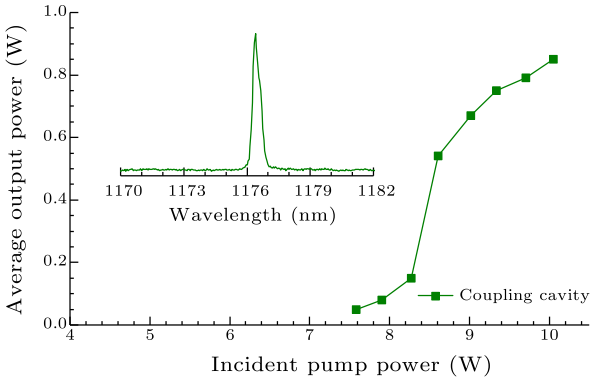

Fig. 5. Total output power versus incident pump power for coupled cavity configuration. The inset shows the pulse width and laser spectra.

Figure 5 shows its output power characteristics and the output laser spectrum. The output power was optimized under the incident pump power of 10 W. Maximum output power of 0.85 W and conversion efficiency of about 8.5% were achieved. The misalignment of laser cavity for $LuVO_4$ Raman operation also results in much higher threshold in Fig. 5 compared to that using the shared cavity in Fig. 2. Therefore, the coupled cavity was not optimized for lacking of suitable input mirror. If the Nd:YVO_4 self-Raman can be inhibited using an input mirror IM with high transmission at 1175.8 nm, the output power of $LuVO_4$ Raman laser could be further improved.

The temporal pulse profiles for the first-Stokes output with both shared cavity and coupled cavity were measured. The temporal pulse profile was recorded by an InGaAs free-space photo detector (model DET08C, Thorlabs), and displayed on a 500 MHz oscilloscope. Both temporal pulse profiles measured at an incident pump power of 10 W are shown in Fig. 6. Though the laser system with coupled cavity was not well opti-

mized for $LuVO_4$ Raman laser output, its pulse width was still much narrower than that using the shared cavity. Pulse widths of about 19 and 11 ns were measured for the shared cavity and the coupled cavity, respectively. Therefore, the short Raman cavity with high first-Stokes density for the coupled cavity could result in narrow pulse. We also investigated the polarization of the output laser using the Glan–Faucault prism. The polarization of the first Stokes converted in both the Nd:YVO_4 and $LuVO_4$ crystals was the same as the fundamental laser parallel to the *c*-axis of the Nd:YVO_4 crystal.

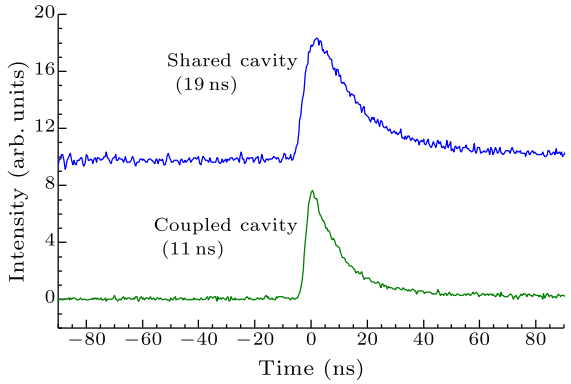

Fig. 6. Temporal pulse profile for laser output with shared and coupled cavities at an incident pump power of 10 W.

In conclusion, we have investigated the output characteristics of the diode end-pumped acousto-optic Q-switched Nd:YVO_4/$LuVO_4$ Raman laser. Both YVO_4 and $LuVO_4$ have a great Raman gain and the slightly different active vibration modes of both crystals can result in different first-Stokes wavelengths. The Raman competition between the YVO_4 and $LuVO_4$ crystals for both the shared cavity and the coupled cavity is experimentally investigated. For the shared cavity, simultaneous Raman conversions in both the YVO_4 and $LuVO_4$ crystals can be obtained with dual-wavelength output at 1175.8 nm and 1177.1 nm. The relative intensity between both Stokes lines depends not only on their Raman gain coefficient but also on the cavity mode on both the crystals, which can vary with the radius of curvature of cavity mirrors. In our experiment, the maximum output power up to 1.03 W for the plane-concave cavity is achieved with the corresponding conversion efficiency of 10.3%. For the coupled cavity, 0.85 W single first Stokes wavelength at 1177.1 nm converted in the $LuVO_4$ crystal is obtained. The further improvement of output power is hindered because of the Nd:YVO_4 self-Raman operation. The coupled cavity with a short Raman cavity can obtain narrower pulse width compared to the shared cavity. The separated laser crystal and Raman gain media with different vanadates in a shared cavity has advantages in achieving dual-wavelength lasers with small frequency intervals.

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