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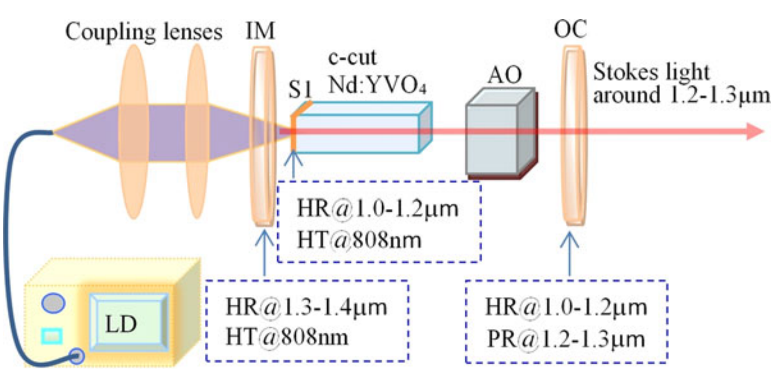

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Cascaded Self-Raman Laser Emitting Around 1.2–1.3 μm Based on a c-cut Nd:YVO_4 Crystal

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Abstract: An acousto-optic Q-switched self-Raman laser emitting around 1.2–1.3 μm based on cascaded conversion with the Raman shifts of 259 and 890 cm^{-1} was demonstrated in a c-cut Nd:YVO_4 crystal. The laser starts with single Stokes emission at 1215 nm. As the incident pump power is increased, Stokes emissions at 1255 and 1316 nm also appear in sequence. When the incident pump power reaches 17.1 W and the pulse repetition frequency is set at 10 kHz, multi-Stokes output is obtained, and the average output power of the laser is 1.02 W, corresponding to a slope efficiency of 9.1%. The multi-Stokes laser output has a pulsewidth of 5.2 ns. Therefore, self-Raman laser lines were enriched with the participation of small Stokes shift of 259 cm^{-1} in the c-cut Nd:YVO_4 crystal.

Index Terms: Raman conversion, Nd:YVO4, 1.2–1.3 μm laser.

1. Introduction

Solid-state Raman conversion is proved an efficient way of enriching laser wavelengths and has been widely investigated in recent years [1]. Different crystals, such as the vanadates [2]–[6], and tungstates [7]–[10], were used as the Raman crystals due to their large Raman gain coefficient. Some Raman crystals could be doped with rare earth ions such as the Nd^{3+} and Yb^{3+}. They are also laser gain media, allowing self-Raman generation under the laser operation. Nd:YVO_4 crystal, as a representative self-Raman material, has attracted growing attention due to its capability of

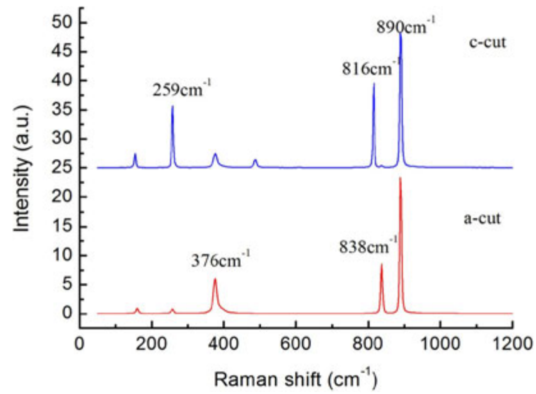

Fig. 1. Spontaneous Raman scattering spectra with Z(XX)Z and X(ZZ)X Raman configurations in the c-cut and a-cut YVO_4 crystals, respectively.

generating new infrared and visible wavelength laser emissions. YVO_4 and $GdVO_4$ are two typical vanadate crystals. They were predicted as Raman active materials by Kaminskii *et al.* [11].

Self-Raman laser based on the Nd:YVO_4 and Nd:$GdVO_4$ crystals were first demonstrated by Chen [12]. The first-Stokes self-Raman operation [13]–[15] and frequency mixing under existence of another non-linear crystals [16]–[19] were widely studied. A diode-to-visible conversion efficiency up to 30% was achieved in the second-harmonic generation of a YVO_4/Nd:YVO_4/YVO_4 composite crystal self-Raman laser [20]. Recently, Chen *et al.* further reported 2.4 W second-Stokes emission at 1313 nm with a conversion efficiency of 16% [21], and Du *et al.* reported 0.99 W second-Stokes at 1764 nm with a conversion efficiency of 2.9% [22]. Both the second-order Stokes emissions were generated in an a-cut YVO_4/Nd:YVO_4/YVO_4 composite crystal self-Raman laser. Continuous-wave self-Raman emissions at the wavelengths of 1109 nm, 1158 nm and 1231 nm were also achieved in an a-cut Nd:YVO_4 laser based on the Raman shifts of 893 and 379 cm^{-1} [23]. For the c-cut Nd:YVO_4 Raman, the first-Stokes emission with the Raman shift of 890 cm^{-1} and its frequency mixing of a c-cut Nd:YVO_4 Raman laser have been studied [24], [25]. Fan *et al.* and Wu *et al.* reported actively and passively Q-switched c-cut Nd:YVO_4 Raman emission at 1097 nm with the Raman shift of 259 cm^{-1}, respectively [26], [27], but its cascaded self-Raman emission around 1.2–1.3 μm has hardly been reported. In this paper, we demonstrated multi-Stokes cascaded self-Raman emissions with Raman shifts of 259 and 890 cm^{-1} in a c-cut Nd:YVO_4 Raman laser. At an incident pump power of 17.1 W, 1.02 W Stokes output was achieved over three Stokes Raman wavelengths at 1215, 1255 and 1316 nm, respectively.

2. Raman Spectra of Nd:YVO_4 Crystal

The Nd:YVO_4 crystal belongs to the crystallographic D_{4h} tetragonal space group of the zircon type. Therefore, both the laser and Raman characteristics are difference between a-cut and c-cut Nd:YVO_4 crystals. Its stimulated emission cross section (σ) strongly depends on the polarization characteristic of the transition spectral line. The cross section of the fundamental laser emission at 1064 nm of an a-cut crystal is four times higher than that of a c-cut crystal [12]. However, the smaller cross section of the c-cut crystal is usually advantageous in Q-switch operation [12], [24]. The spontaneous Raman scattering spectra of YVO_4 crystal with X(ZZ)X and Z(XX)Z Raman configurations according to Porto notations were measured by using NXR FT-Raman spectrum analyzer with the pumping polarization along c-axis and a-axis. The spectra were shown in Fig. 1. The results show that both Raman configurations in the YVO_4 crystal have different active vibration modes. The Raman gain of small vibration mode at 259 cm^{-1} of the c-cut crystal with Z(XX)Z Raman configuration is stronger than that of 376 cm^{-1}. Therefore, the c-cut Nd:YVO_4 crystal is promise for Raman operation with small vibration mode.

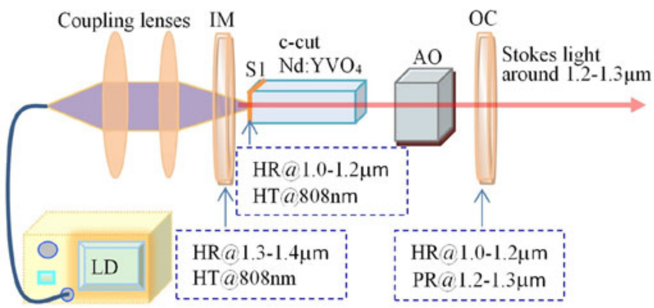

Fig. 2. Experimental arrangement of a c-cut Nd:YVO_4 cascaded self-Raman laser.

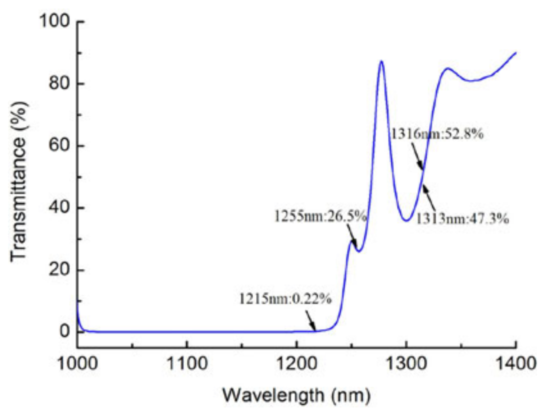

Fig. 3. Transmittance curve of the OC at the fundamental and different Stokes wavelengths obtained in this experiment.

3. Experimental Setup Design

The experimental arrangement of a c-cut Nd:YVO_4 cascaded self-Raman laser for Stokes ouput around 1.2–1.3 μm is shown in Fig. 2. The laser was actively Q-switched with an acousto-optic Q-switcher. The c-cut Nd:YVO_4 crystal (0.3-at.% Nd^{3+} doped, $3 \times 3 \times 20$ mm^3 in size) and its coating are the same as those reported before for the second-harmonic generation of its first-Stokes [26]. The crystal was wrapped with indium foil and mounted in a copper block whose temperature was actively controlled at about 20 °C. The incident facet of the crystal was high-transmission coated at pump wavelength of 808 nm, high-reflection (HR) coated at fundamental wavelength of 1066 nm and the first-Stokes wavelength of 1178 nm, and the opposite side was anti-reflection (AR) coated at both the fundamental and the first-Stokes wavelengths. Because the coating design of the Nd:YVO_4 crystal was only considered for the first-Stokes operation, the transmission at 1316 nm for the incident facet was about 70%. In order to realize high order Stokes oscillation, a mirror (IM in Fig. 2) HR coated from 1200 to 1400 nm and HT coated at 808 nm was used as the HR cavity mirror. The output coupler (OC in Fig. 2) with a radius of curvature of 320 mm was HR ($R > 99.9\%$) coated from 1000 to 1200 nm and the transmission increased from 1200 nm. The transmittance curve of the OC from 1000 to1400 nm was shown in Fig. 3. Between the Nd:YVO_4 crystal and the output coupler, a 30-mm-long acousto-optic Q-switch module (AO, Model No:QS041-10G-GHI2, Gooch & Housego Co.) was inserted for the Q-switching operation. The interaction material of AO is crystal quartz with AR coated at 1.06 μm for both surfaces. Therefore, the reflectivity was increased to about 2.5% per surface at 1316 nm, and both surfaces of the crystal quartz were set strictly perpendicular to the beam path to reduce the reflective loss. The overall cavity length was about 73 mm. A fiber coupled laser diode array operating at 808 nm (core diameter of 100 μm and

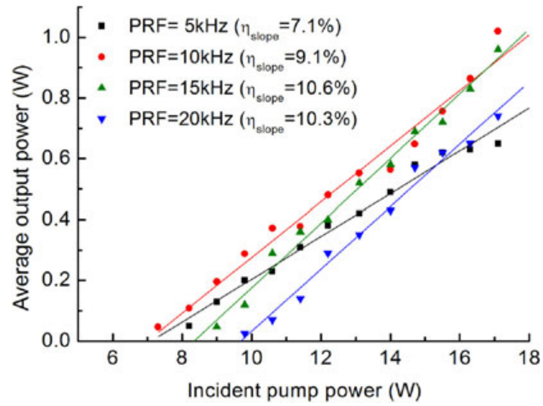

Fig. 4. Average output power versus the incident pump power at the different pulse repetition frequency (PRF).

a numerical aperture of 0.22) was used as the pumping source. The pump light without polarization was re-imaged into the Nd:YVO_4 crystal with a spot size of about 330 μm in diameter using a pair of AR coated achromatic lenses with a focal length of 30 mm and 100 mm, respectively. The average output power was measured by a thermal sensor power meter (Model: PM310D, Thorlabs Inc).

4. Results and Discussions

We optimized the laser output power by varying the pulse repetition frequency and the incident pump power. A maximum average output power of 1.02 W, with a conversion efficiency of 6.0% and slope efficiency of about 9.1%, was achieved at the pulse repetition frequency of 10 kHz and incident pump power of 17.1 W. The output power fluctuation was less than 5% in ten minutes. The Fig. 4 plots the average output power versus the incident pump power at the different pulse repetition frequency of 5, 10, 15 and 20 kHz. The threshold increased with the pulse repetition frequency except 5 kHz whose fundamental intensity was reduced too much and resulted in high threshold. The highest slope efficiency of 10.6% with respect to the incident pump power was achieved at the pulse repetition frequency of 15 kHz.

The output spectra under different pump powers at the pulse repetition frequency of 10 kHz were measured with a grating monochromater (ZOLIX, model Omni-λ500 with the resolution of 0.05 nm) and the results are displayed in Fig. 5. At the incident pump power of 17.1 W three emission wavelengths located at 1215, 1255 and 1316 nm, respectively were detected. It is well known that the Raman conversion leads to beam cleanup and significantly improvement of the Stokes components [21]; therefore, the beam center for different Stokes always well overlapped. In the Fig. 5, the spectra was measured with beams center passing the entrance slit of monochromator. The 1316 nm line is the second-order Stokes with Raman shift of 890 cm^{-1}. The ones at 1215 and 1255 nm are the Stokes light with mixed Raman shifts of 259 and 890 cm^{-1} as show in Table 1. At incident pump power of 6.5 W, only the Stokes line at 1215 nm was detected. Because the laser cavity was HR coated with only 0.22% transmission at 1215 nm, as the pump power was increased part of the 1215 nm Stokes started to convert to 1255 nm Stokes with the Raman shift of 259 cm^{-1}. At the incident pump power of 9.8 W, the second-order Stokes with the Raman shift of 890 cm^{-1} was detected at 1316 nm. At the onset of the 1316 nm oscillation the intensity of 1215 and 1255 nm emissions turned down and the Stokes at 1296 nm was not detected due to the competition between the different Raman shifts. Continuously increasing the pump power, the 1316 nm increased quickly. The higher order Stokes at 1362 nm was not appeared due to high loss induced by the output coupler with the transmittance up to 81%.

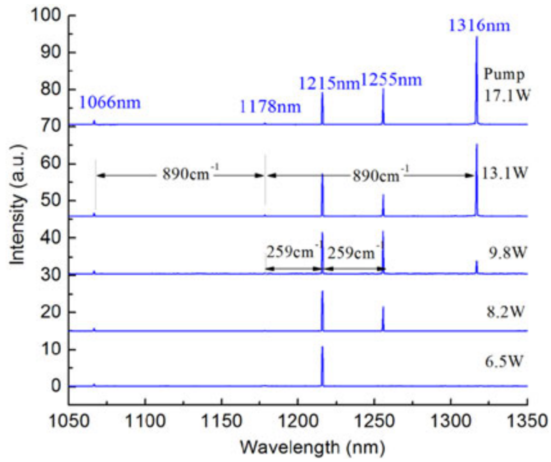

Fig. 5. Optical spectra of the Raman laser under different pump power level at the pulse repetition frequency of 10 kHz.

TABLE 1
Transmittance of the OC for Different Stokes Wavelengths Among 1.2–1.3 μm

Wavelength (nm)	Transmittance(%)	Raman contributed frequency $\omega_{R1} = 259$ cm^{-1}, $\omega_{R2} = 890$ cm^{-1}
1215	0.22%	$\omega_{R1} + \omega_{R2}$
1255	26.5%	$2\omega_{R1} + \omega_{R2}$
1296	37.2%	$3\omega_{R1} + \omega_{R2}$
1316	52.8%	$2\omega_{R2}$
1362	81.1%	$\omega_{R1} + 2\omega_{R2}$

The temporal pulse profile of the multi-Stokes output was recorded with an InGaAs free-space photo detector (5 GHz, Thorlabs) and displayed on a 500 MHz oscilloscope (Model DPO3052B). Because of the close separation of them the multi-Stokes light couldn't be separated, only temporal pulse profile of the total output was detected. Fig. 6 shows the temporal pulse profile and pulse train at the pulse repetition frequency of 10 kHz and the incident pump power of 17.1 W. The pulse width was about 5.2 ns.

In the experiment no emission related to the Raman shift of 379 cm^{-1}, which is the secondary Raman shift of the a-cut Nd:YVO_4, was detected. This also shows the difference between the c-cut and the a-cut crystals for the self-Raman operation. The multi-Stokes output was obtained in our experiment, however, the output can be optimized for special Stokes operation. According to the evolution of the output spectra shown in Fig. 5 and the transmission parameters shown in Table 1, the single Stokes at 1316 nm emission may be achieved if its threshold can be decreased through increasing the reflectivity of the output coupler. High power single Stokes at 1215 nm or dual-wavelength oscillations at 1215 and 1255 nm could be obtained by suitable design of their reflectivity. The close-spaced multi-frequency radiation produced by small Stokes shift (259 cm^{-1}) might be a potential pump source for the terahertz generation based on the nonlinear difference frequency method. Therefore, the laser wavelengths can be enriched based on the Nd:YVO_4 cascaded self-Raman with mixed Raman shifts.

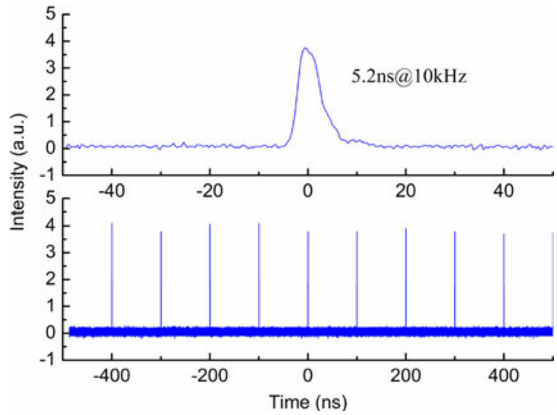

Fig. 6. Temporal pulse profile and pulse train for multi-Stokes output at the pulse repetition frequency of 10 kHz.

5. Conclusion

In summary, we demonstrated an acousto-optic Q-switched self-Raman laser with Raman shifts of 259 and 890 cm^{-1} in a c-cut Nd:YVO_4 crystal. The self-Raman laser started with single Stokes emission at 1215 nm. As the pump power was increased, Stokes emission at 1255 and 1316 nm further appeared in sequence, leading to multi-Stokes output. Under an incident pump power of 17.1 W, the maximum average output power of 1.02 W was obtained at the pulse repetition frequency of 10 kHz, the corresponding conversion efficiency and slope efficiency are 6.0% and 9.1% with respect to the incident pump power, respectively. The laser output pulse width was about 5.2 ns. According to the result, one could predict that high power single-Stokes light around 1.2–1.3 μm, as well as close-spaced dual-wavelengths radiation produced by small Stokes shift (259 cm^{-1}), could be realized by optimizing the reflectivity of the cavity mirrors, and the close-spaced dual-wavelengths radiation might be a potential pump source for the terahertz generation based on the nonlinear difference frequency method.

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