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An efficient cw laser at 560 nm by intracavity sum-frequency mixing in a self-Raman Nd:$LuVO_4$ laser

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Abstract
We report for the first time efficient continuous wave (cw) laser emission at 560 nm by sum-frequency mixing of the fundamental and first-Stokes fields generated within a Nd:$LuVO_4$ self-Raman laser. Intracavity sum-frequency mixing with LiB_3O_5 nonlinear crystal yielded 4.2 W of visible yellow emission, corresponding to an optical conversion efficiency of 22.9% with respect to the incident pump power; the output power stability over 4 h was better than 3.5%. We discuss the balance that must be maintained between the two nonlinear processes of Raman generation and sum-frequency mixing in order to obtain maximum emission at 560 nm.

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser sources in the 550–600 nm range are of interest for many applications in medicine, spectroscopy, information storage, ladar, atmosphere detection, and so on. Therefore all-solid-state lasers in the 550–600 nm range have attracted much attention in recent years. It is difficult to produce laser emission in this range efficiently by frequency-doubling Nd-doped lasers due to the absence of fundamental lasers that can operate efficiently in the range of 1100–1200 nm, so other ways have been investigated intensively. Stimulated Raman scattering (SRS) in crystals is an effective method to obtain all-solid-state yellow lasers and significant developments have been made in recent years [1, 2]. A well-known representative is Nd:YVO_4, which has been widely used in both research and commercial devices. Another vanadate crystal, Nd:$GdVO_4$, which has been confirmed to be superior to Nd:YVO_4 with respect to thermal properties, has also been investigated extensively. Recently, another member from the vanadate family, Nd:$LuVO_4$, has attracted much attention because of its larger absorption and emission cross sections than Nd:YVO_4 and Nd:$GdVO_4$ [3]. Moreover, Nd:$LuVO_4$ crystal has a high damage threshold, and it is easy to process [4]. Some papers about Nd:$LuVO_4$ lasers operating at 1.06 μm [5, 6], 1.34 μm [7] and 0.9 μm [8] have appeared recently. In 2001, Kaminskii *et al* predicted that Nd:YVO_4 and Nd:$GdVO_4$ would be promising self-Raman crystals [9], and then this was first proved by Chen [10, 11]. In recent years, efficient intracavity second-harmonic generation (SHG) of Q-switched and cw self-Raman lasers has been widely developed [12–15]. However, intracavity sum-frequency generation (SFG) of the fundamental and Stokes is still seldom reported. Quite recently, Chang *et al* have reported efficient conversion in a pulsed self-Raman Nd:YVO_4 laser with intracavity SFG, generating 1.67 W at 559 nm [16]. Pask *et al* have reported 0.77 W pulsed output at 559 nm from an intracavity Q-switched diode-pumped Nd:YAG/KGW Raman laser, with intracavity SFG in a β-BaB_2O_4 crystal [17]. Lee *et al* have reported 5.3 W cw laser operation at 559 nm, based on intracavity SFG in a Nd:$GdVO_4$ self-Raman laser. Output powers up to 5.3 W have been generated with an optical efficiency of 21% [18].

In this article we report cw laser operation at 560 nm, based on intracavity SFG of the fundamental and first-Stokes wavelengths oscillating in a $Nd:LuVO_4$ self-Raman laser. Continuous wave output powers up to 4.2 W have been generated with an optical (diode to visible) efficiency of 22.9%.

2. Theory

We take an approach after [19] to construct appropriate rate equations for the present laser. The most relevant rate equation is the one concerned with the Stokes field,

$$\frac{\mathrm{d}P_\mathrm{S}}{\mathrm{d}t} = P_\mathrm{F}P_\mathrm{S}\left(\frac{2cg_\mathrm{R}l_\mathrm{SR}}{lA_\mathrm{SR}} - \frac{ckl_\mathrm{SF}^2}{lA_\mathrm{SF}}\right) - \frac{4}{1+\lambda_F/\lambda_S} - \frac{P_\mathrm{S}}{\tau_S}, \quad (1)$$

where P_F and P_S are fundamental and Stokes intracavity powers and τ_S is the lifetime of Stokes photons. In the self-Raman and SFG crystals, A_SR and A_SF are the mode areas for the respective beams and l_SR and l_SF are the crystal lengths. l is the optical cavity length, g_R is the Raman gain coefficient, λ_F and λ_S are the fundamental and Stokes wavelengths and k denotes the strength of the sum-frequency process. The first term is the rate of generation of first-Stokes photons, the second term accounts for loss of these photons through sum-frequency mixing with the fundamental and the third term accounts for passive resonator losses. The loss of Stokes photons through the sum-frequency process is determined first by estimating the output power at the SFG wavelength $P_\mathrm{SF}^\mathrm{out}$, neglecting depletion of the fundamental and Stokes fields,

$$P_\mathrm{SF}^\mathrm{out} = \frac{4\varepsilon_0 cn^3\lambda_\mathrm{SF}^2 l_\mathrm{SF}^2 P_\mathrm{F} T_\mathrm{SF}}{\pi^2 d_\mathrm{eff}^2 A_\mathrm{SF}}, \quad (2)$$

where d_eff is the effective nonlinearity of the sum-frequency process, n is the refractive index of the SFG crystal, λ_SF is the sum-frequency wavelength and T_SF is the output-coupler transmission at the sum-frequency wavelength. This power is then extracted from the Stokes and fundamental fields in the ratio $\lambda_\mathrm{F}:\lambda_\mathrm{S}$, since equal photon numbers are extracted from the fields.

In principle, there exist laser designs for which the SFG is too strong and so prevents the buildup of the Stokes field; the first term in equation (1) can become negative, and the Stokes field will always see a net loss. Physically, this situation corresponds to Stokes photons being removed by SFG at a faster rate than they are amplified by the Raman process. According to equation (2), for relatively weaker SFG there exists a balance where the cascade to the Stokes wavelength proceeds to just the right extent so that the maximum value of $P_\mathrm{F}P_\mathrm{S}$ is achieved to maximize the SFG output.

3. Experimental setup

The experimental setup is shown schematically in figure 1. The optical pumping was carried out by using fiber-coupled

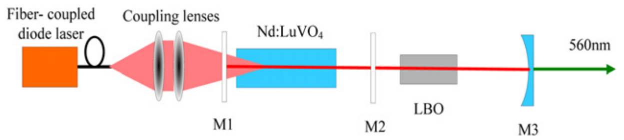

Figure 1. A schematic of the experimental setup.

(diameter 200 μm and numerical aperture $NA = 0.22$) diode lasers. The 880 nm emitting diode outputted 20 W of pump power with an emission bandwidth of 3.0 nm. An optical system made of two achromatic lenses was employed in order to image the fiber end into the $Nd:LuVO_4$ crystal. A conventional a-cut $Nd:LuVO_4$ crystal with dimensions of 4 mm × 4 mm × 15 mm and a doping concentration of 0.3 at.% was selected as the self-Raman laser medium. Both surfaces of the $Nd:LuVO_4$ crystal were coated for high transmission at 880, 1066 and 1178 nm. It was mounted in a thermoelectric cooled copper block with its surface temperature kept at about 20 °C. The Raman spectrum is dominated by an intense Raman peak at 900 cm^{-1} with a linewidth of 5 cm^{-1}. The Raman gain coefficient is reported to be greater than 3.2 cm GW^{-1} [20]. For operation on the 1066 nm line of the Nd^{3+} ion, the $LuVO_4$ host generates first-order Raman Stokes emission at 1178 nm.

A plane input mirror (M1) and a concave (radius of curvature 300 mm) output coupler (M3), both coated for high reflectivity ($R > 99.993\%$ at 1064 nm and $R > 99.995\%$ at 1176 nm) and high transmission ($T > 98\%$ at 560 nm), were used. A plane mirror (M2) coated for high transmission at 1066 and 1178 nm and high reflectivity at 560 nm was used to reflect the back propagating sum-frequency light. The geometric cavity length (M1–M3) was about 40 mm. An LBO crystal cut for type-I critical phase matching in the principal plane XY ($\theta = 90°$, $\varphi = 7.9°$ with $d_\mathrm{eff} = 0.84$ pm V^{-1}) was chosen as the nonlinear crystal due to its high anti-damage threshold (19.6 GW cm^{-2}) and much smaller walk-off angle (about 4.8 mrad). Both end faces of the LBO crystal ($3 \times 3 \times 10$ mm^3) were coated for high transmission at 1064, 1178 and 560 nm. It was wrapped with a thin indium foil and mounted in a copper holder, which was cooled by a thermoelectric cooler for active temperature control.

4. Results

The thermal lensing in the self-Raman crystal is complex and, as noted in [21], is stronger than can be accounted for by the processes of diode pumping and SRS alone. The analysis is complicated by the fact that each process deposits heat with a different spatial profile. The heat deposition associated with diode pumping is determined by the pump spot size and divergence, the absorption depth in the crystal and the overlap with the resonator mode, while the heat associated with SRS and other mechanisms is deposited over the more confined region where the Stokes photons are generated. While the thermally induced change in the refractive index distribution may be approximately parabolic over the region where heat deposition occurs, outside this region the temperature will decrease more slowly so that larger modes experience an

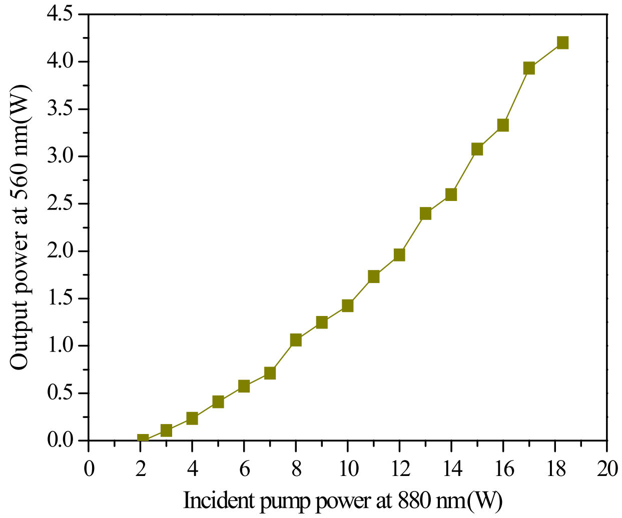

Figure 2. The dependence of the output power at 560 nm on the incident pump power.

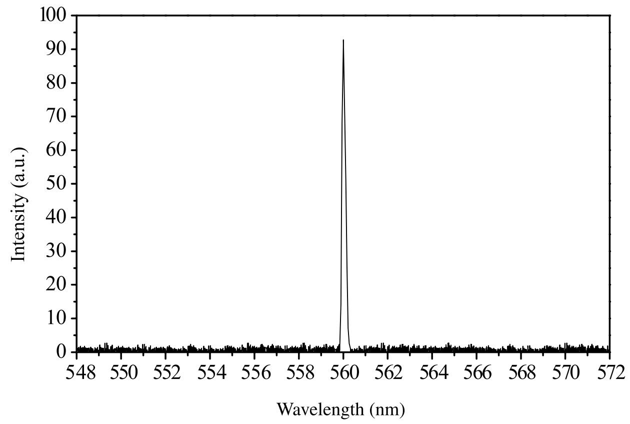

Figure 3. The optical spectrum of the yellow laser at a pump power of 18.3 W.

effectively weaker but highly aberrated thermal lens. At this stage we are unable to distinguish whether the improved power scaling and reduced beam quality at 560 nm reflect reduced thermal loading or larger fundamental and Stokes modes interacting with the strong thermal lens. The output power at 560 nm as a function of pump power was measured with a laser power meter, as shown in figure 2. The threshold of the 560 nm laser was about 4.2 W. With an incident pump power of 18.3 W, a cw output power of 4.2 W at 560 nm yellow emission was obtained, corresponding to an optical conversion efficiency of 22.9% with respect to the incident pump power. The M^2 factors were about 2.65 and 3.13 in the X and Y directions respectively measured by laser beam diagnostics. A stability of better than 3.5% for 4 h was measured by a FieldMaster-GS power meter. Figure 3 shows the measured optical spectrum for the yellow laser at a pump power of 18.3 W.

5. Conclusion

In conclusion, we have demonstrated 4.2 W cw laser emission at 560 nm with high efficiency (22.9% pump to visible) from intracavity sum-frequency mixing of fundamental and first-Stokes emission in a self-Raman $Nd:LuVO_4$ laser. The output power was limited by the available power from the pump laser diode. Inspection of the rate equations shows that there is an optimal balance between the nonlinear processes of Raman generation and sum-frequency mixing. Moreover, the output 560 nm yellow emission power could be increased further by using more efficient nonlinear crystals or by using a greater pump power.

References

[1] Pask H M, Dekker P, Mildren R P, Spence D J and Piper J A 2008 Wavelength-versatile visible and UV laser sources based on intracavity sum frequency generation of solid-state Raman lasers *Prog. Quantum Electron.* **32** 121

[2] Piper J A and Pask H M 2007 Crystalline Raman lasers *IEEE J. Sel. Top. Quantum Electron.* **13** 692

[3] Maunier C, Doualan J L, Moncorgé R, Speghini A, Bettinelli M and Cavalli E 2002 Growth, spectroscopic characterization, and laser performance of $Nd:LuVO_4$, a new infrared laser material that is suitable for diode pumping *J. Opt. Soc. Am.* B **19** 1794

[4] Zhao S *et al* 2004 Growth and characterization of the new laser crystal $Nd:LuVO_4$ *Opt. Mater.* **26** 319

[5] Yu H H, Zhang H J, Wang Z P, Wang J Y, Shao Z S and Jiang M H 2007 CW and Q-switched laser output of LD-end-pumped 1.06 μm *c*-cut $Nd:LuVO_4$ laser *Opt. Express* **15** 3206

[6] Liu J, Zhang H, Wang Z, Wang J, Zhao Z, Jiang M and Weber H 2004 Continuous-wave and pulsed laser performance of $Nd:LuVO_4$ crystal *Opt. Lett.* **29** 168

[7] Zhang H J, Liu J H, Wang J Y, Xu X G and Jiang M H 2005 Continuous-wave laser performance of $Nd:LuVO_4$ crystal operating at 1.34 μm *Appl. Opt.* **44** 7439

[8] Zhang C Y, Zhang L, Wei Z Y, Zhang C, Long Y B and Zhang Z G 2006 Diode-pumped continuous-wave $Nd:LuVO_4$ laser operating at 916 nm *Opt. Lett.* **31** 1435

[9] Kaminskii A A *et al* 2001 Tetragonal vanadates YVO_4 and $GdVO_4$–new efficient $\chi^{(3)}$-materials for Raman lasers *Opt. Commun.* **194** 201

[10] Chen Y F 2004 Compact efficient self-frequency Raman conversion in diode-pumped passively Q-switched $Nd:GdVO_4$ laser *Appl. Phys.* B **78** 685

[11] Chen Y F 2004 High-power diode-pumped actively Q-switched $Nd:YVO_4$ self-Raman laser: influence of dopant concentration *Opt. Lett.* **29** 1915

[12] Zhu H, Duan Y, Zhang G, Huang C, Wei Y, Chen W, Huang Y and Ye N 2009 Yellow-light generation of 5.7 W by intracavity doubling self-Raman laser of $YVO_4/Nd:YVO_4$ composite *Opt. Lett.* **34** 2763

[13] Zhu H, Duan Y, Zhang C, Huang C, Wei Y, Shen H, Zheng Y, Huang L and Chen Z 2009 Highly birefringent vaterite microspheres: production, characterization and applications for optical micromanipulation *Opt. Express* **17** 21544

[14] Lee A J, Pask H M, Dekker P and Piper J A 2008 High efficiency, multi-Watt CW yellow emission from an intracavity-doubled self-Raman laser using $Nd:GdVO_4$ *Opt. Express* **16** 21958

[15] Lü Y F, Zhang X H, Li S T, Xia J, Cheng W B and Xiong Z 2010 All-solid-state cw sodium D2 resonance radiation based on intracavity frequency-doubled self-Raman laser operation in double-end diffusion-bonded $Nd^{3+}:LuVO_4$ crystal *Opt. Lett.* **35** 2964

[16] Chang Y T, Chang H L, Su K W and Chen Y F 2009 High-efficiency Q-switched dual-wavelength emission at 1176 and 559 nm with intracavity Raman and sum-frequency generation *Opt. Express* **17** 11892

[17] Pask H M, Mildren R P and Piper J A 2008 Optical field dynamics in a wavelength-versatile, all-solid-state intracavity cascaded pulsed Raman laser *Appl. Phys.* B **93** 507

[18] Lee A J, Pask H M, Spence D J and Piper J A 2010 Efficient 5.3 W cw laser at 559 nm by intracavity frequency summation of fundamental and first-Stokes wavelengths in a self-Raman Nd:$GdVO_4$ laser *Opt. Lett.* **35** 682

[19] Spence D J, Dekker P and Pask H M 2007 Modeling of continuous wave intracavity Raman lasers *IEEE J. Sel. Top. Quantum Electron.* **13** 756

[20] Kaminskii A A, Rhee H, Eichler H J, Ueda K, Oka K and Shibata H 2008 New $\chi^{(3)}$-nonlinear-laser manifestations in tetragonal $LuVO_4$ crystal: more than sesqui-octave Raman-induced Stokes and anti-Stokes comb generation and cascaded self-frequency tripling *Appl. Phys.* B **93** 865

[21] Dekker P, Pask H M, Spence D J and Piper J A 2007 Continuous-wave, intracavity doubled, self-Raman laser operation in Nd:$GdVO_4$ at 586.5 nm *Opt. Express* **15** 7038