A continuous wave $SrMoO_4$ Raman laser

Haohai Yu,[1] Zhen Li,[1] Andrew J. Lee,[2,*] Jing Li,[1] Huaijin Zhang,[1] Jiyang Wang,[1] Helen M. Pask,[2] James A. Piper,[2] and Minhua Jiang[1]

[1]*State Key Laboratory of Crystal Materials and Institute of Crystal Materials, Shandong University, Jinan 250100, China*

[2]*MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia*

**Corresponding author: andrew.lee@mq.edu.au*

Received December 13, 2010; accepted January 3, 2011;
posted January 21, 2011 (Doc. ID 139573); published February 15, 2011

We demonstrate a cw, laser diode-pumped Nd:$GdVO_4$/$SrMoO_4$ crystalline Raman laser. First Stokes laser output at 1173.5 nm of 2.18 W was achieved with a diode-to-first Stokes efficiency of 8.7%. With intracavity frequency doubling in LiB_3O_5, 3.1 W of cw yellow emission at 586.8 nm was obtained with a 12.4% diode-to-yellow efficiency. The experimental results show that $SrMoO_4$ is an excellent stimulated Raman scattering gain material for high-power cw near-IR Stokes and yellow lasers.

OCIS codes: 140.3550, 190.2620, 140.3380.

Stimulated Raman scattering (SRS) is a third-order, nonlinear optical process that offers a simple and efficient means of frequency conversion [1–4]. In theory, this process can shift the wavelength of all kinds of lasers, and, when combined with frequency doubling, wavelengths spanning the UV to IR can be generated [5]. Such application of SRS and frequency doubling in crystalline materials has led to the generation of cw, solid-state laser sources with multiwatt outputs in the yellow spectral region [6], for which there are numerous applications in medicine, remote sensing, and detection.

Because SRS is an inelastic process, it generates heat within the Raman-active material; thus, the Raman-active material must have favorable thermal properties. In particular, crystalline Raman-active materials should have high thermal conductivity and a low thermo-optic coefficient (dn/dT) and thermal expansion, in addition to high Raman gain coefficients and low optical loss. Vanadates, tungstates, and molybdates, such as YVO_4, $GdVO_4$, $BaWO_4$, $SrWO_4$, $KGd(WO_4)_2$, $KLu(WO_4)_2$, $CaWO_4$, $PbMoO_4$, and $CaMoO_4$ have been identified as promising Raman crystals [6–11].

Strontium molybdate ($SrMoO_4$) has a tetragonal structure with a space group of $I41/a$, belonging to the sheelite family, and the growth of high-quality crystals using the Czochralski method has been well established [12,13]. $SrMoO_4$ has a Raman gain coefficient (5.7 cm/GW at 886 cm^{-1} for polarization along the c axis) superior to that of a number of established Raman crystals (e.g., $GdVO_4$ 4.5 cm/GW) [14,15] and similar thermal expansion (5.9×10^{-6} $°C^{-1}$ along the a axis) [16], although the thermal conductivity and thermo-optic coefficients have not been reported to the best of our knowledge. Self-Raman laser operation of Nd:$SrMoO_4$ at the first Stokes wavelength 1163 nm has previously been demonstrated in the pulsed regime at low average powers [14].

Self-Raman laser configurations have advantages in terms of miniaturization and minimizing resonator losses; however, their wavelength options are restricted due to a fixed fundamental wavelength and Raman shift. Also, because of the combined effects of quantum defect and Raman heating, they suffer significant heat loading, which can limit their output power and beam quality. When separate laser and Raman crystals are used, a diversity of output wavelengths can be achieved, and, since the thermal load is distributed across two crystals, thermal lensing is decreased and resonator stability is improved at higher incident pump powers, resulting in higher Raman laser output power.

In this Letter, we report for the first time a cw Raman laser based on crystalline $SrMoO_4$ in an intracavity configuration with a diode-pumped Nd:$GdVO_4$ laser generating the fundamental field for SRS. cw multiwatt output powers have been achieved for first Stokes Raman output and the second harmonic (586.8 nm) generated by intracavity second-harmonic generation (SHG) in lithium triborate (LBO).

The $SrMoO_4$ Raman crystal used in the experiments was grown at State Key Laboratory of Crystal Materials, Shandong University, using the Czochralski method. An a-axis $SrMoO_4$ crystal was used as the seed, and the resultant crystal was cut along the a axis (having lowest thermal expansion) with dimensions of 3 mm × 3 mm × 20.5 mm. The two end faces were polished and antireflection (AR) coated at 880, 1063, and 1173 nm. To the best of our knowledge, the thermo-optic coefficient for $SrMoO_4$ has not previously been reported, yet it is an important property predicting the thermal lensing that may occur in the Raman-active crystal. We used a He–Ne laser (633 nm) and Mach–Zehnder interferometer to observe small changes in optical path length as the crystal was heated from 25 °C to 70 °C and found that there was no net change in optical path length as the crystal temperature varied. Using the measured value for thermal expansion of $SrMoO_4$, 5.9×10^{-6} $°C^{-1}$ along the a axis reported in [16], we determined that the crystal had a corresponding thermo-optic coefficient of -11.24×10^{-6} $°C^{-1} \pm 0.3 \times 10^{-6}$ $°C^{-1}$ for 633 nm light polarized along the c axis.

The laser resonator used to investigate laser performance at the first Stokes wavelength and intracavity frequency-doubled first Stokes (yellow at 586.5 nm) output is shown in Fig. 1. The pump source used in the experiment was a 25 W, fiber-coupled laser diode (200 μm core diameter, 0.22 NA) with a central emission wavelength of 880 nm. It was focused to a 430 μm spot diameter (63 mrad half-angle divergence) and was incident on a 4 mm× 4 mm × 10 mm, a-cut, 0.3 at.% Nd:$GdVO_4$ laser crystal, which was AR coated at 880, 1063, and 1173 nm.

The $SrMoO_4$ crystal was oriented such that the fundamental and first Stokes emissions were polarized along

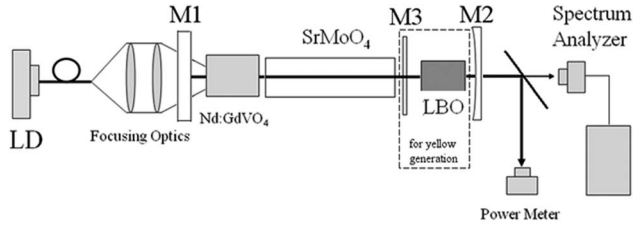

Fig. 1. Experimental configuration of the $SrMoO_4$ Raman laser.

the c axis. The crystal axes were determined by examining the spontaneous Raman spectrum, shown in Fig. 2 for the cases of laser excitation polarized along the a and c axes. The spectra were obtained using a Raman spectrometer (Enwave, Sense-I-250) with an excitation wavelength of 532 nm, spectral resolution of 6 cm^{-1}, and spectral coverage 250–4000 cm^{-1}.

The input mirror M1 was plano and high transmission (HT) coated at 880 nm and high reflecting (HR; $R > 99.994\%$) at 1063 and 1173 nm. To investigate the first Stokes Raman laser performance, the output coupler (OC) M2 was a concave mirror HR coated at 1063 and 1173 nm ($R = 99.99\%$ at 1063 nm and $R = 99.4\%$ at 1173 nm) with radius of curvature 250 mm. Mirror M3 and the LBO crystal were excluded. To investigate performance at the frequency-doubled first Stokes wavelength, M2 was replaced with a concave mirror, radius of curvature 100 mm, HR coated ($R > 99.994\%$) at 1063 and 1173 nm and HT coated at 586 nm. The mirror M3 was plano and AR coated ($R < 0.06\%$) at 1063 and 1173 nm on the side facing the $Nd:GdVO_4$ and AR coated at 1063 and 1173 nm and HR coated ($R = 98.7\%$) at 586 nm on the side facing the LBO crystal.

The LBO crystal with dimensions of 4 mm × 4 mm × 10 mm was AR coated for 586, 1063, and 1173 nm. The LBO was cut for noncritical phase matching ($\theta = 90°$, $\varphi = 0°$) and was maintained at a temperature of 44.8 °C for frequency doubling of the first Stokes wavelength. The laser and Raman crystals were wrapped with indium foil, mounted in water-cooled copper blocks, and maintained at a constant temperature of 20 °C.

Raman laser operation at the first Stokes wavelength at 1173.5 nm (corresponding to 886 cm^{-1} Stokes shift for polarization parallel to the c axis of the $SrMoO_4$ crystal) was achieved with a threshold of 2.4 W. As shown by the data in Fig. 3, a maximum first Stokes power of 2.18 W was obtained for an incident pump power of 25 W, corresponding to an optical (diode to first Stokes) conversion efficiency of 8.8%. The first Stokes power was observed to saturate for incident pump powers greater than 20 W, which also correlated with an observed increase (of 12%) in the far-field diameter of the fundamental mode emitted from the resonator, indicative of strong thermal lensing within the laser and Raman crystals at high incident pump powers [17].

The laser emission spectrum was examined (using a high-resolution Ocean Optics fiber-coupled spectrometer) for any evidence of self-Raman generation in the $Nd:GdVO_4$ crystal, which would occur at the nearby wavelength of 1173.0 nm and would be in competition with the $SrMoO_4$ Stokes line. No self-Raman shifting by the $Nd:GdVO_4$ was observed: this is because of the higher Raman gain in the $SrMoO_4$ crystal resulting from a higher Raman gain coefficient, longer crystal length, and smaller mode size in the Raman crystal than in the laser crystal. We note that blue emission was observed from the $SrMoO_4$ crystal when the system was operated above the threshold for first Stokes emission. This emission peaked at 475 nm with a bandwidth of ~10 nm (FWHM); similar blue emission has been previously reported with Raman shifting in $BaWO_4$ [7], $Nd:GdVO_4$ [18], and KGW [19] crystals.

The dependence of yellow (586.8 nm) output power generated by intracavity SHG on incident diode pump power is also shown in Fig. 3. The threshold pump power for yellow output was 2 W, lower than for first Stokes operation due to the very high Q (at the first Stokes wavelength) of the resonator used for the yellow laser. A maximum yellow output power of 3.1 W was achieved for maximum incident pump power of 25 W, representing an overall diode-to-yellow optical conversion efficiency of 12.4%. We note that the yellow power scaling curve does not rollover as in the case of the first Stokes resonator, and there was no observable increase in the

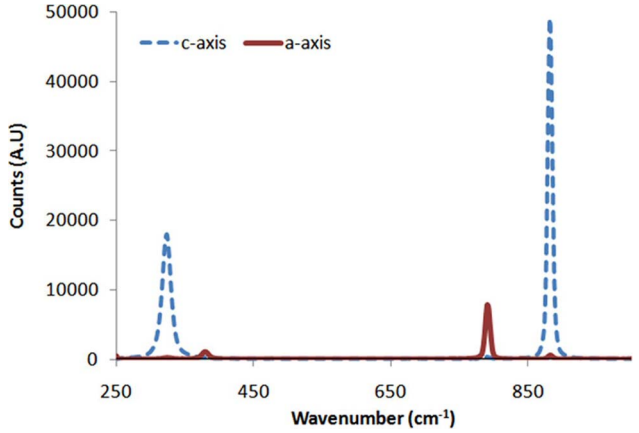

Fig. 2. (Color online) Spontaneous Raman spectrum of the $SrMoO_4$ crystal for laser excitation at 532 nm, polarized along the a and c axes.

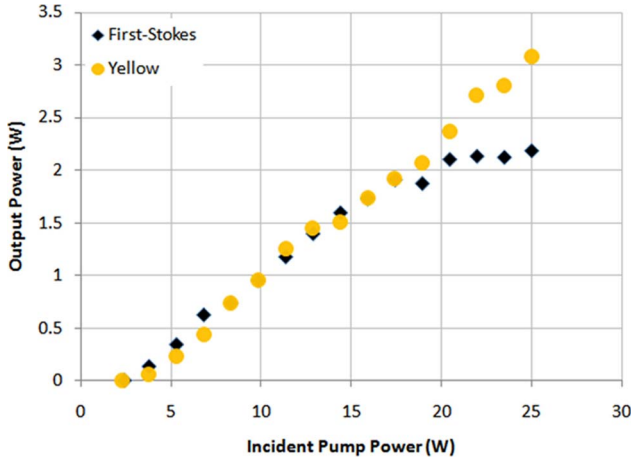

Fig. 3. (Color online) Output power versus incident pump power at the first Stokes and yellow wavelengths.

diameter of the fundamental mode through the OC. This is a result of increased resonator stability offered by the shorter radius of curvature OC. Additionally, as the thermal lens increased, the effective mode diameter in the LBO crystal decreased, which would further improve the SHG conversion efficiency.

It is valuable to compare the diode pump power thresholds and overall conversion efficiencies achieved for the first Stokes and yellow outputs with $SrMoO_4$ to those results reported for a $BaWO_4$ Raman laser using near-identical pump and resonator configurations. The $SrMoO_4$ Raman laser exhibited both a lower first Stokes (2.4 W cf. 2.5 W) and lower yellow threshold (2.0 W cf. 2.5 W) and higher overall optical conversion efficiencies, 8.8% cf. 7.8% at the first Stokes and 12.4% cf. 11% in the yellow, respectively. This was achieved using a substantially shorter Raman crystal length for $SrMoO_4$ (20.5 mm) than for $BaWO_4$ (48 mm). These comparisons suggest that the optical losses in the $SrMoO_4$ crystal are substantially lower than for the $BaWO_4$ crystal used in the experiments. In the near future, we plan to make *in situ* measurements of resonator loss and Raman gain using the technique described in [20]. There was no evidence of optical damage to the $SrMoO_4$ crystal within the range of pump powers employed in the current experiments. This, along with the lack of rollover in the yellow output power at maximum pump power, suggests that crystalline $SrMoO_4$ is well-suited for medium- to high-power (3–5 W) cw yellow generation.

In conclusion, we have reported the first (to our knowledge) cw $SrMoO_4$ Raman laser operating at the first Stokes and frequency-doubled first Stokes wavelengths of 1173.5 and 586.8 nm, respectively. A maximum first Stokes laser power of 2.18 W was achieved at an 8.7% optical conversion efficiency from the diode pump, and a maximum yellow output power of 3.1 W, limited by the maximum available diode pump power, was obtained at a diode-to-yellow conversion efficiency of 12.4%.

This work is supported by the National Natural Science Foundation of China (NSFC; grants 50911120021, 50672050, 50721002, 60978027), and the Commonwealth of Australia under the International Science Linkages Australia-China Special Fund Program.

References

1. P. Cerny, H. Jelinkova, P. G. Zverev, and T. T. Basiev, Prog. Quantum Electron. **28**, 113 (2004).
2. J. A. Piper and H. M. Pask, IEEE J. Sel. Top. Quantum Electron. **13**, 692 (2007).
3. G. Eckhardt, D. P. Bortfeld, and M. Geller, Appl. Phys. Lett. **3**, 137 (1963).
4. Y. F. Chen, Opt. Lett. **29**, 1251 (2004).
5. H. M. Pask, P. Dekker, R. P. Mildren, D. J. Spence, and J. A. Piper, Prog. Quantum Electron. **32**, 121 (2008).
6. A. J. Lee, D. J. Spence, J. A. Piper, and H. M. Pask, Opt. Express **18**, 20013 (2010).
7. A. J. Lee, H. M. Pask, J. A. Piper, H. J. Zhang, and J. Y. Wang, Opt. Express **18**, 5984 (2010).
8. A. A. Kaminskii, J. Dong, K. Ueda, M. Bettinelli, M. Grinberg, and D. Jaque, Laser Phys. Lett. **6**, 782 (2009).
9. Z. H. Cong, X. Y. Zhang, Q. P. Wang, Z. J. Liu, S. T. Li, X. H. Chen, X. L. Zhang, S. Z. Fan, H. J. Zhang, and X. T. Tao, Opt. Lett. **34**, 2610 (2009).
10. X. H. Chen, X. Y. Zhang, Q. P. Wang, P. Li, S. T. Li, Z. H. Cong, G. H. Jia, and C. Y. Tu, Opt. Lett. **33**, 705 (2008).
11. Y. F. Chen, Opt. Lett. **29**, 2632 (2004).
12. S. Preziosi, R. R. Soden, and L. G. Van Uitert, J. Appl. Phys. **33**, 1893 (1962).
13. S. P. S. Porto and J. F. Scott, Phys. Rev. **157**, 716 (1967).
14. T. Basiev, M. Doroshenko, L. Ivleva, I. Voronina, V. Konjushkin, V. Osiko, and S. Vasilyev, Opt. Lett. **34**, 1102 (2009).
15. A. A. Kaminskii, S. N. Bagaev, K. Ueda, K. Takaichi, and H. J. Eichler, Crystallogr. Rep. (Transl. Kristallografiya) **47**, 653 (2002).
16. X. Ma, Z. You, Z. Zhu, J. Li, B. Wu, Y. Wang, and C. Tu, J. Alloys Compd. **465**, 406 (2008).
17. P. Dekker, H. M. Pask, D. J. Spence, and J. A. Piper, Opt. Express **15**, 7038 (2007).
18. A. J. Lee, H. M. Pask, P. Dekker, and J. A. Piper, Opt. Express **16**, 21958 (2008).
19. H. P. Pask, Opt. Lett. **30**, 2454 (2005).
20. J. Lin, H. M. Pask, A. J. Lee, and D. J. Spence, Opt. Express **18**, 11530 (2010).

Optics Letters

BACK TO RESULTS

Basic Description | Other Editions/ Formats | Abstracting/ Indexing & Article Access | Publisher & Ordering Information | Advertising, Rights, Demographics | Reviews

JCR Web

Click highlighted text for a new search on that item.

Table of Contents:	Click here to view
ISSN:	0146-9592
Title:	Optics Letters Additional Title Information
Publishing Body:	Optical Society of America
Country:	United States
Status:	Active
Start Year:	1977
Frequency:	Semi-monthly
Volume Ends:	Jan - Dec
Document Type:	Journal; Academic/Scholarly
Refereed:	Yes
Abstracted / Indexed:	Yes
Media:	Print
Alternate Edition ISSN:	1539-4794
Size:	Standard
Language:	Text in English
Price:	USD 2,650 combined subscription per year domestic to institutions (Print & Online Eds.) USD 2,735 combined subscription per year in Canada to institutions (Print & Online Eds.) USD 2,840 combined subscription per year elsewhere to institutions (Print & Online Eds.) (effective 2010)
Subject:	PHYSICS - OPTICS
Dewey #:	535
LC#:	QC350
CODEN:	OPLEDP
Special Features:	Illustrations
Article Index:	Index Available
Composition:	Web, offset
Editor(s):	Alan E Willner (Editor-in-Chief)
URL:	http://www.opticsinfobase.org/ol/journal/ol/about.cfm
Description:	Covers the latest research in optical science, including atmospheric optics, quantum electronics, fourier optics, integrated optics, and fiber optics.

ADDITIONAL TITLE INFORMATION

Alternate Title:	Medline Abbreviated title: Opt Lett; Abbreviated title: O L

Back to Top

Add this item to: (select a list) + ADD

Request this title: I'd like to request this title. GO

Corrections: Submit corrections to Ulrich's about this title. GO

Publisher of this title? If yes, click GO! to contact Ulrich's about updating your title listings in the Ulrich's database. GO

Print • Download • E-mail

Back to Top