Peter Dekker, Helen M. Pask, and James A. Piper, "All-solid-state 704 mW continuous-wave yellow source based on an intracavity, frequency-doubled crystalline Raman laser," Opt. Lett. **32**, 1114-1116 (2007).

# All-solid-state 704 mW continuous-wave yellow source based on an intracavity, frequency-doubled crystalline Raman laser

**Peter Dekker, Helen M. Pask, and James A. Piper**

*Centre for Lasers and Applications, Macquarie University, Sydney, New South Wales 2109, Australia*

Received December 8, 2006; revised February 1, 2007; accepted February 6, 2007;
posted February 12, 2007 (Doc. ID 77922); published April 3, 2007

Continuous-wave operation at 588 nm of a diode-pumped Nd:GdVO$_4$ laser with intracavity Raman shifting [in KGd(WO$_4$)$_2$, KGW] and frequency-doubling (in LiB$_3$O$_5$, LBO) is reported. A maximum cw power at 588 nm of 704 mW was obtained for diode pump powers of 13.7 W. Quasi-cw yellow powers up to 1.57 W at a 50% duty cycle (to reduce thermal load in the laser crystal) indicate that power scaling to over 1 W is feasible. © 2007 Optical Society of America

*OCIS codes:* 140.3550, 190.5650, 190.2620.

There is significant current interest in continuous-wave (cw) solid-state yellow laser sources for a diverse range of applications including ophthalmology, biomedical diagnostics based on fluorescence detection, and visual displays, and several promising approaches have been reported recently. These include an extracavity, frequency-doubled, diode-pumped Yb fiber laser generating 40 mW at 575 nm with a diode–yellow conversion efficiency of 7%,[1] a 3 W, 589 nm source based on extracavity frequency doubling of the 1179 nm output of a Raman fiber laser pumped by a diode-pumped Yb fiber laser[2] (estimated overall optical efficiency ~3%), a 0.75 W, 593.5 nm laser source based on sum-frequency mixing of the 1064 and 1342 nm lines of two Nd:YVO$_4$ lasers with a diode–yellow conversion efficiency of ~11%,[3] and a frequency-doubled Nd:YAG laser generating 1.67 W cw at the somewhat shorter wavelength[4] of 556 nm (optical efficiency 10.4%). Our approach to developing all-solid-state yellow sources uses diode-end-pumped Nd$^{3+}$ lasers incorporating intracavity Raman shifting and second-harmonic generation (SHG) in crystalline materials; these devices have few components and small physical size and promise efficient, robust operation at low–medium powers (mW–W range).

Pulsed (*Q*-switched) operation of crystalline Raman lasers in the near-infrared at multiwatt powers is well established[5]; by including intracavity SHG or sum-frequency generation, visible outputs in the 530–630 nm spectral range at average powers up to 2 W have been demonstrated with high optical efficiency[6] (~8% diode-to-visible). Very recently there have been several reports of cw crystalline Raman lasers. Grabitchov *et al.*[7] reported cw Raman conversion in Ba(NO$_3$)$_2$ using an external resonator with a 514 nm Ar$^+$ laser pump source resulting in a first-Stokes power of 164 mW at 543 nm. Demidovich *et al.*[8] demonstrated a cw self-Raman laser using Nd:KGd(WO$_4$)$_2$ with first-Stokes (1181 nm) output powers of 54 mW, Orlovich *et al.*[9] cw output of 178 mW at 1177 nm based on a diode-pumped Nd:YVO$_4$ laser with an intracavity PbWO$_4$ Raman crystal, and Pask[10] 800 mW cw output on the first-Stokes line at 1176 nm from a diode-pumped Nd:YAG laser with intracavity Raman conversion in KGd(WO$_4$)$_2$ (KGW).

In this Letter we report an intracavity frequency-doubled cw Raman laser based on a diode-pumped Nd:GdVO$_4$/KGW combination generating 704 mW in the yellow at 588 nm. The Raman laser configuration is illustrated in Fig. 1. The pump source was a 30 W fiber-coupled 808 nm diode laser ($\phi$=400 $\mu$m, NA ~0.22), imaged with unity magnification through the pump mirror onto an antireflection (AR)-coated (1064–1200 nm) *a*-cut 0.3 at. % Nd:GdVO$_4$ crystal (3 mm × 3 mm × 10 mm). Quoted diode pump powers relate to powers incident on the laser crystal. Raman shifting was obtained by using a KGW crystal with dimensions of 5 mm × 5 mm × 25 mm, AR coated for the near-infrared and cut and oriented for propagation along the $N_p$ axis with the plane of polarization parallel to $N_m$. KGW was selected for its superior thermal properties, good Raman gain coefficient, and high damage threshold.[11] SHG of the 1176 nm Stokes line was obtained by using a temperature-controlled (~45 °C), 3 mm × 3 mm × 10 mm noncritically phase matched ($\theta$=90°, $\phi$=0°) LiB$_3$O$_5$ (LBO) crystal AR coated at 1064–1200 nm.

The resonator was formed by a pair of flat mirrors having high transmission at 808 and 5.88 nm and high reflectivity at 1063 and 1176 nm. Two sets of mirrors were used in the experiments. Mirror set A, for operation at the first Stokes wavelength, and also for the yellow, had coatings with 85 transmission (%T) at 808 nm, 0.09%T at 1063 nm, 0.4%T at

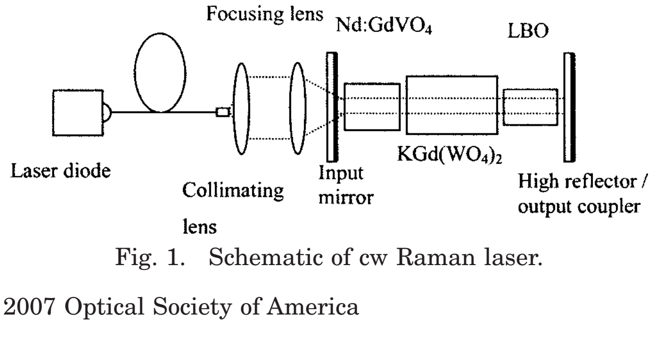

Fig. 1. Schematic of cw Raman laser.

1176 nm, and 93%T at 588 nm. Mirror set B, used to obtain the highest yellow powers, had coatings with 96%T at 808 nm, <0.006%T at 1063 nm, <0.004%T at 1176 nm, and 95%T at 588 nm. Resonator stability was achieved by way of the strong positive thermal lens in the laser crystal. (The focal length of the thermal lens formed in the Nd:$GdVO_4$ crystal with 21 W of incident pump power was estimated to be +66 mm from resonator stability measurements when operating at the fundamental wavelength only with 5% output coupling.) The resonator length was 45 mm for operation at 1176 nm (Nd:$GdVO_4$ and KGW only) and 62 mm for operation at 588 nm (LBO crystal included).

Mirror set A was used to investigate lasing at the first Stokes wavelength (1176 nm). The threshold for lasing at the fundamental occurred for 0.7 W of incident diode-pump power, and the first-Stokes Raman threshold was reached at 6.6 W of incident power. Above threshold the 1176 nm first-Stokes Raman power measured at the output mirror increased approximately linearly with incident pump power, reaching 1.56 W for an 18 W pump. Since the transmission of the input mirror was equal to that of the output mirror (0.4%T at 1176 nm), approximately 1.5 W of Raman power was also lost through the input mirror. Moreover, the low output coupler transmission at 1176 nm (0.4%) in comparison with the total round-trip losses (estimated to be around 2%) substantially limited the Raman laser output that could be obtained. Even so, this is the highest cw Raman power yet reported, and optimization of mirror coatings for first-Stokes output can be expected to result in further cw power increases, at least to the 3 W level.

Above 18 W of pump power, Raman laser operation became increasingly unstable and sensitive to alignment, with changes to spatial beam characteristics typical of an approach toward the boundary of resonator stability. At lower diode powers (<15 W), however, the Stokes output occurred in the lowest-order transverse mode, with a mode diameter some 2–3 times smaller than the highly multimode fundamental output beam. Given that the effective resonator length was only about 33 mm (the 25 mm long KGW Raman crystal has refractive index $n=2$), the thermal lens formed in the laser crystal is obviously much stronger for Raman laser operation than for operation on the fundamental alone (under which the thermal lens was measured). Although it is not yet fully understood, we attribute this largely to the increased thermal loading of the laser crystal as a result of high circulating infrared powers (estimated at ~400 W in the present case) in combination with weak ground state absorption, e.g., from residual impurity ions.[12]

Nonlinear output coupling of the Stokes optical field through SHG is particularly well suited to extracting the Stokes power efficiently. Low Raman thresholds are possible (due to low passive resonator losses from the high-*Q* cavity for the Stokes optical field), while at higher circulating fundamental and Stokes powers, losses are dominated by the nonlinear conversion to visible light, coupled from the resonator through a dichroic end mirror.

Experimental studies of cw visible generation by intracavity SHG of the Raman optical field were conducted for both mirror sets A and B. Because the resonator length had to be increased to 62 mm to accommodate the LBO doubling crystal, the maximum cw incident pump power for which resonator stability could be maintained decreased to around 14 W. To explore the potential for generating higher cw yellow output powers at higher pump powers, we undertook experiments in which the diode pump was operated at a reduced (50%) duty cycle (using a mechanical chopper inserted into the pump beam path, which gave a 200 Hz square-wave pump train). The reduced thermal load in the laser crystal in this quasi-cw mode of operation permitted instantaneous pump powers up to 20 W to be achieved before the onset of resonator instability.

Figure 2 shows cw output powers (open circles) and quasi-cw output powers (filled squares) obtained in the yellow at 588 nm as a function of diode pump power incident on the laser crystal for the low-loss mirror set B. The maximum cw yellow output power was 704 mW for an incident diode pump power of 13.7 W. For operation at a 50% duty cycle, quasi-cw yellow output powers of 1.57 W (corresponding to 787 mW of average power) were obtained for an instantaneous diode pump power of 19.9 W (9.95 W of average power). Diode-to-yellow optical conversion efficiency was 5.1% for cw operation and increased markedly, to 7.9%, for quasi-cw operation.

These results strongly suggest that much higher cw output powers should be possible if the resonator is redesigned to accommodate the strong thermal lens in the laser crystal or if an alternative $Nd^{3+}$ crystal host with superior thermal properties to Nd:$GdVO_4$ is used. Improvements to the resonator design to collect the yellow propagating in the backwards as well as the forwards direction (as we have previously reported for *Q*-switched frequency-doubled Raman lasers[6]) can also be expected to bring significant increases in yellow output power. In the

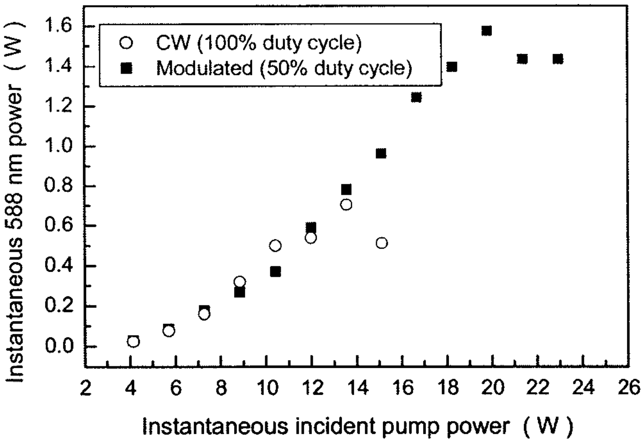

Fig. 2. Yellow (588 nm) output powers as a function of instantaneous pump power for cw and quasi-cw (50% duty cycle) pumping (mirror set B).

present resonator the yellow beam propagating back along the resonator is largely absorbed in the Nd:$GdVO_4$ laser crystal (the absorption coefficient at 588 nm was measured to be $2\ cm^{-1}$), further exacerbating thermal loading there.

Output characteristics at 588 nm for mirror sets A and B are summarized in Table 1. Mirror set B provided a cavity with much higher cavity $Q$ for both the fundamental and the Stokes optical fields, resulting in substantially lower (2.7-fold) thresholds and an approximate doubling of yellow output powers, both in fully cw and quasi-cw (50% duty cycle) operation. We estimate that the total round-trip resonator losses (including output coupling, scattering, ground state absorption) at the fundamental and Stokes wavelengths are around 1% and 2%, respectively, for mirror set A, and around 1% at both wavelengths for mirror set B. Although true resonator losses are difficult to determine for such short resonators where the elements are aligned at near-normal incidence, it is clear that large increases in the generated yellow power are achieved for relatively small reductions in round-trip losses. We therefore expect further increases in output power if the resonator losses can be reduced further, e.g., by using super-AR coatings or applying high-reflection coatings directly to the laser and LBO crystals or by diffusion bonding of crystals.

The spectral characteristics of the cw output were investigated by using an optical spectrum analyzer with 0.06 nm resolution, and the (time-averaged) yellow spectrum was found to consist of a single peak at 588 nm with <0.1 nm bandwidth. There was some structure apparent in the fundamental (1063 nm) spectrum with an ~1 nm bandwidth; this spectrum was most stable when the circulating fundamental power was strongly depleted by Raman conversion. We note that corresponding wavelength variations of the Stokes output are well within the wavelength acceptance bandwidth of the LBO (~20 nm cm).

The cw yellow output had measured $M^2$ values in the range 2.1–2.5 at maximum power. The fundamental (at 1063 nm) was observed to be highly multimode, having a much higher measured $M^2$, around 7.0. The substantially lower $M^2$ value for the yellow than the fundamental beam is strong evidence of Raman beam cleanup.[10] At maximum output power, the amplitude stability of the yellow was measured (with a fast, nanosecond photodiode) to be 9.5% ($2\sigma$/av), while the long-term power stability (measured over 10 min) was 6.5%. We attribute a significant portion of the observed amplitude instability to competition for Raman gain between a number of transverse modes.

**Table 1. Summary of Threshold Pump Power and Maximum 588 nm Output Powers**

| Laser Performance | Mirror Set A | Mirror Set B |
|---|---|---|
| Raman threshold (cw) | 6.9 W | 2.5 W |
| Maximum cw 588 nm output | 320 mW | 704 mW |
| (Incident cw pump power) | (17.6 W) | (13.7 W) |
| Raman threshold (quasi-cw) | 7.0 W | 2.5 W |
| Max quasi-cw 588 nm output | 692 mW | 1.57 W |
| (Incident cw pump power) | (21.6 W) | (19.9 W) |

In conclusion, we have demonstrated an all-solid-state cw visible source based on an intracavity frequency-doubled crystalline Raman laser. While we have identified a number of approaches to increasing output power and efficiency, the 704 mW cw output at 588 nm and 5.1% diode-to-yellow conversion efficiency already demonstrated are comparable with powers and efficiencies of several of the alternative technologies. Indeed, the results for quasi-cw operation show that cw yellow powers >1 W and diode-to-yellow efficiencies of ~8% are achievable. Particular advantages of all-solid-state Raman lasers for generating yellow-orange powers up to ~1 W over the competing technologies are the simplicity of the laser configuration (the three key active optical components of the present device can even be reduced to two for the case of self-Raman laser crystals), the potential to make very compact devices, and the flexibility to produce different output wavelengths through the choice of different laser and Raman materials.

H. Pask's e-mail address is hpask@ics.mq.edu.au.

## References

1. S. Sinha, C. Langrock, M. J. F. Digonnet, M. M. Fejer, and R. L. Byer, Opt. Lett. **31**, 347 (2006).
2. D. Georgiev, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Bulkov, S. V. Popov, and J. R. Taylor, Opt. Express **13**, 6772 (2005).
3. J. Janousek, S. Johansson, P. Tideraand-Lichtenberg, S. H. Wang, J. L. Mortensen, P. Buchhave, and F. Laurell, Opt. Express **13**, 1188 (2005).
4. F. Jia, Q. Zheng, Q. Xue, Y. Bu, and L. Qian, Opt. Commun. **259**, 212 (2006).
5. H. M. Pask, Prog. Quantum Electron. **27**, 3 (2003).
6. R. P. Mildren, H. M. Pask, H. Ogilvy, and J. A. Piper, Opt. Lett. **30**, 1500 (2005).
7. A. S. Grabtchikov, V. A. Lisinetskii, V. A. Orlovich, M. Schmitt, R. Maksimenka, and W. Kiefer, Opt. Lett. **29**, 2524 (2004).
8. A. A. Demidovich, A. S. Grabtchikov, V. A. Lisinetskii, V. N. Burakevich, V. A. Orlovich, and W. Kiefer, Opt. Lett. **30**, 1701 (2005).
9. V. A. Orlovich, V. N. Burakevich, A. S. Grabtchikov, V. A. Lisinetskii, A. A. Demidovich, H. J. Eichler, and P. Y. Turpin, Laser Phys. Lett. **3**, 71 (2006).
10. H. M. Pask, Opt. Lett. **30**, 2454 (2005).
11. I. V. Mochalov, Opt. Eng. **36**, 1660 (1997).
12. J. C. Bienfang, W. Rudolph, P. A. Roos, L. S. Meng, and J. L. Carlsten, J. Opt. Soc. Am. B **19**, 1318 (2002).