Continuous-wave VECSEL Raman laser with tunable lime-yellow-orange output

Jipeng Lin,[1,*] Helen M. Pask,[1] David J. Spence, [1] Craig J. Hamilton,[2] and Graeme P. A. Malcolm[2]

[1]*MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney, New South Wales 2109, Australia*
[2]*M Squared Lasers Ltd, 1 Technology Terrace, Todd Campus, Maryhill Road, Glasgow, G20 0XA, Scotland*
[*]*jipeng.lin@mq.edu.au*

Abstract: We report a compact CW KGW Raman laser with intracavity nonlinear mixing, pumped by the intracavity field of a VECSEL. By temperature tuning an intracavity LBO crystal, we obtained two separate tunable emissions bands, namely 548.5 - 566 nm for sum-frequency-generation (SFG) of the fundamental and Stokes wavelengths, and 577.5 - 596 nm for second-harmonic-generation (SHG) of the Stokes wavelength. The maximum output powers for SFG and SHG were 0.8W @ 560nm and 0.52W @ 592.5nm, with corresponding diode-to-visible optical conversion efficiencies of 4.2% and 2.9%. These preliminary results show strong potential for expanding the spectral coverage of VECSEL lasers.

OCIS codes: (140.3550) Lasers, Raman; (140.7260) Vertical cavity surface emitting lasers; (140.3600) Lasers, tunable; (140.3515) Lasers, frequency doubled.

References and links

1. M. Kuznetov, "VECSEL semiconductor lasers: A path to high-power, quality beam and UV to IR wavelength by design," in *Semiconductor Disk Lasers: Physics and Technology*, O. G. Okhotnikov, ed. (Wiley Online Library, 2010), 1–71.
2. S. H. Park, J. Kim, H. Jeon, T. Sakong, S. N. Lee, S. Chae, Y. Park, C. H. Jeong, G. Y. Yeom, and Y. H. Cho, "Room-temperature GaN vertical-cavity surface-emitting laser operation in an extended cavity scheme," Appl. Phys. Lett. **83**(11), 2121–2123 (2003).
3. N. Schulz, B. Rosener, R. Moser, M. Rattunde, C. Manz, K. Kohler, and J. Wagner, "An improved active region concept for highly efficient GaSb-based optically in-well pumped vertical-external-cavity surface-emitting lasers," Appl. Phys. Lett. **93**(18), 181113 (2008).
4. T. L. Wang, Y. Kaneda, J. M. Yarborough, J. Hader, J. V. Moloney, A. Chernikov, S. Chatterjee, S. W. Koch, B. Kunert, and W. Stolz, "High-power optically pumped semiconductor laser at 1040 nm," IEEE Photon. Technol. Lett. **22**(9), 661–663 (2010).
5. M. Fallahi, F. Li, Y. Kaneda, C. Hessenius, J. Hader, H. Li, J. V. Moloney, B. Kunert, W. Stolz, and S. W. Koch, "5-W yellow laser by intracavity frequency doubling of high-power vertical-external-cavity surface-emitting laser," IEEE Photon. Technol. Lett. **20**(20), 1700–1702 (2008).
6. T. Baer, "Large-amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd: YAG lasers," J. Opt. Soc. Am. B **3**(9), 1175–1180 (1986).
7. A. Harkonen, J. Rautiainen, T. Leinonen, Y. A. Morozov, L. Orsila, M. Guina, M. Pessa, and O. G. Okhotnikov, "Intracavity sum-frequency generation in dual-wavelength semiconductor disk laser," IEEE Photon. Technol. Lett. **19**(19), 1550–1552 (2007).
8. D. J. Stothard, J. M. Hopkins, D. Burns, and M. H. Dunn, "Stable, continuous-wave, intracavity, optical parametric oscillator pumped by a semiconductor disk laser (VECSEL)," Opt. Express **17**(13), 10648–10658 (2009).
9. M. Scheller, J. M. Yarborough, J. V. Moloney, M. Fallahi, M. Koch, and S. W. Koch, "Room temperature continuous wave milliwatt terahertz source," Opt. Express **18**(26), 27112–27117 (2010).
10. D. C. Parrotta, W. Lubeigt, A. J. Kemp, D. Burns, M. D. Dawson, and J. E. Hastie, "Continuous-wave Raman laser pumped within a semiconductor disk laser cavity," Opt. Lett. **36**(7), 1083–1085 (2011).
11. D. C. Parrotta, A. J. Kemp, M. D. Dawson, and J. E. Hastie, "Tunable continuous-wave diamond Raman laser," Opt. Express **19**(24), 24165–24170 (2011).
12. A. J. Lee, D. J. Spence, J. A. Piper, and H. M. Pask, "A wavelength-versatile, continuous-wave, self-Raman solid-state laser operating in the visible," Opt. Express **18**(19), 20013–20018 (2010).

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13. A. J. Lee, H. M. Pask, P. Dekker, and J. A. Piper, "High efficiency, multi-Watt CW yellow emission from an intracavity-doubled self-Raman laser using Nd:$GdVO_4$.," Opt. Express **16**(26), 21958–21963 (2008).
14. T. D. Raymond, W. J. Alford, M. H. Crawford, and A. A. Allerman, "Intracavity frequency doubling of a diode-pumped external-cavity surface-emitting semiconductor laser," Opt. Lett. **24**(16), 1127–1129 (1999).
15. A. J. Lee, J. Lin, and H. M. Pask, "Near-infrared and orange-red emission from a continuous-wave, second-Stokes self-Raman Nd:$GdVO_4$ laser," Opt. Lett. **35**(18), 3000–3002 (2010).

1. Introduction

Optically-pumped semiconductor vertical-external-cavity surface-emitting lasers (VECSELs) have evolved rapidly during the past decade [1]. They are a very versatile type of laser, because a wide range of semiconductor materials can deliver a selection of emission wavelengths and tunability, and because the open cavity design enables easy integration of intracavity components and nonlinear processes. The direct emission from VECSELs has ranged from violet at 390 nm [2] to mid-infrared [3], and output powers up to 40 W output power have been reported to date [4].

Intracavity second harmonic generation (SHG) is well established as a means of substantially expanding the spectral coverage of VECSELs, and the yellow region is one that has been particularly targeted [5]. Intracavity-doubled VECSELs also benefit from the short carrier life time in semiconductors (typically a few ns) and the lack of spatial hole burning in the periodic gain structure, and therefore their output has low amplitude noise. This is in contrast to the so-called "green problem" [6], in which longitudinal-mode competition often causes strong intensity noise in intracavity doubled conventional solid-state lasers. Other intracavity second-order nonlinear processes that have been reported for VECSELs are sum-frequency generation [7], optical parametric oscillation [8] and difference frequency generation [9].

Recently, Parrotta *et al.* have demonstrated a VECSEL-pumped intracavity CW Raman laser [10], in a new approach to combine the tunability from VECSELs with wavelength shifting from stimulated Raman scattering (SRS). They pumped a KGW crystal within a VECSEL cavity and shifted the fundamental emission wavelength around 1.06 μm to 1.14 μm, with a tunable range from 1133 - 1157 nm. Subsequently they used another Raman crystal, CVD-diamond to replace KGW and achieved up to 1.3 W Stokes emissions at 1227nm, with tunability between 1217 and 1244 nm [11].

In this paper, we propose and demonstrate a novel scheme for frequency extension of VECSELs enabling tunable output over two or more wavelength bands. It is the first time to our knowledge that intracavity SHG or SFG has been implemented in a VECSEL Raman laser. Intracavity SRS enables the generation of a first Stokes wavelength as in [10, 11], and it can then be converted via intracavity SFG of fundamental and first-Stokes or SHG of first-Stokes to two new visible wavelength bands. Of course these are in addition to the band that can be generated by SHG of the fundamental wavelength. The scheme could also be extended to include generation of the second Stokes, and thus an additional two visible bands. The separation of the bands can be managed by selecting a Raman crystal with an appropriate Raman shift. The scheme builds on previous work on wavelength-selectable crystalline Raman lasers [12] in which multi-Watt output powers were demonstrated at three discrete wavelengths: 532 nm, 559 nm and 586 nm by intracavity SFG and SHG in a Nd:$GdVO_4$ self-Raman laser. In contrast, the tunability of the VECSEL fundamental wavelength enables several *tunable* bands to be generated, rather than several discrete wavelengths. Here, we have demonstrated this scheme using a VECSEL with a fundamental wavelength tunable from 1040 - 1076 nm, a KGW crystal that generated Stokes emission at 1148 - 1192 nm via SRS, and a temperature-tuned LBO crystal for SFG and SHG. Two separate tunable visible bands were achieved, namely 548.5 - 566 nm for SFG of the fundamental and Stokes wavelengths, and 577.5 - 596 nm for SHG of Stokes wavelength. The SHG of fundamental wavelength was not demonstrated here due to the high temperature requirement for LBO (130 - 150 °C), which was hard to reach with the available temperature controller. The maximum powers achieved were 0.8W @ 560nm for SFG and 0.52W @ 592.5nm for SHG, with optical conversion efficiencies (diode to visible) of 4.2% and 2.9% and slope efficiencies of 5.9% and 4.5% respectively.

2. Experimental setup

The optical arrangement is shown in Fig. 1. The semiconductor disk (SD) was GaAs based with a strained InGaAs quantum well structure, and produced tunable output over the range 1040 - 1076 nm. It was contacted to a water-cooled copper mount on one side, and optically-bonded to a piece of planar uncoated 0.5 mm-thick diamond on the other for heat removal. A fiber-coupled laser diode at 808 nm (Φ = 200 µm, N.A. = 0.22) was used to pump the SD, with imaging optics to produce a pumping spot of about 150 µm radius. About 14% of the incident pump power was lost due to the reflection from the uncoated diamond, and the maximum absorbed power was 20 W which was limited by the pumping source. A 2.5 mm thick MgF birefringent filter (BF) was placed at Brewster's angle in the cavity for wavelength selection and tuning. The cavity for the fundamental laser was formed by the distributed Bragg reflector (DBR) which had high reflectivity (R>99.9%) at the fundamental wavelength, and a concave mirror (radius of curvature 150 mm) M1, with high-reflectivity (R>99.99%) at both fundamental and Stokes wavelengths. The KGW crystal was 25 mm long, cut for propagation at 45° to the N_g axis in the N_g and N_m plane and oriented so that the fundamental was polarized along the N_p axis. The crystal was placed in a rotating mount for optimising the laser output power. The Raman resonator was bounded by M1 and an intracavity flat dichroic mirror (DM) which was highly transmitting (T>99.5%) at fundamental wavelengths and highly reflecting (R>99.9%) at the Stokes wavelengths. The 10 mm long LBO crystal was cut for non-critical phase matching (NCPM) and could be temperature-tuned for intracavity SFG/SHG. The optimum cavity lengths were 75 mm and 50 mm for the fundamental and Stokes beams respectively. The TEM_{00} mode radius for the fundamental emission was 150 µm on the SD, providing a good match to the pump spot. The TEM_{00} mode radius was 180 µm for the fundamental beam and 150 µm for the Stokes beam in the KGW crystal, and 200 µm for the fundamental beam and 165 µm for the Stokes beam in the LBO crystal.

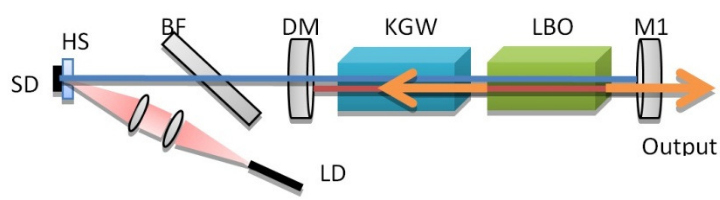

Fig. 1. Schematic of VECSEL pumped CW Raman laser. SD: semiconductor disc; HS: diamond heat-spreader; BF: birefringent filter; DM: dichroic mirror; M1: output coupler.

3. Results and discussion

We first characterized the Raman laser performance without inserting the LBO in the cavity. The KGW crystal was orientated to select the 901 cm^{-1} shift and to optimise the frequency conversion via SRS. No effort was made to optimise the output coupling of the first Stokes, since the emphasis of this paper is on generating visible output. The Stokes wavelength could be tuned from 1148 nm to 1192 nm by rotating the BF. The overall Stokes wavelength tuning range of 42 nm in this paper is larger than 24 nm in [10] and 27 nm in [11]. The output power vs. wavelength is shown in the inset of Fig. 2, when absorbing 20 W of pump power. The tuning range was continuous, in contrast to the modulated tuning curve reported in [10], and this is attributed to careful orientation so that the polarisation of the fundamental and Stokes fields were aligned with the N_p axis of the biaxial KGW crystal.

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The highest powers were obtained at 1184 nm, for which laser performance is shown in Fig. 2. The SRS threshold was 5.7 W of absorbed pump power, similar to 5.6 W in [10] and 5.3 W in [11]. Although more sophisticated cavity designs in [10, 11] provided a much smaller beam spot size in the Raman crystal, the use of fewer cavity mirrors, and each having higher reflectivity at the Stokes wavelength in our compact cavity equalized the SRS thresholds. The intracavity optical power was estimated by detecting the leaking laser output from M1. From the transmission of the output coupler, we estimate that the residual fundamental power which was measured to be clamped at ~20 mW above the SRS threshold, corresponded to ~400 W intracavity circulating power. Similarly, we estimate that the maximum output power of 150 mW corresponded to ~3000 W intracavity circulating Stokes power.

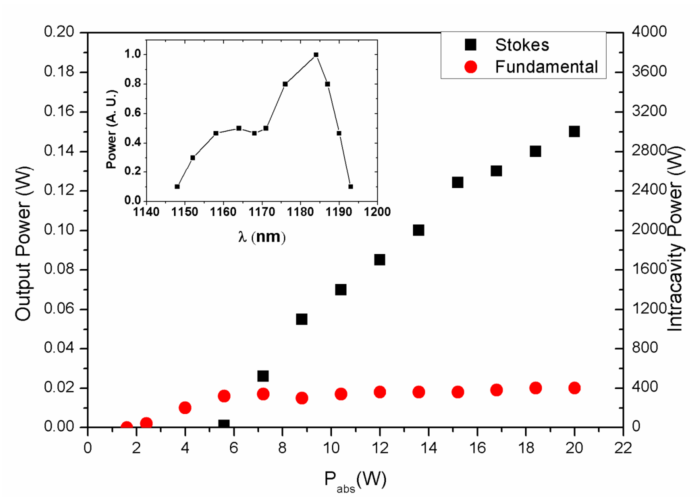

Fig. 2. Output and intracavity power of Stokes and fundamental optical fields vs. absorbed pump power. Inset shows the normalized Stokes output tuning by rotating BF.

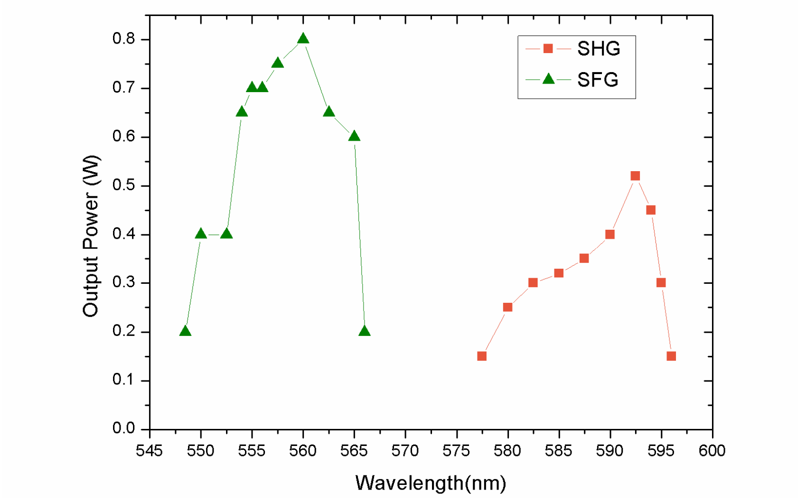

Fig. 3. Tuning of visible emissions from 577.5 to 596 nm by SHG and from 548.5 to 566 nm by SFG.

When the LBO crystal was inserted, two separate visible emission spectral bands were obtained. The temperature of LBO was tuned from 79°C to 120°C for lime emission at 548.5 to 566.0 nm which was obtained by SFG of the fundamental and Stokes optical fields, and

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tuned from 30°C to 55°C for yellow-orange at 577.5 to 596.0 nm by SHG of the Stokes field. The output power as a function of wavelength is shown in Fig. 3. The highest output powers occurred at 560 nm for SFG and 592.5 nm for SHG, and the corresponding power transfers are shown in Fig. 4. The threshold for both 560 nm and 592.5 nm corresponded to 5 W absorbed power. For 560 nm, the maximum output power of 0.8 W was obtained for 19.2 W absorbed pump power, with 5.9% slope efficiency and overall (pump to visible) conversion efficiency of 4.2%. For 592.5 nm, the maximum output power of 0.52 W was achieved for 17.7 W absorbed power, corresponding to 4.5% slope efficiency and an overall (pump to visible) conversion efficiency of 2.9%. Considering that both M1 and DM had very high transmission (>80%) from 500 to 600 nm, the output power (and conversion efficiency) could potentially be almost doubled by re-designing the coating of DM to have high reflectivity at visible wavelength so that the backwards-generated visible emission could be usefully coupled out. A similar scheme was used successfully for a crystalline solid-state Raman laser [13]. The beam quality of the visible output was examined qualitatively by expanding the output beam using a spherical lens. It showed circular beam shape and no complex transverse structure, implying relatively good beam quality of low order transverse mode. We were unable to quantitatively evaluate the beam quality due to the lack of suitable equipment.

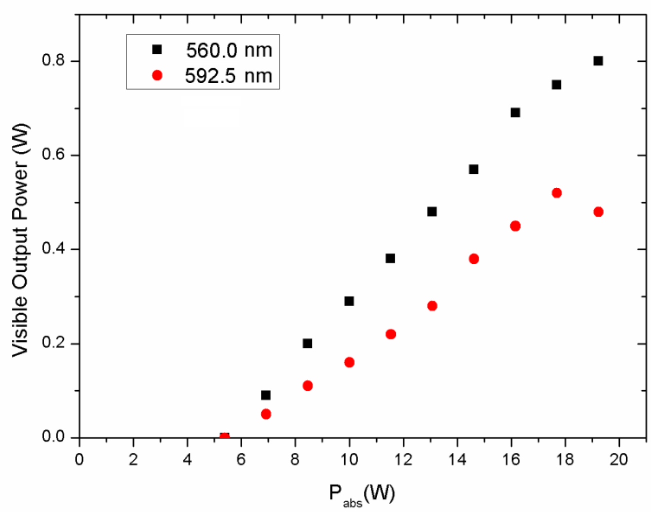

Fig. 4. Power transfer diagram for 592.5 and 560.0 nm emissions.

The optical spectrum was measured with an optical spectrum analyser (Ocean-optics HR4000, resolution 0.2 nm), and is shown in Fig. 5. The linewidth of fundamental emission increased dramatially from less than 0.2 nm below threshold for SRS, to ~1.5 nm above threshold. The linewidth of Stokes and visible were about 1 nm and 0.5 nm respectively, containing about three to five modulated peaks caused by étalon effects in the uncoated diamond heat-spreader. Similar spectral broadening has been observed in an intracavity VECSEL pumped OPO system [8] and an SHG system [14]. Each of these non-linear processes presents wavelength-dependent losses around the VECSEL emission wavelength, that can force the fundamental wavelength away from the spectral regions of highest loss. In the present case, the Stokes field presents a wavelength-dependent loss to the fundamental field that is determined by the Stokes spectrum and the linewidth of the Raman transition (5.4 cm^{-1} for $901cm^{-1}$ shift in KGW). If the Raman linewidth is narrower than the effective gain bandwidth defined by the BF (and the VECSEL emission spectrum), then the fundamental emission will no longer be constrained to the peak transmission wavelength of the BF, and the emission bandwidth will increase. As a side effect of this, since the observed fundamental

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bandwidth is broader than Raman linewidth, the effective Raman gain coefficient will be reduced, compromising the conversion efficiency achievable compared to that with a narrowband fundamental field. One strategy for maintaining narrow fundamental emission linewidth is to decrease the effective gain bandwidth set by the BF: this can be done by increasing the polarisation-dependent loss in the cavity as in [8], or by lengthening the BF to increase the polarisation change per pass. We note that in the laser presented in [11], the bandwidth of the fundamental was constrained to 0.22 nm by using a 4mm-long quartz BF.

Another factor that adversely affected the overall conversion efficiency was an insertion loss at the fundamental wavelength associated with the KGW crystal. We used an output coupler of T = 2.5% at 1064 nm to characterize fundamental laser performance, and found that inserting the KGW in the cavity led to a 30% drop in fundamental output power if the BF was in the cavity. The insertion loss was minimal if the BF was out of the cavity. This suggests that the KGW was acting as a waveplate, which in combination with the BF resulted in depolarisation losses for the fundamental wavelength. In reality, the round-trip loss is probably only around 1%, however in a high-Q resonator, this is significant. The first Stokes field did not experience such depolarisation losses since the BF was outside the Stokes cavity. In our ongoing work we will investigate this in more detail, with a view to more precisely orienting the fundamental polarisation along an optical axis of KGW or using an alternative Raman crystal to avoid depolarisation losses.

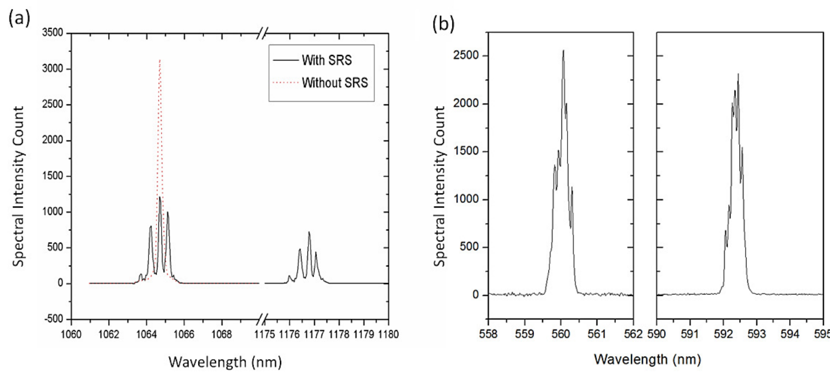

Fig. 5. Optical spectrum of (a) fundamental and first-Stokes wavelengths with/without SRS; (b) visible wavelength of 560nm and 592.5nm

4. Conclusion

In conclusion, we have demonstrated a novel scheme for frequency extension of VECSELs. Two separate, tunable bands of CW visible laser emission have been achieved by intracavity SFG/SHG of a VECSEL-pumped intracavity KGW Raman laser. A 17.5 nm tuning range and maximum of 0.8 W at 560 nm in the lime band, and an 18.5 nm tuning range and maximum of 0.52 W at 592.5 nm in the yellow-orange band has been achieved, considerably expanding the spectral coverage of a single VECSEL. In the future, improved linewidth control, the use of an intracavity visible reflector and selection of a Raman crystal to avoid depolarisation losses should result in higher conversion efficiencies, similar to the 10-20% efficiencies achieved for crystalline Raman lasers [11]. Also, since SRS is a cascading process, broader mirror coatings should also enable the second-Stokes wavlength to be resonated [15], increasing the number of tunable bands that can be generated. Further, with the availability of Raman crystals having frequency shifts ranging from 270 cm^{-1} in KTA to 1332 cm^{-1} in diamond, there is great potential for tailoring the spectral coverage from a single VECSEL to suit specific applications.

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