Continuous-wave diamond Raman laser at 1.2 μm with 85 W output power in a single pump pass configuration

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ABSTRACT

Diamond possesses a unique combination of both the highest Raman gain and thermal conductivity among any solid-state bulk material. This makes it the most suitable crystal for high-power laser sources at alternative wavelengths. Technical limitations for the power scaling of diamond Raman lasers (DRL) are linked to the size of commercially available synthetic diamond crystals, the quality of anti-reflection coatings on the diamond surfaces, pump emission polarisation and linewidth, thermal lensing, and optical isolation. A diamond Raman laser is demonstrated operating under single pump pass, eliminating the need of any optical isolator. The maximum output power was 85 W at 482 W of incident pump power with the slope efficiency 21%. Thermal analysis of the DRL indicated that resonator misalignment due to heating of the input mirror was the main limitation to further power scaling and stability improvements

Keywords: Diamond, Raman laser, high power, fibre laser

1. INTRODUCTION

Raman scattering in various substances—whether gas, liquid, or solid-state—enables the conversion of the pump laser wavelength to a new wavelength determined by the intrinsic molecular properties of the substance [1]. This wavelength-shifted output is valuable for a range of practical applications and is often challenging to achieve through other methods, such as direct laser generation or alternative non-linear wavelength conversion techniques.

Diamond possesses a unique combination of both the highest Raman gain and thermal conductivity among any solid-state bulk material [2]. This makes it the most suitable crystal for high-power laser sources at alternative wavelengths.

The majority of the results with high-power DRLs in the continuous-wave (CW) and quasi- continuous-wave (QCW) regimes [3–14] are obtained in a "classical" external cavity Raman laser configuration with a double pass of the pump beam through the diamond crystal, and the pump emission polarised along the <111> axis of the diamond.

The highest output power from a diamond Raman laser pumped in "true" CW regime was reported recently to be 213 W under 544 W pump power [6].

In QCW mode, the highest quasi-steady-state Raman laser output power was reported to be 1.2 kW under 2.3 kW pump power [5]. In this case significant improvement in the Raman laser beam quality was observed: the pump beam M^2 factor of 15 was improved to 1.25 for the Raman laser output, giving a spatial brightness enhancement factor of 56.

An external 2-mirror cavity has proven to be a reliable resonator configuration for the majority of high power DRLs [3–5,7–14]. The 2 mirror cavity configuration minimizes the number of the resonator optical elements (reducing the passive losses), which is important for power scaling of DRL in CW mode, where minimal resonator passive losses (usually associated with imperfect coatings of resonator mirrors) are essential.

Technical limitations for the power scaling of DRL are linked to the size of commercially available synthetic diamond crystals, the quality of anti-reflection coatings on the diamond surfaces, pump emission polarisation and linewidth, thermal

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This is a peer-reviewed, accepted manuscript of the following paper: Summers, P. A., Barber, M. J., Watkins, B., Terry, D. J., Kemp, A. J., & Savitski, V. G. (2026). Continuous-wave diamond Raman laser at 1.2μm with 85W output power in a single pump pass configuration. In M. Mcquage, A. Clark, & C. R. Wilson (Eds.), Proceedings of SPIE (Vol. 14022). Article 140220A (Proceedings of SPIE; Vol. 14022). SPIE. https://doi.org/10.1117/12.3094210

lensing, and optical isolation. Another practical limitation, particularly when pumping with modern high-power CW fibre lasers, is the use of double-pass pumping.

In a 2-mirror DRL resonator, having the output mirror with high reflectivity at the pump wavelength is a proven method to reduce the Raman laser threshold. This approach works well as long as the back-reflected pump emission does not affect the performance of the pump source, or an optical isolator is used to prevent any back-reflected light entering the pump. Use of an optical isolator requires either polarised pump emission or a polarisation-insensitive isolator. For high power CW fibre lasers approaching kW powers, the output emission is unpolarised, and commercial off the shelf polarisation-insensitive isolators are not available at this power level. For those reasons, a double-pass pumping scheme is not feasible with high power laser pumping at ~ 1 kW level. Use of a single-pass pumping will result in somewhat higher Raman laser threshold.

In this paper we demonstrate that commercial-of-the-shelf laser sources and components can be used for building a high power DRL operating in a single-pump-pass configuration without the need for an optical isolator and under circular polarised pump emission (simulating unpolarised pumping), reducing the cost and complexity of the setup. The main task was to demonstrate the diamond crystal capabilities of operating under continuous-wave pumping at ~500 W of pump power. The DRL was designed to operate under single pass pumping through the diamond crystal and to avoid any back reflections of pump emission from any optical elements of the cavity, eliminating the need to use any optical isolator in the system. The maximum output diamond Raman laser power was 85 W at 482 W of incident pump power. The laser slope efficiency was 21%. The Raman laser emission was linearly polarised when circular polarised pump emission was used.

2. EXPERIMENTAL SETUP

The principal optical setup for DRL experiments is shown in Fig. 1. The pump source was a kW- class commercial off the shelf (COTS) polarisation maintaining fibre amplifier from IPG photonics seeded with a COTS narrow linewidth laser source (NKT Koheras ADJUSTIK).

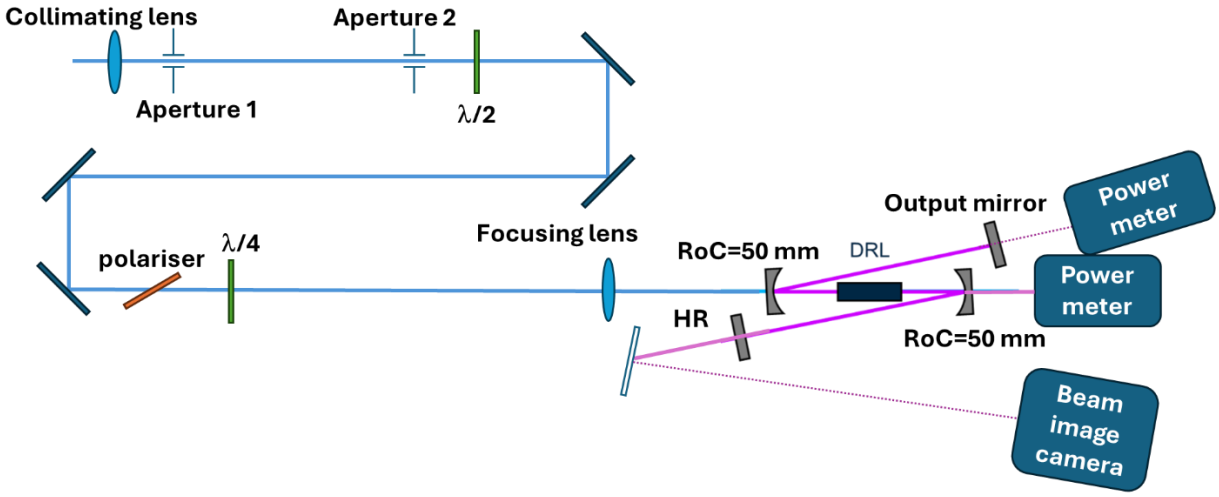

Figure 1. Principal optical scheme of the experiments on the high-power diamond Raman laser.

The output of the fibre laser system was collimated with a 100 mm focal length lens to a diameter of 5.4 mm ($1/e^2$). The beam was focused inside the diamond by a focusing lens with the focal length of 75 mm. The diameter of the pump beam focus was measured to be 35 μm after the curved resonator mirror.

The pump laser emission was linearly polarised at the fibre output. For experiments with the DRL the polarisation was changed to circular with a combination of a half wave plate, a polariser, and a quarter wave plate (λ/2 and λ/4, see Fig. 1). It is expected that future high power fibre laser sources to be used for pumping the DRL will have unpolarised output emission.

The DRL resonator is a four-mirror Z-fold one formed by two curved mirrors (radius of curvature (RoC) of 50 mm) and two plane mirrors (the high-reflector (HR) and the output mirror in Fig. 1). The diamond crystal was positioned between the two curved mirrors. The distance between the curved mirrors and the end face of a diamond was 24-27 mm. The length of two resonator arms between the curved and plane mirrors was 125 mm. The output mirror had reflectivity of 98.9% at the 1st Stokes wavelength of 1240 nm and 0.71% at the pump wavelength of 1064 nm.

The diamond crystal tested in experiments had dimensions of 2×2×6 mm. Both 2×2 mm end faces were anti-reflection (AR) coated for minimal reflection at 1240 nm, which is the expected wavelength of the DRL oscillation at the 1st Stokes wavelength when pumped at 1064 nm. The coating reflectivities at 1064 and 1240 nm are, correspondingly ~1 and ~0.3 %.

The diamond crystal was glued to the brass mount with the silver paint or with the thermal paste. The mount was water cooled. The diamond had thermal contact with the brass mount only via a 2×6 mm surface.

The crystal was tilted inside the resonator by ~ 1˚ to prevent reflection of the pump emissions going back into the pump source.

A significant rise in temperature (up to 120˚C at 504 W of input pump power) in the diamond crystal was noticed during the first series of measurements (see Fig. 2).

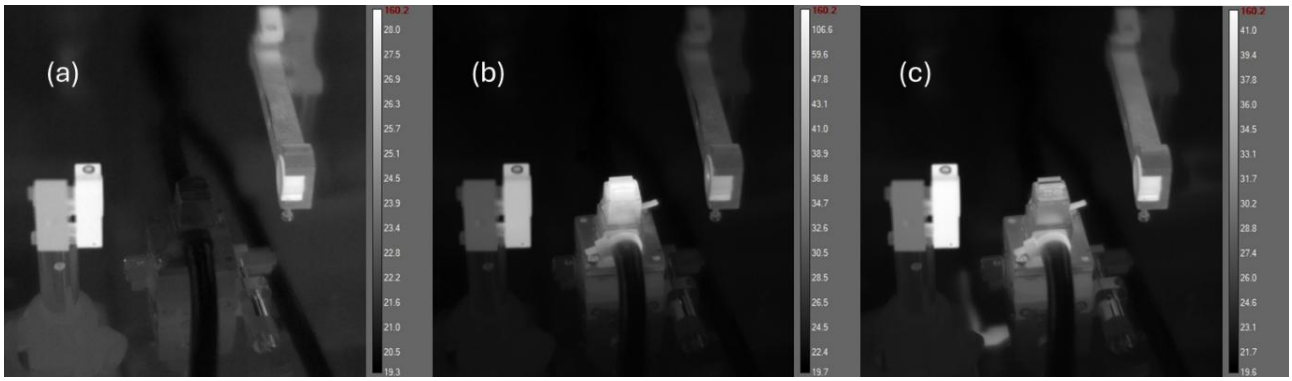

Figure 2. Thermal images of the diamond crystal and DRL curved mirrors taken with the FLIR thermal camera A655sc: (a) 3 s after DRL oscillation at 1240 nm, (b) 48 s after DRL oscillation (just before turning the pump laser off), and (c) 5 s after the pump laser is off. The units are degrees-C.

For that reason, the measurements of the output characteristics of the DRL as a function of pump power were taken using the following procedure:

- the pump source is turned on at certain output power level,
- DRL characteristics are recorded for a period of ~45 seconds,
- the pump source is turned off,
- the curved mirrors of the DRL resonator are given some time to cool down,
- output power of the pump source is increased and the pump is turned on as soon as the mirrors cool down to the temperature of ~30-35 ˚C.

Damage of AR coatings of the diamond was noticed occasionally. This resulted in gradual decrease of the output power of the DRL during measurements and required re-positioning of the diamond inside the resonator, by moving the crystal perpendicular to the optical axis. For that reason, a few series of measurements during experiments were taken with different crystal positions and different alignments of the resonator mirrors.

3. EXPERIMENTAL RESULTS

Power transfer characteristics of DRL

The highest output power achieved with the DRL during experiments was 85 W at the incident pump power of 482 W (Fig. 3, green triangles). The calculated slope efficiency was 21% (green line in Fig. 3).

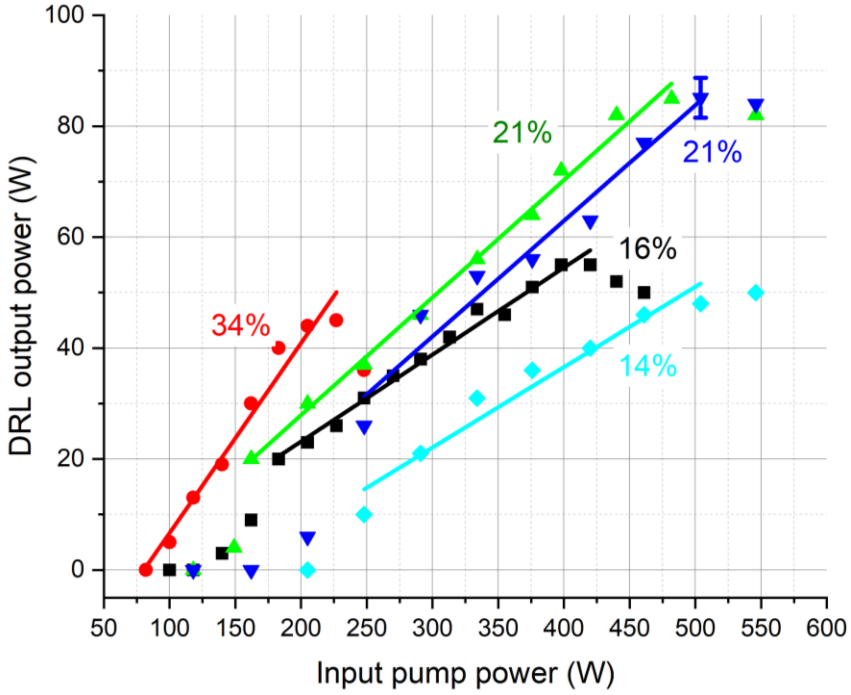

Figure 3. Power transfer characteristics of the DRL pumped by a fibre laser with circular polarisation at 1064 nm. Symbols – experimental data, solid lines – linear fit. Numbers with different colours near each line show the corresponding slope efficiency of the DRL at given set of measurements. A few series of measurements during experiments were taken with different crystal positions, corresponding to different colours of the data sets.

The highest slope efficiency of the laser was calculated to be 34 %, but with the corresponding max DRL output power of 45 W (red circles in Fig. 3).

It should be noted that each HR mirror of the DRL transmitted some emission at the wavelength of the 1st Stokes (1240 nm). This transmitted laser power was about 10% of the one measured after the output mirror. For example, with the DRL output power of 85 W measured after the output coupler, the corresponding output power at the 1st Stokes wavelength measured after one of the HR mirrors was ~8.5 W.

This means that the total output power of the DRL is at least 30% higher than that measured after the output mirror, taking into account the fact that the DRL resonator is formed by 3 HR mirrors.

DRL beam profile

The DRL output beam profiles for the power transfer set of measurements corresponding to the highest output power (blue triangles in Fig. 3) are shown in Fig. 4.

DRL laser beam profiles (Fig. 4) vary with output power. The beam has somewhat distorted shape at DRL output powers >53 W. The reason for that could be misalignment of the DRL cavity or optical damage of the diamond crystal coatings at high powers. The cavity misalignment could be caused by thermal lens inside the diamond crystal or (and) heating of the curved resonator mirrors (Fig. 2). It was found that the chosen cavity is stable within the wide range of thermal lens focal lengths in diamond, down to 25 mm, while the expected focal length of thermal lens at a DRL output power of ~70 W is ~134 mm. This means that the most probable cause of any resonator instability at high DRL output power and corresponding change of the shape of the output DRL beam is heating of curved resonator mirrors. The thermal modelling of the DRL will be discussed in the next section.

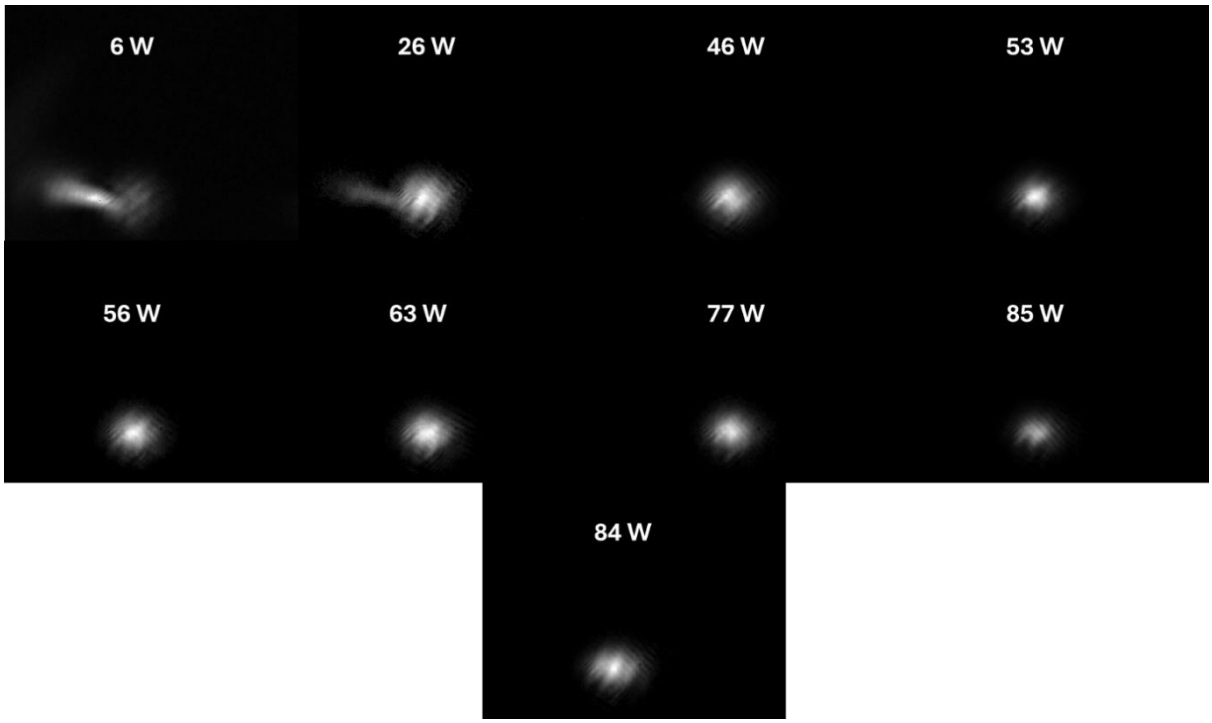

Figure 4. DRL output beam profile at 1240 nm as functions of the DRL output power for all experimental points shown in the power transfer characteristics in Fig. 3 with blue triangles.

DRL emission spectrum

The DRL emission spectra for the power transfer set of measurements corresponding to the highest output power (blue triangles in Fig. 3) is shown in Fig. 5.

DRL output emission spectrum demonstrates systematic blue shift of the Raman laser wavelength with increasing DRL output power. This shift was observed with all the sets of measurements of DRL output characteristics. The pump laser wavelength at 1064 nm was stable within the whole range of powers and was measured to be 1063.70±0.01 nm. Therefore, the observed blue shift is consistent with the known reduction in the Raman shift with temperature [15].

When the DRL output power increases, the diamond crystal temperature increases as well (Fig. 6). Increase in crystal temperature causes the Raman frequency (or the Stokes shift) to reduce. With the fixed pump wavelength, smaller values in the Stokes shift of the crystal means the DRL will emit at shorter wavelengths. This was observed experimentally in Fig. 5 for elevated DRL output powers.

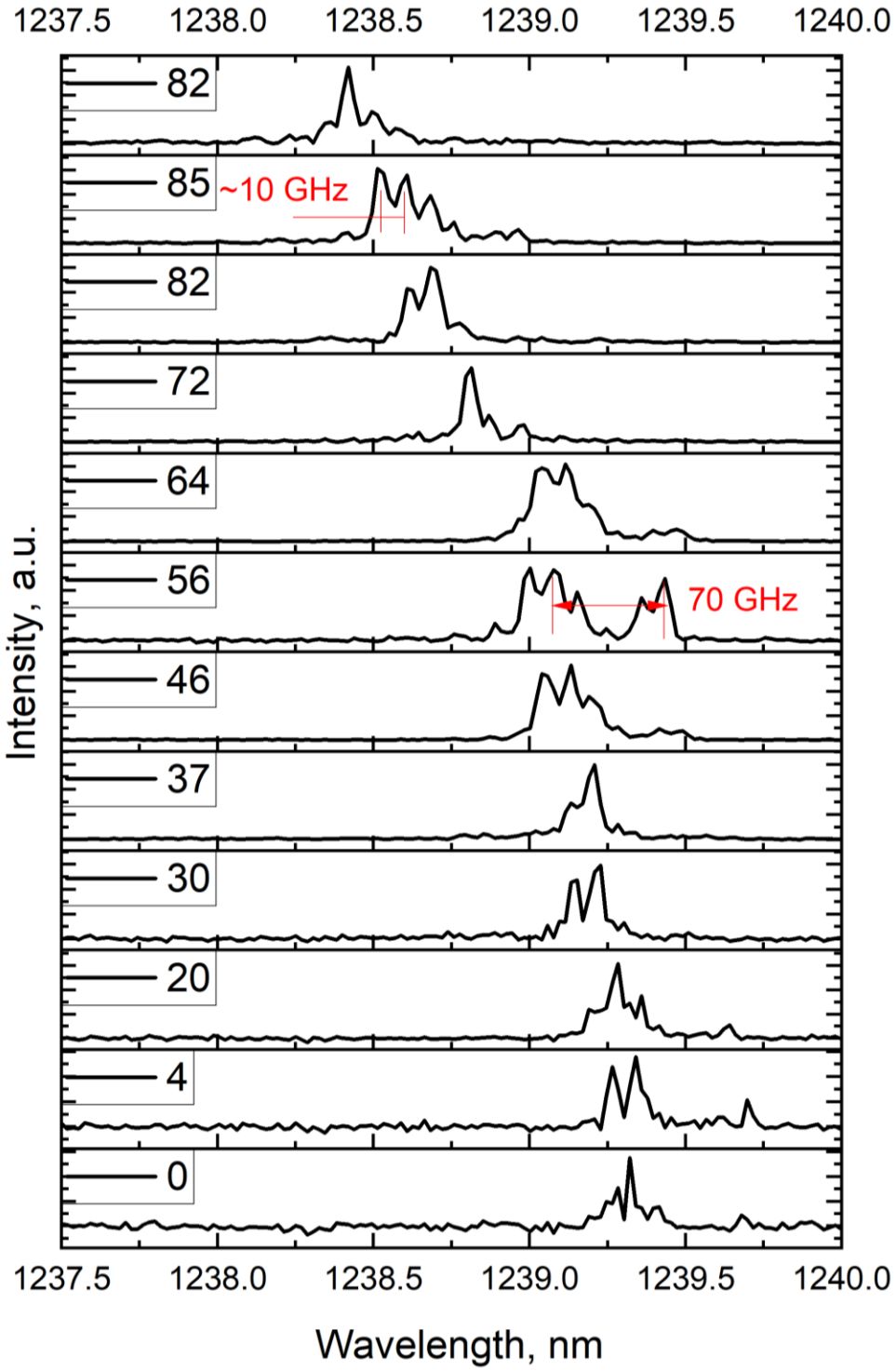

Figure 5. DRL output emission spectra at 1240 nm as functions of the DRL output power (bottom picture corresponds to the DRL threshold, top picture corresponds to the max output power) for all experimental points shown in the power transfer characteristics in Fig. 3 with green triangles. Spectral separation of 10 GHz and 70 GHz between peak in the emission spectrum of the DRL at 85 W and 56 W of output power correspondingly is shown. 10 GHz spectral separation most probably corresponds to free spectral range of a 6 mm long diamond crystal. 70 GHz spectral separation corresponds to SBS peak in the emission spectrum.

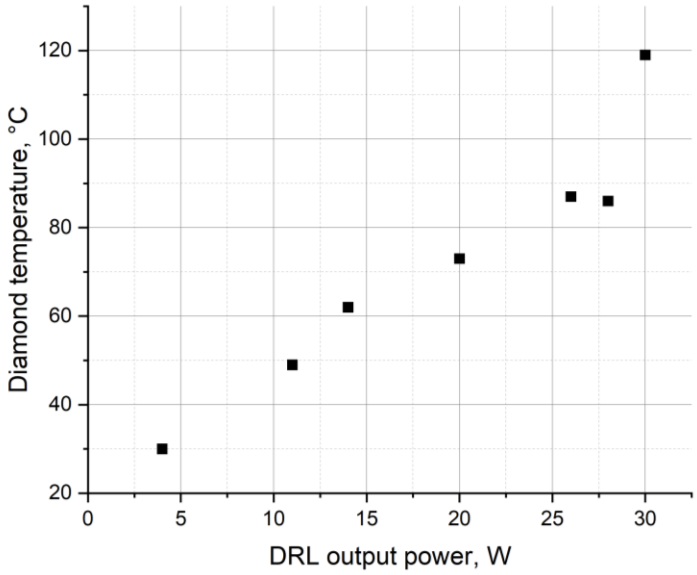

Figure 6. Diamond crystal temperature as a function of DRL output power at 1240 nm.

Multiple peaks observed in some emission spectra of DRL in Fig. 5 (e.g. at DRL power of 85 W) have wavelength separation of ~0.09-0.05 nm, which corresponds to frequency separation of ~18-10 GHz. Considering that the spectral resolution of the optical spectrometer (Thorlabs OSA 205) used for these measurements is 7.5 GHz, this frequency separation is very close to the free spectral range of 10.4 GHz calculated for a 6 mm long diamond crystal with an index of refraction of 2.4. Thus, even though the diamond has an AR coating on it, there appears to be enough residual reflection to result in a coupled cavity.

Stimulated Brillioun Scattering (SBS) in the DRL

DRL output emission spectra (Fig. 5) can also be characterised with double peaks at some output powers, separated by ~70 GHz (e.g. at output powers of 4, 46, 56, 64 and 86 W). The nature of this second peak was described in several papers on high-power DRLs [8–11] and was attributed to intracavity stimulated Brillouin scattering (SBS), which has a Stokes shift of ~71 GHz [8–11]. The 1st Stokes emission in DRL has high intracavity power and sufficiently narrow linewidth to produce SBS. SBS emission is observed as a secondary peak in Raman emission spectrum, next to the Stokes wavelength.

SBS emission reduces the output power of the Raman laser due to nonlinear coupling from the SRS field [9]. For example, in [8] SBS power accounted for 2.5 % of the total output power. In addition, gain competition between the SBS and SRS can cause significant pulsing in the output of DRL, which can trigger optical damage of the intracavity coatings [8–10].

DRL Output emission polarisation measurements

The polarisation extinction ratio (PER) of the DRL output emission was measured as a function of input pump power at 1064 nm, Fig. 7. The PER is ~3.6 dB at the threshold of DRL oscillation (pump power of 227 W), and then reaches values of 10-12 dB within the pump power range of 270-482 W.

Linearly polarised output emission from DRL under pumping with circular polarised emission at 1064 nm suggests that all possible input polarizations of the pump are coupled into a single polarization mode of the Raman emission. With circular polarised pump emission, both orthogonal components of the electric field have the same amplitude. These two orthogonal components will contribute equally to the Raman gain in diamond for output Raman polarisation along a <110> direction [2 16].

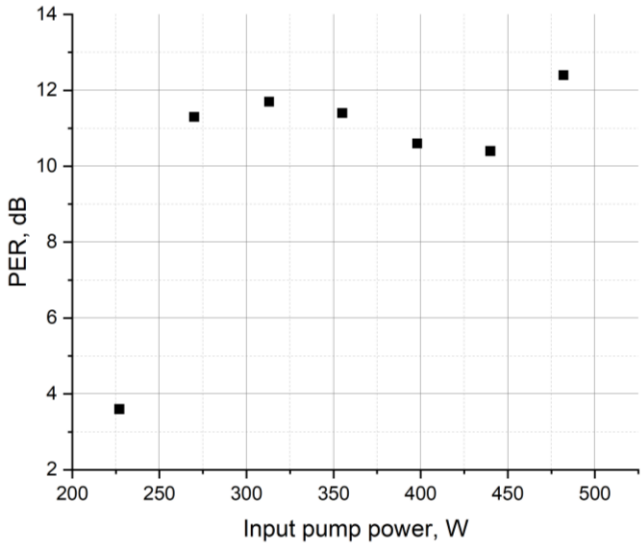

Figure 7. Polarisation extinction ratio (PER) of the DRL output emission as a function of pump power.

4. THERMAL ANALYSIS OF DIAMOND RAMAN LASER

The diamond crystal had dimensions of 2 x 2 x 6 mm and was attached to a brass heat sink using a thin layer of conductive paint, with the temperatures measured using a FLIR A655sc thermal imaging camera. The DRL utilised a 482 W input pump beam, resulting in an output power of 85 W from the Raman crystal, and 64 W of heat dissipation in the crystal (determined from the measured residual pump power and mirror leakage losses). The beam passing through the crystal was assumed to have a Gaussian intensity distribution with a $1/e^2$ beam diameter of 0.5 mm. A photograph of the diamond and heat sink configuration that were used in the DRL setup is shown in Fig. 8 alongside the modelled equivalent.

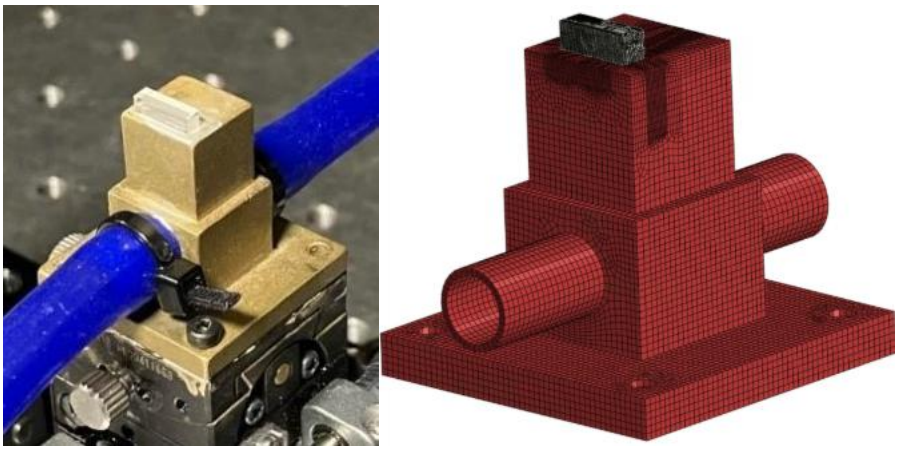

Figure 8: Photograph of the 85 W DRL heat sink configuration (left) and the reconstruction for thermal modelling (right).

The modelled temperature distribution for the heat sink is shown in Figure 9, for which a good match has been achieved between the measured and modelled temperatures at the bottom of the mount (Point A, 57.5 °C from the measurements). However, near the top of the mount down (Point B, 88.8 °C, from the measurements), the model is predicting a higher temperature than is seen in the thermal camera image.

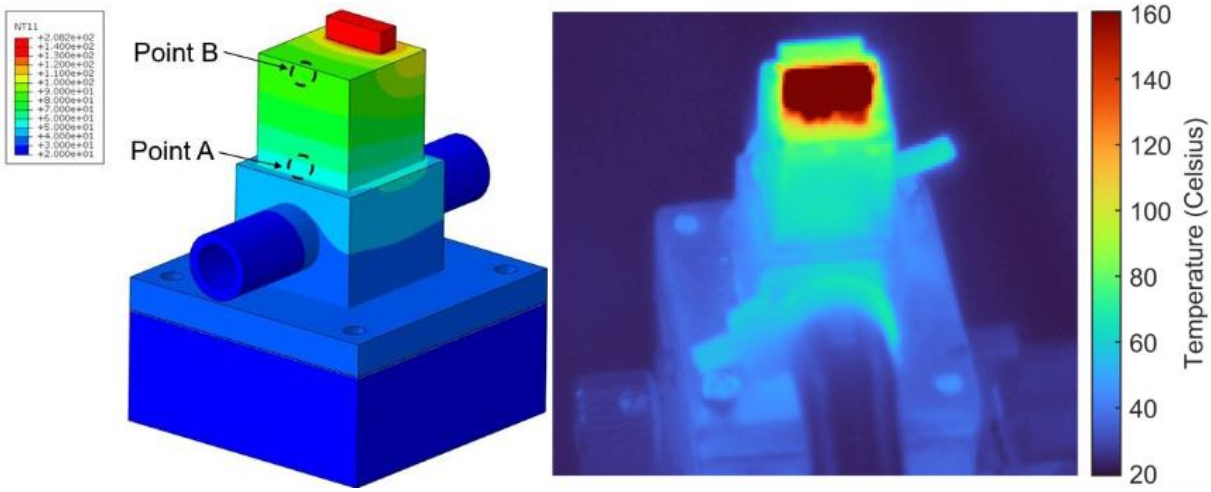

Figure 9: Modelled temperature distribution map for the 85 W DRL (left) and the corresponding thermal camera image of the experimental setup (right). The colour bar for the model is in units of degrees-C. The two images have different colour scales for temperature.

Potential contributions to errors in the temperature interpreted from the camera image are diffuse reflections, a slight mismatch in the assumed emissivity of the brass mount compared to the real value, or a mismatch in the position that the temperature was extracted from the image during post processing due to the relatively low resolution of the thermal camera imagery.

Post-processing of the raw thermal data in Fig. 2 has allowed the temperature variations of the DRL components to be estimated with their own emissivity values. While the black anodised aluminium of the pump input coupler mount used emissivity = 0.85, the brass emissivity was estimated at 0.42 from a calibration run using a thermal patch on the mount of known emissivity, and the pump output coupler mount used emissivity = 0.2. Although extracting temperature values from low emissivity objects can be inaccurate, it gives information on relative thermal changes within each power measurement.

The temperature rises experienced by the pump input coupler mount, brass mount, pump output coupler mirror, and pump output coupler mount during the different data points are shown in Fig. 10 as a function of pump power (a) and output power (b). The heating of the pump and output mirrors, and the mounts, likely due to the black anodised aluminium absorbing scattered pump light from the diamond surface, is believed to be a major cause of cavity misalignment at high power levels. Indeed, it was shown recently that water cooling of the mirror mounts was essential for power scaling of DRL to 213 W in CW regime. [6]

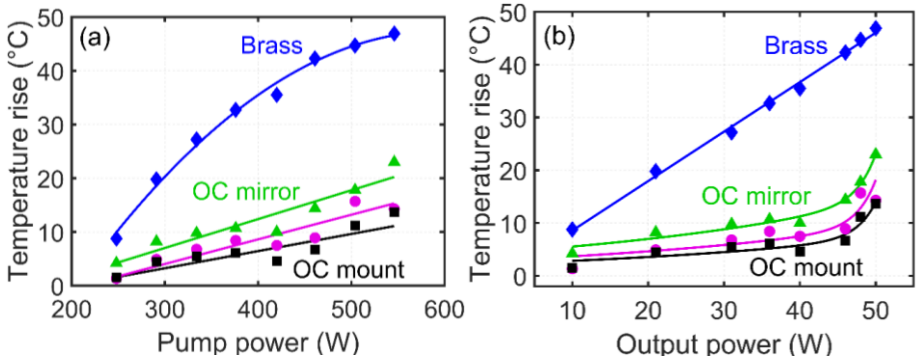

Figure 10. Temperature rises experienced by the pump input mirror mount (pink line), brass mount, output mirror, and the output mirror mount as a function of (a) input pump power, and (b) DRL output power.

5. CONCLUSION

Diamond Raman laser at 1240 nm was demonstrated with the output power of 85 W at the incident pump power of 482 W. This is the record output power from the DRL under a single pump pass configuration with a circular polarised pump laser emission at 1064 nm. The system did not require any optical isolator reducing the cost and complexity of the setup.

The output DRL emission was linearly polarised with a circular beam output profile. DRL power scaling capabilities at the recorded output powers started to be affected by the parasitic SBS effect.

The heating of the pump input coupler and the mount, likely due to the black anodised aluminium absorbing scattered pump light from the diamond surface, is believed to be a major cause of cavity misalignment at high power levels and corresponding instability of the output power.

REFERENCES

[1] Raman, C. V and Krishnan, K. S., "A new type of secondary radiation," Nature **121**, 501–502 (1928).

[2] Savitski, V. G., Friel, I., Hastie, J. E., Dawson, M. D., Burns, D. and Kemp, A. J., "Characterization of single-crystal synthetic diamond for multi-watt continuous-wave raman lasers," IEEE J. Quantum Electron. **48**(3), 328–337 (2012).

[3] Kitzler, O., McKay, A. and Mildren, R. P., "Continuous-wave wavelength conversion for high-power applications using an external cavity diamond Raman laser," Opt. Lett. **37**(14), 2790–2792 (2012).

[4] Sun, Y., Li, M., Mildren, R. P., Bai, Z., Zhang, H., Lu, J., Feng, Y. and Yang, X., "High-power continuous-wave single-frequency diamond Raman laser at 1178 nm," Appl. Phys. Lett. **121**(14), 141104 (2022).

[5] Antipov, S., Sabella, A., Williams, R. J., Kitzler, O., Spence, D. J. and Mildren, R. P., "1.2 kW quasi-steady-state diamond Raman laser pumped by an M2 = 15 beam," Opt. Lett. **44**(10), 2506–2509 (2019).

[6] Li, M., Sun, Y., Jiang, H., Yang, X. and Feng, Y., "A 213.4 W continuous-wave diamond Raman laser at 1240 nm with polarization-combined pumping," High Power Laser Sci. Eng. **13**, 2025/10/24, e83 (2025).

[7] Li, M., Li, P., Zhang, X. and Chen, X., "21.8 W CW second-Stokes CVD-diamond Raman laser at 1516 nm," Appl. Phys. B **124**(8), 165 (2018).

[8] Heinzig, M., Palma-Vega, G., Walbaum, T., Schreiber, T., Eberhardt, R. and Tünnermann, A., "Diamond Raman oscillator operating at 1178 nm," Opt. Lett. **45**(10), 2898–2901 (2020).

[9] Sun, Y., Li, M., Kitzler, O., Mildren, R. P., Bai, Z., Zhang, H., Lu, J., Feng, Y. and Yang, X., "Stable high-efficiency continuous-wave diamond Raman laser at 1178 nm," Laser Phys. Lett. **19**(12), 125001 (2022).

[10] Heinzig, M., Palma-Vega, G., Yildiz, B., Walbaum, T., Schreiber, T. and Tünnermann, A., "Continuous-wave cascaded second Stokes diamond Raman laser at 1477 nm," Opt. Lett. **46**(5), 1133–1136 (2021).

[11] Williams, R. J., Nold, J., Strecker, M., Kitzler, O., McKay, A., Schreiber, T. and Mildren, R. P., "Efficient Raman frequency conversion of high-power fiber lasers in diamond," Laser Photon. Rev. **9**(4), 405–411 (2015).

[12] Bai, Z., Williams, R. J., Jasbeer, H., Sarang, S., Kitzler, O., Mckay, A. and Mildren, R. P., "Large brightness enhancement for quasi-continuous beams by diamond Raman laser conversion," Opt. Lett. **43**(3), 563–566 (2018).

[13] Williams, R. J., Kitzler, O., McKay, A. and Mildren, R. P., "Investigating diamond Raman lasers at the 100 W level using quasi-continuous-wave pumping," Opt. Lett. **39**(14), 4152–4155 (2014).

[14] Bai, Z., Williams, R. J., Kitzler, O., Sarang, S., Spence, D. J. and Mildren, R. P., "302 W quasi-continuous cascaded diamond Raman laser at 1.5 microns with large brightness enhancement," Opt. Express **26**(16), 19797–19803 (2018).

[15] Liu, M. S., Bursill, L. A., Prawer, S. and Beserman, R., "Temperature dependence of the first-order Raman phonon line of diamond," Phys. Rev. B **61**(5), 3391–3395 (2000).

[16] McKay, A., Sabella, A. and Mildren, R. P., "Polarization conversion in cubic Raman crystals," Sci. Rep. **7**, 41702 (2017).