High power single-longitudinal-mode diamond laser using Hänsch-Couillaud-type stabilization

Soumya Sarang[1], Ondrej Kitzler[1], Oliver Lux[2], Zhenxu Bai[1,3], Robert J. Williams[1], David J. Spence[1]
and Richard P. Mildren[1]

[1]MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia

[2]Now at Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

[3]National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China

***Abstract*—We report a cavity stabilization scheme to enable single longitudinal mode operation from a diamond Raman laser at increased power. An output power of 7.2 W is demonstrated using a simple standing-wave laser cavity without the addition of frequency-selection elements.**

Keywords—Raman; stress-induced birefringence; cavity length stabilization; diamond.

I. INTRODUCTION

Continuous-wave (CW) diamond Raman lasers are becoming increasingly attractive for frequency conversion owing to the high Raman gain, superior thermal conductivity and low thermal expansion coefficient of diamond [1]. Recently the spatial-hole-burning-free nature of the Raman gain has been exploited to enable single longitudinal mode (SLM) operation with up to 4 W of output power from a standing-wave cavity without the incorporation of intracavity frequency selective elements [2]. However, at higher output powers operation becomes unstable due to the coupling between the Stokes power and the effective cavity length via diamond thermal expansion and the thermo-optic effect.

In order to improve stability, we now investigate compensation of the thermal effects through active cavity-length feedback control. We use a Hänsch-Couillaud-type method [3] for locking the cavity length to the pump frequency with the aim of stabilizing SLM operation and increasing the SLM output power. In this technique, polarization dependent shifts in the resonance of the pump input beam with the cavity, in the presence of polarization dependent loss [3] or birefringence [4], provide an error signal that is used to compensate for thermally induced shifts in cavity length. Here we show that the polarization-dependent Raman gain properties of diamond, and the fact that it often contains significant in-grown stress birefringence, may be exploited for this purpose.

II. EXPERIMENTAL SETUP

The cavity stabilization system is illustrated in Fig. 1. The pump beam back-reflected from the Raman cavity was sampled using the input collimating lens and directed to the detection system. Any residual Stokes in the beam was filtered out using a dichroic mirror (PM; HT @ pump, HR @ Stokes). A quarter-wave plate (QWP) was used to convert the elliptically polarized pump beam such that the power incident on the photodetectors (PD1, PD2), after passing through the polarizing beam splitter (PBS), were approximately equal. The photodetector signals were amplified before sending into the stabilization controller (Laselock digital, TEM Messtechnik). The controller uses a PID servo-loop to generate a control signal to achieve top-of-fringe stabilization without cavity modulation. The controller altered the cavity length via a piezoelectric translator (PZT) applied to the output coupler.

The pump laser and basic Raman laser design have been described previously in ref. [2]. In these experiments the reflectivity of the input coupler (IC) was 0.74% and 99.94% at the pump and Stokes wavelengths, respectively, and the output coupler (OC) had a reflectivity of 90% and 99.5% at the pump and Stokes wavelengths, respectively. Note that in this system, the cavity finesse for the pump is relatively low compared to typical resonant systems. We used a single-crystal diamond having a stress-induced birefringence of approximately $1\text{x}10^{-5}$ (similar to that used in [5]). This birefringence introduces a retardance in the <111> polarized pump which provides at least one source of a locking signal for cavity stabilization [4].

The longitudinal mode structure of the Stokes beam was characterized by a Fabry-Perot interferometer (Thorlabs, model SA210) and the wavelength stability was monitored by a laser spectrum analyzer (Bristol instruments, model 771A-NIR).

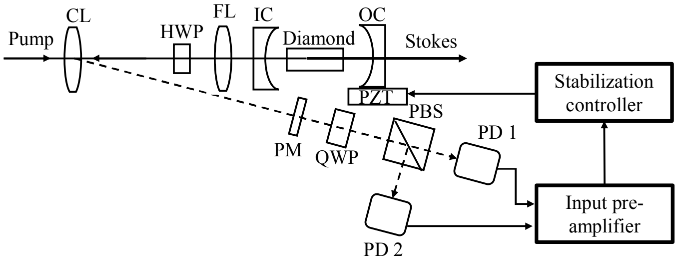

Fig. 1. Experimental setup for the cavity-locked DRL; CL–collimating lens, HWP–half –wave plate, FL–focussing lens, IC–input coupler, OC–output coupler, PZT–piezoelectric translation stage, QWP–quarter-wave plate, PM–plane mirror, PBS–polarizing beam splitter, PD1 and PD2–photodetectors.

III. RESULTS AND DISCUSSIONS

The DRL had a threshold pump power of 23 W, above which the output power increased linearly with a slope efficiency of 70% as shown in Fig. 2. The residual pump power was also measured and shows good depletion of the pump is obtained above the Raman lasing threshold. Without the cavity stabilization control activated, the longitudinal mode spectrum revealed stable SLM operation for output powers up to approximately 2 W, above which multiple modes were observed.

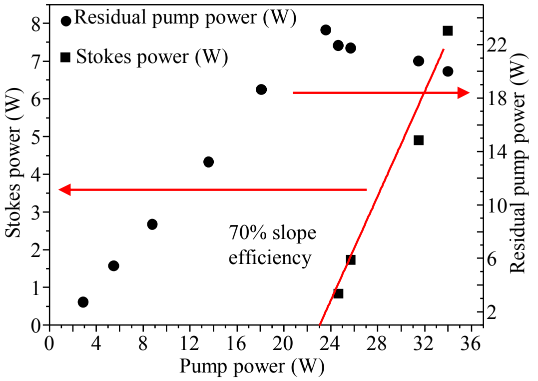

Fig. 2. The Stokes power and residual pump power versus the incident pump power without cavity stabilization.

With stabilization activated, an adequate error signal for locking the cavity to the pump wavelength was only achieved when the Raman laser was above threshold. This indicates that the birefringence in the diamond is not alone sufficient to enable the feedback electronics to achieve locking. Above laser threshold, SLM output was observed for output Stokes power up to 7.2 W for several seconds. The Fabry-Perot scan shown in Fig. 3 confirms the pure mode spectrum. Stability improved when the Stokes power was lowered to about 4.5 W, yielding SLM operation for several minutes. As shown in Fig. 4, the SLM output was stable to within an approx. 125 MHz for 120 s and transitioned to multimode output for longer times.

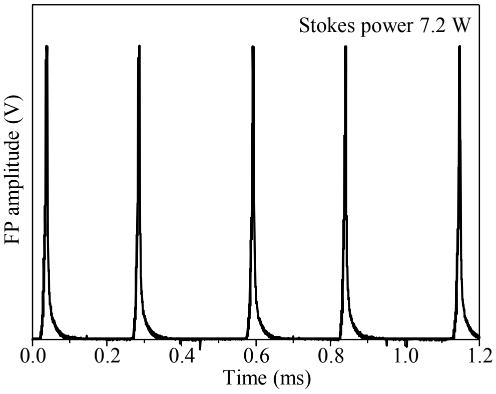

Fig. 3. The Fabry-Perot interferometer plot shows single longitudinal mode at 7.2 W when the laser was locked.

We expect that locking is achieved above threshold due to the additional polarization discrimination provided by the polarization dependent nature of Raman gain [6,7]. In the present system, the birefringence value in the diamond and the cavity finesse is not sufficient to provide locking on its own. As noted in [4], a higher cavity finesse and using crystals of higher birefringence produce higher quality (steeper) error signals and hence will likely lead to increased laser stability. This may provide a path towards higher stable SLM powers and improved frequency stability.

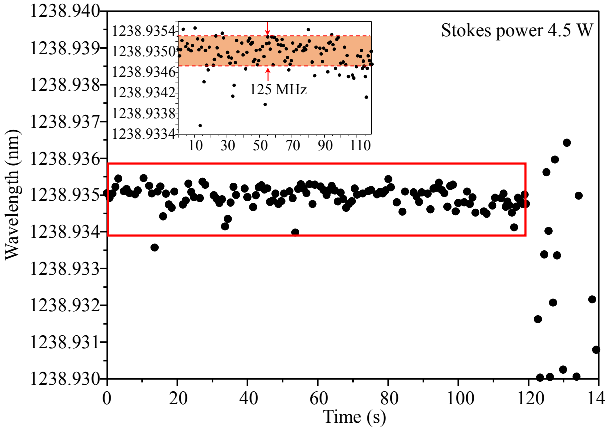

Fig. 4. Wavelength stability of the cavity stabilized Raman laser measured by the laser spectrum analyzer. The inset shows the wavelength fluctuations of about 125 MHz at 4.5 W.

IV. CONCLUSION

We investigated a Hänsch-Couillaud-type locking technique for a diamond Raman laser. We found that locking is achieved only above laser threshold and for output powers up to approximately 7 W. We deduce that a higher cavity finesse at the pump wavelength and/or a higher birefringence in the diamond is likely to assist stable SLM operation for longer/continuous duration as well as increased frequency stability and higher output powers.

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