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# High-power single-pass pumped diamond Raman oscillator

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## ABSTRACT

We present our recent advances on power scaling of a high-power single-pass pumped CVD-diamond Raman oscillator at 1.2  $\mu\text{m}$ . The single pass scheme reduced feedback to the high gain fiber amplifier, which pumps the oscillator. The Yb-doped multi-stage fiber amplifier itself enables up to 1 kW output power at a narrow linewidth of 0.16 nm. We operate this laser in quasi-cw mode at 10% duty cycle and on-time (pulse) duration of 10 ms. With a maximum conversion efficiency of 39%, a maximum steady-state output power of 380 W and diffraction limited beam quality was achieved.

**Keywords:** Nonlinear frequency conversion, CVD Diamond, Raman laser, High-power lasers, narrow linewidth source

## 1. INTRODUCTION

To date rare-earth-doped high-power fiber lasers or amplifiers are among the most versatile laser sources in scientific research and industrial applications, not only because of their high beam quality and high efficiency, but also because of their wide range of potential emission spectra. In recent years researchers have successfully scaled the average power and achieved multi kW level with Yb-doped fiber lasers around 1  $\mu\text{m}$  [1-2]. The transmission range or the spectral gain of the active medium often limits the output power of highly demanded laser sources at uncommon wavelengths.

Stimulated Raman frequency conversion represents a versatile approach to expand the spectral range at high power levels and thus improves wavelength-dependent applications. An incident pump beam passing through a Raman-active medium can generate and amplify a Stokes beam of longer wavelength due to the material-specific frequency shift of the Raman active medium. Raman-induced frequency conversion in solid-state media has been successfully demonstrated in the continuous-wave (CW) [3-5], and several pulsed [6-8] regimes. Chemical vapor deposition (CVD) grown Diamond is a new attractive medium for Raman lasers and especially suitable for high power laser application due to its unique combination of thermal and optical properties, such as high thermal conductivity of 2200 W/mK [9], a high Raman gain coefficient of 10.5 cm GW<sup>-1</sup> at 1  $\mu\text{m}$  wavelength [10], a very wide optical transmission window (from 225 nm to far IR) [11], low-birefringence ( $\Delta n < 2 \times 10^{-6}$ ) and a low thermal expansion coefficient  $0.8 \times 10^{-6} \text{ K}^{-1}$ .

In this paper, we report Raman frequency down-conversion of a 1 kW Yb-doped multi-stage fiber amplifier in a linear external diamond Raman cavity. Compared to our previous result [5], the pump is only used in a single pass instead of a double pass in the cavity, greatly reducing back-propagating signal to the amplifier. Quasi-CW output powers of 380 W at the Raman laser wavelength of 1234 nm with a linewidth of 0.12 nm were achieved.

## 2. EXPERIMENTAL

### 2.1 Pump laser system

For continuous wave Raman scattering process in diamond requires a high beam quality and narrow linewidth pump laser for achieving moderate thresholds and an efficient frequency conversion. The experimental set up for the Raman laser is shown in Fig. 1.

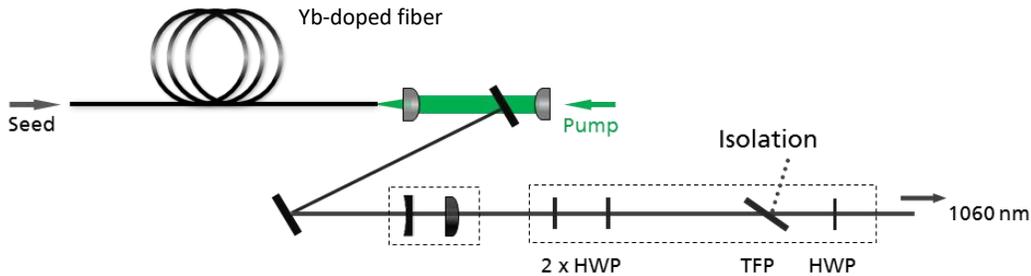


Figure 1. Experimental setup of the pump laser system. The green beam represents the pump for the Yb-doped fiber laser. HWP = half-wave plate, TFP = thin film polarizer

The Yb-doped fiber is seeded with a single frequency external-cavity diode laser prior wavelength of 1060 nm and is protected against back reflections with a Faraday isolator. The seed linewidth output of 0.16 nm is controlled by an external white-noise phase modulation. The fiber amplifier was free space counter-pumped by a fiber-coupled diode laser at 976 nm. The double-clad gain fiber had a length of 17 m, an inner core diameter of 20  $\mu\text{m}$  and a numerical aperture  $\text{NA}=0.06$ . A 1:2 telescope expands the collimated beam up to 3.9 mm diameter. To reduced thermal effects in the lenses at high powers, OH-free fused silica was used. To protect the pump source against backward propagating light from the cavity, a thin-film polarizer and a quarter-wave plate, with the wave-plate axis being oriented at  $45^\circ$  against the polarization direction, is used as isolation, already discussed in [5]. This amplifier generates 10 ms pulses in quasi-cw mode at 10% duty cycle with maximum 1.6 kW on-time output power.

### 2.2 Low-birefringence synthetic diamond

The CVD-grown single-crystal diamond is used as the Raman gain crystal. The crystal sample is 6 mm long, with a 1.5 mm  $\times$  6.0 mm cross-section. The side facets (1.5 mm  $\times$  6.0 mm) are all perpendicular to the  $\langle 110 \rangle$  crystallographic axis (Fig 2).

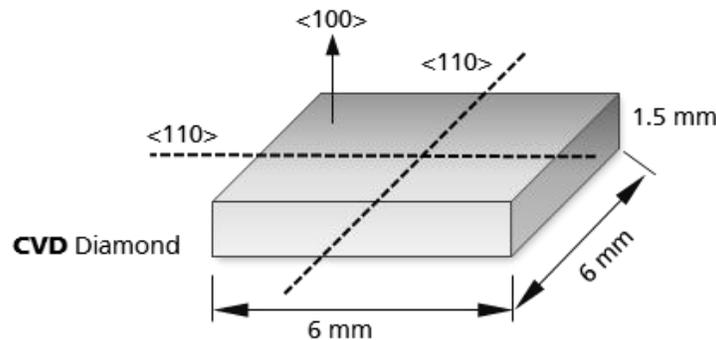


Figure 2. Dimensions and crystallographic orientation of the diamond sample. Crystal growth direction  $\langle 100 \rangle$ , dashed lines perpendicular to the  $\langle 110 \rangle$  crystallographic axes.

An anti-reflection (AR) coating for the pump and Stokes wavelength were applied for the front and back surfaces (side facets - 1.5 mm × 6.0 mm) to reduced loss in the cavity and back reflection into the pump source (Table 1). The design of the coatings was optimized for high laser induced damage threshold and adherence of the coating layers of the diamond substrate. The stress-induced local birefringence has been mapped along the diamond <110> axis using the Mueller polarimetry [12] technique. Figures 3 show the magnitude of the optical path difference through the 6 mm long crystal. The correspond birefringence is plotted below with  $\Delta n = 1.2 \times 10^{-6}$  in the middle region.

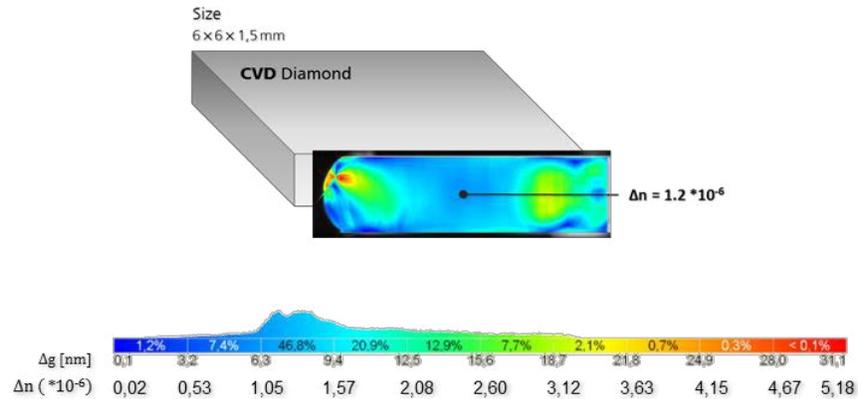


Figure 3. Maps of the optical path difference where  $\Delta n$  is the calculated birefringence with an crystal length of 6 mm. The associated value of  $\Delta n$  is shown the center location which will be used for the diamond Raman cavity.

### 2.3 Diamond Raman oscillator configuration

The optical schematic of experimental setup is shown in Fig. 4. The external Raman oscillator consisting of two concave mirrors (input coupler IC, output coupler OC) and is designed as a linear, near-concentric cavity to provide a small Stokes mode radius in the diamond. The radius of curvature for both mirrors was 100 mm. The combined distances between the IC and OC was 202 mm in order to match the beam waist size of the Stokes field to that of the fundamental field inside the diamond crystal.

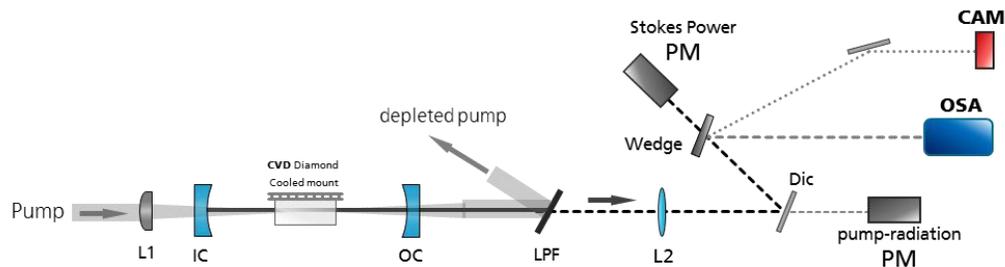


Figure 4. Schematic of the diamond Raman oscillator and the setup for characterization. L1 = 100 mm focus lens, IC = input coupler, OC = output coupler, L2 = 150 mm collimated lens, LPF = long pass filter, Dic = dichroic mirror

The concave IC is highly transparent for the pump wavelength on both sides and highly reflective for the first Stokes wavelength. To avoid critical limitations due to backward-amplified light in the high gain fiber amplifier, the OC is transparent for the pump. The coating specifications for each mirror and the diamond facets are summarized in Table 1.

Table 1. Summary of mirror and diamond coatings.

	Pump (1060 nm)	Stokes (1235 nm)
Mirror 1 (IC) AOI 0°	T = 99%	R > 99,95%
Mirror 2 (OC) AOI 0°	T > 99%	R = 96%
Diamond facets	R < 1%	R < 0.2%

The pump beam is focused into the diamond using a  $f = 100$  mm plan/convex lens (L1) to provide a pump beam spot radius of  $55 \mu\text{m}$  ( $1/e^2$ ), according to an input beam diameter of 3.9 mm. Figure 5 shows the focused beam profile in the center of the cavity.

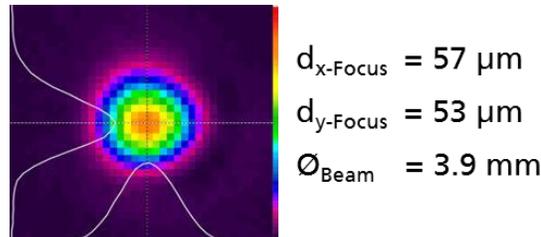


Figure 5. Shows the Focused pump beam profile in the center of the cavity

In order to reduce heating and thermal effects in the lens at high powers, a OH-free fused silica lens was used. The pump beam propagated along the  $\langle 110 \rangle$  axis of the 6 mm long single-crystal diamond and was circular polarized (Section 2.1). The diamond sample is mounted on a water cooled, low vibration copper platform. Additionally, the diamond is slightly tilted to reduced back reflection of the pump from the plane facets of the diamond. The Stokes field collimated with a 150 mm lens and separated from the pump by a dichroic mirror for characterization and detecting of the depleted pump. The optical spectra of the Stokes field were monitored through dichroic mirror using a fiber-coupled optical spectrum analyzer.

## 2.4 Results

The performance and efficiency of the diamond Raman oscillator is shown in Fig. 6. The threshold was approximately 500 W, beyond the output increased linearly with a slope efficiency of 79%. The maximum measured output power was 380 W for 968 W of injected pump power with a conversion efficiency of 39%. The beam propagation factor  $M^2$  of the Stokes output was measured to be 1.2 at the maximum output power.

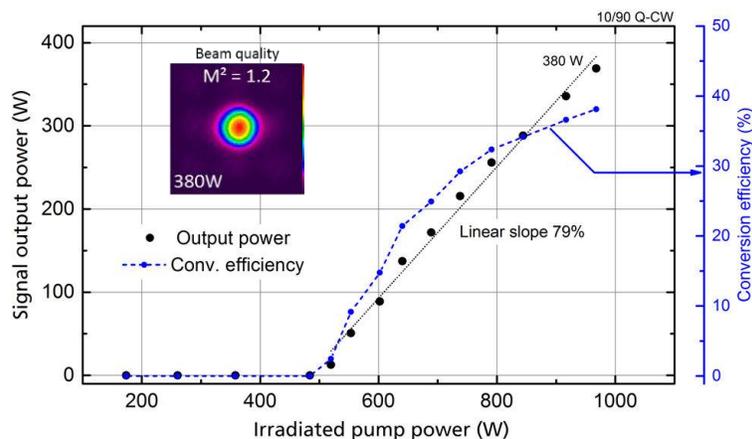


Figure 6. Total Raman output power versus pump power. Power curve of the 380 W diamond Raman oscillator, showing output power (black dots) and conversion efficiency (blue dots / dashed line). The inset image shows the Stokes profile at maximum output power.

The laser was operated in quasi-CW mode with 10 ms on-time duration to determine the performance with a minimum influence by thermal effects in the free beam optics. The measured spectrum is shown in Fig. 7 on a decibel scale. The peak is centered at 1235.5 nm with a spectra linewidth of 0.12 nm. The spectrum is measured with a signal-to-noise ratio (SNR) over 60 dB, no evidence of Brillouin scattering is observed in the spectrum.

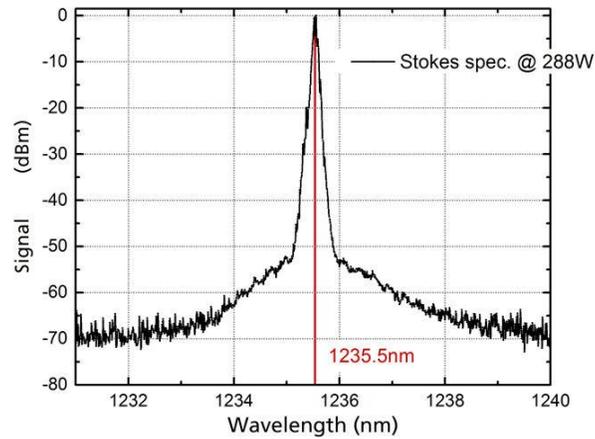


Figure 7. Optical spectrum of the diamond Raman oscillator at 854 W pump power with 288 W output power at 1235.5 nm and 0.12 nm linewidth. The spectral resolution of the optical spectrum analyzer is 0.02 nm.

### 3. CONCLUSION

We have demonstrated single pump pass Raman induced frequency conversion in diamond at high-power levels of 380 W output power (10 ms on-time) and a diffraction limited beam quality of  $M^2 = 1.2$ . This pumping scheme is beneficial for the fiber amplifier, which pumped the diamond laser, as it does not generate parasitic feedback. We achieved total conversion efficiency to the first-Stokes of 39%.

### 4. ACKNOWLEDGMENT

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