High-power deuterium Raman laser at 632 nm

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We demonstrate a continuous-wave deuterium Raman laser that generates more than 160 mW of Stokes output power despite severe thermal effects. This output power represents nearly an order-of-magnitude increase over any previously reported continuous-wave Raman laser and is the first such system to our knowledge that uses deuterium gas as the Raman medium. The high output power is achieved through careful consideration of the electronic feedback design, frequency actuators, and pump-laser intensity noise. © 2004 Optical Society of America

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1. Introduction

Far-off-resonance continuous-wave (cw) Raman lasers in gases have become topics of interest primarily because of their frequency-conversion capabilities and narrow emission linewidths.[1] These systems utilize significant optical power enhancement of both the pump and the Stokes wavelengths within high-finesse cavities (HFCs) to compensate for the meager far-off-resonance Raman gain. Previous systems have employed hydrogen as the Raman medium[1–4] and have demonstrated lasing on both vibrational and rotational Raman transitions.[1–4] The output powers observed from these devices have thus far been limited to approximately 20 mW by the available pump powers.[4] Thermal effects that are inherent in the inelastic Raman laser process have also been observed and have complicated the creation and behavior of these devices. These effects include Raman laser cavity length tuning and thermal lensing.[5,6] In hydrogen gas, tens of megahertz of cavity mode pulling are observed per milliwatt of generated Stokes power for typical cavities.[5] The thermal lensing causes the resonant pump and Stokes cavity modes to depend on the generated Stokes optical power.[5,6] These thermal effects have significant ramifications on the steady-state behavior as well as the Raman laser design.

In this paper we present a cw Raman laser in deuterium gas, with generated output powers in excess of 160 mW. Deuterium is chosen because of its 2987-cm^{-1} Raman shift. This shift can ultimately lead to a red (Stokes 633-nm), green (pump 532-nm), and blue (anti-Stokes 459-nm) device with a single pump source. A significant thermal lens is observed that changes the laser mode spot size by 50%. This manuscript is outlined in the following manner: In Section 2 we describe the methods required to stabilize a high-power cw Raman laser. In Section 3 we describe the cw Raman laser apparatus and provide threshold data. In Section 4 we describe the observed thermal effects of the laser, and in Section 5 we provide some concluding remarks.

2. Discussion of High-Power Raman Laser Stabilization

As discussed in previous publications,[1–4,7] the pump laser must be frequency stabilized to a HFC that contains the Raman gas. The thermal mode pulling significantly complicates this task. First, a minimum servo bandwidth of ~100 kHz is typically required to suppress thermal instabilities even when the pump-laser's linewidth is very narrow[7] ($\Delta\nu_{\mathrm{pump}} << \Delta\nu_{\mathrm{HFC}}$). Second, the choice of optical frequency actuators and their relative influence at various Fourier frequencies becomes critical. Specifically, if corrections are performed solely on the pump-laser frequency and not the HFC length, then the intensity-dependent mode pulling results in optical frequency tuning and frequency fluctuations of the

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Stokes laser output for Fourier frequencies below the characteristic thermal response of the medium.[7] Because of these effects, the preferred frequency stabilization scheme is to perform low-Fourier-frequency corrections to the HFC length with a piezoelectric transducer (PZT) with the laser acting as the frequency reference, and the high-Fourier-frequency corrections are performed on the pump-laser's optical frequency with the HFC acting as the frequency reference. In this way, the thermally induced optical cavity length instabilities are compensated by physical cavity length changes. In practice, the crossover point for the frequency actuator stability loops (from the cavity PZT to the laser frequency actuator) is typically limited by the frequency response of the Raman cavity PZT to $<$1 kHz. The ideal crossover point, which minimizes the thermal frequency noise effects, is typically an order-of-magnitude larger than this and is determined by the maximum Fourier frequency of the thermal medium response.[7]

Unfortunately, the thermal mode pulling not only dictates the proper Fourier frequencies for when we perform the optical frequency corrections, it can also place significant demands on the performance of the frequency actuators. In a Raman laser, some of the optical power as well as the intensity noise of the pump laser is transferred to that of the Stokes laser output.[1,8] Furthermore, the Stokes optical power and intensity noise are coupled to frequency fluctuations through the thermally induced cavity length fluctuations. Because these cavity length fluctuations can be quite large in magnitude (relatively speaking) and at moderate Fourier frequencies, the feedback actuators' slew rates and dynamic ranges become critical performance characteristics. The precise performance requirements depend, of course, on the amount of output Stokes optical power and intensity noise. For example, a 100-mW Raman laser with 1% intensity noise will exhibit frequency instabilities of the order of 20 MHz. These frequency instabilities will typically occur between frequencies of 1 and 10 kHz where the lower limit is determined by the Raman PZT loop filter bandwidth, and the upper limit is determined by the medium response.[7] As a result, these frequency instabilities are corrected by the pump-laser's frequency actuator, thereby setting its slew rate and dynamic range requirements. Therefore we believe it is worthwhile to spend some time reducing the intensity noise of the input pump laser to ease the burden on the actuators.

We reduced the intensity noise by using an electro-optic noise eater, wherein an electro-optic modulator and a polarizing beam splitter are configured to vary the pump-laser optical power. Because an electro-optic modulator is used, the correction bandwidth electronic is limited to approximately 500 kHz. The feedback signal for the noise eater was taken after the HFC, and the noise eater loop filter was tailored for the low-pass characteristic of a HFC. By use of a feedback signal after the HFC, the noise eater effectively increases the locking bandwidth of the Raman HFC loop. Although the noise eater does not change the frequency of the pump laser, it does stabilize the HFC length. By reducing the intensity noise circulating inside the HFC, the intensity-dependent changes in the index of refraction are reduced. This minimizes the frequency pulling induced by medium heating. The experimental results demonstrated in this study were obtained only with substantial pump-laser intensity noise reduction, which we discuss in Section 3.

3. Raman Apparatus and Laser Threshold

Figure 1 shows the experimental schematic of the cw deuterium Raman laser. The Raman laser cavity is composed of two ultralow-loss mirrors with highly reflective coatings for both the pump and the Stokes wavelengths, which are spaced by three 1-in. (2.54-cm) cylindrical PZTs. The Raman cavity free spectral range is 2 GHz and the PZT actuator coefficient is 44 MHz/V. The Raman cavity is enclosed in a hermitically sealed container filled to 8 atm of D_2, giving a Raman linewidth of 1.06 GHz.[9] The Raman gain coefficient is 0.45 cm/GW at 633 nm, which is approximately a factor of 5 smaller than that measured in hydrogen.[9,10] The Raman shift in deuterium is 2987 cm^{-1}, and the thermally induced mode pulling is $\sim$25 MHz/mW. Thus 100 mW of Stokes power causes Raman cavity mode pulling of 2.5 GHz or 57 V. The maximum frequency response of the PZT servo system is limited by PZT resonances less than 1 kHz.

The HFC is optically pumped by a 10-W, single-mode, frequency-doubled cw Nd:YAG laser (Coherent Verdi V-10) with a free-running laser linewidth of 1 MHz; the amplitude noise of the laser is below 1%. Frequency corrections are performed on the pump laser by means of double passing an acousto-optic modulator.[11] The actuator coefficient is 8 MHz/V and the maximum tuning range is 40 MHz. Thermal issues present in the acousto-optic modulator limit the optical pump power below 2 W. The Pound–Drever–Hall method is used to phase and frequency lock the pump laser to a Raman cavity resonance[12] for optical power buildup. The HFC converts pump frequency noise to amplitude noise within the cavity bandwidth. As a result, further amplitude noise reduction is achieved with an electro-optic modulator, thereby extending the effective correction bandwidth to approximately 500 kHz. Optical feedback for the noise reduction feedback is taken at the exit of the HFC. The optical pump power is adjusted by a change in the lock point of the noise reduction feedback loop. A small portion of the beam is diverted by a glass slide to monitor the pump power. A prism is used to spatially separate the pump and Stokes beams at the exit of the Raman cavity. Calibrated photodiodes are used to measure the output power of the Raman cavity.

Figures 2 and 3 show the output Stokes power and transmitted pump power as functions of the pump power incident on the cavity, respectively. The experimental data are represented by circles for both

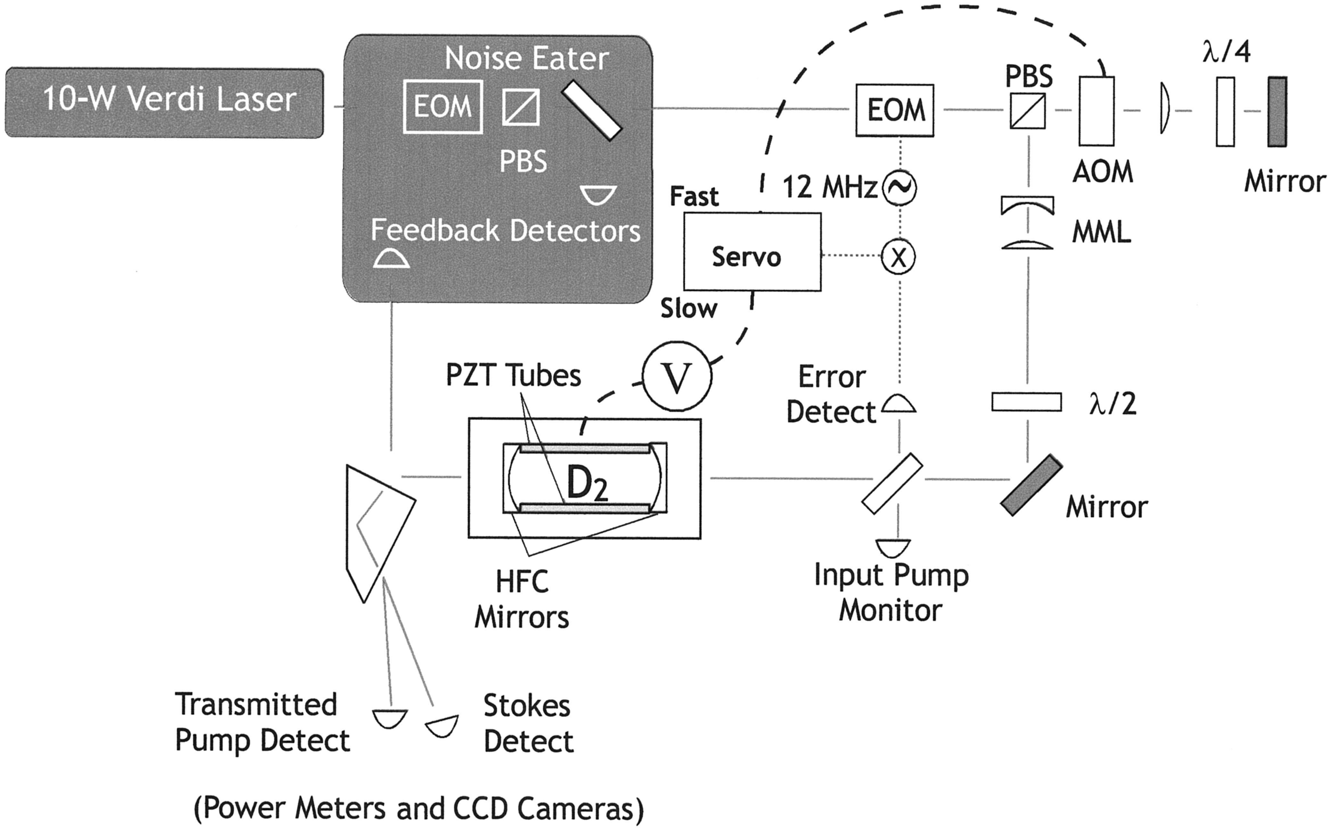

Fig. 1. Experimental diagram of the cw deuterium Raman laser. EOM, electro-optic modulator; PBS, polarizing beam splitter; AOM, acousto-optic modulator; MML, mode-matching lens.

the output Stokes power and the transmitted pump power. Theory describing the deuterium Raman laser, which includes thermal effects, is shown by the dashed curves.[6,8,13] The pump and Stokes mirror reflectivies are measured to be 0.99555 ± 0.00005 and 0.99987 ± 0.00001, respectively, by cavity ring-down. The empty cavity coupling efficiency is measured to be $65 \pm 3\%$. The plane-wave gain coefficient used in the fit was 0.34 GW/cm, compared with 0.45 GW/cm that was used in Ref. 9. This discrepancy is believed to be a result of the Stoke laser's being detuned from the Raman resonance. There is a region of instability in the output power observed at approximately two times the threshold. Similar instabilities were previously reported[4] and may be caused by a resonance between the servo control electronics and the heating of the Raman active medium.

Deviations from the theory at pump powers greater than 200 mW occur for the transmitted pump power,

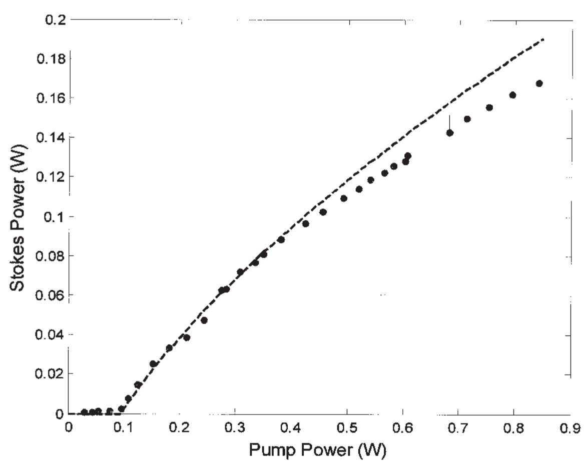

Fig. 2. Output Stokes power as a function of incident pump power.

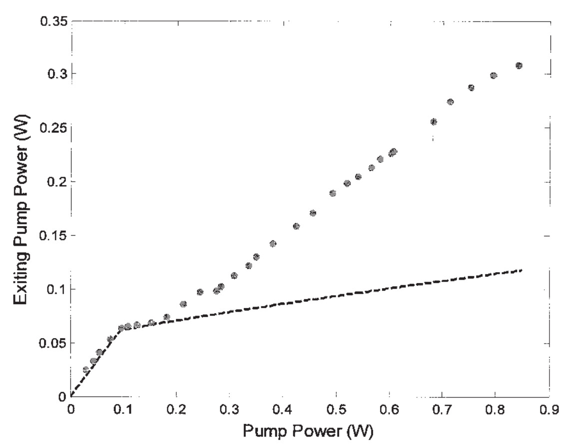

Fig. 3. Exiting pump power as a function of incident pump power.

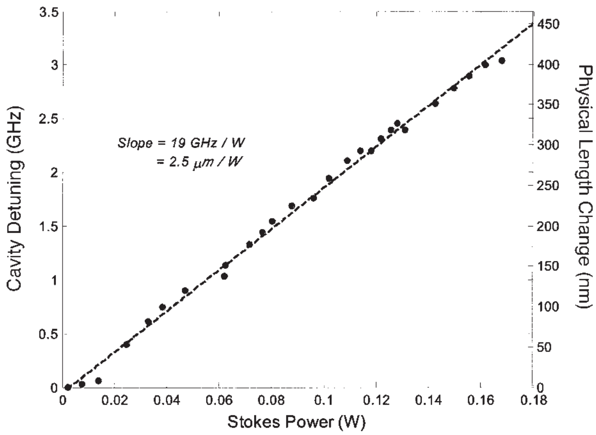

Fig. 4. Cavity detuning as a function of emitted Stokes power.

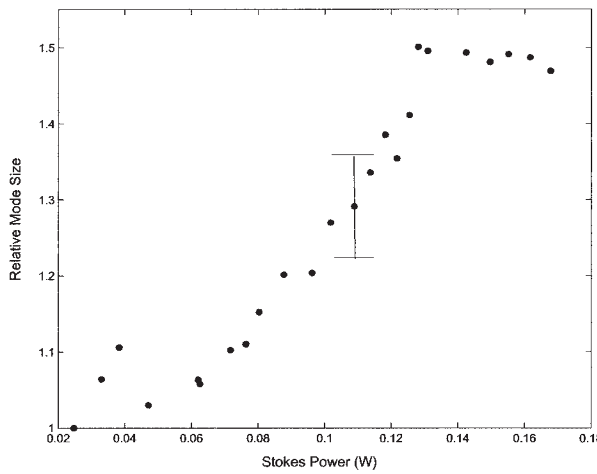

Fig. 5. Laser mode spot-size change as a function of emitted Stokes power.

whereas significant deviations are not observed until 400 mW for the Stokes output power. This discrepancy in optical power can be attributed to the uncertainty in the mirror absorptions, whereas deviations from the theory may be a combination of mirror heating (which renders the coupling efficiency that was calculated below threshold invalid) and assumptions of the thermal model. The thermal model approximates the heat addition as a quadratic duct[8,14] that cannot predict spherical aberrations caused by the thermal lens at higher powers. The spherical aberrations will decrease the quality factor of the HFC, increasing the Raman laser threshold. A subtle effect may be caused by the high circulating powers inside the HFC. For a pump power of 825 mW, 165 mW of Stokes power is generated with 313 mW of pump power transmitted through the cavity corresponding to internal mirror irradiances of 2.0 and 0.25 MW/cm^2 for the Stokes and pump beams, respectively. The damage threshold of these mirrors is estimated to be 10 MW/cm^2. However, heating will cause the dielectric stacks of the mirrors to distort and the stack period to change, which can distort the spatial mode and reduce the effective mirror reflectivities. This effect will therefore limit the maximum irradiance inside the resonator. The resulting distortions were not investigated in this study.

4. Thermal Optical Lens and Spatial Output Mode

As stated in Section 1 the inelastic-scattering process associated with the Raman scattering leads to a quanta of heat being released with each Stokes photon. When the output powers become large (over 100 mW), the spatial mode of the laser resonator and the resonant frequency of the cavity change significantly. Figure 4 shows the change in the physical cavity length as a function of output power. To maintain lasing we compensate for the thermal effects on the laser cavity length by adjusting the physical cavity length. For 160 mW of Stokes power, the physical length of the cavity must change by approximately 0.5 μm corresponding to 3 GHz of cavity tuning. One concern is that, with this large amount of cavity detuning, the resonant Stokes mode will detune from the Raman resonance. In the case of deuterium, the index of refraction at 532 and 632 nm differ by only approximately 10 parts per million; thus for 3 GHz of tuning, only a relative detuning of 30 kHz is seen. This small detuning has a minimal effect on the Raman laser gain because the pressure-broadened linewidth is of the order of 1 GHz.

The medium heating will also create a thermal lens that will alter the mode spot size of the Raman laser and introduce spherical aberrations. The mode diameter as a function of Stokes output power is shown in Fig. 5. For large output powers a 50% change in laser mode spot size is observed. The increase in mode spot size has the effect of increasing the Raman laser threshold by more than a factor of 3, as can be seen by the change in throughput pump power shown in Fig. 3. Changes in the mode spot size of the Raman laser will ultimately limit the output power of the Raman laser. We did not undertake characterization of the spherical aberrations as a function of output power. We point out that, by careful design of the Raman cavity, these thermal effects can be reduced by a factor of 2–5, allowing for output powers on the several-watt level for a static gas cell. Additional output power can be achieved in a flowing gain system.

5. Conclusions

In conclusion, we demonstrated a high-power cw deuterium laser. Despite an order-of-magnitude reduction in laser gain compared with hydrogen, we generated 165 mW of Stokes power. The high output power was possible only through reductions in the pump-laser intensity noise and proper frequency actuator considerations. The existing thermal models predict the behavior of this laser well for lower output powers, but deviate for higher powers. The observed deviations may be due to thermally induced warping of the high-finesse mirrors, which has not yet been theoretically modeled to our knowledge.

The Raman output power is still limited ultimately by the available input power.

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