# Widely tunable continuous-wave Raman laser in diatomic hydrogen pumped by an external-cavity diode laser

**L. S. Meng, K. S. Repasky, P. A. Roos, and J. L. Carlsten**

*Department of Physics, Montana State University, Bozeman, Montana 59717*

Received December 8, 1999

What is to the authors' knowledge the first experimental demonstration of a nonresonant cw Raman laser pumped by a tunable external-cavity diode laser (ECDL) is presented. The ECDL is phase-frequency locked to a high-finesse Raman laser cavity containing diatomic hydrogen ($H_2$) by the Pound–Drever–Hall locking technique. The Stokes lasing threshold occurs at a pump power of 400 ± 30 $\mu$W, and a maximum photon conversion efficiency of 12.0 ± 1.3% is achieved at 1.6 mW of pump power. A 40-nm tuning range of the cw Stokes emission, 1174–1214 nm, is obtained by tuning of the wavelength of the ECDL pump source. © 2000 Optical Society of America

*OCIS codes:* 140.3550, 140.3600, 190.2640, 190.2620, 300.6340.

The cw nonresonant Raman laser was realized by Brasseur *et al.* in 1998.[1] It was fabricated with a high-finesse cavity[2] (HFC) filled with a Raman gain medium of diatomic hydrogen ($H_2$) and was pumped by a frequency-doubled Nd:YAG laser. Making the HFC doubly resonant at both the pump and Stokes wavelengths produced cw Stokes output. This system exhibited ~2-mW threshold, indicating the possibility of pumping with diode lasers. Roos *et al.* then demonstrated a diode-pumped cw Raman laser, using a free-running diode laser and a passive optical locking technique.[3] However, accurate wavelength selectivity was difficult with the passively locked system, and the tuning range was limited to only 10 nm.

Since its appearance, the external-cavity diode laser (ECDL) has become a widely used and commercially available laser source because of its compactness, relatively low cost, and broad tunability. We describe a cw Raman laser pumped by an ECDL and employing the active electronic locking, Pound–Drever–Hall technique.[4] Using this pumping mechanism and locking technique, we obtain widely tunable and highly stable cw Raman-shifted output in the near-infrared spectral region (1174–1214 nm).

The ECDL pump source uses a 100-mW laser diode with a center wavelength of 792 nm in a Littman-style external cavity.[5] With appropriate alignment of the laser diode and the external cavity, single-longitudinal-mode laser output with 50-dB side-mode suppression ratio is obtained. The output wavelength can be tuned over an 18-nm range (from 789 to 807 nm) by adjustment of the external cavity length. Mode hops occur over this tuning range because the diode possesses only a standard manufacturer's antireflection coating of approximately 2–5%. However, large ranges of mode-hop-free continuous tuning are not useful for this application because the continuous-tuning range of the Stokes output is limited instead by the double-resonance requirement of the high-finesse cavity (HFC; of the order of the Raman gain linewidth, ~500 MHz FWHM[6]). When a standard, commercially available diode with no additional antireflection coating is used, the ECDL exhibits ~20-GHz continuous tuning, which is more than sufficient for tuning over the entire Raman resonance.

Figure 1 illustrates the experimental setup. First the output beam from a temperature-stabilized ECDL passes through an anamorphic prism pair to have its elliptical spatial shape corrected. Two Faraday isolators are used to minimize optical feedback to the ECDL. Next the laser beam travels through two lenses that mode match the beam into the HFC.[2] An electro-optic modulator (EOM) is used to add rf sidebands (12 MHz in this setup) on the optical carrier frequency as required for Pound–Drever–Hall locking. The combination of a polarizing beam splitter (PBS) and a quarter-wave plate ($\lambda/4$) allows for a photodetector (D1) to receive the reflected light from the front mirror of the HFC. A rotatable half-wave plate ($\lambda/2$) is placed before the PBS to vary the incident pump power on the HFC. A 12-MHz electronic sine-wave generator serves as the local oscillator. The 12-MHz signal is sent to the electro-optic modulator as well as to an electronic mixer. The mixer multiplies this 12-MHz sine

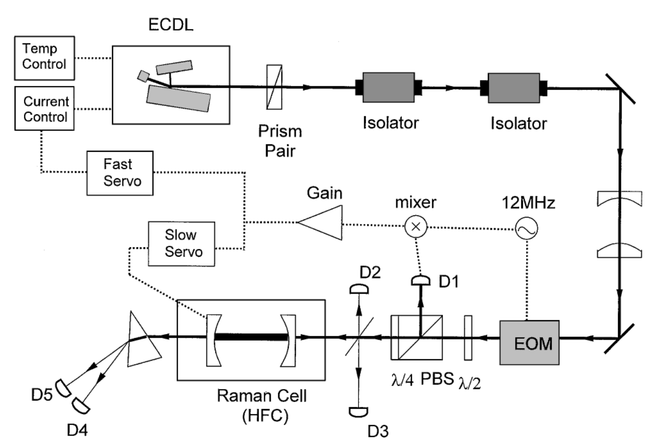


Fig. 1. Experimental setup. A beam splitter with 5% transmission at the pump wavelength is used before the cavity to monitor the input pump power (detector D3) and the reflected pump power (D2). Two other detectors, D4 and D5, are put behind the cavity to measure the power of the transmitted pump and the Stokes beams. Dotted lines represent electronic wires.

0146-9592/00/070472-03$15.00/0 

wave with the detected signal from the cavity reflection to produce an error signal. The error signal is then received by two electronic servos. The fast servo feeds the error signal back to the ECDL's current controller for fast corrections to the laser's frequency (from dc to 1.4 MHz). At the same time the slow servo sends feedback to the HFC's piezoelectric transducer to adjust the HFC's length slowly (from dc to 1.5 kHz). With a low-noise error signal and appropriate servo responses the ECDL and the HFC can be locked stably. The HFC is enclosed within a hermetically sealed container filled with 10 atm of $H_2$ gas.

By setting the ECDL's output wavelength to 795 nm we obtain Stokes emission at 1187 nm. We measure the power of the transmitted pump, the reflected pump, and the transmitted Stokes beam from the HFC while varying the input pump level. Figure 2 shows the results of these measurements. The apparent threshold, which does not account for mode-matching losses into the HFC, is measured to be 570 ± 30 $\mu$W. From the behavior of the system below threshold, the coupling efficiency into the HFC can be calculated to be 70.4 ± 0.2%.[7] When we account for this imperfect coupling, the real threshold is 400 ± 30 $\mu$W.

The curves in Fig. 2 are the predictions from theory.[8–10] To fit the theory and the data, we first obtain the HFC's mirror reflectivities $R_p = 0.99996$ at the pump wavelength and $R_s = 0.99993$ at the Stokes wavelength measured from cavity ringdowns.[11] The mirror transmission and the coupling efficiency for the pump can be calculated from the cavity behavior below threshold,[7] i.e., $T_p = 33$ parts in $10^6$ and $C = 70.4\%$. The HFC's length is $l = 7.63$ cm, and its confocal parameter is $b = 26.5$ cm. Then the best fit is obtained by choice of these two parameters: $\alpha_g = 0.82 \times 10^{-9}$ cm/W (Raman plane-wave gain coefficient[12]) and $T_s = 20$ parts in $10^6$ (mirror transmission at the Stokes wavelength). We find that the theory agrees well with the experimental data. The Raman plane-wave gain coefficient predicted by the empirical formulas in Ref. 12 is $1.53 \times 10^{-9}$ cm/W for a pump wavelength of 795 nm and 10-atm $H_2$ pressure. One possible reason for the nearly 50% lower gain coefficient in our study is the polarization losses that are due to the birefringence in the HFC mirror coatings. In addition, for the transmitted pump there is some disagreement near threshold. Both of these discrepancies are currently under investigation.

Photon conversion efficiency as a function of input pump power is shown in Fig. 3. The curve and the open circles represent theory and experimental data, respectively; again the data agree with theory very well. The maximum photon conversion efficiency is 12.0 ± 1.3% and occurs at 1.6-mW coupled input pump power. The reason for this rather low efficiency is the large initial pump reflection from the HFC's front mirror (see Fig. 3; 8.7 of 12-mW pump power is reflected). If we lowered the reflectivity of the front mirror for the pump such that more pump power could enter the cavity, higher conversion efficiency would be expected to occur. Indeed, our theory has predicted that >80% photon conversion efficiency can be realized if we use asymmetrically coated mirrors.[9]

This cw Raman laser exhibits wide discrete tunability in the near infrared. The ECDL that we use as the pump laser emits a single longitudinal mode when it is tuned from 789 to 807 nm, which results in cw Stokes beams from 1174 to 1214 nm (the Raman shift in $H_2$ is 4155 cm$^{-1}$). This gives a 40-nm wavelength tuning range. Figure 4 shows the wavelength measurements of the pump and Stokes beams. When we set the pump laser at three different wavelengths (top): 789, 798, and 807 nm, we obtain the Stokes beams (bottom) at 1174, 1194, and 1214 nm, respectively. The Stokes tuning range is determined by the tunability of the pump. For example, an ECDL with a tuning range of more than 40 nm at 825 nm has been made.[13] A

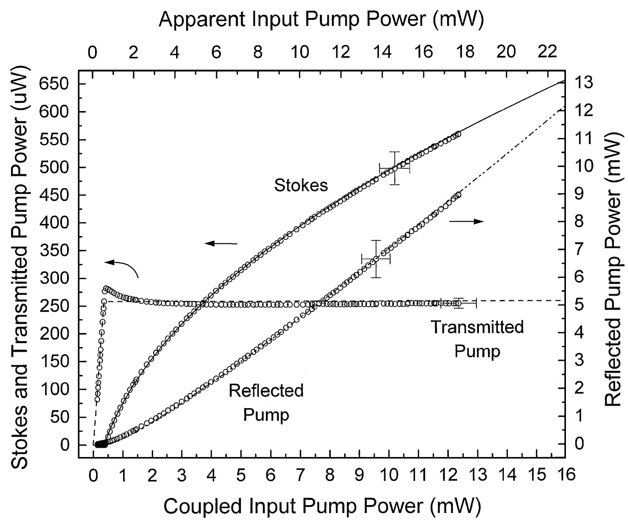


Fig. 2. Experimental data and theoretical fits of the ECDL-pumped cw Raman laser. Open circles, measured powers of the cavity transmitted pump, reflected pump, and Stokes beams as we change the input pump power. Curves, predictions from theory. The apparent threshold is 570 ± 30 $\mu$W; the actual threshold is 400 ± 30 $\mu$W because of the 70.4% coupling efficiency.

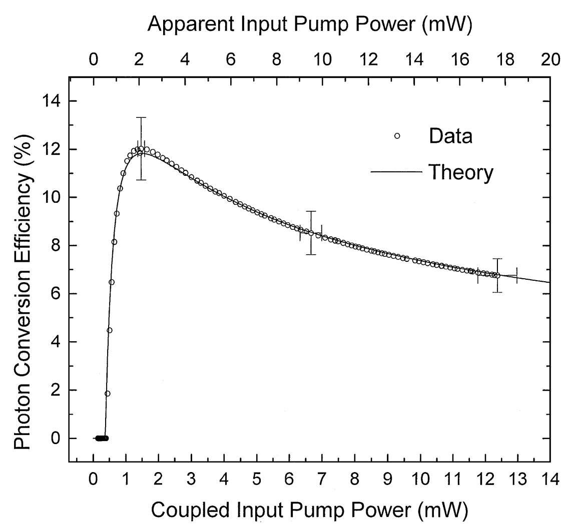


Fig. 3. Photon conversion efficiency from pump to Stokes beams as a function of input pump power. The maximum efficiency is 12 ± 1.3% and occurs at 1.6-mW input pump power.

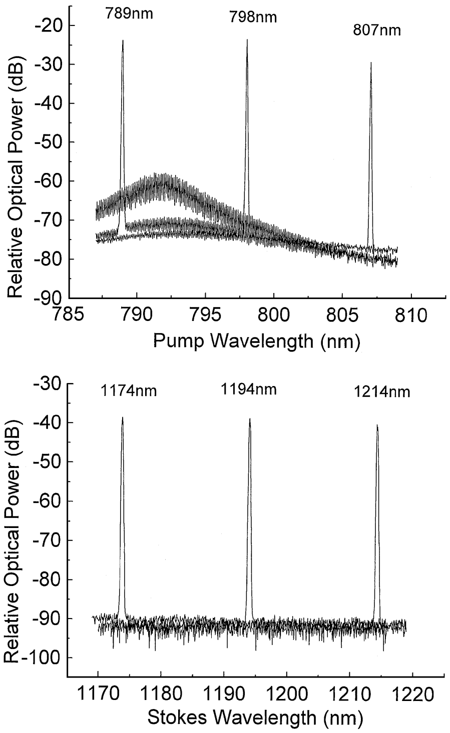


Fig. 4. Tunability of the ECDL-pumped cw Raman laser. The 18-nm wavelength range of the pump beam (top) results in a 40-nm tunable Stokes beam (bottom). The wavelength measurements were taken with a HP optical spectrum analyzer. Top, when the ECDL pump laser is tuned to its long-wavelength limit of 807 nm the background emission starts to rise, as shown by the broad emission near 792 nm.

cw Raman laser in $H_2$ pumped by such a source will produce a Stokes output that has a 92-nm tuning range if, of course, the high-reflection mirror coating can satisfy the same bandwidth. It should be noted that, as we have pointed out, because of the double-resonance requirement a full-range continuous tuning of the Stokes emission is not possible under the current configuration. For the system that is demonstrated in this Letter, 1.5-GHz continuous tuning with the fundamental Gaussian spatial mode of the Stokes output is measured.

The Stokes output shows excellent short-term and long-term power stability. Power fluctuations of 0.5% have been measured over times of 10 min, and of less than 5% during 7 h. This power stability together with the broad tunability and predicted high spectral purity[10] make the ECDL-pumped cw Raman laser highly useful for laser spectroscopy, atomic physics, and remote sensing for which conventional diode lasers cannot reach the proper wavelengths for the respective absorptions and resonances.

This research is supported by National Science Foundation grant PHY-9731602. We thank Greg Switzer for providing the ECDL and Pete Sellin and Jay Brasseur for their help with diode-laser locking. J. L. Carlsten's e-mail address is carlsten@physics.montana.edu.

## References

1. J. K. Brasseur, K. S. Repasky, and J. L. Carlsten, Opt. Lett. **23,** 367 (1998).
2. K. S. Repasky, L. E. Watson, and J. L. Carlsten, Appl. Opt. **34,** 2615 (1995).
3. P. A. Roos, J. K. Brasseur, and J. L. Carlsten, Opt. Lett. **24,** 1130 (1999).
4. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B **31,** 97 (1983).
5. T. Day, M. Brownell, and I. F. Wu, Proc. SPIE **2378,** 35 (1995).
6. W. K. Bischel and M. J. Dyer, Phys. Rev. A **33,** 3113 (1986).
7. Below the Stokes threshold, the reflected pump power $P_r$ and the transmitted pump power $P_t$ are both linear functions of the incident pump power: $P_r = B_r P_{i0}$ and $P_t = B_t P_{i0}$, where $B_r = [R(1 - T - R)^2/(1 - R)^2]C + R(1 - C)$ and $B_t = [T^2/(1 - R)^2]C$ are two constants related to mirror reflectivity $R$, transmission $T$, and cavity coupling efficiency $C$. From the data below threshold in Fig. 2, we found that $B_r = 0.318 \pm 0.0007$ and $B_t = 0.476 \pm 0.001$. Using $R = 0.99996 \pm 0.00001$ measured from cavity ringdown, we can calculate that $T = (33 \pm 0.1) \times 10^{-6}$ and $C = (70.4 \pm 0.2)\%$.
8. K. S. Repasky, J. K. Brasseur, L. Meng, and J. L. Carlsten, J. Opt. Soc. Am. B **15,** 1667 (1998).
9. K. S. Repasky, L. Meng, J. K. Brasseur, J. L. Carlsten, and R. C. Swanson, J. Opt. Soc. Am. B **16,** 717 (1999).
10. J. K. Brasseur, P. A. Roos, K. S. Repasky, and J. L. Carlsten, J. Opt. Soc. Am. B **16,** 1305 (1999).
11. G. Rempe, R. J. Thompson, and H. J. Kimble, Opt. Lett. **17,** 363 (1992). The Stokes cavity ringdown is performed with a laser source at 1178 nm. The mirror reflectivity quoted by the manufacturer (Research ElectroOptics, Inc.) is 0.99995 for both the pump and the Stokes wavelengths.
12. W. K. Bischel and M. J. Dyer, J. Opt. Soc. Am. B **3,** 677 (1986).
13. D. Wandt, M. Laschek, K. Przyklenk, A. Tunnermann, and H. Welling, Opt. Commun. **130,** 81 (1996).