Two micron continuous wave laser for optical detection of carbon dioxide

Kevin S. Repasky, Christopher Melton, John L. Carlsten, Joseph A. Shaw, and Lee H. Spangler

Kevin S. Repasky
Electrical and Computer Engineering, Cobleigh 610, Montana State University, Bozeman, MT 59717
Phone 406 994-6082, Fax 406 994-5958, repasky@ece.montana.edu

Abstract

Measuring and monitoring carbon dioxide (CO_2) levels can be achieved optically by measuring the transmission of a continuous wave (cw) laser as it tunes across an absorption feature of CO_2. Calculations indicate that the transmission for a 200m path length will drop by 25% as a laser is tuned across a CO_2 absorption line near 1.955μm. We report on the development of a tunable cw laser near two microns for optically sensing CO_2 concentrations.

I. Introduction

The increase in the atmospheric concentration of carbon dioxide (CO_2) resulting from fossil fuel burning can affect the balance of heat trapped by the Earth's atmosphere and influence the long term climate. A proposal to alleviate the amount of CO_2 released into the atmosphere is based on the sequestration of the CO_2 in underground aquifers and porous rock layers. The effectiveness of the underground storage of the carbon dioxide will be compromised if any of the carbon dioxide leaks back into the atmosphere. Thus a sensitive method of above ground monitoring for carbon dioxide leaks is needed.

A plot of the transmission through a 200m path length as a function of wavelength is shown in figure 1 using the 1976 standard atmospheric model[1]. Near 2μm, the absorption of CO_2 affects the transmission properties of the atmosphere. The percent transmission through the atmosphere changes as the concentration of CO_2 changes allowing for optical monitoring of CO_2 concentrations. An optical detector for CO_2 monitoring requires a laser source capable of tuning onto and off of one of the absorption features seen in figure 1. In this paper, a design for a tunable continuous wave (cw) laser near 2μm for optical measurements of CO_2 concentrations is presented. The laser is based on the nonlinear Raman scattering process.

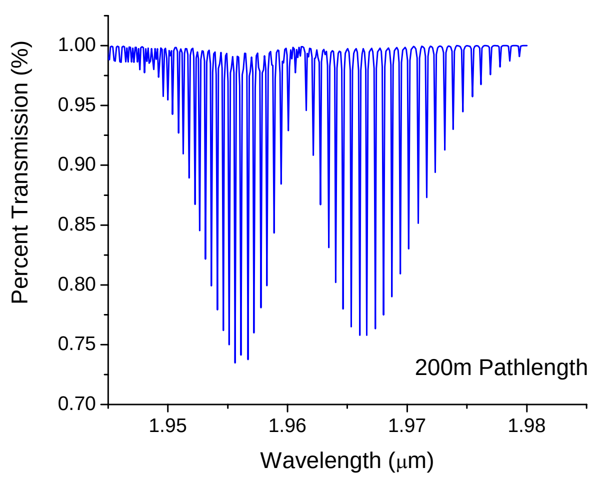

Figure 1 Atmospheric transmission near 2μm due to CO_2.

The paper is organized as follows. Section II contains an introduction to Raman scattering and Raman lasers. The design of a tunable Raman laser near 2μm is presented in section III. Finally, some brief concluding remarks are given in section IV.

II. Raman Scattering and Raman Lasers

The Raman scattering process is shown in figure 2. A pump photon is incident on a molecule initially in its ground state. The pump photon scatters off of the molecule leaving the molecule in an excited state. From conservation of energy, the scattered photon has less energy than the incident photon and thus has a longer wavelength. The scattered photon is referred to as the Stokes shifted photon.

The difference between the ground state and first excited vibrational state of diatomic hydrogen is 4155cm^{-1}. A pump laser with a wavelength of 1.075μm incident on diatomic hydrogen will produce a scattered photon with a Stokes shifted wavelength of 1.943μm. As the wavelength of the pump photon changes, the wavelength of the scattered Stokes photon must change accordingly so that the energy difference between the two photons remains 4155cm^{-1}.

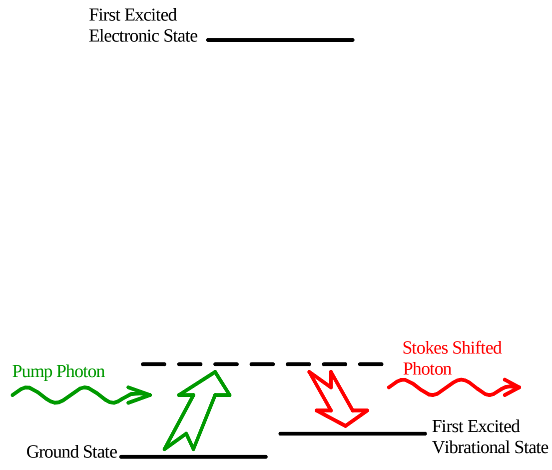

Figure 2 A schematic of the Raman scattering process.

A Raman laser based on Raman scattering can be realized as shown schematically in figure 3. A tunable external cavity diode laser (ECDL) is used as a pump laser. The

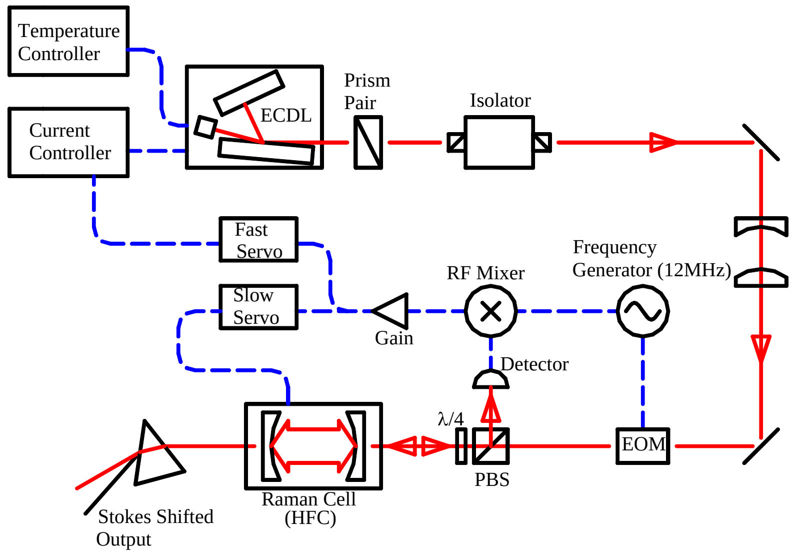

Figure 3 Schematic of a tunable cw Raman laser. A tunable ECDL is used to pump a Raman laser cavity filled with diatomic hydrogen to produce a Stokes shifted output.

ECDL passes through a Faraday isolator that prevents optical feedback from affecting the performance of the ECDL. Light next passes through mode matching lenses that allow the pump beam to be mode matched with the non confocal Raman laser cavity. After the mode matching lenses, the light passes through an electro optic modulator that allows frequency side bands to be added to the laser output. The output of the electro optic modulator passes through a polarizing beam splitter and a quarter wave plate producing circularly polarized light. The light is finally incident on the Raman laser cavity. Light reflected from the front of the Raman laser cavity passes back through the quarter wave plate producing polarized light that is rejected by the polarizing beam splitter and directed to a detector. The RF driver for the electro optic modulator beats with the reflected light from the Raman laser cavity to provide an error signal used for frequency locking the pump laser and Raman laser cavity. This error signal passes through electronic locking servos allowing the pump laser and Raman laser cavity to remain frequency locked.

The Raman laser cavity consists of two curved highly reflective mirrors. Typically, the mirrors have a radius of curvature between 0.5m to 1m and are separated by 5cm to 50cm, thus the Raman laser cavity is in a non confocal configuration. The mirrors are highly reflective at both the pump and Stokes shifted wavelengths. Typical reflectivity for the Raman laser cavity mirrors at the two wavelengths is greater than 99.99%. Thus, the Raman laser cavity is a high finesse cavity with high inter-cavity optical intensities.

The first diode pumped cw Raman laser was demonstrated at Montana State University[2]. A tunable external cavity diode laser in a Littrow cavity configuration was used as a pump laser. Figure 4 shows the output power as a function of wavelength for the pump laser that can be tuned between 798nm and 807nm. This laser was used to pump a Raman laser cavity formed by two high reflectivity mirrors and filled with diatomic hydrogen. The Stokes shifted output of the Raman laser is shown in figure 5 in which the optical power is plotted as a function of wavelength. The pump laser can be tuned from 789nm to 807nm and the corresponding Stokes shifted output tuned between 1174nm to 1214nm as expected from the Raman shift of 4155cm^{-1}.

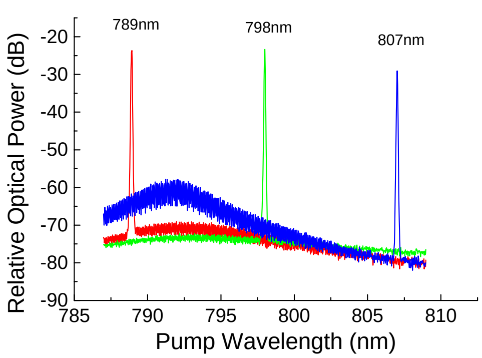

Figure 4 Plot of the output power as a function of wavelength for the pump laser.

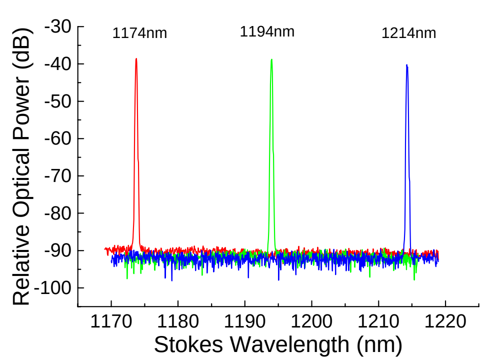

Figure 5 Plot of the output power as a function of wavelength of the Stokes shifted output of the Raman laser

III. 2μm Raman Laser

A semi-classical theory that takes into account the Raman scattering process in the Raman laser cavity has been developed and presented in the literature[3]. Using the results of the semi-classical theory, performance of a cw Raman laser near 2μm was modeled. The parameters used in the modeling of the cw Raman laser include a pump wavelength of 1.077μm corresponding to a Stokes shifted wavelength of 1.949μm. The cavity mirror parameters include a reflectivity at both the pump and Stokes wavelength of 99.99% and a mirror absorption of 50ppm. The cavity length was set at 7.6cm. A plot of the output power at the Stokes shifted wavelength as a function of the input pump power is plotted in figure 6. A lasing threshold of 3mW is expected for the cw Raman laser.

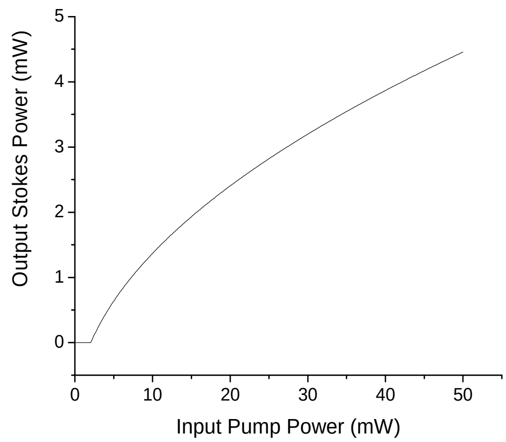

Figure 6 A plot of the output optical power as a function of the input pump optical power. The lasing threshold pump power of 3mW is see in this plot.

The realization of the 2μm Raman laser is based on the schematic shown in figure 3. A tunable external cavity laser based on a diode laser with a center wavelength of 1.075μm and placed in a Littrow cavity configuration was built as the pump laser. A picture of this laser is shown in figure 7. Light from the diode laser is collimated using an aspheric lens with a focal length of 4.5mm and a numerical aperture of 0.55. The light is then incident on a diffraction grating with 1200 lines/mm. The zeroth order reflection is used as the output of the external cavity laser while the first order reflection spatially separates the spectral components of the laser. One of these spectral components is fed back into the diode forcing the external cavity laser to operate at the wavelength of the optical feedback. By rotating the grating, different wavelengths of light can be fed back to the diode thus allowing the output of the external cavity laser to be tuned. A plot of the optical power as a function of wavelength for the laser shown in

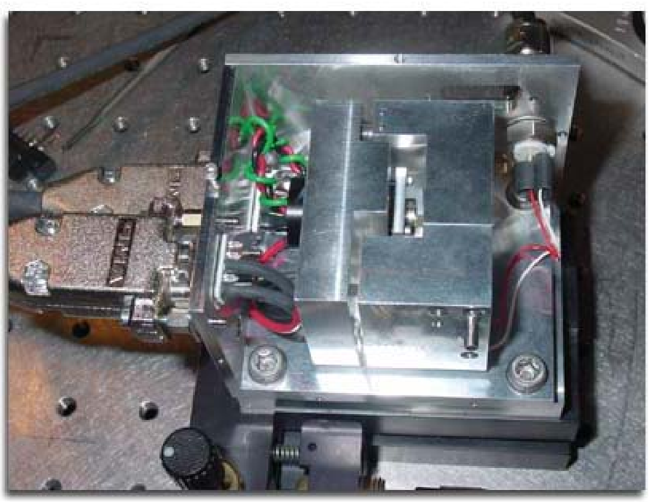

Figure 7 The external cavity diode laser used as a tunable pump laser for the 2μm Raman laser.

figure 7 is shown in figure 8. The external cavity laser has a demonstrated tuning range from 1.068μm to 1.081μm corresponding to a Stokes shifted wavelength range of 1.907μm to 1.962μm in diatomic hydrogen. The maximum output power for the external cavity laser is 25mW corresponding to a maximum Stokes shifted output power of 2mW.

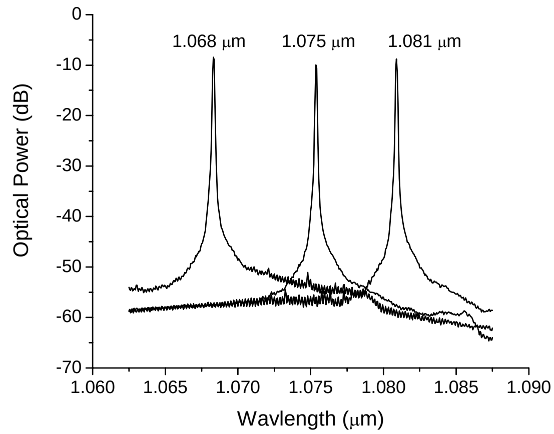

Figure 8 The optical power as a function of wavelength for the external cavity laser shown in figure 7. A tuning range of 13nm is seen from this plot

The mirrors used in the Raman laser cavity have manufacturer quoted reflectivity at the pump and Stokes shifted wavelengths greater than 99.99% with transmission losses less than 50ppm. The mirrors have a radius of curvature of 1000mm and are placed in the Raman laser cavity shown in figure 9. The mirrors are spaced by three piezo-electric tubes placed in series for a total cavity length of7.6cm corresponding to a Raman laser cavity free spectral range of 2.0GHz. Applying a voltage to the piezo-electric tubes allows the cavity length to change. A plot of the cavity transmission as a function of time is shown in figure 10 as a ramp voltage is applied to the piezo-electric tubes. The main peak is the laser transmission while the two smaller peaks are the frequency sidebands added at 12MHz with the electro optic modulator.

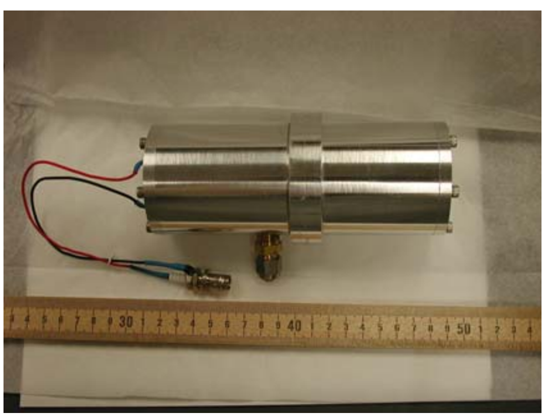

Figure 9 The Raman laser cavity built for the 2μm laser. The cavity has a mirror spacing of 7.6cm corresponding to a free spectral range of 2.0GHz.

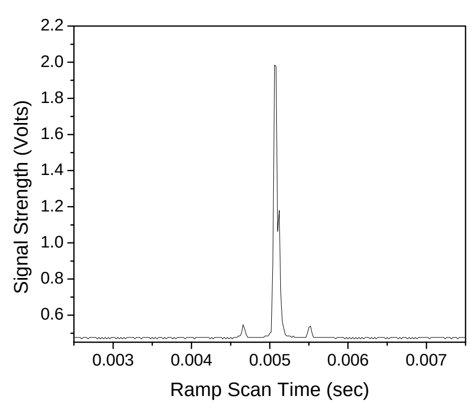

Figure 10 The Raman laser cavity as a function of time as the cavity length is scanned. The main peak corresponds to the laser while the frequency sidebands at 12MHz were added with the electro optic modulator

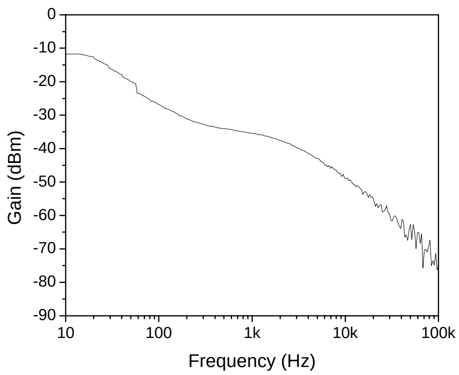

Figure 11 The Bode plot of the locking servo.

Light reflected from the front of the Raman laser cavity travels back to the detector shown in figure in figure 3. The RF driver for the electro optic modulator beats with the reflected light from the Raman laser cavity to provide an error signal used for frequency locking the pump laser and Raman laser cavity[4]. This error signal is sent through a control servo that adjusts the Raman cavity length to keep the pump laser and Raman laser cavity frequency locked. The frequency transfer function for the locking servo was measured using an RF spectrum analyzer and is shown in figure 11.

A picture of the 2μm Raman laser is shown in figure 12. The major components needed for the Raman laser including the pump laser, the electro optic modulator, the locking detector, and the Raman laser cavity are labeled in this figure We are currently finishing work the electronics needed for the frequency locking.

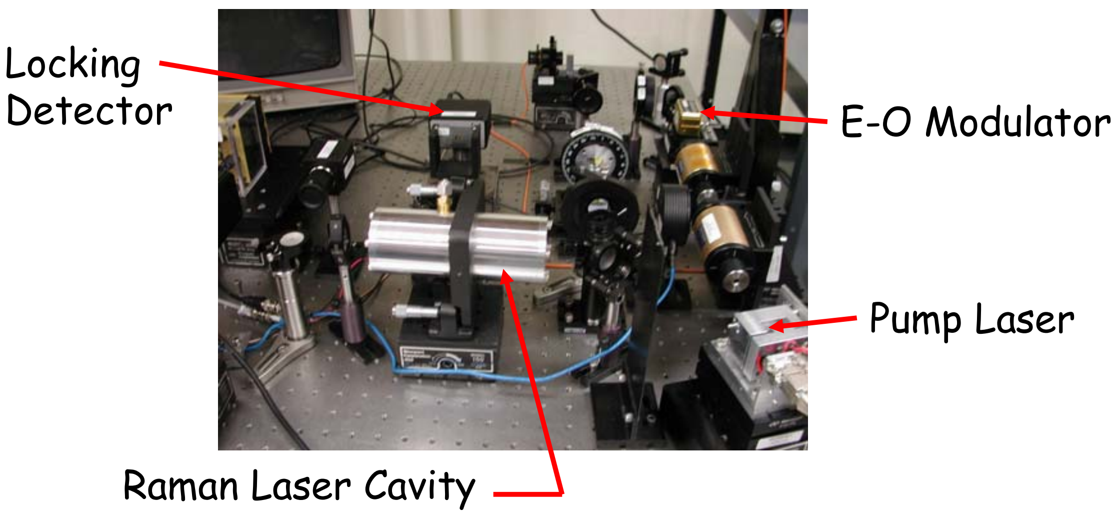

Figure 12 The 2μm tunable cw Raman laser.

IV. Conclusions

A design was presented for a tunable cw Raman laser with an output near 2μm. This laser uses the nonlinear Raman scattering process to shift room temperature diode lasers out to wavelengths suitable for optical detection of CO_2. Tuning the laser through the absorption features shown in figure 1 and monitoring the percent transmission through the atmosphere, the number of CO_2 molecules in the laser path can be monitored in real time.

Acknowledgements
ZERT is funded by the United States Department of Energy, under Award No. DE-FC26-04NT42262. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

References

1. Hitran Data Base, Ontar Corporation, 9 Village Way, North Andover, MA 01845-2000.

2. L.S. Meng, K.S. Repasky, P.A. Roos, and J.L. Carlsten, “Widely tunable continuous-wave laser in diatomic hydrogen pumped by an external-cavity diode laser”, Opt. Lett., 25, 2000, (472-474).

3. K.S. Repasky, J.K. Brasseur, L. Meng, and J.L. Carlsten, “Performance and design of an off-resonant continuous-wave Raman laser”, JOSA B, 15, 1998, (1667-1673).

4. R.W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough, G.M. Ford, A.J. Munley, and H. Ward, “Laser phase and frequency stabilization using an optical resonator”, Appl. Phys. B, 31, 1983, (97-105).