Construction and noise studies of a continuous wave Raman laser
by Jason K Brasseur

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University


Abstract:
The first non-resonant cw Raman laser in H2 is presented in this thesis. A time-dependant theory is presented that describes the cw Raman laser in the high pressure limit, so population dynamics can be ignored. The theory is tested in the steady-state regime and it matches well against the experimental data obtained. The theory also predicts the relaxation oscillations of the cw Raman laser and provides insight to minimize these oscillations. The theory predicts the relative intensity noise of the cw Raman laser, which is in good agreement with experimental results. Finally the cw Raman laser linewidth is measured to be 4kHz over a 10ms scan, and the Allan variance of the laser linewidth is experimentally measured.

# CONSTRUCTION AND NOISE STUDIES OF A CONTINUOUS WAVE RAMAN LASER

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APPROVAL

of a thesis submitted by

Jason K. Brasseur

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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# TABLE OF CONTENTS

LIST OF FIGURES

Figure

# ABSTRACT

The first non-resonant cw Raman laser in $H_2$ is presented in this thesis. A time-dependant theory is presented that describes the cw Raman laser in the high pressure limit, so population dynamics can be ignored. The theory is tested in the steady-state regime and it matches well against the experimental data obtained. The theory also predicts the relaxation oscillations of the cw Raman laser and provides insight to minimize these oscillations. The theory predicts the relative intensity noise of the cw Raman laser, which is in good agreement with experimental results. Finally the cw Raman laser linewidth is measured to be 4kHz over a 10ms scan, and the Allan variance of the laser linewidth is experimentally measured.

# CHAPTER 1

# INTRODUCTION

If you were to take a poll and ask a group of laser physicists: "What do you think the laser field as a whole needs in the future?", the answers would vary, but there would be an underlining theme. They would want to have a narrow linewidth laser at every wavelength in the spectrum, ultra-violet, visible and infrared parts of the spectrum, with a gaussian spatial mode for the output. So why would we want to have all of these lasers? What good would they be?

The needs vary from making more stable atomic clocks to monitoring of atmospheric gasses. Imagine if we could put a small laser system on a smoke stack that could tell us what pollutants a factory was putting out. We could place these laser systems around airports and monitor the wind conditions and monitor for wind shear, by using a laser that is in the "eye" safe region of the spectrum. Both of these lasers are needed in the 2-5 μm infrared region of the spectrum. Now how can we make these dreams of bigger and better things become a reality? Either we can make new lasers, or take existing lasers and externally shift the wavelength.

Currently available lasers in this region have some disadvantages. For example, a lead salt laser can produce laser light into the infrared but it has small output powers (~tens of μW) and needs to be cooled at liquid nitrogen temperatures. An alternative is to take existing lasers and double, or triple the frequency of the laser by using second harmonic generation and other nonlinear effects. We also can make optical parametric oscillators which can form laser frequencies lower than the original laser. However, all of these devices have drawbacks that range from output linewidths to the multi-mode spatial outputs of the optical parametric oscillator to the high thresholds often needed to construct the lasers, typically in the 50 to 100 mW range [1,2]. In addition, the cost of some of these devices is ~$100k and up.

Another method to shift the frequency of a laser is to use Raman scattering. Laser induced Raman scattering, first studied in 1962 [3], occurs when an incident photon interacts with a molecule (or an atom) and generates a red shifted photon resulting from the conservation of energy when the excitation in the molecule occurs. The molecular excitation can be rotational, vibrational, or electronic, which accounts for the possibility of many different wavelengths. For example, figure-1.1 shows the levels involved for vibrational Raman scattering of a 532 nm laser in $H_2$ to 683 nm. At high intensities the Raman process can have gain and produce stimulated Raman scattering, and, because of the high intensities needed, Raman scattering is most often studied in the high power pulsed regime. Stimulated Raman scattering has also been utilized in the continuous wave (cw) regime to make cw Raman lasers.

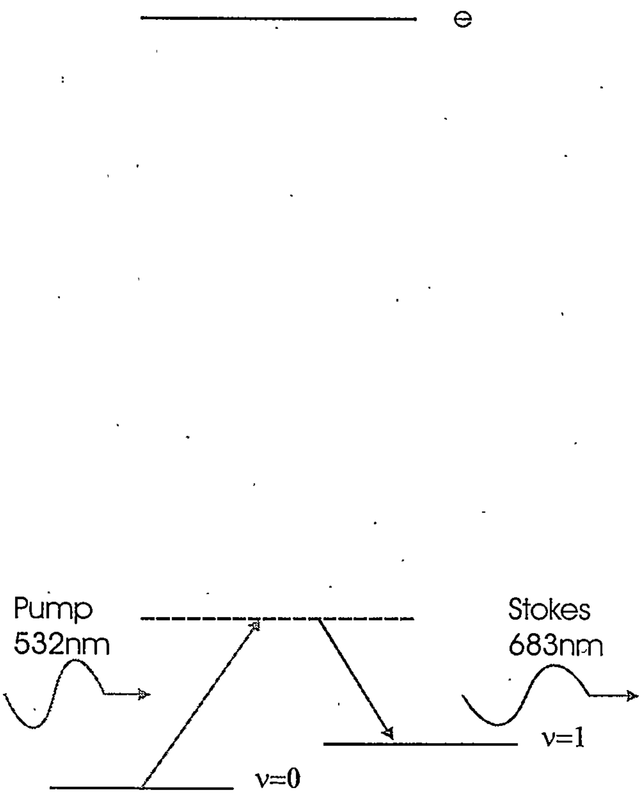

Figure 1.1 Energy level diagram for $H_2$, to scale.

However, because of the lower intensity of the cw pump lasers, these cw Raman lasers generally operate near a molecular (or atomic) resonance to increase the Raman gain and are therefore tunable only over a narrow regions near the resonance.

A few examples of near resonant Raman lasers include a 67μm cw Raman laser in $NH_3$ [4], a cw sodium Raman laser near the Na D lines [5], a two photon pumped cw Rb Raman laser near 776nm [6], and various cw Raman lasers near the Ne resonances in the He-Ne laser discharge tube [7-9]. In addition, cw Raman lasing is also possible in optical fibers where the long interaction length of the fiber and the small spot in the fiber increase the gain so cw Raman lasing can occur. However, typically input pump powers on the order of a watt are need to pump these Raman fiber lasers [10]. In addition, the Raman shift in the optical fiber is only ~440 $cm^{-1}$ and is inconvenient if one is looking for substantial shifts of wavelength.

Recent developments in mirror coating technology have lead to the availability of new mirrors with reflectivies of 99.995% and higher. To put this number in perspective a bath-room mirror only reflects ~96% of the light that is incident on it while the 4% is typically absorbed, these new mirrors absorb only 10 parts per million an improvement of over three orders of magnitude. These low loss mirrors have been used to build nonconfocal cavities or optical resonators with finesses of 50,000 and higher [11,12] ( a Q-factor of ~$10^9$ and greater). By the use of the nonconfocal cavity we have a focusing geometry which makes the spot size of the beam on the mirrors on the order of 100μm, so the degradation of the finesse (Q-factor) that is due to wavefront distortion is minimized and the high finesse cavity is achieved.

With the advent of this new technology of high finesse cavities it now becomes possible to consider using these cavities to do studies in nonlinear optics with cw lasers in the milliwatt range of power. Specifically, it is now possible to use the high finesse cavities to build a widely tunable cw Raman laser that can be pumped by a laser in the milliwatt range, namely low cost diode lasers. If we consider all of the room temperature diode lasers, and a few gasses to perform Raman scattering in, namely $H_2$, and $CH_4$, we can cover the 1-4μm range of the spectrum. Figure-1.2 illustrates this point. This provides a lot more possibilities for new lasers. This thesis will describe a non-resonant cw Raman laser in $H_2$, the first of its kind [13].

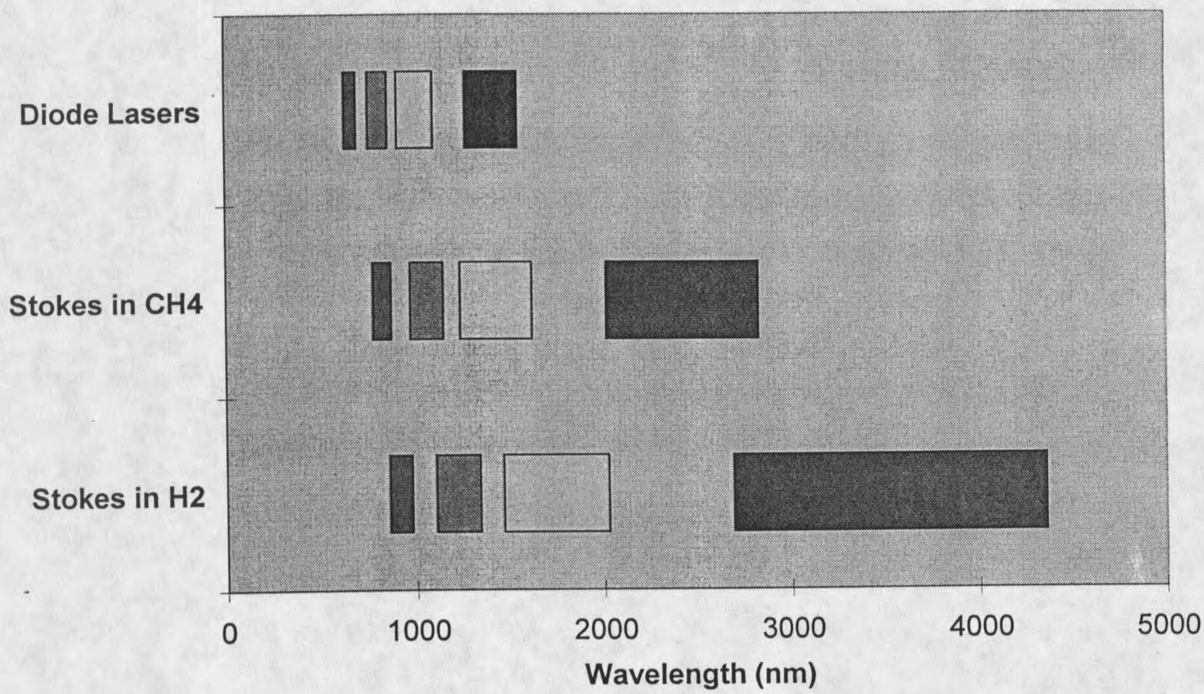


Figure-1.2 Shows the possible cw Raman lasers for various gasses.

This thesis is arranged in the following manner. Chapter 2 describes the proof of concept experiment and familiarizes the reader with the idea of the threshold of the cw Raman laser with a back of the envelope calculation. The output mode of the cw Raman laser is characterized as well. Chapter 3 develops the cw Raman laser equations that will be used throughout this thesis. Chapter 4 studies the steady-state nature of the cw Raman laser. In chapter 5 a linearized theory is developed to explain the relaxation oscillations that the laser is seen to exhibit. Chapter

5 also predicts and explains the amplitude noise on the cw Raman laser. Chapter 6 measures the Raman laser linewidth and the stability of the Raman laser frequency. Chapter 7 gives brief concluding remarks, and a few appendices are included to describe some of the devices and methods used in this thesis. So off to the second chapter.

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# CHAPTER 2

# THRESHOLD PREDICTIONS, AND PROOF OF CONCEPT EXPERIMENT

## Theoretical Prediction of Threshold

As stated in the previous chapter, this thesis presents the first non-resonant cw Raman laser in $H_2$. In this chapter we will go though the initial thought process that led to the realization of a cw Raman laser.

An important concept when describing lasers is the threshold condition, since this is when the light exiting the cavity exhibits laser-like qualities, i.e. coherence. Threshold happens when the gain equals the loss in a system. To predict the threshold of the cw Raman laser we start with the single-pass gain G in a focused geometry[1]:

$$G = \frac{1}{2}\frac{4\alpha}{\lambda_p + \lambda_s}\tan^{-1}\left(\frac{\ell}{b}\right)P_p. \qquad 2.1$$

Where G is the Raman gain per pass, $\alpha$ is the Raman gain coefficient, $\lambda_p$ ($\lambda_s$) is the wavelength of the pump (Stokes) field, $\ell$ (b) is the interaction length (confocal parameter[2]) of the beam, and $P_p$ is the incident pump power. The factor of one half accounts for the standing wave that is formed inside of the resonant cavity instead of a traveling wave. The Raman gain coefficient, $\alpha$, has the following functional form[3]:

$$\alpha = \frac{D(\nu_p - \nu_v)}{(\nu_i^2 - \nu_p^2)^2} = \frac{D\nu_s}{(\nu_i^2 - \nu_p^2)^2} \qquad 2.2$$

Where D is a constant that incorporates the pressure of the gas at the linewidth of the transition, $\nu_p$ ($\nu_s$) is the pump (Stokes) frequency, and $\nu_i$ ($\nu_v$) is the resonant electronic (vibrational) frequency of the transition. Equation 2.2 assumes that the pump frequency $\nu_p$ is far from the resonance $\nu_I$. For diatomic hydrogen, $\nu_I$=8.48x10$^4$cm$^{-1}$, and $\nu_v$=4155cm$^{-1}$. Note that $\nu_i$ corresponds to a resonance at 118nm in the UV, so $\nu_I^2$-$\nu_p^2$ will be a slowly varying function for $\nu_p$ in the visible and the IR parts of the spectrum. Thus the cw Raman laser in $H_2$ is expected to be broadly tunable. For a pump wavelength of 532nm (18,800 cm$^{-1}$), $\alpha$ is 2.5x10$^{-9}$ cm/W in the high-pressure limit[3]. To generate a spontaneous Stokes photon in a single pass we need on the order of 300kW of pump power. Since typical cw lasers are in the milli-watt to watt range, we need a way of increasing our cw power to have cw Raman lasing.

One way to increase the circulating power of the pump laser is to pump an optical cavity, or a high finesse cavity (HFC). To see this effect, we start with an interferometer and focus on the intensity build up inside of the HFC. Because we are looking at an interference effect, we sum the electric field to build up the intensity inside of the HFC. Figure 2.1 demonstrates how the fields build up inside of the HFC.