

# POWER BUILD-UP CAVITY COUPLED TO A LASER DIODE

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## Abstract

In many Raman applications there is a need to detect gases in the low ppb range. The desired sensitivity can be achieved by using a high power laser source in the range of tens of watts. A system combining a build-up cavity to enhance the power and an external cavity laser diode setup to narrow the bandwidth can give the needed power to the Raman spectroscopy system.

## Introduction to Laser Diodes

An important characteristic of all lasers is the mode structure. The mode structure refers to both the lasing frequency and the spatial characteristics of the laser. Laser diodes are all formed with some type of cavity, which forms equally spaced longitudinal (frequency) modes. The longitudinal modes are spaced by  $c/2nL$  with  $c = c_0/n$ :  $c_0$  being the speed of light in a vacuum,  $n$  the index of refraction of the cavity, and  $L$  the cavity length. The combination of these longitudinal modes forms the bandwidth of the laser.

The spatial or dispersive characteristics of the laser diode are defined by the transverse modes. These modes refer to the spatial characteristics in a two dimensional plane and can be seen by looking at the laser output. The transverse modes are referred to by  $TEM_{mn}$  (Transverse Electro-Magnetic), with  $m$  and  $n$  referring to the respective axis of propagation.<sup>1</sup> The  $TEM_{00}$  mode is a circular shaped, gaussian mode and has the smallest dispersion. The  $TEM_{01}$  mode provides two circular shapes in a vertical line, the  $TEM_{10}$  has two circular modes in a horizontal line. The combination of the  $TEM_{01}$  and  $TEM_{10}$  modes gives the  $TEM^*_{10}$  mode which forms a doughnut shape.

A basic semiconductor laser diode is a combination of different elements such as Aluminum (Al), Gallium (Ga), Indium (In), Phosphorous (P), Arsenic (As), or Antimony (Sb). The different

combination of these elements will emit photons at different frequencies. The ends of these semiconductor devices are cleaved to form mirrors that bounce the photons back and forth within the cavity. The photons excite more electrons, which form more photons (referred to as optical pumping).<sup>2</sup> A certain portion of the photons emit through the front and back cleaved surfaces of the laser diode. The amount of photons that get through the cleaved surfaces can be adjusted by coating the surface or installing other mirrors.

The planar cleaved surfaces of the laser diode form a Fabry-Perot cavity with set resonance frequencies ( $\nu_F$ ).<sup>3</sup> The typical laser diode has a spacing of 150  $\mu\text{m}$  with an index of refraction of 3.5, yielding a resonance frequency of 285 GHz. The wavelength spacing ( $\Delta\lambda$ ) between longitudinal modes is given by  $\lambda^2\nu_F/c$  which gives a value of .425 nm for a wavelength of 670 nm.

A bandwidth in the range of 5 nm results in 11 competing longitudinal cavity modes. The competition between modes causes the intensity to shift between adjacent peaks. The instability makes it very difficult to detect the Raman signal of molecules with shifts of similar wavelength. Methane has a peak that is separated from an Oxygen peak by less than 1 nm. Any shift or competition between longitudinal cavity modes would make detection difficult since the peaks would begin to overlap.

## Explanation of Feedback

Most methods of limiting the bandwidth of a laser diode incorporate some device which feeds light back into the laser diode. The light has been limited in some form to reduce the overall bandwidth of the laser diode and stabilize the frequency fluctuations. A good model of a feedback system is a mirror that will only pass back to the laser diode select frequencies spaced by  $\nu_F$ . The time it takes the laser light to reach the mirror and return to the laser diode is  $\tau = 1/\nu_F$ . The laser diode is a cavity with a round trip time of  $\tau_{in} = 2L/c$ . The

two cleaved surfaces of the laser diode have complex amplitude reflectance equal to  $r_1$  and  $r_2$ . The square of complex amplitude reflectance gives the power reflectance which is typically 90% for the back mirror ( $RR_2$ ) and 10% for the front mirror ( $RR_1$ ). The complex amplitude reflectance of the mirror is  $r_3$  and will vary depending on the system.

The optical feedback is given by the equation:

$$\kappa\tau = \tau \frac{1 - r_1^2}{\tau_{in}} \sqrt{\frac{r_3}{r_1}} \quad (1)$$

The value of  $\kappa\tau$  will either indicate a stable or chaotic system depending on the amount of reflectance in the system. The current will effect the optical feedback since a larger current relative to the threshold current will provide more laser build-up. The build-up from the reflectance will need to be increased accordingly, to compensate for the increased current.

A large value of optical feedback indicates the system is in the stable regime, since the feedback from the mirror is large enough to control the frequency modes of the laser diode. Smaller values of optical feedback leaves the modes uncontrolled and the exact frequency becomes chaotic.<sup>4</sup>

To achieve strong external feedback the reflectance of the external mirror system should be at least 100 times the reflectance of the front laser diode facet. The semiconductor-air interface of the laser diode front facet has a reflectance of about 0.3; yet, the typical reflectance of the external mirror system is only around 0.1 - 0.3. The only way to achieve the necessary difference is to reduce the front facet reflectance.<sup>5</sup>

The best way to increase optical feedback is to reduce  $r_1$ , this is done by using a dielectric antireflection coating. The coating reduces the facet reflectance to about  $10^{-4}$ , greatly increasing the optical feedback ratio and keeping it in the stable regime. Another way to increase the optical feedback is to increase the reflectance of the mirror; however, if the reflectance is already large this will have a small affect.

The external cavity mirror system forms a secondary cavity with the back cleaved surface of the laser diode. The secondary cavity spacing is small

compared the cavity spacing of the laser diode since the spacing is inversely proportional to cavity length. The reflectance of the laser diode front facet causes a Fabry-Perot filtering effect that broadens the pulses and locks the external cavity modes within each laser diode cavity mode. Figure 1 shows the result of the mirror system on the mode structure. The external cavity longitudinal modes are locked into the spacing of the laser diode cavities. The power will fluctuate between external cavity modes within the same laser diode cavity mode; but, the modes in different laser diode cavities are independent of each other.

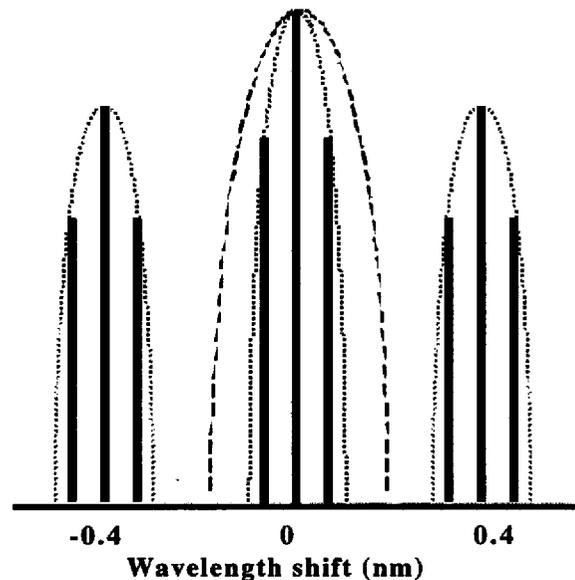


Figure 1 Effect of diffraction grating on the laser diode.

Two methods are available to reduce the effect of independent mode fluctuations caused by the Fabry-Perot laser diode. The first is to use a bandwidth limiting device, such as a diffraction grating, to reduce the number of laser diode modes (as shown by the large dashed line in Figure 1, limiting the bandwidth to a single laser diode mode). The second is to use an antireflection coating, which will reduce the effect of the Fabry-Perot resonator. The power build-up cavity coupled to laser diode uses both of these techniques to control the longitudinal modes.<sup>6</sup>

#### External Cavity Laser Diodes

One enhancement used to limit the bandwidth is a diffraction grating. The diffraction grating feeds a portion (~20-60 %) of the light back into the laser

diode. The optical feedback is large enough to keep the system very stable without any antireflection coating. Since the light has been spread out in wavelength by the grating, only a small portion of the entire wavelength range enters the laser diode. The optical pumping occurs in the small range of wavelength and limits the bandwidth of the laser diode.

Feedback introduced by back scattering from the sample is so small compared to the external cavity optical feedback that it is negligible and does not effect the frequency or the intensity of the laser diode. Moreover, since external feedback is not an issue no expensive optical isolator is needed and thus greatly reducing the cost of the laser diode/ diffraction grating system (commonly referred to as an external cavity laser diode). The diffraction grating forms a secondary cavity with the back cleaved surface of the laser diode.

The secondary cavity is large (~2 cm) and results in small resonant frequencies compared to the laser diode. The single mode from the laser diode will jump between these adjacent secondary longitudinal cavity modes. The overall shift, however, is so small that the spectrometer can not see the difference because of the limited resolution of the grating (~.2 nm).

Many different styles of external cavity laser diodes have been developed by many different companies.<sup>7-12</sup> The Raman Center developed an external cavity laser diode using a volume holographic grating and a temperature controlled mount. The volume holographic grating allowed for a smaller system since no diffraction grating mirror was required to send the light back in the original propagation direction. A temperature controlled mount allows for increased stability of the external cavity laser diode system.<sup>13</sup>

There are many advantages to using an external cavity laser diode. The frequency locking of the external cavity laser diode effectively controls shifting of the laser diode caused by mode hopping, temperature and current fluctuations, and other environmental contaminants. The frequency locking of the external cavity laser diode also makes it very stable thus maintaining the set frequency for a long period of time without fluctuations.

The small size of the laser diode allows for a more portable device, making Raman spectroscopy much more applicable in different commercial

applications. Finally, the tunability of the laser diode allows for small adjustments to the source wavelength of about 2 to 5 nm.

The current concern with using near infrared laser diodes is that they do not have enough power, especially after an external cavity is used which reduces the power by about 25 - 40 percent. Near infrared lasers are further limited because scattering decreases by approximately  $\lambda^4$ . There is also a concern with the limited range of a silicon CCD camera which can only detect up to about 1,000 nm.

#### Build-Up Cavity Equations

One well known technique to enhance the Raman spectroscopy system is to use a set of mirrors to build-up energy from a laser source. The mirrors are made with very high reflectivity and low transmittance. Once the laser light is introduced into the build-up cavity the power will increase until it reaches a point when the input laser power and the system losses stabilize each other. Therefore, to get a high power build-up cavity the reflectance of the two mirrors should be high and losses should be kept to a minimum.<sup>14</sup>

The tested mirror system had two mirrors of equal radii, but with different reflectance. One important parameter of a build-up cavity, is that a beam waist is located somewhere in the cavity depending on the radii of the mirrors. Since the radii of the two mirrors used is the same, the beam center is found at the center point of the two mirrors.

The stability of the cavity (excluded fluctuations from laser and contaminants) depends up on the radii of the two mirrors. The cavity is usually stable as long as the combined radii distances are greater than the concave mirror distances. Finesse of the cavity is a parameter that is used to show how much build-up will result in the cavity. There are other factors that may effect the build-up or the finesse of the cavity, including the dust in the air, imperfections on the mirrors, and slight adjustments of the cavity over time due to gravity or misalignment.

The typical build-up cavity has high reflectance and therefore only feeds a small portion of light back to the laser diode. In order to have high optical feedback in the system the reflectance of the front entrance mirror of the laser diode has to be reduced. Antireflection coated

laser diodes should always be used with a build-up cavity, if not the build-up cavity will not be able to control the laser diode frequencies and the system will be unstable and chaotic.

The high reflectance of the front mirror of the build-up cavity means that only light spaced at the frequency spacing of the build-up cavity will pass into the cavity. All other light will be blocked and sent back to the laser diode. The light sent back from the front entrance mirror is unwanted and will cause instability in the system. The front entrance mirror should always be tilted to reduce this feedback and keep it from entering the laser diode. The effect of this slight rotation is small for transmitted light from the cavity, but much larger for the reflected light.

#### Build-Up Cavity Designs

Build-up cavities can provide large or small power increase. Some build-up cavities pass the laser light back and forth between two flat mirror surfaces, others use a high finesse cavity that can provide  $10^5$  times the initial power. Work being done by David King<sup>15-17</sup>, who works for Hewlett Packard, utilizes high finesse cavities for gas Raman spectroscopy.

The build-up cavity design by David King incorporates an external cavity approach to stabilize and narrow the bandwidth of the laser diode. The transmittance is slightly increased for one of the mirrors allowing some of the light to be feedback into a low power laser diode. A grating-mirror combination is used to narrow the bandwidth by only allowing a small wavelength band to pass through into the mirror and then back into the diode. Mode matching optics are used to spatial match the curvature of the wavefronts to the radius of curvature of the entrance cavity mirror.

The laser diode is coated with an antireflection coating to help limit the feedback from the front cleaved surface of the laser diode. The entrance or front mirror is also coated with an antireflection coating to limit feedback. Some feedback from these and other surfaces still occurs; however, this will not affect the system since it is small compared to the feedback of the build-up cavity. A slight rotation of the front mirror limits the amount of feedback from the back of this mirror.

The build-up cavity coupled to a laser diode design developed at the University of Utah used a

combination of the volume holographic grating external cavity laser diode along with the build-up cavity design by David King. The volume holographic grating replaced the grating-mirror combination of David King's design. The volume holographic grating made the system more compact. The reduction in components, by replacing a grating and a mirror by a volume holographic grating, made the system much easier to align since the light always traveled in one direction.

Once the build-up cavity is designed and in place a cell is used to introduce gases to the cavity and then Raman measurements can be taken of the scattered light. The gases may cause fluctuations in the cell thus affecting the power of the laser; however, a power detector can be used to detect and adjust the results. Room air makes for a good calibration gas and is also used to clean out the sample cell. It is important that the gas be clean so that the power in the build-up cavity remains high enough to give the desired sensitivity.

#### Power Build-Up Cavity Setup

The power build-up cavity laser diode tested utilized a volume holographic grating as described in the previous chapter. A 9 mm can laser diode was used with a wavelength of 670 nm and an antireflection coating on the front cleaved surface to reduce feedback. The laser diode provided approximately 10 mW of power at 70 mA. The dimensions of the laser diode are  $1 \times 3 \times 250 \mu\text{m}$  with an index of refraction of 3.6.

A 0.23 pitched Graded Index (GRIN) lens matched the output of the laser diode to the beam waist and mirror curvature of the build-up cavity. A 900 grooves/mm volume holographic grating reduced the bandwidth of the laser diode. The 5 cm radius of curvature build-up cavity spherical mirrors had different transmittance values. The front (entrance) mirror transmits 340 ppm, while the back mirror only transmits 10 ppm. An optical power meter measures the output from the back mirror. The power reading is  $10^5$  times lower than the build-up power. Typical power readings are around 35 Watts, which is a power build-up of about 7,000 (if 5 mW gets into the cavity).

The cavity spacing was set at 7 cm, which results in a radius at the beam waist of  $70 \mu\text{m}$  (diameter of  $140 \mu\text{m}$ ) centered between the 5 cm radius of curvature mirrors. The Rayleigh range is 2.3 cm from the beam waist, indicating the point of maximum beam

curvature. The finesse of the cavity is calculated to be about  $10^4$ , not including contaminants to the system. The system contaminants reduce the power to a value of about 7,000 - 9,000, depending on the amount of the contaminants.

The alignment for this laser diode and high finesse cavity is not trivial. Cleaning of the each lens is very important, use 3 or 4 drops of acetone on a cotton swab and brush the face of the mirrors to make sure they are clean. Set the 10 mW - 670 nm laser current initially at about 65 mA.

The laser diode in the grin assembly should be placed so that the fast axis is perpendicular to the table. The fast axis refers to the smaller dimension of the rectangular diode. The light from the 1  $\mu\text{m}$  dimension diffracts at a larger angle than the 3  $\mu\text{m}$  dimension. The fast axis is kept parallel to the gratings of the volume holographic grating. The volume holographic grating is placed about a centimeter from the laser diode and the front mirror of the build-up cavity, with the cavity spacing set at about 7 cm. Rotate the volume holographic grating until the maximum power is in the first order mode.

The build-up cavity should be placed in the optical axis of this first order mode of the volume holographic grating. Adjust the front mirror, using the internal detector of the diode, until the photocurrent from the laser diode reaches a peak. The peak value of the photocurrent is about 2 mA. Put in the back mirror and adjust it until a TEM<sub>00</sub> mode is visible, with as much power as possible. Finally, adjust the front mirror along the fast axis, or the direction parallel to the table. The adjustment will reduce the feedback between the mirror and the laser diode and increase the feedback from the cavity. Finish by optimizing the power by slightly adjusting the position of the mirrors. The build-up cavity provides power of 30 - 40 Watts.

It is difficult to experimentally match the beam waist of the build-up cavity to the laser light from the diode. Matching the wave curvature of the laser light to the radius of curvature of the mirror is also very difficult to do experimentally. The distance between devices may be adjusted to try to completely optimize the power. It should be noted, however, that the wavefronts of a laser diode are not completely gaussian and thus build-up cavity equations will only be approximate values. Experimentation showed that exact

distance between the laser diode, volume holographic grating, and build-up cavity did not matter as long as the previously stated procedure was followed.

### Power Diode Build-Up Cavity Data

The build-up cavity modes interact with the laser diode modes in the same way as an external cavity laser diode. The build-up cavity modes are very small (.0064 nm) compared to the modes of the laser diode (.4 nm). Measurements taken without the volume holographic grating show the different modes of the laser diode which overlap the modes of the power build-up cavity as the power fluctuates between these modes.

Figure 2 shows a snap shot of the fluctuation between the different modes as captured with a enhanced Spex spectrometer (wavelength range of about 8 nm) and a CCD video camera. The video camera showed movement in the modes as the power fluctuated between the different overlapping modes.

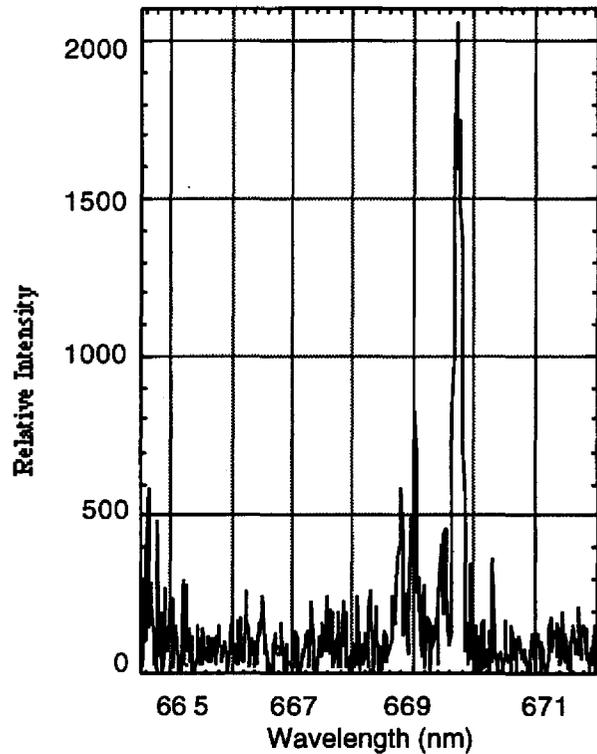


Figure 2 Several modes of cavity without the volume holographic grating.

Figure 3 shows the effect of the volume holographic grating on the mode structure. As seen with the external cavity laser diode, there is only one laser diode mode fluctuating between several build-up cavity modes. The 900 grooves/mm volume holographic grating does not completely block the side modes and fluctuation will occasionally introduce a second mode. The modes, however, are close enough not to effect the less sensitive Raman spectrograph. A higher number of grooves/mm would reduce this problem; however, good Raman data was obtained using the 900 grooves/mm grating.

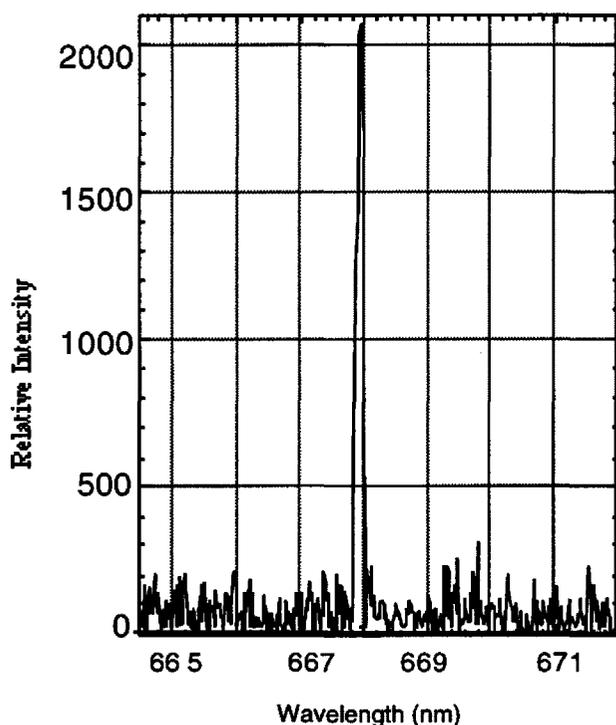


Figure 3 Single mode of cavity with a volume holographic grating.

The antireflection (AR) coating on the laser diode, as previously mentioned, is very important to achieve build-up. A non-AR coated laser diode, with the exact same specifications as the AR coated laser diode, was tested in the build-up cavity to see the effect of the AR coating. The laser diode with no AR coating and no external feedback, has an internal feedback of 60 mW. The AR coated laser diode provides a non-detectable amount of internal feedback to the laser diode. The large internal feedback makes it difficult for the non-AR coated laser diode to provide stable build-up.

In order to stabilize the cavity and create a large power cavity the build-up would have to provide about 200 mW of power back into the diode. The diode can only produce 10 mW, of which only a small portion will enter the cavity and build-up. Measurements show that the cavity with no AR coating has a peak build-up of 1 Watt, indicating that at peak current 100  $\mu$ W is entering the cavity. The cavity can then only provide .34 mW (340 ppm mirror) of power to the laser diode. The only way to get stability with this cavity is to produce 588 W of power, which would take a very complicated and difficult system.

### Raman Spectra

Raman spectra of room air and natural gas were taken using an ISA/Spex HR 460 Spectrometer. The HR 460 spectrometer is a double pass spectrometer with a motorized changeable grating. The light enters from a front entrance slit then bounces off a collimating lens to the diffraction grating then bouncing off a second collimating lens and then to the CCD camera. The entrance slit is usually set at about 150  $\mu$ m, close to the beam waist of the build-up cavity. A Princeton Instruments (TEA model) CCD camera captures the light and sends it to the computer. The array size of the CCD camera is 576 x 384, with all 384 vertical pixels binned together to give maximum intensity.

Two 300 grooves/mm gratings were used in the spectroscopy system. One blazed (point of highest efficiency) at 500 nm and the other blazed at 1,000 nm. A 680 nm high pass Spectrogon optical filter blocked the Rayleigh light, increasing the sensitivity of the spectrometer. A 50 mm Nikon lens captured the Rayleigh and Raman scattered light from the cavity.

An Argon lamp with a monochromator was used to evaluate the performance of the Raman system. The power of the Argon lamp was collected over the wavelength range of 700 - 1100 nm every 10 nm. The Argon spectra was then collected with the Raman spectroscopy system and the total area compared. The two spectra are very similar with the only difference being an increase in detection ability near 1,000 nm for the grating blazed at 1,000 nm. The results show that no ppm or ppb sensitivity will be possible past 900 nm. There are available near IR enhanced CCD cameras that respond better in the 900 nm range; however, they are very expensive and not available at this university.

The low power laser diode build-up cavity has a very high finesse, making it very sensitive to vibrations and dust. Any reduction in build-up cavity power will reduce the feedback to the laser diode. A data sample of power fluctuation over a period of half an hour was taken resulting in 5 W of power fluctuation. The 5 Watts of power fluctuations will effect the Raman signal; however, by continuously measuring the power any Raman data can be corrected. Data was taken of power fluctuation with 500 counts/second, once again the fluctuation was about 5 Watts and fluctuations very similar to the 1 Count/second setting.

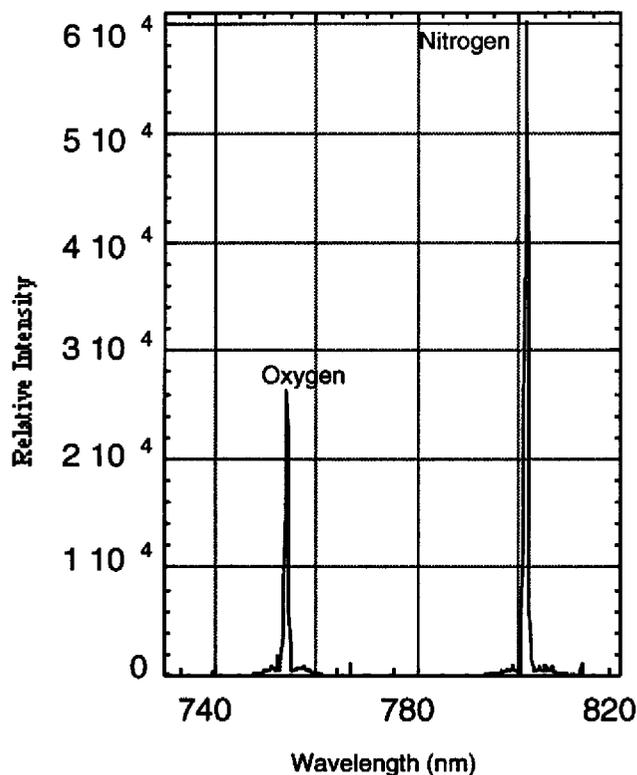


Figure 4 Raman Spectra of Room Air

Figure 4 shows a Raman spectrum of Nitrogen and Oxygen in room air. The area of the Nitrogen signal (78%) should be about 3.7 times the Oxygen signal (21%). The areas for one second give this 3.7 to one ratio; however, longer time durations give a much smaller ratio. The reason for the discrepancy is that most CCD cameras do not increase linearly when they get close to saturation. The CCD camera used in the experiments saturates at about 65,000 counts. The Nitrogen peak in the figure will be reduced while the

much smaller Oxygen peak will give accurate results. The resulting ratio of about 2.5 for the figure shows this camera effect.

To obtain accurate results with the CCD camera the exposure time should be kept so that the highest peak on the desired spectrum is about 50% of saturation (32,000 counts). A method to get larger counts is to take several spectrum, and then add them together to get a large value for a longer exposure time.

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