Matthew Sonn

Section 401

Dr. Jon Velazquez

The Carbon Dioxide Laser

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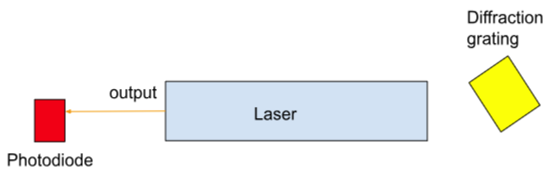


Summary and Overview: A carbon dioxide laser was used during this study to analyze the concepts of diffraction and diffraction grating. Figure 1[1] shows the experimental setup as seen from above. The angle at which the diffraction grater was positioned with respect to the incident laser beam was slowly changed, and the photodiode response at the output was measured in volts.

A carbon dioxide laser takes advantage of the vibrational and rotational energies stored in excited carbon dioxide molecules to create a population inversion and produce a continuous wave laser beam. Vibrational energy levels for carbon dioxide are described with three vibrational quantum numbers, and rotational energy is described as J, which is a rotational quantum number. At higher vibrational energy levels, such as the energy level of the excited carbon dioxide in our laser, only odd J values exist. At lower vibrational energy levels, only even J values exist. Therefore, when a molecule of carbon dioxide drops down to a lower energy level, two situations may take place: the change in the J value is +1 or it is -1. This is because an odd J level must drop down to an even one, but there are two possibilities of going one integer above or below the J value. When the change in J is -1, a laser beam is produced but at a lower energy level than the +1 drop because more energy is released during the +1 process. This creates two separate branches, or spikes, in intensity, the p branch and the r branch. The p branch has lower energy and is associated with the -1 change in J, while the r branch has higher energy and is associated with the +1 change in J. There are two different energy transitions in which the process described above can happen: the carbon dioxide molecule can drop from its excited vibrational state (001) down to (100), or it can drop from (001) to (020). When the first option occurs, in phase photons (laser light) with wavelength 10.6 microns are released. When the second option occurs, the wavelength of the laser is 9.6 microns. When lasing occurs, it occurs as the carbon dioxide molecule drops in energy, and the energy is used to produce a photon.

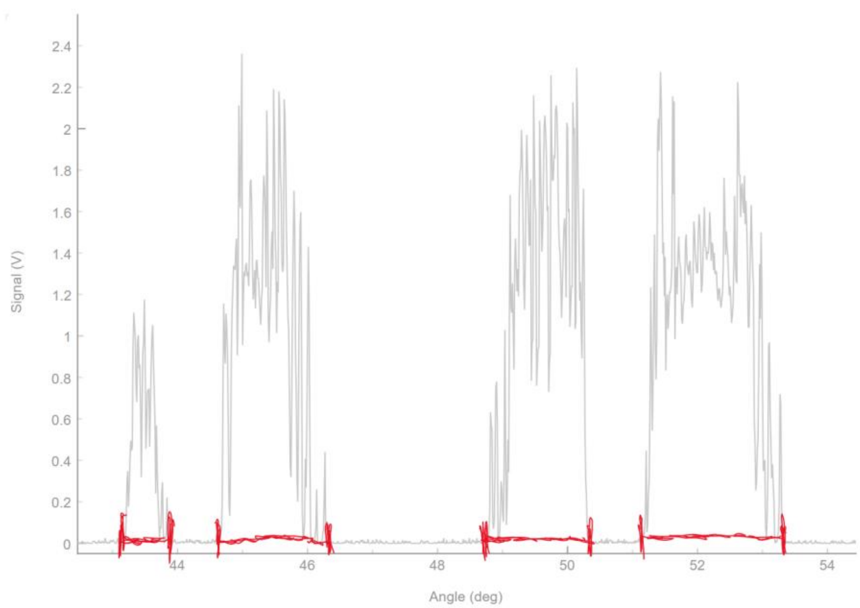
Answers to Questions: There are three main gases used in the carbon dioxide laser: carbon dioxide, helium, and nitrogen. First, electron impacts excite the nitrogen molecules from their ground state, (v=0), to an excited state, (v=1). Since nitrogen is a diatomic molecule, it only has one term for vibrational energy, hence the v=0 state representing the ground state and the v=1 representing the excited state. These excited nitrogen molecules then transfer their energy to carbon dioxide in the ground state, (000), exciting them to a higher state (001). The forms of these excitations are vibrational and rotational, with three terms for vibrational energy representing the three possible forms of vibrational energy for a triatomic molecule such as carbon dioxide: symmetric and asymmetric stretching, and bending. The helium is present to cause the carbon dioxide to drop in energy back to its ground state. The vibrational and rotational energy in the carbon dioxide is transferred to translational kinetic energy in the helium molecule because helium is monotonic—it can not have vibrational energy due to its monotonic property. Water was used to make sure the laser remained cool throughout its operation.

Some types of carbon dioxide lasers are continuous wave, pulsed, and excimer pumped. The continuous wave carbon dioxide laser is usually used for cutting in various settings. These lasers have the ability to operate at high power—around 20 kW—for a long time. As a result, the continuous wave lasers are used a lot in industry as cutting lasers due to their high and continuous power and their ability to be focused well using a lens. These types of lasers are also

[1] **Figure 1:** The experimental setup as seen from above. The diffraction grater slowly rotates, and the photodiode measures the intensity/power of the signal from the laser in Volts.

used in the drilling and welding industries too. Another type is the pulsed carbon dioxide laser. Pulsed carbon dioxide lasers are used for very precise processes such as material ablation, micro-machining, and drilling. The pulsed laser emits very short, high-powered pulses that enables it to be extremely precise when manipulating a material. Another benefit of this type of laser is the minimization of heat damage on the surrounding material due to the short, focused pulse that is delivered when manipulating the material. Another type is the excimer pumped carbon dioxide laser. An excimer pumped laser is used for material and semiconductor processing in the ultraviolet range, and laser annealing. These processes require a laser that has high energy and shorter wavelengths. The excimer pumping improves the efficiency of the laser, thus resulting in higher energy pulses. The shorter wavelength allows for more precision when working on a small scale[2].

When determining what materials are best to use as a lens, two factors must be considered: whether 10.6 um light can pass through the material easily (infrared light from the laser), and whether the material will focus the laser light properly rather than absorbing or scattering the light energy. Three good materials that have the above properties are zinc selenide, gallium arsenide, and germanium. These three materials will allow 10.6 um wavelength light to pass through the material and will focus this light so that a material can be cut. They also have similar refractive indices at the 10.6 um wavelength of about 2.6. Some materials that do not have these properties are glass and plastic, which have indices of refraction of 1.5 and 1.3-1.7 respectively. These materials will absorb the infrared laser light, thus making them bad materials for a carbon dioxide laser lens. The lower indices of refractions indicate that light will bend less when traveling through the material, making the focus point further away than where the focus point would be for zinc selenide[3].



[4]The carbon dioxide laser is used in many soft tissue surgeries because the soft tissue of humans absorbs 10.6 um wavelength very well. Additionally, the carbon dioxide laser can be used in place of a scalpel to make sanitary and safe cuts that immediately cauterize due to the heat of the laser. As a result, the patient will bleed less, the surgery can be more precise, and there is a lower risk of infection due to the lack of surgical instruments used. Some disadvantages can arise from the fact that the soft tissue absorbs this

[2] See Works Cited for sources used in writing this paragraph.

[3] See Works Cited for sources related to this paragraph.

[4] **Figure 2:** The signal at the photodiode as a function of incidence angle. The setup in Figure 1 was used to collect this data. The reflection grating slowly turned, and the output at the photodiode was recorded as the angle changed.

wavelength of light. This means that the laser can not make deeper cuts, so surgeries that require this would not be able to use this type of laser. Another disadvantage is cost and practicality. The cost of carbon dioxide lasers is high, but more importantly, the laser cavity of a carbon dioxide laser is bulky and hard to move around easily. Attempting to make the laser cavity smaller while maintaining power would increase the cost of the laser dramatically and would most likely not be worth the cost in a medical setting[5].

The first spike in Figure 2 (see previous page) corresponds to a carbon dioxide vibrational energy transition from (001) to (020). This means that this spike corresponds to the r-branch of the 9.6 micron laser beam (r-branch because the smaller angle corresponds to a smaller wavelength which corresponds to higher energy. The r-branch has higher energy than the p-branch, so the r-branch should appear first). Since this is the r-branch, the rotational quantum energy transition was a +1 transition. The second major spike still indicates a vibrational energy transition from the (001) state to the (020) state. However, this second branch is the p branch of this vibrational energy transition, meaning the rotational quantum number undertook a -1 transition. The third major spike indicates a vibrational energy transition from the (001) state to the (100) state, and this is the r-branch of the 10.6 micron laser beam corresponding to a +1 rotational quantum number transition. The fourth major spike still indicates a vibrational energy transition from the (001) state to the (100) state, but this branch is the p-branch, so the rotational quantum number, J, undertook a -1 transition.

The general equation for diffraction is $-sin\theta_i + sin\theta_d = m\frac{\lambda}{a}$. In the Littrow Configuration position, we know that $\theta_i = -\theta_d$. Substituting that into the general equation for diffraction and using the fact that sine is an odd function ($sin - \theta = -sin\theta$), we have $-2sin\theta_i = m\frac{\lambda}{a}$. Multiplying both sides by negative one we get the given Littrow Configuration equation, $2sin\theta_i = -m\frac{\lambda}{a}$.

Letting $m = -1$, $\lambda = 10.6\ \mu m$, and $\theta_i = 52°$ (from data), we can obtain a value for a, our grating period, that is $a = 6.73\ \mu m$. At normal incidence, the general equation for diffraction becomes $sin\theta_d = m\frac{\lambda}{a}$, as $\theta_i = 0$. Plugging in $\lambda = 10.6\ \mu m$ and the previously solved for value of a, we get the equation $sin\theta_d = 1.57m$. We know that m must be an integer value that represents the order of diffraction. Since the range of the sine function is negative one to positive one, 1.57m must be within that range. The only integer value that remains in that range is $m = 0$, so there is only one order of diffraction when using this grating at normal incidence with the carbon dioxide laser. For the He-Ne laser, we substitute $\lambda = 633\ nm$ and convert our grating spacing into nanometers: $a = 6730\ nm$. The new equation is now $sin\theta_d = 0.1m$. To maintain the range of the sine function, our maximum value of m will be 10, and our minimum value of m will be -10. Including zero, we have 21 possible diffraction orders with the He-Ne laser.

The regions where light is output are the regions with spikes in intensity in Figure 2. They are marked by the vertical and horizontal red lines on the figure. To find the corresponding wavelengths, we use the equation $\lambda = 2asin\theta_i$. This is simply the previously derived Littrow Configuration equation rearranged by multiplying both sides by a and setting $m = -1$. Using the excel spreadsheet, the angle ranges at which light is output and the laser is tunable are $43.25 \leq \theta_i \leq 43.85$, $44.70 \leq \theta_i \leq 46.10$, $48.75 \leq \theta_i \leq 50.35$, and $51.20 \leq \theta_i \leq 53.31$. We convert these ranges to wavelengths (in microns) by using the above equation, and the previously solved

[5] See Works Cited for sources related to this paragraph.

for value of a, 6.73 microns: $9.22 \leq \lambda \leq 9.32$, $9.46 \leq \lambda \leq 9.70$, $10.1 \leq \lambda \leq 10.4$, $10.5 \leq \lambda \leq 10.8$. Knowing that smaller wavelengths indicate higher energy, we can make the statement that the first spike is the r branch, then the second spike is the p branch, third is r branch again, and fourth is p branch again.

A mathematical representation of efficiency can be (output energy) / (input energy), where higher values correspond to higher efficiency—more output energy with less input energy indicates a higher efficiency. Using this equation, we have that the efficiency of the Ar+ laser is 0.06, meaning 6% of the input energy exists in the resultant photon. The efficiency of the carbon dioxide laser is 0.43, meaning 43% of the input energy exists in the resultant photon. Therefore, we can make the statement that the carbon dioxide laser is more efficient because a higher percentage of the input energy was used to create the photon rather than being lost in some other form.

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