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Section 401

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Nitrogen Laser Demonstration and Experiments

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Summary: Prior to the lab, a nitrogen laser consisting of three major components—pulse generator, pulse amplifier, and chassis unit—was built. These components were set up so the output of the pulse generator was an input of the pulse amplifier and the output of the pulse amplifier was an input of the chassis unit. The chassis unit also received input from a 0-30 kVDC power supply. Each of the three components had 110 VAC input from a wall outlet. The first experiment was conducted to measure how the intensity of the laser light changed in response to a change in power supply voltage. This was done using the voltage output of a photodiode on an oscilloscope (Figure 1[1]). The next experiment was conducted to determine how photodiode voltage output varied based on the nitrogen pressure. The same set up was used but with a different independent variable. The next experiment was conducted to experimentally measure the speed of light. One photodiode was placed directly in front of the laser beam. Another photodiode was placed one meter behind the first. The time between the pulses was measured. The second photodiode was moved backward at one-meter intervals to collect more data (Figure 2[2]).

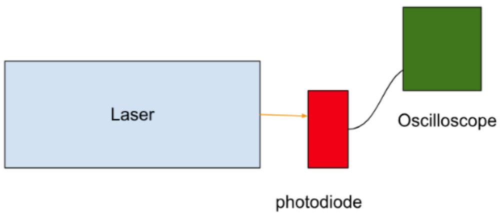
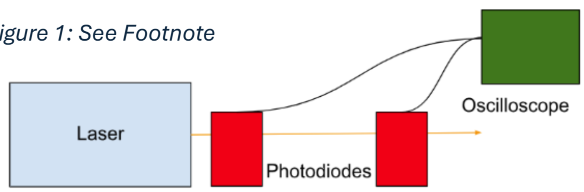


Figure 2: See Footnote

Figure 1: See Footnote



Answers to Questions: The two ends of the nitrogen laser cavity are $75.0 \pm 0.5\ cm$ apart. The longest round-trip time for intracavity light occurs when the light travels both down and back the laser cavity, meaning it travels a distance of $1.50 \pm 0.01\ m$ at the speed of light, $3 \times 10^8\ m/s$. Therefore, the longest round-trip time for intracavity light is $5 \times 10^{-9} \pm 3.33 \times 10^{-11}$, or 5 ns. The light output of the laser was first apparent at a voltage of 13,000V, but it became more focused at 15,000V.

There are two light emission processes responsible for the light observed as voltage was increased. Before the light was focused, the main form of light emission was spontaneous emission. Spontaneous emission occurs when a nitrogen molecule in the C energy state spontaneously releases energy in the form of a photon and in turn goes down to the B state. Spontaneous emission produces light, but this light is not focused because the photon is not in phase with other photons produced through spontaneous emission. This is the process that is occurring from 13,000-15,000V provided by the power supply. As the laser light becomes more focused, another process called stimulated emission is occurring more frequently than spontaneous emission. This is the condition for lasing. Stimulated emission occurs when a photon interacts with a nitrogen molecule in the C state such that it causes it to drop down to the B state and release another photon. These two photons end up being in phase with each other, constructively interfering to produce a more focused laser beam. This is the process mostly occurring when over 15,000V were provided to the laser by the power supply. A high voltage is

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[1] **Figure 1:** The three components of the laser work together to produce laser light (orange arrow) that is measured by the photodiode. Data is displayed and was read from the oscilloscope.

[2] **Figure 2:** First photodiode is placed directly in front of laser. Second is placed some distance back. This distance was varied as the independent variable. Data is displayed and was read from the oscilloscope.

needed for stimulated and spontaneous emission to overpower any absorption of photons because a very small amount of nitrogen molecules are naturally in the C state as compared to the B state. For emission to overpower absorption, more nitrogen molecules need to exist in the C state than the B state. Therefore, a population inversion needs to be induced within the population of nitrogen molecules. This is done when enough voltage is provided by the power supply for the three circuit components to work together to create a population inversion. It was also observed that the laser light was a horizontal line. This was determined to be because of the horizontal orientation of the electrodes within the body of the laser.

With a photodiode set up as indicated in Figure 1, the photodiode voltage—which is proportional to the intensity of the laser light—was measured as a function of power supply voltage. The results are displayed on Figure 3.[3] Uncertainties were estimated and recorded. These uncertainties are plotted in Figure 3 but are so small that they are hard to see. The power supply voltage that corresponds to the lasing threshold pump power of the laser is somewhere between 10,500V and 11,000V. The jump in voltage from 0.86 to 3.52 between these two data points is indicative of the start of lasing, in which stimulated emission dominates spontaneous emission. The concepts of light intensity and light wave interference are closely related. Depending on the phase difference between the two waves, the intensity varies. When two waves are in phase with each other, they constructively interfere, and intensity is high. Photons are in phase with each other when stimulated emission occurs more often than spontaneous emission, or in other words, when lasing is occurring. Therefore, the major jump in photodiode voltage is indicative of a jump in light intensity caused by the constructive interference of the waves during stimulated emission. From 10,000V-10,500V, spontaneous emission is producing out of phase photons which destructively interfere, resulting in lower intensity. The plot's functional form for values near but greater than the threshold value seems to be linear. This is especially true for the first three points after the threshold voltage (11,000V-12,000V), as a positive linear relationship exists between them. This makes sense because as more voltage is added, more nitrogen molecules are being excited. This continues until most of the population is excited, hence why we see the graph level off. The system saturates at around 20,000V, as can be seen by the leveling off on the graph.

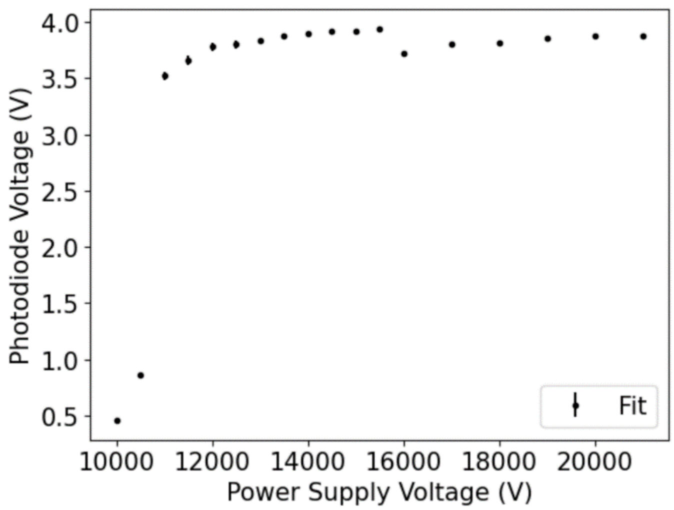

Figure 3

The duration of the laser pulse at 15,000V from the power supply is 22.3 ns. This is a reasonable value. The lifetime of a nitrogen molecule in the C state before spontaneously emitting is around 40 ns. When lasing is occurring, both stimulated and spontaneous emission are causing molecules to drop from the C to the B state, so population inversion goes away faster

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[3] **Figure 3:** Plot one depicts the photodiode voltage as a function of power supply voltage. Note the drastic increase in photodiode voltage from 10,500V to 11,000V. The photodiode voltage leveled out at a value of 3.88 after 20,000V were inputted via the power supply.

than 40 ns. Additionally, lasing only occurs when more stimulated emission occurs than spontaneous emission, so that decreases the time as well.

The nitrogen laser must be a high gain laser. After 8% of the light in the nitrogen laser gets reflected, we get an equation for power in the form $P_1 = P_0 G^2 R$, where R=0.08. G is squared because we pass through the gain twice. We know that the ratio of ${P_1}/{P_0} \geq 1$ for the laser to continue functioning. Therefore, $G \geq \frac{1}{\sqrt{R}}$. Since R is small, G must be big, so the nitrogen laser is a high gain laser. If the laser had an output coupler of R=0.8, it would require 5 trips down and back the laser cavity for all light from a pulse to be emitted. Using previous calculations, this would take around 25 ns. However, the lifetime of the lasing state is only 22.3 ns, so stimulated absorption would occur for the last couple nanoseconds. Therefore, the pulse would not have more energy with an output coupler.

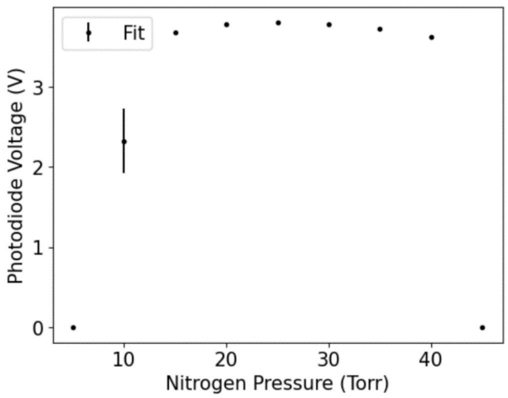

Figure 4

The photodiode voltage is plotted as a function of pressure to the left in Figure 4[4]. This was measured using the set up in Figure 1. At low pressure, the photodiode voltage is very low. This makes sense, as less nitrogen molecules naturally indicates less stimulated emission due to the need for multiple nitrogen molecules in the C state for stimulated emission to occur. At very high pressure, the photodiode voltage is also low. This is because the mean free path of the electrons—the distance that the electrons in the medium can travel before interacting with something or losing energy—is lower at higher pressure. These collisions result in a loss of energy and less nitrogen molecules in the C state. The data in Figure 5[5] was collected using the set up in Figure 2. Two photodiodes were used, and the time between the pulse at the photodiode directly in front of the laser and the pulse at another photodiode some distance behind the first was recorded. The slope of this line, calculated to be 290,000,000 m/s, is an experimental value of the speed of light. To calculate this value, the first and last point can be used, as they lie on the line of best fit. Our x error was 1 cm, and the y error was 0.1 ns. When subtracting the x and y values to find the slope between these points, we simply add the errors. However, when dividing these values, error propagation strategies change. The value of R in this case is $\frac{\Delta x}{\Delta y} = 2.9 \times 10^8 = R$. Using the error propagation equation for division: $\delta R = R\left(\frac{\delta x}{x} + \frac{\delta y}{y}\right)$. The error becomes 2900000. Therefore, our final value of the slope is $2.9 \times 10^8 \pm 2{,}900{,}000\ m/s$. The value of the y-intercept is -7.8 m. When both photodiodes were placed at

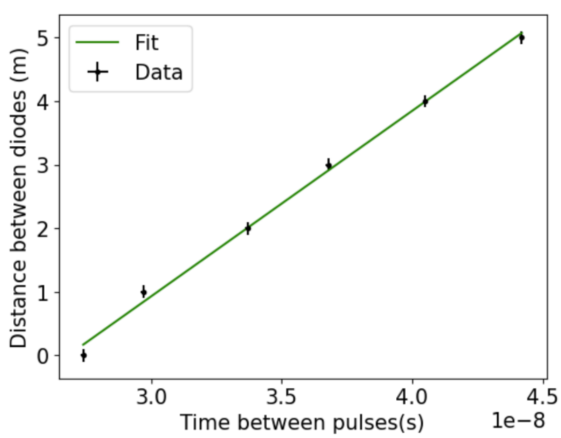

Figure 5

[4] **Figure 4:** Photodiode voltage as a function of pressure. Note that high and low pressures result in low voltages.
[5] **Figure 5**: Distance between diodes as a function of time. Slope represents the speed of light.

the same location, one pulse arrived later than the other due to the different lengths of wire. In order for both pulses to arrive at the same time (t=0), the second photodiode must be 7.8m in front of the photodiode directly in front of the laser (positive values of distance indicate distance *behind* the first photodiode). This would only be feasible if the first photodiode was moved back from directly in front of the laser.

Discussion of Major Systems: The physics behind the laser and the overall workings of the laser was previously described in detail when answering the second question (see that paragraph for description of the apparatus). One omitted piece of information is that stimulated absorption can also occur when a photon interacts with a molecule in the B state and brings it up to the C state. We do not want this to occur during lasing because it takes away a photon.

The first major system is the pulse generator. The pulse generator's main component is the 555 timer, which is essentially a switch that controls when the output pin, pin 3, outputs voltage. First, 117VAC is converted to 18VDC. This 18VDC is at pin 8 on the 555 timer, and is known as the Vcc voltage. When pin 2's voltage is less than Vcc/3, or 6V, the 555 timer opens a switch, preventing current from flowing. As a result, charge will build up on the 2.2 capacitor, and the output voltage at pin 3 is simply Vcc, or 18VDC. The next situation occurs when pin 2's voltage is greater than 2Vcc/3. When this occurs, the switch closes between pins 7 and 1, and the current flows to ground. As a result, the output at pin 3 is 0V, and the capacitor discharges through the 100K. Therefore, the output of this system is a square-like voltage pulse that occurs at 3 Hz (3 times per second). The voltage is 18V for .33 s then 0V for .33 s. This pulse goes to the pulse amplifier.

The next major system is the pulse amplifier, whose main component is a Silicon Controlled Rectifier (SCR) switch that operates based on the input from the pulse generator. When the pulse generator sends a voltage of 18VDC, the voltage at the gate (G) is positive, as the voltage simply passes through the .47 capacitor. When the pulse at G is positive, the path from A to K becomes conductive, meaning the top plate of the 1.0 capacitor is connected to the ground. This results in the 400V from this capacitor being increased to 1600V by the transformer. The output we get during this pulse is a fast spike up to 1600V then a slower decrease in voltage with a small negative piece at the end. The 18V of charge at G decreases as the .47 capacitor charges. Eventually, the capacitor is charged to 18V and the voltage at G is 0V. Next, the voltage from the pulse generator becomes 0V. This essentially connects the left plate of the .47 capacitor to the ground, leaving a negative charge on the right-hand plate. As a result, current flows from the ground through the diodes, which have an inherent voltage drop across them. Therefore, the voltage after passing through the diodes is negative, giving a negative pulse to G and opening the switch and preventing current from flowing through A to K. Since the 1.0 capacitor isn't connected to the ground anymore, this capacitor charges up, waiting for the path from A to K to become conductive again so it can amplify the 400V. The 400V at the 1.0 capacitor comes from the amplification and conversion of 110 VAC from a wall outlet to 400VDC.

The chassis is the next major system, which runs using the thyratron. The chassis discharge unit is where the conditions for lasing are met. The pulse amplifier signal goes to the grid of the thyratron, making it conductive. While the thyratron was not conductive, the C1 capacitor was charging. Once the thyratron becomes conductive, C1 discharges to C2. There are now 2 ways for C2 to discharge, depending on the voltage provided to the chassis unit from the power supply: If the voltage from the power supply is low, C2 will discharge through the resistor, R2. If it is high enough, C2 discharges through the laser cavity, filled with nitrogen gas.

This electrical discharge excites the nitrogen molecules and causes the population inversion needed for lasing.

The thyratron has a heater and reservoir circuit that causes a phenomenon called Townsend Discharge to occur, which is ultimately what makes the thyratron conductive when the pulse amplifier pulse arrives at the grid. Essentially, the heater portion of the circuit creates a population of free electrons from the cathode using a process called thermionic emission. The reservoir circuit contributes to this by creating low pressure gas in the thyratron. As a result, the free electrons and low-pressure hydrogen cause a Townsend Discharge to occur, which is the process of accelerating electrons by an electric field and creating a multiplication/avalanche effect with these electrons. The end result is conduction within the thyratron. As the pulse amplifier signal becomes negative, the conduction stops and the C1 capacitor in the chassis unit begins charging again.