Effects of Lasing on the Fluorescence Emission Spectrum

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Lab name: HeNe Laser
Lab station: PHAS-OPTICS4
Lab section: L2B
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Lab #: 3
Note to teaching team:

Abstract

Due to the prevalence of lasers technology in modern society, it is important to understand there operational principals and characteristics. To that end, this lab investigates the shape and stability, and spectral and polarization properties of a Helium-Neon (HeNe) laser system. To characterize the shape of the resonating beam, a wire was translated through the laser cavity, forcing specific TEM_{lm} modes to occur. To determine the polarization of the output beam, it was passed through a linear polarizer that was continuously rotated, revealing an entirely linearly polarized beam. Lastly, the spectrum of the fluorescence was analyzed while lasing action was occurring and absent. Counter-intuitively, it was found that the power from the lasing transition was reduced while lasing action was occurring. This result was attributed to the reduction in electron population in the excited state of the lasing transition, reducing the number of *spontaneous* transitions for the lasing transition.

RESEARCH NOTE

It was found that the strength of light in the fluorescence of a HeNe laser attributed to the lasing transition is reduced while lasing action is occurring. This phenomenon was attributed to the reduction of the electron population in the high energy state of the lasing transition due to stimulated emission. It was additionally observed that the strength of light corresponding to transitions to lower energy levels from the lower energy level of the lasing transition was greatly increased during lasing action, agreeing with the theory that stimulated emission modifies the electron populations of the energy levels associated with the lasing transition.

This result was demonstrated majorly by the use of a lock-in amplifier and a monochromator. A stepper motor was used to scan through a wavelength spectrum of 570nm to 650nm and a rotating disk with holes modulated the laser light so that the lock-in amplifier could be aligned. Using this setup, Figure 1 was plotted. Upward peaks from the horizontal indicate wavelengths that had increased intensity during lasing action while downward peaks indicate reduced intensity during lasing action. Notably, the transitions associated with wavelengths of 594.15nm and 609.50nm had the greatest increase, both of which start at the $3p(J = 2)$ energy level, which is the lower energy level of the lasing transition.

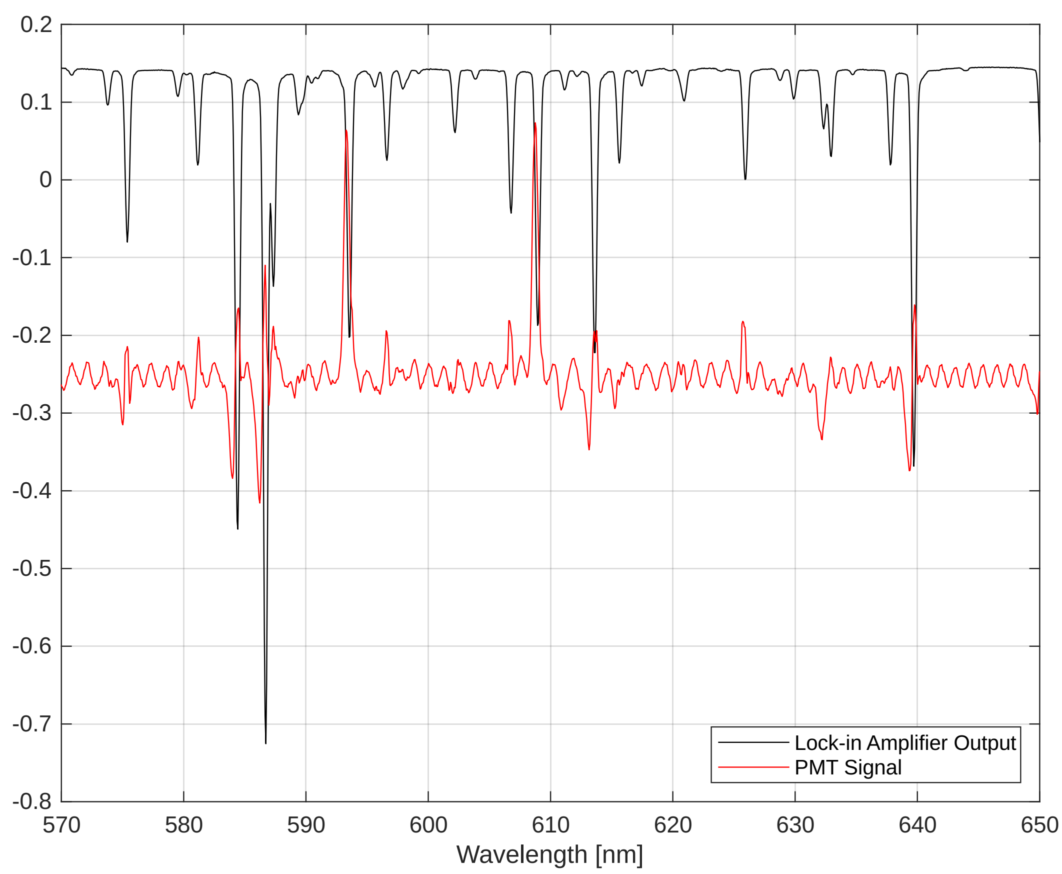

Figure 1: Spectrum scan of the signal from the lock-in amplifier and photo-multiplier-tube. Note the downward peak at 632.84nm indicating reduced intensity of light from the lasing transition while lasing action is occurring. Also note the two large upward peaks at 594nm and 609nm, showing increased light intensity from transitions starting at the lower energy lasing transition energy level during lasing action.

EXPERIMENTS

1 Laser Alignment and Stability

(A) Using a planar mirror for the OC mirror, the radius of curvature of the fixed HR mirror was determined to be 56cm. This was done by using the stability condition for a spherical mirror cavity. From [Saleh and Teich(2019)] equation 10.2-5,

$$0 \leq \left(1 + \frac{L}{R_1}\right)\left(1 + \frac{L}{R_2}\right) \leq 1 \quad \implies \quad 0 \leq 1 + L/R_2 \leq 1$$

for $R_1 \to \infty$ as the OC mirror is planar here. Then, $0 \leq L \leq -R_2$, implying that R_2 must be concave.

(B) Replacing the planar mirror with a spherical mirror with radius of curvature 60cm and repeating the experiment above, the radius of curvature of the HR mirror was measured to be 42cm. This is an unfortunate discrepancy that is likely due to not being able to sufficiently align the OC mirror sufficiently at cavity lengths much more than 1m. The longest stable cavity length observed was 102cm. If a length of 1.1m was stable the ROC would instead by 50cm.

2 Transverse Laser Modes

(A) The highest observed mode structure was TEM_{30}.

(B) When the iris was moved towards the closed position, the higher-order modes became the TEM_{00} mode.

(C) While the wire was being translated through the laser cavity, the modes went 00, 20, 10, 20, 00.

(D) The wire was positioned to isolate for the TEM_{10} and TEM_{20} modes. The positions of the wire for these transverse modes are shown in the table below. Note that the TEM_{20} mode occurs twice while the wire is translated across the beam as the TEM_{20} mode has two nodes.

Position [mm]	7.00	7.35	7.48	7.62	7.99
Mode TEM_{lm}	00	20	10	20	00

(E) The waist size of the beam at the wire was determined using the equation for the intensity of the TEM_{20} beam. Given just below equation 3.3-11 in [Saleh and Teich(2019)] and the measurements of the nodes of the transverse modes. That is, the intensity distribution along the x axis of the TEM_{20} beam is given by

$$I(x) = I_0 \left(8(x/W(z))^2 - 2)e^{-(x/W(z))^2}\right)^2$$

The zero intensity position in this distribution correspond to the measured positions. Finding the center of the beam with the TEM_{10} measurement, and expecting 0 intensity at $x/W(z) = 1/2$, the beam waist at the wire was determined to be 0.28 ± 0.005 mm.

(F) The relations

$$z_1 = \frac{-d(R_2 + d)}{R_2 + R_1 + 2d} \qquad z_0^2 = \frac{-d(R_1 + d)(R_2 + d)(R_2 + R_1 + d)}{(R_2 + R_1 + 2d)^2}$$

as seen in [Saleh and Teich(2019)] section 3. Using $R_1 = -60$cm and $R_2 = 50$cm, and $d = 43$cm, the Raleigh length was $z_0 = 0.197$m and the minimum beam waist was $z_1 = 0.096$m, that is 9.6cm from the OC mirror.

3 Polarization of Laser Light

(A) The laser is polarized if the output beam is polarized. That is, the direction of the electric field is periodic. The polarization of the laser output was measured to be completely linearly polarized.

(B) We might expect linear polarization as the HeNe light source is contained by a mirror placed at Brewster's angle, transmitting the P polarization through with 0 reflection losses to the OC mirror.

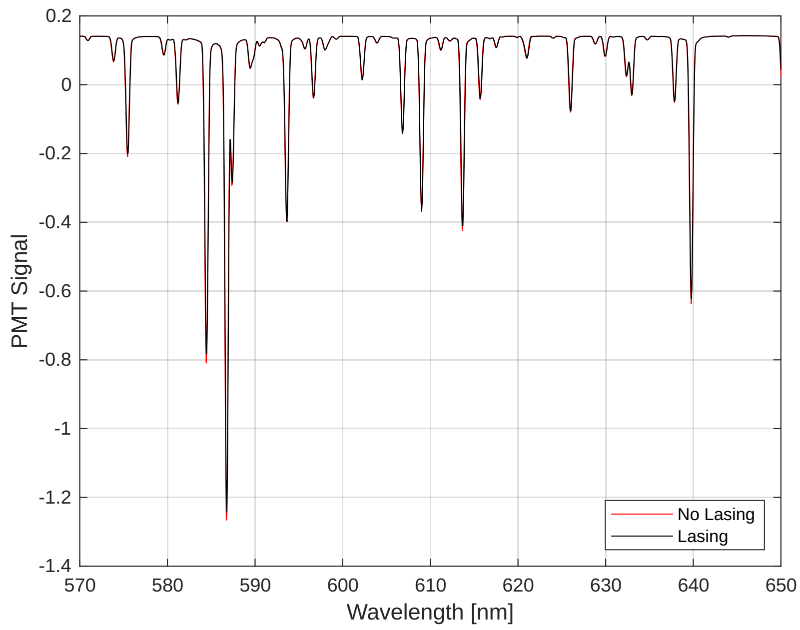

Figure 2: Comparison of photo-multiplier-tube spectrum for for fluorescence and fluorescence while lasing is occurring. Note the slight difference in peaks in the two datasets.

4 Spectral Properties of Emitted Light

(A) First, focusing on the fluorescence alone, its spectrum was measured with and without lasing present. This was done using a monochromator to filter the output intensity of the fluorescence to a single wavelength which was amplified by a PMT and measured using an A2D device. See Figure **??** for a plot of spectrums of the fluorescence with and without lasing being present. Some of the peaks decreased while others slightly increased.

(B) The major transitions observed in the prior referenced spectrum are, in order of strongest observed peak to weakest, as follows:

Wavelength [nm]	Transition
587.22	$4d(J=2) \rightarrow 3p(J=1)$
584.93	$3p(J=0) \rightarrow 3s(J=1)$
640.27	$3p(J=3) \rightarrow 3s(J=2)$
614.15	$3p(J=2) \rightarrow 3s(J=2)$
594.15	$3p(J=2) \rightarrow 3s(J=2)$
609.50	$3p(J=2) \rightarrow 3s(J=1)$
575.95	$4d(J=4) \rightarrow 3p(J=3)$
607.34	$3p(J=0) \rightarrow 3s(J=1)$
616.59	$3p(J=1) \rightarrow 3s(J=0)$
638.41	$3p(J=1) \rightarrow 3s(J=1)$
632.82	$5s(J=1) \rightarrow 3p(J=2)$
616.19	$3p(J=1) \rightarrow 3s(J=0)$

This means the relevant energy level transitions to the lasing transition at 632.8nm were 614.15, 594.15, and 609.50nm.

(C) To further characterize the laser, the laser output beam was redirected into the monochromator to have its spectral properties measured. See Figure 3 for the spectrum of the laser and the fluorescence. By allowing the laser light to enter the PMT, the peaks at 632.8nm, 594.15nm and 609.50nm where all increased. The peaks that were increased were the ones corresponding to the transitions that had an energy level that was the same as the laser transition. The laser transition was increased much, much more than any other peak.

(i) The laser line does not correspond to the strongest fluorescence peak. I think this is because the strongest fluorescence peaks are going to come from the most common energy level transitions, while the laser transition requires a specific mechanism to enable it to "activate" and begin lasing/become a strong peak.

(D) The laser was periodically blocked by a spinning disk with cutouts. This was to modulate the laser intensity at a known frequency to use a lock-in amplifier to analyse the laser and fluorescence spectrum. This modulation was done at 118Hz. The reference phase was 138

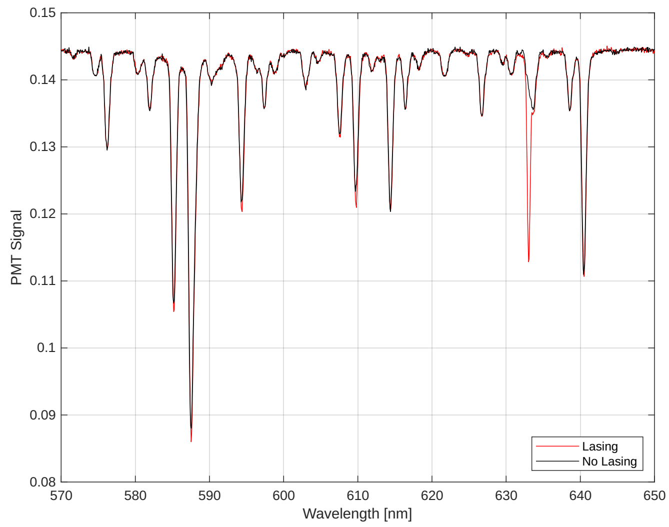

Figure 3: Spectrum of the fluorescence and diffused laser light from the photo-multiplier-tube. Note the large difference in PMT signal for the lasing transition at 632.8nm and the reduction in the peaks at 594nm and 609nm.

degrees, giving a phase for the maximum at 228 degrees. This is a phase difference of 90 degrees as expected. When the phase is flipped by 180, the output's sign is flipped. At the phase for maximum output, the generated square wave is aligned with the input signal, meaning a multiplication of their voltages is always positive. Flipping the phase by 180 degrees makes the generated wave and input waves have opposite signs always. Hence, halfway between the max phase and min phase is the reference phase when the output is 0.

(E) When blocking the lasing from happening, the lock-in amplifier's output flipped sign. This is because the intensity of the light going into the PMT was greatly decreased.

(F) Repeating the spectral analysis of the fluorescence using the lock-in amplifier instead of the PMT, the transitions that are affected by the lasing action were studied. The scan from the lock-in amplifier can be seen in Figure 4. The identified relevant transitions of 594.15nm, 614.15nm, and 609.50nm were not all affected in the same way by lasing action. However, the transitions at 594.15nm and 609.50nm changed in the same manner. That is, the upwards peaks in the lock-in amplifier signal indicated these transitions happened much more often when lasing was occurring. This is because the population of the $3p(J = 2)$ state is elevated while lasing action is occurring as photons stimulate electrons to go through the lasing transition, which transfers electrons from the $5s(J = 1)$ state to majorly the $3p(J = 2)$ state (among others). This behaviour can also be used to explain the downwards peak at 632.82nm.

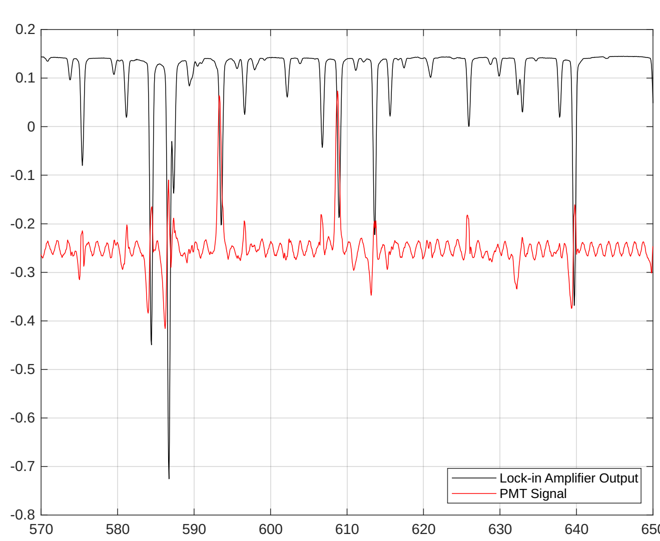

Figure 4: Lock-in amplifier and PMT signals for the fluorescence scan. Note that the prominent peaks of the PMT signal have corresponding upwards or downwards lock-in signal peaks. This is indicative of how the associated energy level transition is affected by lasing action.

References

[Saleh and Teich(2019)] B. Saleh and M. Teich, *Fundamentals of Photonics, 3rd Edition* (John Wiley & Sons, 2019).