I. Introduction

The laser was invented in 1960 by Theodor Maiman. This first laser was constructed of a cylindrical ruby crystal surrounded by a photographic flash lamp, all contained in a polished aluminum cylinder (on left). The flash lamp was used to excite the chromium ions in the sapphire host crystal. As the excited Cr(3+) ions de-excite they emit light as individual photons. Then as these photons travel back and forth in the optical cavity between the mirror-coated ends on the crystal, they induce other excited Cr ions to de-excite causing “stimulated emission.” Rapidly, all of the ions become de-excited and generate a lasing light pulse. The light beam is coherent in the sense that the photons all travel in the same direction and have the same phase. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation.

This type of laser requires three energy levels, as shown in the diagram on the right. Absorbed pump light excites the Cr³⁺ ion into excited states. The lifetime of these levels is short (50 ns), so that the excited ion quickly relaxes by making a transition to the long-lived metastable state. The energy which is lost in this process is nonradiative and goes into heating the crystal by generating phonons or vibrational excitations of the crystal atoms. The metastable energy level must have a lifetime which is long enough to enable the Cr ions to remain excited until a photon having the precise energy comes along to de-excite it. This lab experiment does not produce lasing in ruby, but investigates the excited states via the absorption spectrum and spontaneous fluorescence.

The lasing line in ruby is the so-called “R-line” having a wavelength of 694.3 nm. The fluorescence lifetime of the R-line is 3.5 ms. Fluorescence of the R-line can be excited by light in any of three absorption bands, at 250, 410, and 550 nm. A green laser operating at 530 nm is used here for exciting the R-line fluorescence.
This experiment also introduces the widely used tool – the spectrometer – for optical spectroscopy. A spectrometer is an instrument used for measuring the intensity of light as a function of wavelength. Spectrometers usually contain a diffraction grating (or prism) to disperse the light, thereby spreading out the light of differing wavelengths into different positions. The spectrometer unit used here has an internal CCD (charged coupled device) silicon detector, essentially a digital camera detector, to measure the light intensity at various positions along its length. In the figure, light from an optical fiber enters at position #1; reflects off the collimating mirror #4; is diffracted by the grating #5; reflects from focusing mirror #6; then finally is read out by the CCD detector #9. For more information on Ocean Optics spectrometers see their website, http://www.oceanoptics.com/.

II. Apparatus

- aluminum breadboard with 1/4-20 tapped holes
- green laser diode, 5 mW @ 530 nm
- USB2000-FLG Ocean Optics spectrometer/detector, USB cable
- OOIBase32 software
- lens, 25 mm focal length, for collecting and focusing fluorescence
- mirror, in x-y adjustable mount
- photodiode (PD) detector
- neutral-density (ND) optical filter (black)
- long-pass optical filter (red-orange)
- optical fibers, 50 and 600 micron cores
- ruby crystal, Al₂O₃:Cr, approximately 0.05% Cr

– CAUTION –
Never look directly into any laser beam.
Also, make sure there are no reflections that direct the laser beam into your eye.
This green laser has a power of approximately 5 mW. Compare this to the 1 mW of sunlight that would enter your 1 mm diameter pupil if you looked directly at the sun.
III. Procedures

A. Room Light Spectrum

Insert one end of the 50 micron core fiber optic (FO) into the spectrometer input and the other end pointing at the wall to collect stray room light. Plug in the USB cable and start the software. Adjust the collection (integration) time so that the highest spectral peak is near but not above saturation at 4000 counts. You should see many spectral lines from the excited gases in the fluorescent ceiling lights.

☐ Store the spectrum and include in report.

☐ What is the characteristic linewidth (full-width at half-maximum) of the narrowest spectral line?

☐ List in table form the wavelengths and intensities of the 5 or 6 strongest lines in counts/sec.

☐ What are the colors of the strongest lines? Why are the room lights white?

Optional: Identify the element corresponding to each strong line by their wavelength.
Optional: Calibrate the spectrometer using known wavelengths.

B. Absorption Spectrum

Here, the absorption spectrum \( A(\lambda) \) of the ruby crystal will be measured. Make a new setup where a white light illuminates one end of the 50 micron optical fiber. Leave a space large enough (~ cm) to slide in the ruby crystal just in front of the FO. Cover apparatus with black cloth to remove room light. As before, adjust the collection time and the lamp/FO such that the spectrometer intensity is just below 4000 counts. Collect and store spectra \( I_0(\lambda) \) without the ruby crystal, then collect \( I(\lambda) \) with the ruby crystal directly in front of the input end of the FO (subtract appropriate backgrounds).

☐ First, compute the transmission spectrum, \( T(\lambda) = I(\lambda) / I_0(\lambda) \).

The light intensity after passing through a crystal of length \( L \) is given by

\[
I = I_o (1-R)^2 \exp(-\alpha L),
\]

where \( I_o \) is the initial light intensity (see Appendix). The factor \((1-R)^2\) corrects for reflection losses of the two surfaces, where the reflectivity for one interface is \( R = (n-1)/(n+1)^2 \), and the refractive index of sapphire is \( n=1.75 \). Use a sample length of \( L=2.00\pm0.05 \) mm.

☐ Plot the spectrum of the absorption coefficient as a function of wavelength, \( \alpha(\lambda) \).

☐ Smooth out the noise and discuss the absorption peaks.

☐ What is the “absorption length,” \( 1/\alpha \), at the main absorption peak.

Optional: measure the refractive index from the absolute reflectivity of one ruby surface.
C. Optical Setup

Mount the optical components on the breadboard approximately as shown in the diagram and photograph. Before aligning the beam, you must place the black neutral-density (ND) optical filter in front of the laser to reduce the beam intensity.

D. Ruby Fluorescence Spectrum

Collect laser-excited fluorescence from the ruby crystal and plot its spectrum.

Optical Setup – Before beginning, confirm that the black neutral-density (ND) filter is in front of the laser. First, the collection optics must be finely aligned. Remove the 50 micron FO and insert one end of the 600 micron FO into the mount that points at the collection lens, and shine a white light source into the other end. Using the lens maker’s formula, compute the image and object distances for the $f=25$ mm focal length collection lens. While holding a white piece of paper at the front face of the ruby crystal, adjust the position of the lens and FO so that the white spot image is focused at the front face of the ruby crystal. Now adjust the mirror to overlap the green laser beam and the white spot image on the ruby crystal.

Measurement – Remove the 600 micron FO and replace with the 50 micron FO. Insert one end of the FO into the holder pointing at the collection lens and the other end into the spectrometer. Look for the R-line fluorescence in the spectrum. Maximize the intensity of the R-line emission by turning the adjusting screws on the mirror mount. Cover the breadboard with the black cloth.

☐ Store the spectrum and include in report.
☐ Record the wavelengths of the green laser line and the R-line.
☐ Compute the “photon energies” of the green laser line and the R-line, \[E(\text{eV})=\frac{1239.513}{\lambda(\text{nm})}\].
☐ What other spectral lines are present? Discuss their origin.
**E. Fluorescence Lifetime of Ruby R-line**

This section describes measurement of the lifetime of the ruby R-line fluorescence.

*Laser setup* – Turn the diode laser power switch **OFF** (down). Connect the TTL output of the function generator to the diode laser power supply with a BNC cable. Using a BNC Tee, attach another BNC cable to channel-1 of the oscilloscope. Adjust the function generator to output a square wave having a period of 30 to 50 ms. Trigger the scope on the falling edge of the square wave.

*Collection setup* – Use the 600 micron FO to collect the fluorescence from the collection lens, and attach the other end of the FO to the small photodiode (PD). Connect the BNC output of the PD to channel-2 of the scope. Turn the PD switch on (up). Next, remove the ND filter from the laser beam. Place the long-pass (red-orange) filter between the collection lens and the FO. This blocks (absorbs) the green laser light, while transmitting the red R-line. On the oscilloscope you should see a signal from the PD which is synchronous with the function generator.

- Capture one complete period of the PD output for your report.
- Curve fit the decay of the PD signal to an exponential function.
  - In the region of interest, plot the data as points and the curve fit as a solid line.
- What is the exponential decay time of the fluorescence? What is the uncertainty?

**Conclusion**

- Make a TABLE listing the important final values (with uncertainties) and expected values.
IV. Appendix

A. Lens Maker’s Formula

The lens maker’s formula is used here to determine the parameters for focusing the image of the ruby fluorescence into the optical fiber.

Convex focusing lenses are useful for projecting an image of an object from one side of a lens onto the other side. See the diagrams. The distance of an image from the lens is related to the distance of the object from the lens by the lens maker’s formula,

\[ \frac{1}{i} + \frac{1}{o} = \frac{1}{f}, \]

where \( i \) is the image distance, \( o \) the object distance, and \( f \) the focal length of the lens. The magnification of the lens is \( M = \frac{i}{o} \). A special case of this formula is the focusing of a collimated laser beam. There the object distance is infinite, so the laser beam is focused to a small diameter spot at a distance \( i = f \) from the lens, shown in the lower diagram.

B. Light Absorption

Materials which absorb light, such as the ruby crystal used here, have an absorption coefficient \( \alpha \) which characterizes the depth to which light penetrates into the crystal. The light power \( P \) (or intensity \( I \)) decreases as a function of increasing distance \( x \) into the material given by

\[ P(x) = P_0 \exp(-\alpha x), \]

where \( P_0 \) is the initial power at \( x = 0 \). The absorption length, \( 1/\alpha \), characterizes the penetration depth of the light. Light energy absorbed in the ruby crystal is converted into energy stored in the excited Cr ions (plus some energy lost which goes into heating the crystal). Note that light intensity is the light power divided by the cross sectional area of the light beam, \( I = P/A \).

C. Optical Excitation

Each photon of green light absorbed by the ruby crystal raises the energy of a Cr ion to an excited state. This state rapidly relaxes to the long-lived metastable state having a lifetime \( \tau \). Before the light is turned on, all the Cr ions are in the ground state. After turning on an excitation source, the number of excited ions increases. After time \( t \) of weak excitation, the number of excited ions is given by

\[ N(t) = N_0 [1 - \exp(-t/\tau)], \]

where \( N_0 \) is the number of ions which are excited after the crystal has been weakly illuminated for
a long time $t >> \tau$. Neglecting stimulated emission, the excitation process comes to equilibrium when the rate of excitation equals the rate of decay from the metastable state. The rate at which Cr ions are excited is $P / h\nu$, where $h\nu = hc/\lambda$ is the photon energy. The rate of decay is $1/\tau$. At equilibrium, the number of excited Cr ions per unit volume is given by $n_e = \alpha I \tau / h\nu$. After the exciting light is removed, the number of excited Cr ions decreases exponentially for increasing time as

$$N(t) = N_o \exp(-t/\tau).$$

D. Chromaticity Diagram

All the possible colors of light which the human eye can distinguish can be made by adding relative amounts of the three additive primary colors: red, green and blue. These are related to the three wavelength-dependent photoreceptors in the human eye. These three colors are also used in TV and computer color monitors.

In the mid-19th century, J.C. Maxwell first described a diagram, the Maxwell triangle, to quantitatively represent all possible colors using the three primary colors. Spectra of the three particular primary colors are shown on the left. The Maxwell triangle has been updated into the universally accepted CIE chromaticity diagram, shown on the right. In this diagram, the x- and y-axis are the relative amounts of red and green light, respectively, and the amount of blue is 1-x-y. The outer rim of the “tongue” shape represents pure or saturated colors (hues), and is light of a single wavelength. Going inward from the edge towards the center is equivalent to adding white light, referred to as changing the tint. Pure white light is composed of an equal mixture of the three primary colors, $x=y=z=0.33$. Note that the light from the green laser used in the experiment (530nm) lies on the upper, outer edge at $x=0.21$ and $y=0.77$. It is interesting that after dark you can see many variations of “white” lights that are distinguishable.

http://www.efg2.com/Lab/Graphics/Colors/Chromaticity.htm