Laser Attenuation through Dyed Solution

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After light travels through an opaque solution it appears dimmer. The effect that solutions have on light can be studied precisely by measuring the intensity of a laser beam after it passes through a cell containing diluted dye. As the beam of light travels through the solution, it encounters and interacts with particles of dye. We expect that the presence of these particles will cause an attenuation in the power of the light beam. By comparing the power of light transmitted through a solution to the power of the unimpeded laser, we discover the effect that varying solutions have on a beam of light.

INTRODUCTION

Intuition tells us that when light shines through an opaque fluid it appears dimmer on the opposite side. Imagine trying to find the keys you dropped in a pond with clear water versus one with murky water. The image of the bottom of the pond is dimmer in the murky water.

This phenomenon occurs because the murky water contains suspended particles which can impede the path of a photon. To investigate this effect, we will measure the attenuation of a light as it passes through a cell containing dyed liquid. The results will help build a precise relationship between the properties of a fluid and the attenuation of a beam of light that travels through it.

Results of this experiment will allow us to predict the transmission of light through any fluid. A mathematical model of the attenuation of light through a fluid can be applied in various fields of science. For instance, communication by submarines and by satellites both rely on sending information

THEORY

Light traveling through a dyed fluid is impeded by the particles suspended in that fluid. A photon that travels through a solution of greater concentration has a better chance of encountering a particle, as does a photon that travels a greater distance through a solution.

We suspect that the attenuation of a beam passing through a dyed fluid is dependent on the chance of each photon encountering a suspended particle. Clearly, this chance increases as the number of particles in the photon's path increases. Considering the beam of light as a whole, the total attenuation should depend on the number of suspended dye particles in the beam's path.

To calculate the number of particles in the path of the beam, we first consider in Fig 1 the cylindrical volume of fluid that the laser will interact with. The volume of this region is described by

$$V = 2\pi r_L^2 \cdot d \tag{1}$$

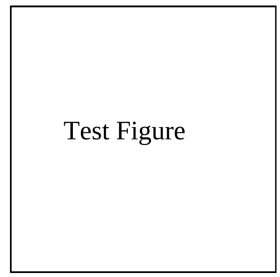

FIG. 1.

where r_L is the radius of the laser beam and d is the length of the cell.

If we define the concentration of the fluid C by Eqn 2, we can calculate the number of particles in the beams path N_p as shown in Eqn 3.

$$C = n\frac{1}{[V]} \tag{2}$$

$$N_p = V \cdot C = 2\pi r_L^2 \cdot d \cdot C \tag{3}$$

Notice in equation 3 that r_L is fixed so N_P only depends on $d \cdot C$. For this reason, we design our procedure to control the length of the cell and the concentration of the dyed fluid to produce varying values of N_P.

EXPERIMENTAL METHODS

In this paper we study the effect that a dyed fluid has on a beam of light by varying the concentration of the dye and the distance the beam travels through it. Light is provided by a 12mW laser producing a red beam.

Varying Distance Laser Travels through Solution

To vary length of the solution we use machined cells of varying lengths as illustrated in Fig 2. The cells are constructed with a metal base, plastic siding, and glass windows on either end. The pieces are glued together.

We vary the length of the cell to change the distance the laser travels the solution, in turn varying N_p.

Varying Concentration of Blue Dye Solution

To vary the concentration of the solution we perform dilutions of a stock blue dye. Dilutions are carried out by measuring a volume of stock solution in a graduated cylinder, adding it to the empty 10cm cell, and then adding a volume of water as measured in a graduated cylinder.

Starting with the base solution of 1.00 concentration, half dilutions are performed by adding 18ml of the current solution to 18ml of water. According to Eqn 4,

$$V_1 \cdot C_1 = V_2 \cdot C_2 \tag{4}$$

starting with 18ml and ending with 36ml, our concentration should reduce by a factor of 2.

Performing dilutions in this way means that we will always have 36ml of each solution which is sufficient to almost fill up the largest cell (Fig 2) which has volume given by Eqn 5.

$$L \cdot W \cdot H = 10\text{cm} \cdot 1.5\text{cm} \cdot 2.5\text{cm} = 37.5\text{cm}^3 = 37.5\text{ml} \tag{5}$$

Smaller cells can be filled by transferring the solution from the previous cell after it has been tested. In this way we can ensure that solution is identical for each cell.

Distances in Setup

The measurement procedure consists of placing the cell on a platform between a laser and the detector that are mounted on a metal track that is about $35cm$ long. The laser, platform, and detector are all free to slide along the track and in this way the distances between the components can be adjusted.

The front face of the cell is always positioned 18cm from the laser and the distance between the laser and the detector is kept fixed at 30cm as illustrated in Fig 3.

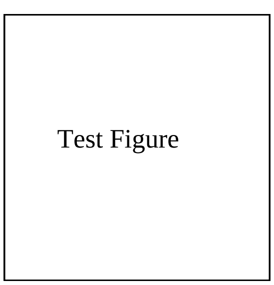

FIG. 2. The 10cm cell

The setup is intended to maximize the distance between the laser source and the cell because, as supported by Fig 4, a greater separation reduces the contribution of factors other than cell length and solution concentration. We suspect that placing the cell close to the window increases the amount of light that is reflected back into the laser source, which in turn affects our measurements.

Angle of Incidence

To ensure that there is little variation in the angle of incidence of the laser upon the cell, we align each cell against the laser housing before sliding it in to position along the rail. In this way the angle of incidence will not only be consistent between cells and trials, but the cell windows will also be aligned nearly perpendicular to the incident laser beam.

Readout

To read out the intensity of the laser we used an electronic power scale in conjunction with a digital multimeter. The scale was zeroed to the ambient light of the room before every use. The scale was also set to read 20mW max power. The output on the multimeter ranged from 0mV to 500mV regardless of the range of the scale. This allows power to be calculated from multimeter readout using Eqn 6.

$$P[\text{mW}] = \frac{V[\text{mV}]}{500\text{mV}} * 20\text{mW} \tag{6}$$

Trials

A trial consists of testing a certain concentration in a certain size cell. Trials were grouped by concentration value, and an addition trial was added at the beginning of each group to measure the intensity of the unimpeded laser.

Before each individual trial, the laser is switched off for at least 10 seconds. During this time the cell is aligned between the laser and the detector. When the laser is turned on, there is a 10 second period where no readout is performed. This is to allow the power to stabilize. After this 10 second period, the detector readout is monitored for 120 seconds during which time the maximum and minimum readout values are recorded.

RESULTS

Figure 5 shows the results of changing cell length for each concentration on a logarithmically-scaled y-axis. The linear trend of each set of points on this plot that

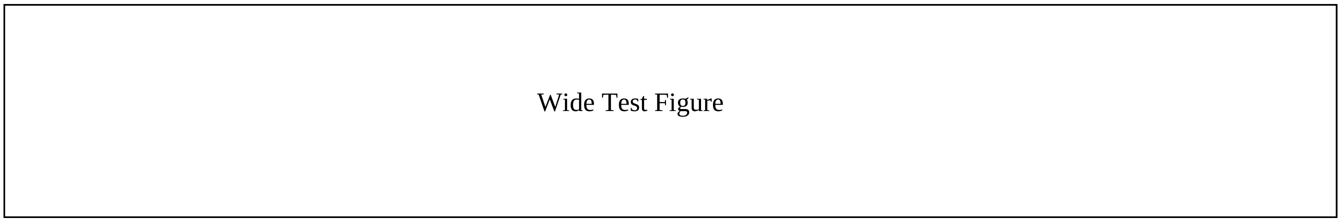

FIG. 3. The alignment of the laser, cell, and detector

appears when scaled as such suggests that the relationship can be modeled using a power function for each cell length. It is important to note that each line approaches near to the same y-intercept. This is an expected result considering concentration of the fluid should have no effect as length approaches 0.

When studying the power transmitted through the solution it is more useful to compare the transmitted power to the unimpeded power of the laser. Figure 6 shows a plot of these ratios.

ANALYSIS

In addition to the effect of the solution on the power of the beam, we must also consider the consequences of the beam traveling through the two glass plates that contain the solution.

We know that light is reflected at a boundary between two materials causing a decrease in power according to

$$P_T = T_b * P_0 \tag{7}$$

where T_b is a constant coefficient which is a property of the specific boundary. We also know that T_b does not depend on which direction the light crosses the boundary.

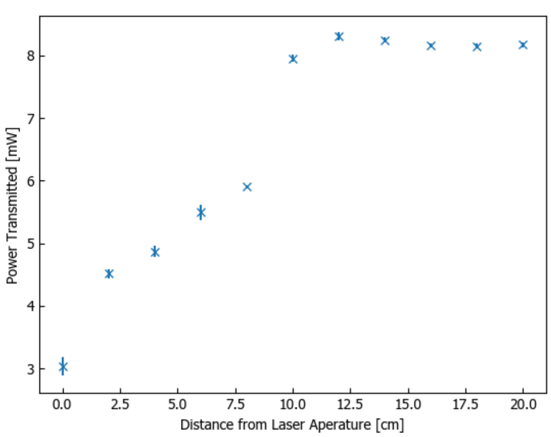

FIG. 4. Power transmitted by laser through an empty cell at varying distances from the laser

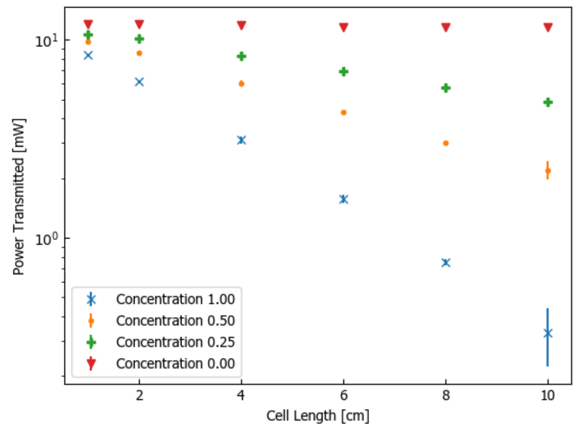

FIG. 5. Power transmitted through varying cell sizes with concentration of 1.00, 0.50, 0.25, and 0.00 units. Plotted on a logarithmically scaled y-axis

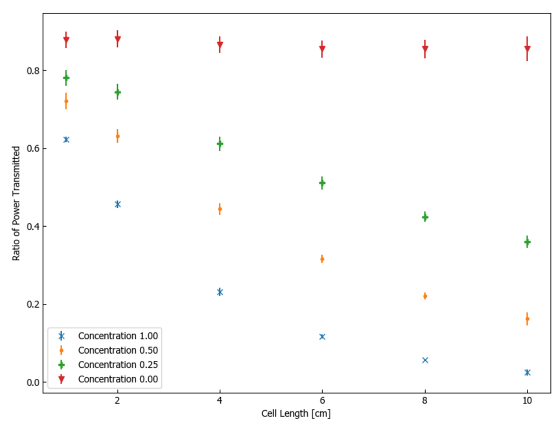

FIG. 6. Ratio of power of laser that is transmitted through the solution

In our experiment we assume that T_b on the boundary of glass and any concentration of solution is the same as T_b on the boundary of glass and water.

In order to account for the effect of light going through two glass panes before incidence upon the detector, we must know T_b for the air-glass boundary (T_1) and for the glass-water boundary (T_2).

If the power transmitted by the laser through the solution without the glass panes is a function

$$P = P(P_0, d, C) \tag{8}$$

where P_0, d and C as inputs represent the power of the laser, the size of the cell, and the concentration of the fluid respectively, then the total power transmitted by the laser would follow

$$P_T = T_1^2 T_2^2 P(P_0, d, C) \tag{9}$$

We solve for T_1 by measuring the transmission of the laser through an empty cell. We know that the laser does not attenuate significantly in air so

$$P(P_0, d, C) = P_0 \rightarrow P_T = T_1^4 * P_0 \tag{10}$$

From here we use our data to give us a value for T_1.

By studying the flat trend of transmission ratios for pure water (concentration 0.00) in Figure 6 we conclude that the laser does not attenuate significantly in water. This gives us

$$P(P_0, d, C) = P_0 \rightarrow P_T = T_1^2 T_2^2 * P_0 \tag{11}$$

We now use our computed value of T_1 and our data for transmission ratio through a cell filled with water to solve for T_2

By defining this constant $T_1^2 T_2^2$ as k we have the relationship

$$P_T = k * P(P_0, d, C) \tag{12}$$

and we can find a function P that will model transmitted power in a case where light does not cross any boundaries.

CONCLUSION