Light is a transverse wave*

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This experiment deals with the nature of light, though we stick to a strictly classical description. Light is a wave in which an electric field propagates in vacuum or inside a medium. A magnetic field rides along. This experiment shows that the electric field is oriented perpendicular to the direction of propagation of light. Such as wave is called a "transverse wave". We will use a laser, a pair of polarizers and a light dependent resistors to probe this phenomenon.

KEYWORDS Polarization · Laser · Photodetectors · Multimeter · Light Dependent Resistor

APPROXIMATE PERFORMANCE TIME 5 hours.

1 Conceptual Objectives

In this experiment we will,

1. manifest the wave nature of light through the concept of polarization,
2. see how a primary physical quantity can be inferred from a measured secondary variable,
3. correlate experimental data with mathematical expressions, and
4. learn that for wave motion, intensities are squares of amplitudes.

2 Experimental Objectives

Besides, there are some experimental objectives we like to achieve which are:

1. learn how to use lasers safely,

2. practice aligning of optical setups,
3. reading off values from angular rotation stages, and
4. using an ohmmeter inside a multimeter to measure resistance.
5. We will also plot data and finally fit to a nonlinear function.

3 Introduction

3.1 Transverse waves

In a transverse wave, all points on a wave oscillate at right angles to the direction in which the wave advances. Surface ripples on water, secondary seismic waves and electromagnetic wave (e.g., radio and light) are examples of transverse waves.

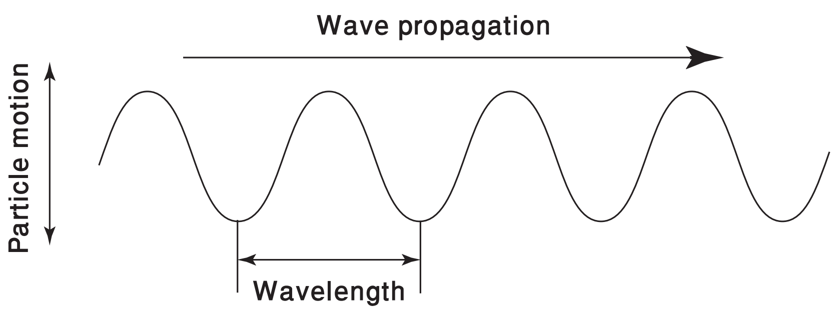

Figure 1: A transverse wave propagating perpendicular to the motion of the particles.

A simple transverse wave can be nicely illustrated with a sine or cosine curve. An example is shown in Figure 1. Suppose we talk about water waves. Then the diagram above could show the picture at any one instant of the medium through which the wave is progressing. Alternatively, it could tell how a single particle on water oscillates up and down as time progresses. Both descriptions are correct. The time required for a point on the wave to make a complete oscillation is called the period of the wave, and the number of oscillations executed per second is called the frequency. Wavelength is the distance between corresponding points on the wave i.e., between two adjacent peaks or troughs.

The transverse nature is described by a property called the polarization. Polarization specifies the geometric orientation of the oscillation of the motion. As per definition of the transverse wave, the motion of the particles is perpendicular to direction of the propagation of the wave. This means that there are a lot of different possibilities for the polarization. If the wave moves along z-axis, the polarization could be along x, along y or any combination of x and y.

3.2 Polarization of light

Light is also a transverse wave but what is actually “waving” inside this wave? It’s really an electric field which is oriented in a plane perpendicular to propagation. The electric field vector always remains perpendicular to the propagation direction. For example, we may have *linearly* polarized waves which could be horizontally or vertically polarized light, wherein the electric field vector vibrates in the horizontal or vertical planes, respectively. We may also have linear polarizations that are titled with respect to these axes, 40°, 60°, 230° and so on. Some varieties of polarization are shown in Figure 2.

We could have more interesting scenarios. For example, the electric field may rotate from horizontal to vertical, back to horizontal and so on. As you may recognize, this still satisfies the perpendicularity constraint for transverse waves. Looking head on the tip of the electric field traverses a circle. Hence this kind of transverse wave is called *circularly* polarized light.

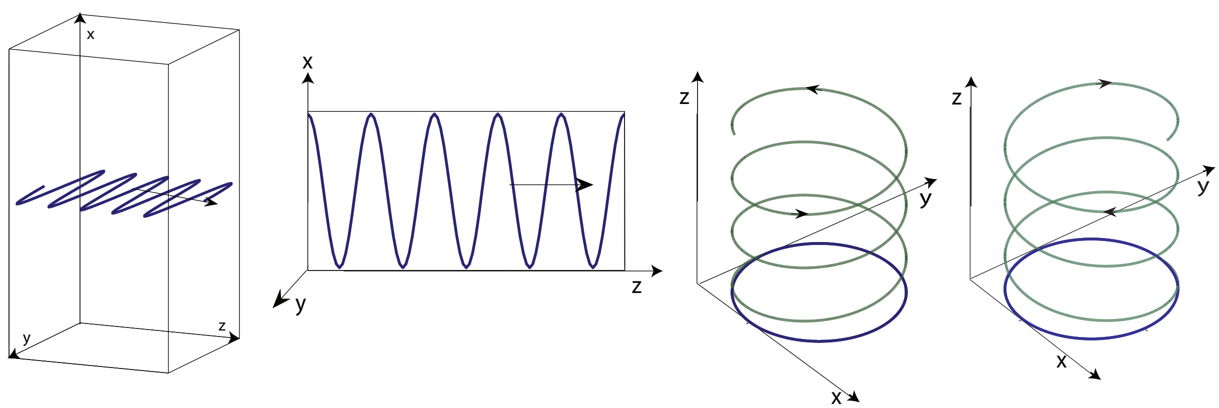

Figure 2: Diagram showing the locus of the tip of the electric field as light propagates in the *z* direction. We respectively show (a) horizontal, (b) vertical, (c) left circularly polarized and (d) right circularly polarized light.

3.3 Filtering Polarization

How can we tell that a wave is transverse? A transverse wave can pass through a slit which is parallel to the wave’s polarization. However, it completely blocks the wave when it is perpendicular. This concept is illustrated in Figure 3.

The slit shown in Fig. 3 works well for a wave inside a medium such as water waves or waves in a rope, but what about light which is a composure of vibrating electric fields? For this purpose we need a specially built optical component called a polarizer. A *polarizer* picks up only plane of vibration from all these random orientations and produces *plane polarized* light. Materials that have this property are generally used in making polarized sunglasses.

Figure 3: In diagram (a) a transverse wave is propagating towards a slit which is parallel to the motion of the wave hence allowing the wave to pass through whereas in (b) the wave gets blocked as its direction of motion is perpendicular to the slit axis.

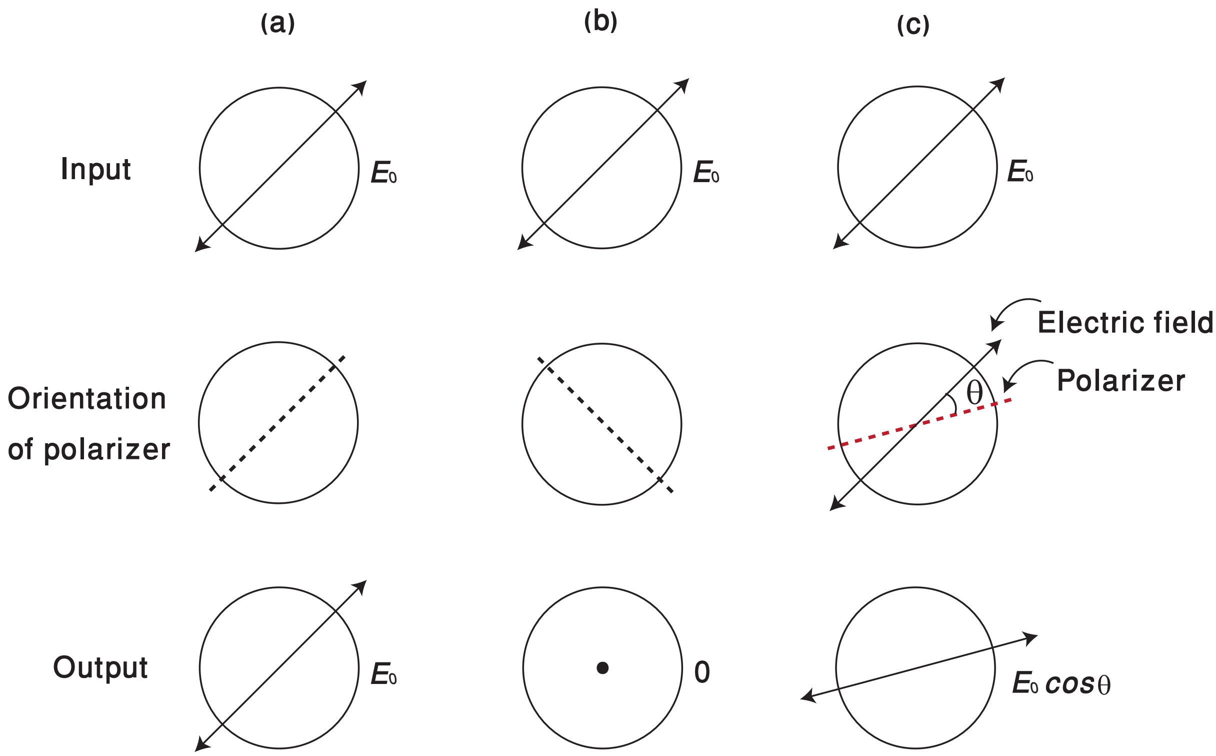

Figure 4: This figure shows various cases in which light wave can interact with polarizer. In the first column (a) the light wave with axis $\mathbf{E}_0$ is propagating towards polarizer whose axis is aligned with the polarity of light wave, resulting in maximum output field $\mathbf{E}_0$. In the second column (b) the light wave with axis $\mathbf{E}_0$ is propagating towards polarizer whose axis is perpendicular to the axis of light wave., resulting in zero output field. In the last column (c) the light wave with axis $\mathbf{E}_0$ is propagating towards polarizer whose axis is at certain angle θ to the axis of light wave, resulting in magnitude $E_0 \cos\theta$ emerging from the polarizer. The emergent electric field is parallel to the polarizer's optic axis.

The direction of the plane of polarization emerging from the polarizer depends on its *optical axis*. Light waves parallel to the optic axis will pass through and the remaining wave gets blocked. The waves which are perpendicular to the axis will be completely blocked.

The action of the polarizer can be understood with reference to Figure 4. Suppose light with electric field $\mathbf{E}_0$ falls on a polarizer. The light is linearly polarized and the optic axis of the polarizer is parallel to $\mathbf{E}_0$. All of this electric field emerges from the polarizer. This is shown in part (a) of the Figure. Furthermore if $\mathbf{E}_0$ is perpendicular to the optic axis, nothing comes out of the polarizer (part (b)). If $\mathbf{E}_0$ is at some angle θ, the strength of the electric field coming out of the polarizer is only the parallel component, $\mathbf{E}_0\ \cos\theta$.

3.4 Malus's Principle

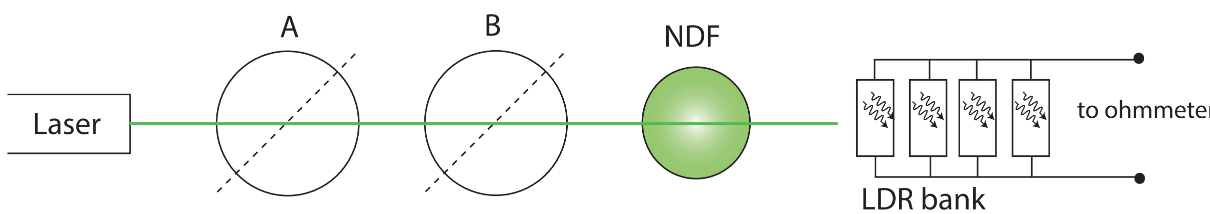

Figure 5: Polarization of laser light can be verified using a setup verifying Malus's principle. A and B are two polarizers, NDF is a neutral density filter and LDR is a light-dependent resistor. Our detector comprises four LDR's strung together in parallel. The green line shows the perceived path of the laser beam.

In our experiment randomly polarized light from a laser pointer of green color passes through two polarizers labeled A and B as shown in Figure 5. The field emerging from B is determined by the relative orientations of the optical axes of A and B. The polarizer B used in this way is called an *analyzer*.

If the relative orientation between A and B is θ, then the emergent electric field after passing through B leads to a *decrease* in the amplitude by a factor of $\cos\theta$. The electric field is $E_0 \cos\theta$. But experimentally, we measure only the intensity, not the electric field. The intensity I is defined as the energy received by the detector per unit time per unit area. Therefore its units are $\mathrm{W/m^2}$. The intensity of a transverse wave is proportional to the square of the electric field,

$$I \propto |E|^2.$$

So if $\mathbf{E}_0$ is the electric field of the linearly polarized wave after polarizer A, the intensity after A will be

$$I_0 = |E_0|^2.$$

After B, the intensity will be

$$\begin{aligned} I &= |E_0 \cos\theta|^2 \\ &= |E_0|^2 \cos^2\theta \\ I &= I_0 \cos^2\theta. \end{aligned} \tag{1}$$

This is a statement of Malus's principle. Many experiments in physics involved with measurements of wave intensities use this principle.

Q 1. Suppose a third polarizer C is placed between A and B. The relative orientation between A and B is unchanged at the value θ. The inclination between A and C is β. What relationship must the angles satisfy to ensure that $I_B = I_A$?

4 Apparatus

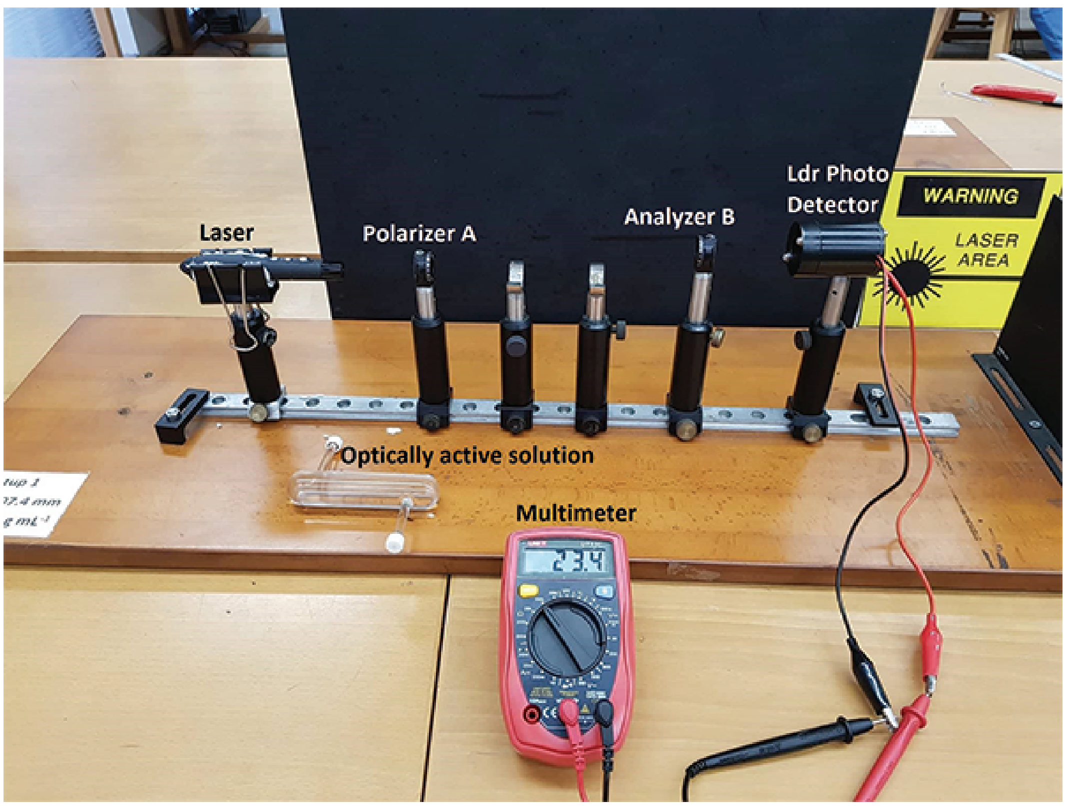

Figure 6: Photograph of the experimental setup. Refer to the Section on Apparatus for a description of the components.

1. **Laser** The source of light in the experiment is a small pen-like handheld device which uses a power source (usually batteries) and diode laser to produce a coherent beam of

monochromatic light. The laser which we will be using in this experiment will produce coherent beam of green color. The output from the laser is randomly polarized.

Lasers can be dangerous if mishandled or if the stated safety procedures are not followed. Always contact the lab staff if you have any doubt. It is important that you always abide by these **safety precautions** for our laser.

- **Never look directly into the laser beam or direct the beam to anyone else or to an area where people are present. This may result in serious visual impairment.**
- Do not scoop down to the level of the table or bring the laser to the level of the eye.

2. **Polarizers and rotation mounts** The experiment uses two polarizers at the positions A and B in the experiment. These polarizers are mounted in rotation mounts. Be careful not to touch the surface of the polarizer. This will scratch the surface resulting in permanent damage. The rotation mount can be locked and unlocked with a hex key that is provided with the setup. The rotation mount is provided with an angular scale, that keeps track of the polarizer orientations.

3. **Natural density filter** The photodetector module includes a neutral density filter whose purpose is to attenuate the amount of light reaching the LDR's. Excessive light will result in low resistances which become difficult to measure with the ohmmeter.

4. **Light dependent resistors** For the photodetctor we will use light dependent resistors (LDR's). The LDR is a piece of semiconducting material whose **resistance is inversely proportional to the light intensity** it receives. The goal is to measure the resistance and infer from it the intensity.

   Q 2. Switch off the lights and measure the resistance of the LDR's. Now turn lights on and measure the resistance.

   Q 3. We have connected four LDR's in parallel. Each one of them receives some portion of the light coming from the laser. Could you describe how putting four LDR's instead of one helps? How would it be different if these LDR's are in series instead of being in parallel?

5. **Multimeter** A multimeter, also known as a VOM (volt-ohm-milliammeter), is an electronic measuring instrument that combines several measurement functions in one unit. A typical multimeter can measure voltage, current, and resistance. We will be using digital multimeter (DMM). Digital multimeters have a numeric display, and may also show a graphical bar representing the measured value. DMM's are now far more common due to their cost and precision, but analog multimeters are still preferable in some cases, for example when monitoring a rapidly varying value.

5 The Experiment

Turn on the laser. Power up the multimeter and change the mode to "resistance" (Ω). Adjust the height and orientation of Polarizer A, and align the polarizer B in the path of the optical beam. Note the reading on the rotation mount A. Call it α. What is the uncertainty in α? Now rotate the angle of the analyzer B, call it β, in steps of 20°, keeping all rotations clockwise or anti-clockwise. Take approximately 20 readings. At each step, record the resistance. Keep α fixed throughout.

Your task is to come up with variables that you can plot to verify Malus's principle. We are not giving you the exact recipe, rather we leave it to you. Understand how the LDR works and what Malus's principle (Equation (1)) entails, to come up with a set of variables to plot.

Then fit your data to a suitable function. In Matlab you may use the application `cftool`. Select variables for X data and Y data. Choose a `custom equation` for data fitting and write an equation to fit the data points. Also note down the variable values which refers to amplitude, frequency, and phase. Also note down and plot the uncertainties in the variables.

Finally interpret and describe your observations.

6 Experience Questions

1. Does the sun emit polarized light?
2. Can a star emit polarized light? If yes / no, what consequences could be seen in nature?
3. Is the light from the sky polarized?
4. A small radio receiver is placed near a radio transmitter. What is the optimum orientation between the transmitter and the receiver that maximizes the reception?
5. At the time of dusk, the atmosphere appears somber blue but looking directly at the sun, it has an orange or pinkish tinge. Reason why.