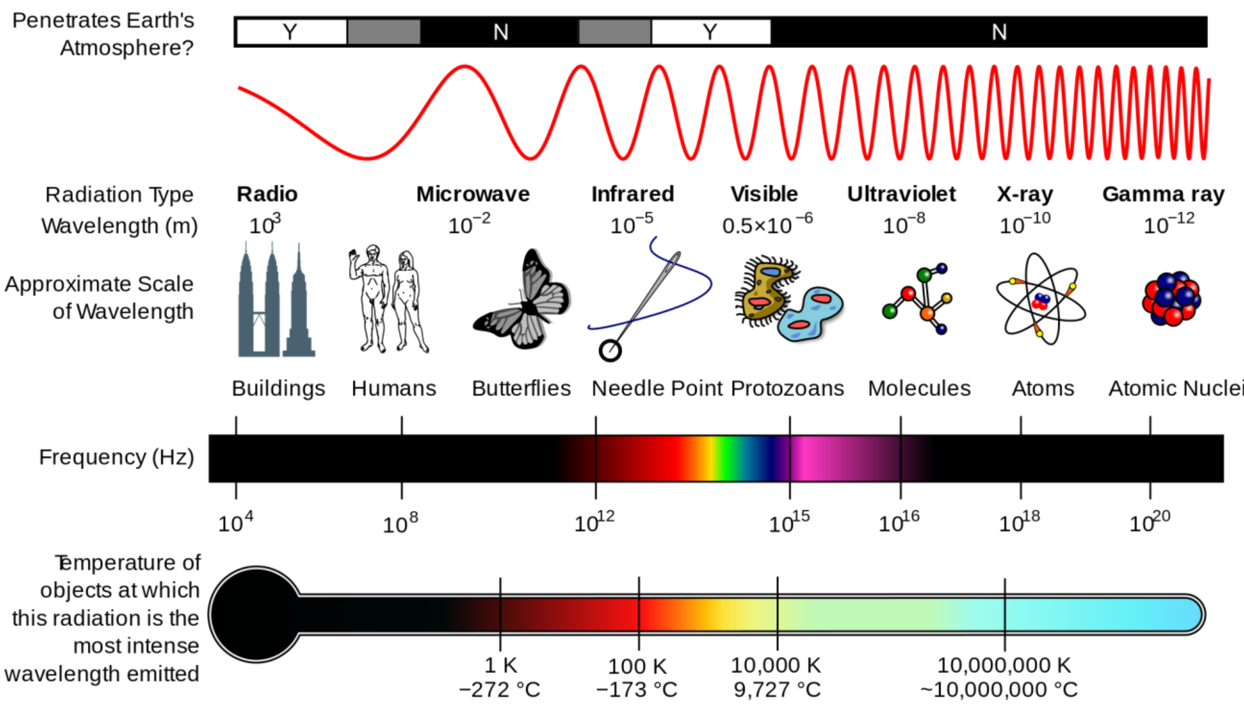
Electromagnetic Waves: Intensity and Polarization of Light

Goals and Introduction

We have many names for electromagnetic waves (radio waves, visible light, infrared light, ultraviolet light, x-rays, etc.) depending on the energy they possess, but all electromagnetic waves share the same fundamental properties. Figure 1 illustrates the many types of electromagnetic waves we find in nature as a function of a frequency of the wave. An electromagnetic wave's energy increases with increasing frequency. Note that only a small portion of the range of energies is represented by the visible light spectrum. Our eyes are able to sample only this small subset of the many types of electromagnetic waves all around us.



https://en.wikipedia.org/wiki/Electromagnetic_spectrum

Figure 1

An electromagnetic wave consists of two oscillating fields that are perpendicular, and in-phase, with each other. One field is an electric field and the other is a magnetic field. By "in-phase", we mean that when one field is at a maximum value, the other is also, and when one field has a value of zero, the other also has a value of zero. Recall from your examination of waves and sound that the wavelength of wave can be thought of as the distance between the peaks in the wave pattern. The preceding statement means that both the electric field wave and the magnetic field wave have the same wavelength. These oscillating fields move in the same direction, at the same speed (in vacuum, the speed of light, $c \approx 3.00\times10^8$ m/s), while maintaining their fixed-phase relationship. A depiction of an electromagnetic wave is shown in Figure 2.

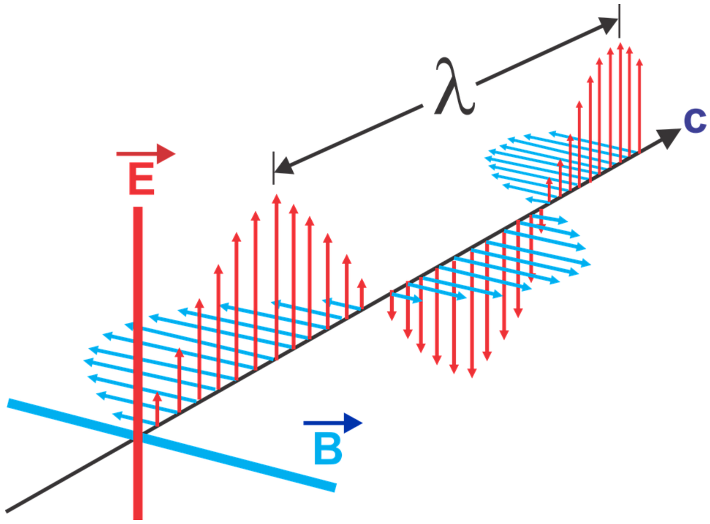


Figure 2

When a source creates electromagnetic waves, the waves themselves have a certain amount of energy, but they also spread outward, away from the source. You are probably familiar with the idea that as you are nearer a source of light (EM waves), it appears brighter. This is not because the waves themselves are more energetic, but because you are nearer to the source and will thus "see" more of them before they are further spread out. One way to think of this is that as you are nearer the source, the area of your eye will intercept, and collect, more light, than when you are further away. This idea is quantified by measuring the *intensity*, I, of the source, measured in units of watts per square meter (W/m^2). As you move further away from a source, the intensity of the source should decrease!

If a source of light emits energy in all directions equally (an isotropic source), there is a predictable way in which the intensity should decrease as you move further away from the source. In this model, the source has some power, P (measured in watts, W). Recall that a watt is a joule per second (W → J/s). This means we can follow the journey of an amount of energy emitted in 1 s, as it spreads out and travels away from the source. Because the energy is emitted in all directions equally, we use the surface area of a sphere ($4\pi r^2$), to identify the surface where we could find all of the energy emitted at an earlier time. As time goes on, and that set of energy spreads outward with the electromagnetic waves, we would have to move to a larger sphere, centered on the source, to find all of the energy emitted at that earlier time. This means that as we travel with the waves away from the source, the energy per unit area is getting less and less, or the intensity is getting less and less. This idea is summarized in Eq. 1.

$$I = \frac{P}{4\pi r^2} \qquad \text{(Eq. 1)}$$

The model behavior of the intensity of electromagnetic waves from an isotropic source allows us to make predictions on what should happen to the intensity of the source as double our distance from it.

Another aspect of the electromagnetic waves created by a source that can be investigated is the orientation of the electric field in the waves, and how that can change when passing through materials. The orientation of the electric field (the direction it oscillates) is called the *polarization* of the wave. In Figure 2, you might describe the polarization of the electromagnetic wave as “up and down” in the picture. Note that this is not the direction the wave is traveling! Both the electric and magnetic field oscillate in directions perpendicular to each other and perpendicular to the velocity of the wave.

Typically, when a source generates electromagnetic waves, the polarization of the wave is random. This means that if you repeatedly measured the direction of the electric field oscillation, as the waves keep moving past your location, you would find a different result each time. We would describe this set of electromagnetic waves as *unpolarized*. This can change, though, when the wave passes through certain materials. *Polarizing sheets* are a material engineered to act as a filter, allowing only components of electric field that are parallel to a transmission axis to pass through the sheet. This means that if you repeatedly measured the direction of the electric field oscillation AFTER they had passed through the polarizing sheet, you would find the same result each time. We would describe this set of electromagnetic waves as *polarized*.

Though the waves may be polarized after passing through the polarizing sheet, you would also find that the intensity of the light is less. This is because not all of the light can get through the filter – only the components of electric field parallel to the transmission axis of the sheet can get through. After passing through one polarizing sheet, the intensity of initially unpolarized light would be knocked down to ½ its initial value. To measure this, you would need to know the intensity at a certain location, place a polarizing sheet in the path of the waves, and then measure the intensity at that location again – ideally, the intensity would be half of what it was initially. We say “ideally,” here, because some intensity may also be lost due to reflection when the waves strike the sheet.

This story changes a bit, however, if the electromagnetic waves striking the polarizing sheet have already been polarized. In this case, there will be a specific angle, θ, that will exist between the transmission axis of the polarizing sheet and the polarization of the wave itself. This means that the wave’s polarization could be aligned exactly with the transmission axis (an angle of 0°) and the intensity of the wave does not change after passing through the sheet, or the wave’s polarization could be perpendicular to the transmission axis (an angle of 90°) and the intensity of the wave would be zero after passing through the sheet. It is also possible that there is an angle between 0° and 90° between the transmission axis and the polarization of the incident wave. In these cases, a component of the polarization will be parallel to the transmission axis and there will be a transmitted intensity less than or equal to the incident intensity. The model for this transmitted intensity, I_t, in terms of the angle and the incident intensity, I_i, is given in Eq. 2. Again, this would be under ideal conditions. Some intensity may not be transmitted due to reflection.

$$I_t = I_i \cos^2 \theta \qquad \text{(Eq. 2)}$$

In today's lab, you will gauge the intensity of a source by measuring the illumination in units of lux. While this is not measuring intensity specifically, illumination is related directly to the intensity of the source, and because the size and shape of our detector is not changing, this measurement will suffice as a gauge of intensity. You will work to test the two predictions described by Eq. 1 and Eq. 2, and verify some of these behaviors of electromagnetic waves by using visible light.

<u>*Goals*</u>:
(1) Predict, measure, and evaluate the behavior of the transmitted intensity of light as a function of distance from the source.
(2) Predict, measure, and evaluate the behavior of the transmitted intensity of light through polarizing sheets, as a function of the angle between the transmission axes of the sheets

Procedure

Equipment – mini-optics bench, light source, slit mask aperture, two component carriers, two circular polarizing sheets, light sensor probe, computer with the DataLogger interface and LoggerPro software

1) Connect the light probe to the DataLogger interface and open LoggerPro by clicking on the **Light vs. Distance** link on http://feynman.bgsu.edu/physics/phys2020/index.html. Plug the light sensor probe into the CH1 port and set the switch on the back of the sensor to "0-600." You can start recording data by clicking the green button at the top of the screen, and stop recording by clicking the red button that appears in its place. If you want, you can also store values by clicking on the "shutter" symbol, next to the record button. You will need to enter a distance from the source when you click on the shutter, and then the value of distance and illumination will be recorded. You can also just keep record of your measurements on paper during the lab.

2) Lay out the lab optics bench from the kit box. Note that the rulers on the sides are in units of mm. You can place components of this lab on this bench during the experiment. Some are magnetic and will be held in place when you place them on the bench.

3) Place the light source from the kit box onto the optics bench at the far end. Be sure to turn the knob on the top of the light source so that the bulb is aligned with its reflector to project light forward. The dot on the knob should be facing forward, in the direction the light will travel from the bulb along the bench. **Record** the location of the bulb in the box, as measured using the ruler on the bench.

4) Place the “slit mask” over the front of the light source (it should have a magnet that holds it in place) so that the slit is aligned vertically and is centered over the window on the light source.

5) Place each of the polarizers onto their own component carriers. They should also have a magnet that holds them in place, centered in the carrier window. If the magnet is missing, clip the polarizer to the top using the binder clip in the kit box. Both of the polarizers should be aligned so that the 0° mark is aligned with the notch at the top of the component carrier (Figure 3).

Figure 3

6) The sensor is in the open end of the tube connected to the light sensor box. Click on the green button on the screen to measure the illumination. You will see the value in the upper left corner of the screen, just above the data table. Point the sensor up near the monitor screen and then away from it to verify that the sensor readings make sense as it is exposed to a brighter source and a dimmer source of light.

7) Place one polarizer (the clipped one if you had to clip one), in front of the light source by placing its carrier on the optics bench. Then place the second polarizer in front of the other one, so that you can read the angle of the second polarizer very easily. Again, both should have their 0° marks aligned with the notch at the top of the component carrier currently.

NOTE: The room lights should be turned down during the rest of the experiment.

8) Hold the light sensor 200 mm in front of the location of the light source that you noted in step 3 and **measure and record** the illumination in lux.

Figure 4

9) Consider Eq. 1 and predict what the illumination would be if the probe is moved so that the distance from the source is halved. **Record** your predicted value. Remember that though illumination is not intensity, they are directly related. Thus, if you think the intensity should be halved, then the illumination would be halved.

10) Consider Eq. 1 and predict what the illumination would be if the probe is moved so that the distance from the source is doubled. **Record** your predicted value.

Question 1: How did you arrive at your predictions in each case? Explain, in detail, your thought process and any equations you used in making your prediction.

11) Move the probe so that it is half as far from the source and then twice as far from the source, compared to the initial distance from the source. **Record** the illumination value at both locations. These are the experimental values at each location.

12) Repeat steps 8 through 11, except choose a different starting distance from the source (not the 200 mm).

13) Now, in this second part of the experiment, place the probe so that it is again 200 mm from the light source and **measure and record** the illumination. This will be treated as the incident intensity in later calculations, since the transmission axes are aligned, here.

14) While keeping the probe in place, the other lab partner should rotate the second polarizer so that the angle, read at the notch at the top of the component carrier, 20°. This means that the transmission axes of the two polarizers will be 20° apart now. **Measure and record** the illumination with this angle between the polarizers. Keep the light sensor in place.

15) Repeat step 14 at the following angles: 30°, 45°, 60°, 70°, and 90°.

16) Repeat steps 13 through 15, but choose a different distance from the source (something other than 200 mm).

As always, be sure to organize your data records for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

Calculate the predicted transmitted illumination, using the value you recorded in step 12 for the incident illumination, and each angle between the transmission axes. Use Eq. 2, even though that is technically for intensity (it will also work for illumination since they are related directly.

Repeat the above set of calculations for the data you gathered in step 16, for the other distance from the source.

Error Analysis

Calculate the percent error between your predicted illumination and experimental illumination in steps 8 through 11.

$$\%error = \frac{\left| I_{\text{experimental}} - I_{\text{predict}} \right|}{I_{\text{predict}}} \times 100\%$$

Repeat the percent error calculations for the data gathered in step 12 (which repeated steps 8 through 11 at a different starting distance.

Question 2: How well did the predicted values match the experimental values, in this part of the experiment? As you always should, comment on the potential sources of error in the measurement process.

Calculate the percent error between your predicted values of transmitted illumination that you found in the Data Analysis section, and the experimental values you measured in steps 14 and 15.

Repeat the last set of calculations for the predicted illuminations that you found in the Data Analysis section, and the experimental values you measured in step 16.

Question 3: How well did the predicted values match the experimental values, in this part of the experiment? As you always should, comment on the potential sources of error in the measurement process.

Questions and Conclusions

Be sure to address Questions 1 through 3 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for "Electromagnetic Waves – Intensity and Polarization of Light," and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) Sean measures the illumination to be 100 lux when he holds the probe 100 mm from the light source. If he doubles the distance from the source, what is the illumination he predicts will occur there? Express your answer in lux.

PL-2) Jannette measures the illumination to be 100 lux when she holds the probe 200 mm from the light source. If she halves the distance from the source, what is the illumination she predicts will occur there?

A) 50 lux

B) 400 lux

C) 200 lux

D) 100 lux

PL-3) Jannette measures the illumination to be 100 lux when she holds the probe 200 mm from the light source. She rotates one of the polarizers so that the angle between the two transmission axes of the two polarizers is 45°. What is the predicted illumination that she should observe at the same location?

A) 50 lux

B) 400 lux

C) 200 lux

D) 100 lux

PL-4) Sean measures the illumination to be 100 lux when he holds the probe 100 mm from the light source. He rotates one of the polarizers so that the angle between the two transmission axes of the two polarizers is 90°. What is the predicted illumination that he should observe at the same location? Express your answer in lux.

PL-5) True or False: "The only real difference between a green, visible light wave and an x-ray is that one has a shorter wavelength than another."