QUANTUM TECHNOLOGY SCHOOL 2021

ACADEMIC PACK

POLARIZATION

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Background

Information may be encoded and transmitted in beams of light. The fastest broadband internet connections use fibre optic cables to transport laser light, carrying data across the network. In this part of the Pack we will explore polarization, a property of light which can be used to encode information, and which is used in particular in quantum communications. Later, we will see how these ideas are used in ***quantum key distribution***, which uses the physics of quantum mechanics to enable perfectly secure communication.

Technical terms: Polarization, polarizing filter/polarizer, photon.

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Task 1.1: Introducing polarization

In the activity pack you will find a set of slides. These are **polarizing filters**, or **polarizers**. In this task you will explore how these affect incoming light.

Exercises:

1. Look out of the window through one of the polarizers provided. What do you see when you rotate the polarizer? If you have an LCD screen (laptop or flatscreen monitor) in your classroom or at home, try looking at this through the polarizer. Now what happens when you rotate the polarizer?

2. Looking out of the window again, hold another polarizer behind and in line with the first. What happens when you rotate one polarizer while keeping the other fixed?
3. Now adjust the angle of the second polarizer to achieve *minimum* transmission of light from the window.
    a. While still looking out of the window through the polarizers, place a third polarizer *in between* the other two, rotated by approximately 45 degrees compared to the slides either side. What do you see?
    b. Try placing other objects in between the two polarizers, e.g. a Perspex ruler, or the protractor provided in the pack, or even the plastic wrapping from the protractor. What do you see?

What's going on?

If you took National 5 Physics you may already know that light is an *electromagnetic wave*, an example of a *transverse* wave. This means that it is made up of oscillating electric and magnetic fields, and that the direction of oscillation is at right angles to the direction in which the light is travelling, as shown in Figure 1. The orientation of the electric field is called the *polarization* of the light. Polarizing filters are materials which can pick out just one direction of polarization – for example a vertical filter allows vertically polarized light to pass through, but blocks horizontally polarized light.

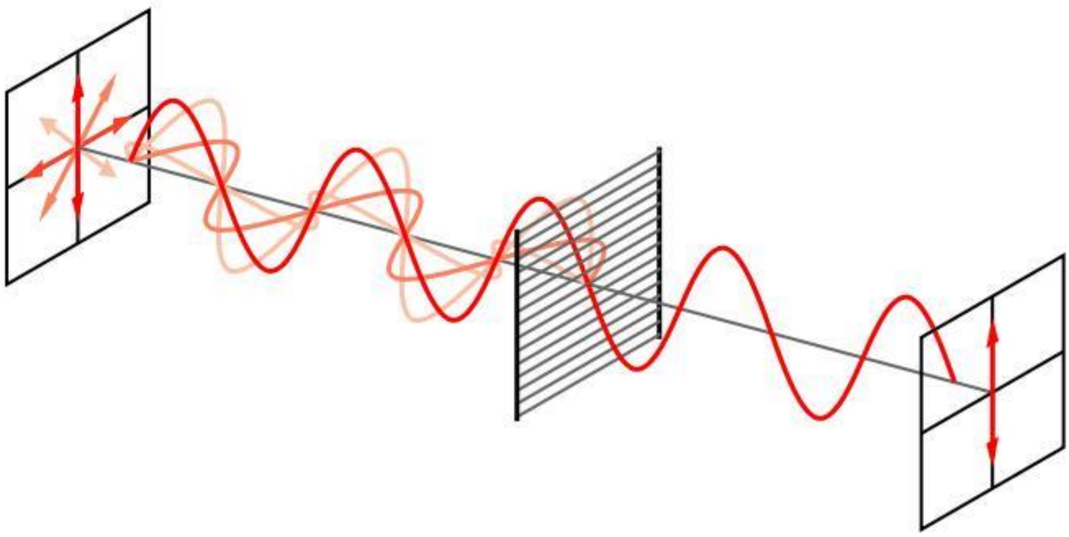

Figure 1: Polarization is in the plane at right angles to the direction along which the light is travelling. Polarizing filters can pick out just one component - or direction - of polarization. [Image from https://physicsopenlab.org/]

All other directions of polarization can be thought of as combinations of horizontal and vertical: think about moving pieces on a chess board, one step right and one step up is the same as moving diagonally. In the same way, light polarized diagonally can be thought of as a combination of some horizontal and some vertically polarized light. The vertical part will pass through a vertical polarizing filter, while the horizontal part will be blocked. As it is only the vertical component that passes, after the filter any light emerging is vertically polarized, regardless of the initial polarization! Light that has passed through a polarizing filter in general has a *different* polarization to that before the filter.

Now can you explain what happened when you placed a third polarizer in between two crossed polarizers?

How about when you viewed the protractor in between the polarizers? Some materials can *rotate* polarization, and the amount of rotation depends on the colour of the light. This effect explains why you may have seen colours when you placed perspex or plastic between the polarizers, even though all the materials you were looking through appeared colourless separately. This effect can be used to measure stress on materials.

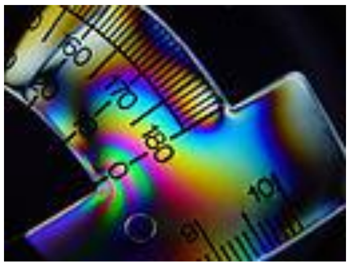

Figure 2: Protractor viewed between polarizers. [Image: CC BY-SA 3.0 via Wikimedia Commons]

Additional resources:

There are many excellent YouTube videos discussing polarization. One of my favourites is by PhysicsGirl: https://www.youtube.com/watch?v=CSu0cV3fqi8

Task 1.2: Malus' law

In this task you'll explore, in a little more detail, how much light passes through two different filters as they are rotated relative to one another. This is a simple demonstration with relatively easily accessible equipment but is enough to demonstrate the main ideas. This requires access to a phone, and that you download and install a (free) app. If you cannot, or prefer not to, you'll find some sample data provided on the next page.

Exercises:

1. Search the Appstore for "Light meter". A number of free apps are available. Choose and install an app for measuring light intensity. Locate the light sensor.
   [We used "Light Meter – Free" by "WBPhoto" for Android, and used the "Camera Meter" function, with the front camera. In this case the sensor is the front camera. For the "Sensor Meter" function, and for other apps such as "Lux Light Meter" for Android the sensor is the phone's light sensor, usually located near the top of the phone at the front. Can you think of any reason why your phone would have a light sensor?]
2. First experiment with the light sensor. Move your phone to areas with different light levels to check its function. Use the reading with units of "lux". Verify that if you block the sensor, the reading drops to (or close to) zero.
3. Place a polarizer in front of the sensor. Add a second polarizer in front of the first. What happens to the intensity recorded by the app as you rotate this polarizer? Adjust the polarizer to achieve maximum transmission; this should be when the orientation of both polarizers is the same.
4. Rotating this second polarizer, record the intensity, as measured by the app, at increments of approximately 10°; record measurements over 90° on the table

provided on the next page. You can use the protractor provided to help, but remember not to place it in between the polarizers! (Why not?).

5. Draw a graph of your results. What do your results show happens as the angle between the two polarizers is increased? Does your data support the description of polarization outlined in the previous task?
6. The fraction of light passing through the second polarizer is given by $\cos^2\Phi$, where Φ is the angle between the orientations of the polarizers. This is known as *Malus's law*. Use the last column of the data table to check whether your data agrees with this (it won't be perfect because the equipment we are using is not very accurate, but you should be able to find reasonable agreement).

Lab data sheet:

Angle of 2nd polariser (∅)	Measured intensity (lux)	$I_0 \cos^2 \emptyset$
$0°$	$I_0 =$	
$10°$		
$20°$		
$30°$		
$40°$		
$50°$		
$60°$		
$70°$		
$80°$		
$90°$		

Sample data:

If you cannot or prefer not to install an app, or if you are unable to obtain data, we have provided some data below:

Angle of 2nd polariser (∅)	Measured intensity (lux)	$I_0 \cos^2 \emptyset$
$0°$	$I_0 = 29$	
$10°$	28	
$20°$	26	
$30°$	20	
$40°$	15	
$50°$	10	
$60°$	8	
$70°$	4	
$80°$	3	
$90°$	3	

Task 1.3: Photons, probabilities, communication

So far we have discussed light as waves – the classical picture. In the early 20th century experiments demonstrated that there is a smallest packet or "quantum" of light, which cannot be divided further, called a *photon*. These experiments and their interpretation led to the birth of quantum mechanics, and it is difficult to overstate their importance. For our purposes however, we just need to know that light is made up of photons, which are indivisible, and that photons can be polarized, just like light beams.

As we saw in the previous task, when a polarized light beam meets a polarizing filter, a fraction $\cos^2 \emptyset$ of the beam passes through, and the rest is blocked. However, we have just learned that photons cannot be divided, so we cannot talk about a fraction of a photon. What happens when a polarized photon meets a polarizing filter? Experiments show that the fraction of light in the classical case becomes a probability in the photon case: the photon passes the filter with probability $\cos^2 \emptyset$, as shown in Table 1.

Table 1: Probability a polarized photon passes a polarization filter

Angle between photon polarization and orientation of filter	Probability of passing through filter ($\cos^2 \emptyset$)
$0°$	1
$10°$	0.97
$20°$	0.88
$30°$	0.75
$40°$	0.59
$50°$	0.41
$60°$	0.25
$70°$	0.12
$80°$	0.03
$90°$	0

Exercises:

A single photon is prepared with polarization oriented in the horizontal direction. A polarizing filter at an angle of 45 degrees to the horizontal is placed in its path. Calculate the probability that the photon passes the filter.

As you saw in the ciphers worksheet, information in phones, computers, and communications is usually encoded as sequences of 0's and 1's. For example, ASCII code tells computers to interpret certain sequences of 0's and 1's as letters, numbers, and other characters. This means that in order to send information, we need only to be able to send 0's and 1's: two distinguishable signals.

Exercises:

How could you use the polarization of a photon to send two different signals? Explain how a sender could prepare the signals, and how a receiver could determine which one was sent.

Is there more than one way to accomplish this? Explain your answer.