Experiment No. 3

Malus' law of polarization of light

Aim:

To study polarization of light and determine the relationship between the intensity of the transmitted light through two polarizers and the angle, ϕ, of the axes of the two polarizers (i.e, to verify Malus' law of polarization).

Experimental apparatus: The experimental setup consists of an optical bench, a diode laser, a light sensor, two polarizers (one is used as polarizer and other as an analyzer).

Malus' Law of polarization (I=I_0 cos$^2\phi$): Assume that a beam of light is linearly polarized by using a polarizer and it has an intensity I_0 after its transmission through a first polarizer. Suppose, it then falls on a second polarizer whose transmission axis is oriented at angle ϕ with respect to the first polarizer. What will be the intensity of light beam after the second polarizer and how does the intensity depend on the angle ϕ? Malus' law answers these questions.

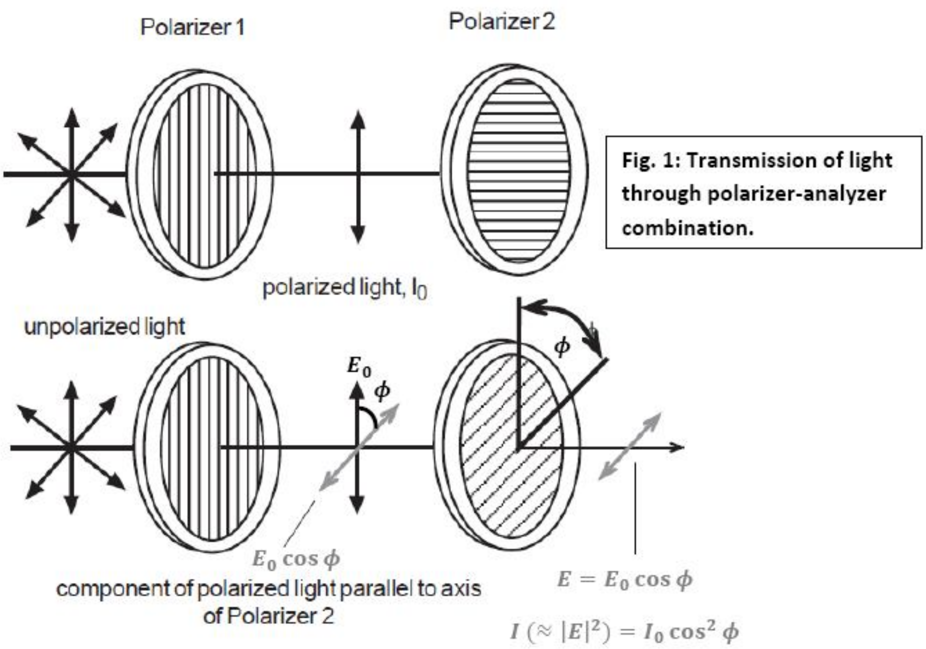

Fig. 1: Transmission of light through polarizer-analyzer combination.

As noted below (see appendix), a polarizer allows light to pass through it only that component of electric field which is parallel to the transmission axis of the polarizer. From Fig. 1, this component (which passes through the second polarizer) is E_0 cosϕ. Since the intensity of light goes as square of the electric field, the transmitted light intensity after the second polarizer (analyzer) will be $\boldsymbol{I}=\boldsymbol{I_0}\ \mathbf{cos^2}\boldsymbol{\phi}$. This is known as Malus' law of polarization of light, after the discoverer E. L. Malus.

Experimental setup: Schematic of the experimental setup and also a photograph of the actual setup is shown in Fig. 2. In this experiment a laser beam is polarized by the first polarizer and it is sent through an analyzer (i.e, second polarizer). The analyzer is rotated and the transmitted light intensity after the analyzer is detected by a light detector as function of the angle between the polarizer and analyzer axes.

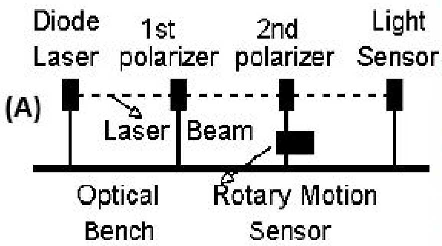

Fig. 2: Experimental setup: (A) schematic and (B) photograph.

A. Preparation for data recording

1. Turn on the diode laser.
2. Insert a white paper between the polarizer and the analyzer.
3. The laser light is already partially polarized. Slowly rotate the (first) polarizer to align its axis along the laser light polarization axis so that maximum intensity of light is transmitted through this (check this visually by looking into the light intensity on the white paper).
4. Leave the polarizer in this position and then remove the white paper.
5. Slowly rotate the analyzer (second polarizer) in step of 10 degree and measure the corresponding light intensity.
6. Do this measurement for one full rotation (i.e, for 360 degree) of the analyzer.

B. Data analysis

1. Plot the data in Origin software. Data looks like an oscillatory function. How do you verify that it satisfies Malus' law?
2. Fit the data with $y=a+b\cos^2(x-c)$ and $y=a+b\cos^4(x-c)$, where y is the light intensity, x is the angular position in radian, and a, b, c are the fit parameters. Which function fits the data better?

3. Ideally, the fit parameters a and c should be zero. Did you get nonzero values for them? Why?
4. Should you also try to fit data by $y=a+b\cos(x-c)$ and $y=a+b\cos^3(x-c)$? If not, why?
5. Plot (i) intensity versus cosine of angular position and (ii) intensity versus square of the cosine of angular position graphs. What should be the nature of these graphs? Do they match the expected behavior? If not, why?
6. Normalize intensity data between 0 and 1 using fit parameter a and b from step 2 for fit function $y=a+b\cos^2(x-c)$. Calculate $\cos(x-c)$ and $\cos^2(x-c)$, where x is the angular position in radian, and c is the fit parameter from step 2 for fit function $y=a+b\cos^2(x-c)$.
7. Plot graphs of (i) normalized intensity versus $\cos(x-c)$ and (ii) normalized intensity versus $\cos^2(x-c)$. What should be the form of these graphs? Do you get, respectively, $y=x^2$ and $y=x$ behavior? Verify by fitting these functions to your plots.

Error Analysis: Comment on accuracy in angle measurement, accuracy in intensity measurement and compare these with parameters c and a, respectively. Are they comparable? If not, why?

Appendix:

Things you need to know (to understand the experiment better):

1. **Transvers wave:** According to classical physics, light is a transverse electromagnetic wave, consisting of mutually orthogonal sinusoidal electric and magnetic fields, oscillating in a plane perpendicular to the direction of light propagation. Electric field (E) of light is much stronger compared to its magnetic field (B), $E/B{\sim}c$ (speed of light).
2. **Polarization:** Polarization of light is decided by the projection of the trajectory of the tip of the oscillating electric field of light in the plane perpendicular to direction of light propagation.
3. **Unpolarized light:** In an unpolarized light the electric field changes its oscillation direction randomly, so the projected trajectory traced by the tip of electric field will fill a circular region completely.
4. **Linearly polarized light:** In a linearly polarized light, the electric field oscillates in a fixed plane and the projected trajectory traced by the tip of the electric field will be a straight line.
5. **Example of linearly polarized light field:** $\boldsymbol{E}=\boldsymbol{\hat{\imath}}\boldsymbol{E_0}\sin(\boldsymbol{\omega t}-\boldsymbol{kz})$ → Linearly polarized in x-direction, propagating in z-direction; $\boldsymbol{E}=\boldsymbol{\hat{\imath}}\boldsymbol{E_0}\sin(\boldsymbol{\omega t}-\boldsymbol{kz})+\boldsymbol{\hat{\jmath}}\boldsymbol{E_0}\sin(\boldsymbol{\omega t}-\boldsymbol{kz})$ → Linearly polarized 45° with respect to x-direction, propagating in z-direction
6. **Circularly polarized light:** In a circularly polarized light the oscillation direction of the electric field changes regularly in such a way that the projected trajectory traced by the tip of the electric field is a circle.

7. **Example of circularly polarized light field:** $\boldsymbol{E}=\hat{\boldsymbol{\imath}}\boldsymbol{E_0}\sin(\boldsymbol{\omega t}-\boldsymbol{kz})+\hat{\boldsymbol{\jmath}}\boldsymbol{E_0}\cos(\boldsymbol{\omega t}-\boldsymbol{kz})$ Note the difference between this the field for 45° linearly polarized light: $\pi/2$ phase difference between x and y-component.
8. **Polarizer/analyzer:** A polarizer is a device which allows passing only that component of electric field which oscillates in a particular plane (along the transmission axis of the polarizer) and completely blocks the component orthogonal to it. So, after passing through a polarizer any unpolarized or polarized (but not linearly polarized) light will become linearly polarized along the transmission axis of the polarizer. Then a second polarizer can be used to detect/analyze the polarization condition of light. The second polarizer is called analyzer.
9. **Diode Laser:** It is a semiconductor diode (p-n junction) which emits laser light. In this experiment, we are using only the directional property of the laser. Otherwise it is just a light source.
10. **Light sensor:** This is a sensor which measures intensity of light in some arbitrary scale. Actually it is a photodiode which gives an output current proportional to the incident light intensity.

Try to find answers to the following questions:
i. Unpolarized light of intensity *I* falls on an 'ideal' polarizer. What will be the transmitted intensity?
ii. Circularly polarized light of intensity *I* falls on an 'ideal' polarizer. What will be the transmitted intensity?
iii. What is a half-wave plate? What is a quarter-wave plate? What are their applications?

(Please consult any standard text book on Optics/web resources to know more about the above mentioned topics)

Procedure

1. Align the polarizer (P1) and analyzer (P2) in crossed position so that the transmitted intensity is minimum.
2. Insert the given retardation waveplate (***WP***) in between the two polarizers. The WP is mounted on a rotational mount. For an arbitrary angle of orientation of the anisotropy axis of the retardation plate, you will see an increase of the intensity transmitted between the crossed polarizers.
3. Now, rotate the retardation plate slowly until you see a minimum in intensity of transmitted light between the crossed polarizers. At this angle of orientation of the anisotropy axis of the retardation plate, it does not change the input linear polarization state. Thus, at this position in the rotation mount, the anisotropy axis of the retardation plate is oriented along the polarization axis of the input linear polarizer. Note down the angle of the retardation plate in the rotation mount.
4. Now, rotate the retardation plate by 45^o. If the retardation plate is a quarter wave retarder (introducing phase difference of $90\ ^o$), the output state of polarization of light (passing through the polarizer P1 and wave plate ***WP***) will be circular polarization.
5. In order to test this, now keep P1 and ***WP*** fixed and rotate the analyzer P2 and record the transmitted intensity as a function of the orientation angle of P2. In case, the combination of P1 and ***WP*** generates perfectly circularly polarized light, you will not see any variation of intensity with changing orientation angle of P2. However, if you see any variation of intensity, then the output light is elliptically polarized. An idea of the ellipticity of the output polarized light can be obtained by taking the ratio of the minimum to the maximum intensity (for changing orientation angle of P2).