UM-SJTU Joint Institute
Physics Laboratory
(Vp241)

Laboratory Report

Exercise 4

Polarization of Light

Name: Zhang Jiache ID: 520370910044 Group: 9

Date: November 5, 2021

1 Introduction

Light can be described in terms of electromagnetic waves. Light is an example of transverse wave, with the plane of oscillations of the electric field vector perpendicular to the direction of light propagation. The so-called natural light is a random mixture of waves with the electric field vector oscillating in all possible transverse directions, and it is also called unpolarized light. If the distribution of of the directions of the electric field vector, in the plane perpendicular to the direction of propagation is not uniform, then the light is called polarized light.

The elctric field vector **E** is described as a time-dependent, propagating electric field by the light vector. In the plane perpendicular to the propagation direction of a light wave, the light vector may have different directions along which its magnitude oscillates. The light for which the light vector maintains a certain oscillation direction is called *linearly polarized* and the axis defining the directio is called the polarization axis.

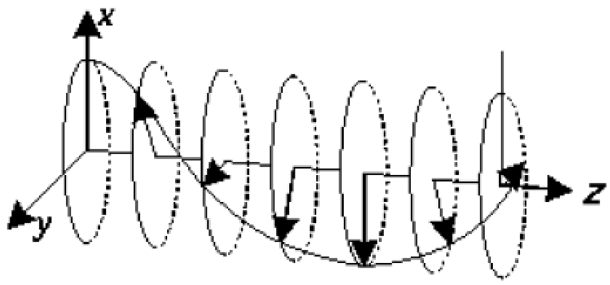

Figure 1. Elliptically polarized light propagating in the z direction.
The light is polarized in the xy plane.

Polarizer is a device used to produce polarized light. It polarizes the light using the principle of dichroism: a selective absorption mechanism tends to allow the light polarized in a certain direction to pass through the material, while the light polarized in all other directions is absorbed. This turns the incident natural light into a linearly polarized. A polarization device can also be used to detect and analyze linearly polarized, natural and partialy polarized light (it is then called an analyzer)

Malus' law says that the light coming out of a polarization device is a change of the light brightness. Suppose that we have two polarizers arranged parallel (a polarizer and an analyzer). Let the angle between their transmission directions be θ. The light is incident normally on the polarizer and then continues to the analizer. The intensity of the linearly polarized light leaving the analyzer is

$$I_{light} = I_{light,0} \cos^2 \theta$$

where $I_{light,0}$ is the intensity of the linearly polarized light incident on the analyzer.

For a single polarizer, if a polarized light is incident on it, then the transmitted light intensity will change periodically when rotating the polarizer. If the incident light is partially or elliptically polarized, the minimum intensity will not be zero as there will be always some component of the light polarized in the transmission direction. The incident light must be natural or circularly polarized if the intensity does not change at all. Hence, by using a polarizer, one can distinguish linearly polarized light from the natural and circularly polarized light.

2 Experimental setup

The measurement setup is composed of: a semiconductor laser, a tungsten iodine lamp, a silicon photo-cell, a UT51 digital universal meter, as well as two polarizers, 1/2-wave and 1/4-wave plates and a lens with a glass sheet. The elements are placed on an optical bench.

The uncertainty of the wave plates are 2°, and the uncertainty for silicon photo-cell is 0.001μA.

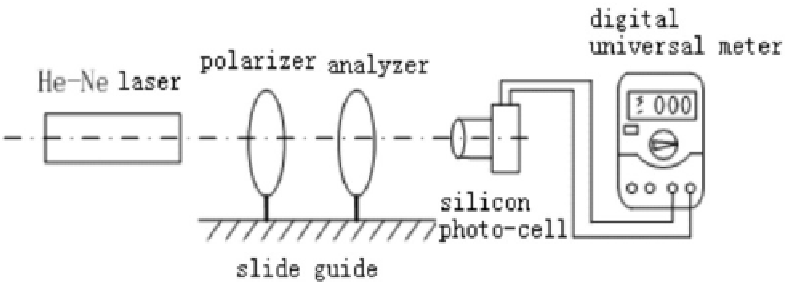

Figure 2. Experimental setup for a demonstration of Malus' law.

3 Measurements

3.1 Demonstration of Malus' Law

1. Assemble the measurement setup according to Figure 2. Make sure the laser passes through the polarizer first.

2. Rotate the analyzer for 360° and observe the change in light intensity to find the maximus elctric current I_0.

3. Set the analyzer to 90° amd adjust the polarizer until the elctric current reaches minimum.

4. Rotate the analyzer from 90° to 0° and record the magnitude of current I every 5°. Record the values in a table and plot the graph I/I_0 s. $\cos^2\theta$.

3.2 Linearly Polarized Light and the Half-wave Plate

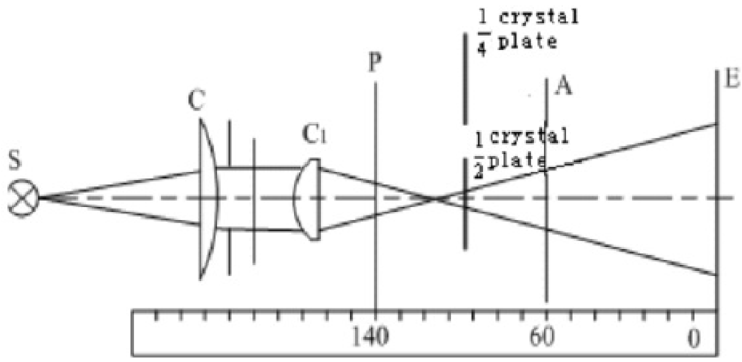

Figure 3. Experimental setup for the 1/2-wave plate.

1. Set up the equipment on the optical bench according to Figure 3. Make the analizer and the polarizer perpendicular to each other, so that the extinction of light can be observed on screen.

2. Insert the 1/2-wave plate and rotate it to make the light extinction appear again. Let it be the initial position.

3. Increase the 1/2-wave plate degree by 10° each time, then rotate the analyzer to make the light extinction appear again. Record the rotation angle of analyzer $\Delta\theta$ in a table.

3.3 Circularly and Elliptically Polarized Light and the 1/4-wave Plate

1. Set up the equipment on the optical bench according to Figure 3. Make the analizer and the polarizer perpendicular to each other, so that the extinction of light can be observed on screen. At this time $\theta = 90°$

2. Insert the 1/4-wave plate and rotate it to make the extinction of the light observed on screen again. This is the initial position and $\alpha = 90°$

3. Rotate the analyzer for 360° and record the light intensity for every 10°. Record the data in a table.

4. Rotate the 1/4-wave plate to $\alpha = 20°$ and $\alpha = 45°$ and repeat the previous step.

4 Results

Uncertainty of θ is 2°

4.1 Demonstration of Malus' Law

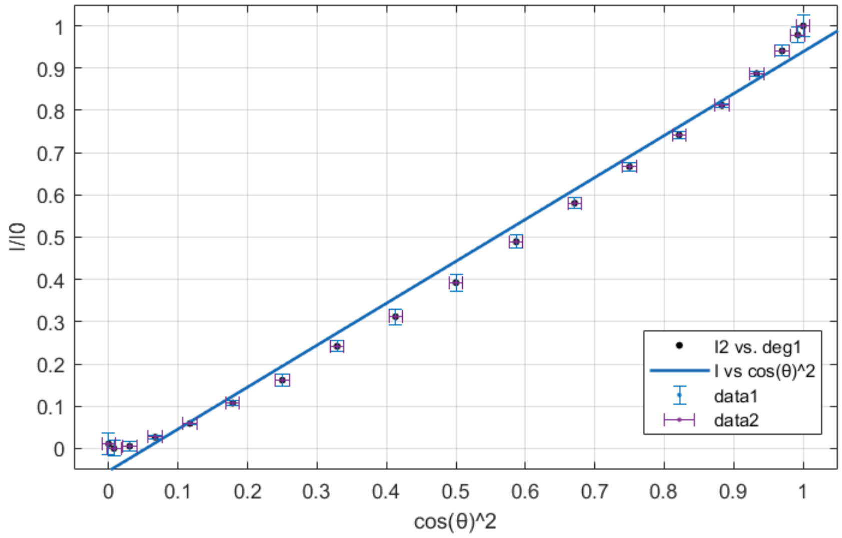

Figure 4. Fit graph for experiment 4.1

The fitting result is:

$$k = \frac{I/I_0}{\cos^2(\theta)} = 0.9921 \pm 0.051$$

4.2 Linearly Polarized Light and the Half-wave Plate

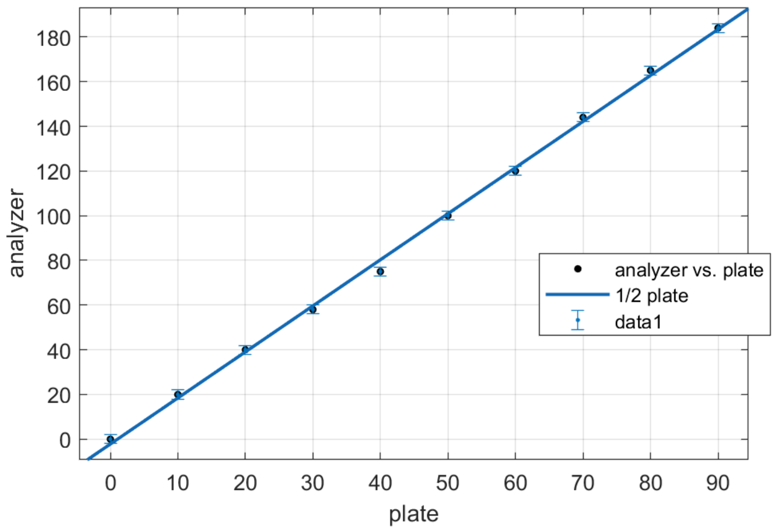

Figure 5. Fit graph for experiment 4.2

The fitting result is:

$$k = \frac{\theta_{analyzer}}{\theta_{plate}} = 2.062 \pm 0.064$$

4.3 Circularly and Elliptically Polarized Light and the 1/4-wave Plate

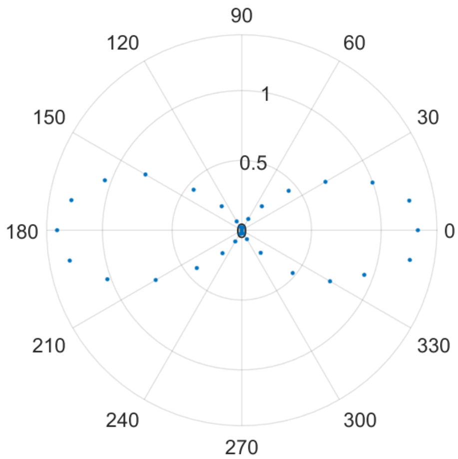

Figure 6. Fit graph for experiment 4.3, $\alpha = 0$

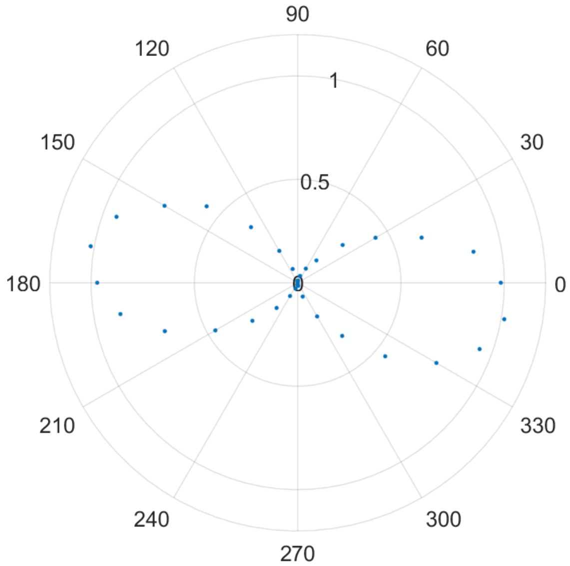

Figure 7. Fit graph for experiment 4.3, $\alpha = 20$

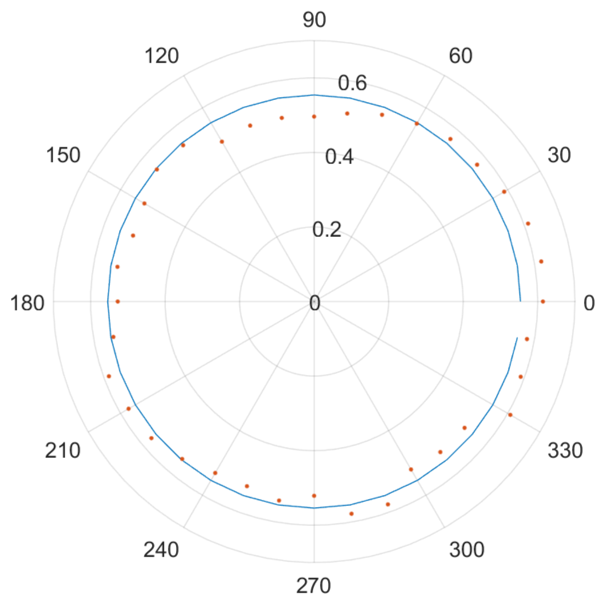

Figure 7. Fit graph for experiment 4.3, $\alpha = 45$

When $\alpha = 70°$:

Rotating angle of the 1/2-wave plate: 70°	
$\theta[°] \pm 2[°]$	10°
$I[\mu A] \pm 0.01[\mu A]$	1.145

Table 1: Measurement data for the 1/2-wave plate ($\alpha = 70°$).

When $\alpha = 20°$, I reaches maximum when $\theta_1 = 170°$
When $\alpha = 70°$, I reaches maximum when $\theta_2 = 10°$
So that $\theta_1 + \theta_2 = 180° = 90° \cdot 2$, which proves the theorem is true.

5 Uncertainties

5.1 Demonstration of Malus' Law

To calculate the uncertainty of $\cos^(\theta)$, we use the uncertainty of θ. Since u_θ is given by 2°:

$$u_{\cos^2\theta} = 2\sin\theta\cos\theta u_\theta$$

We can apply this formula to all θ taken. When $\theta = 0°$:

$$u_{\cos^2 5°} = 2 \times \sin(5°) \times \cos(5°) \times u_\theta = 0.3$$

Here the table lists all the value of $u_{\cos^2\theta}$:

$\theta[^\circ]$	uncertainty $u_{\cos^2\theta}$		$\theta[^\circ]$	uncertainty $u_{\cos^2\theta}$	
0°	$u_{\cos^2 0^\circ}$	0	50°	$u_{\cos^2 50^\circ}$	2.0
5°	$u_{\cos^2 5^\circ}$	0.3	55°	$u_{\cos^2 55^\circ}$	1.9
10°	$u_{\cos^2 10^\circ}$	0.7	60°	$u_{\cos^2 60^\circ}$	1.7
15°	$u_{\cos^2 15^\circ}$	1.0	65°	$u_{\cos^2 65^\circ}$	1.5
20°	$u_{\cos^2 20^\circ}$	1.3	70°	$u_{\cos^2 70^\circ}$	1.3
25°	$u_{\cos^2 25^\circ}$	1.5	75°	$u_{\cos^2 75^\circ}$	1.0
30°	$u_{\cos^2 30^\circ}$	1.7	80°	$u_{\cos^2 80^\circ}$	0.7
35°	$u_{\cos^2 35^\circ}$	1.9	85°	$u_{\cos^2 85^\circ}$	0.3
40°	$u_{\cos^2 40^\circ}$	2.0	90°	$u_{\cos^2 90^\circ}$	0
45°	$u_{\cos^2 45^\circ}$	2.0			

Table 2: Uncertainty of $\cos\theta$

The uncertainty of I/I_0 can be found by applying the uncertainty propagation formula

$$\begin{aligned} u_{I/I_0} &= \sqrt{\left(\frac{\partial I/I_0}{\partial I}\right)^2 u_I^2 + \left(\frac{\partial I/I_0}{\partial I_0}\right)^2 u_{I_0}^2} \\ &= \sqrt{\left(\frac{1}{I_0}\right)^2 u_I^2 + \left(\frac{I}{I_0^2}\right)^2 u_{I_0}^2} \end{aligned}$$

Since $u_I = u_{I_0} = 0.001\mu A$ and $I_0 = 1.860\mu A$, when $\theta = 0^\circ$ and $I = 1.860\mu A$:

$$u_{I/I_0} = \sqrt{\left(\frac{1}{1.860}\right)^2 0.001^2 + \left(\frac{1.860}{1.860^2}\right)^2 0.001^2} = 0.0011$$

Here the table lists all the value of u_{I/I_0}:

I $[\mu A]$	uncertainty u_{I/I_0}	I $[\mu A]$	uncertainty u_{I/I_0}
1.860	0.0011	0.580	0.0006
1.820	0.0011	0.450	0.0006
1.750	0.0011	0.300	0.0006
1.650	0.0010	0.200	0.0005
1.510	0.0010	0.110	0.0005
1.380	0.0009	0.050	0.0005
1.240	0.0009	0.010	0.0005
1.080	0.0008	0.000	0.0005
0.910	0.0007	0.020	0.0005
0.730	0.0007		

Table 3: Uncertainty of u_{I/I_0}

5.2 Linearly Polarized Light and the Half-wave Plate

The uncertainty for all the data is:

$$u_\theta = 2^\circ$$
$$u_{\Delta\theta} = 2^\circ$$

5.3 Circularly and Elliptically Polarized Light and the 1/4-wave Plate

To calculate the uncertainty for $\sqrt{I/I_0}$, we can calculate the partial derivative:

$$\begin{aligned} u_{I^{0.5}/I_0^{0.5}} &= \sqrt{\left(\frac{\partial I^{0.5}/I_0^{0.5}}{\partial I}\right)^2 u_I^2 + \left(\frac{\partial I^{0.5}/I_0^{0.5}}{\partial I_0}\right)^2 u_{I_0}^2} \\ &= 0.5 * \sqrt{\frac{1}{I \cdot I_0} u_I^2 + \frac{I}{I_0^3} u_{I_0}^2} \end{aligned}$$

When $I = 1.263\mu A$ and $I_0 = 1.325\mu A$:

$$u_{I^{0.5}/I_0^{0.5}} = 0.5 * \sqrt{\frac{1}{1.263 \times 1.325} 0.001^2 + \frac{1.263}{1.325^3} 0.001^2} = 0.0005$$

Here the table lists all the value of $u_{I^{0.5}/I_0^{0.5}}$:
When $\alpha = 0^\circ$:

$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$	$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$
0.976323	0.0005	1.000000	0.0005
0.959560	0.0005	0.972451	0.0005
0.867875	0.0005	0.879966	0.0005
0.723200	0.0006	0.733562	0.0006
0.575605	0.0007	0.563681	0.0007
0.411165	0.0009	0.402820	0.0009
0.264931	0.0014	0.264931	0.0014
0.128856	0.0029	0.145369	0.0026
0.047583	0.0079	0.047583	0.0079
0.027472	0.0137	0.027472	0.0137
0.047583	0.0079	0.038851	0.0097
0.137361	0.0027	0.137361	0.0027
0.234722	0.0016	0.236324	0.0016
0.411165	0.0009	0.399055	0.0010
0.583419	0.0007	0.600000	0.0007
0.776057	0.0006	0.742764	0.0006
0.888076	0.0005	0.840036	0.0005
0.967783	0.0005	0.961131	0.0005

Table 4: Uncertainty of $u_{I^{0.5}/I_0^{0.5}}$ when $\alpha = 0^\circ$

When $\alpha = 20^\circ$:

$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$	$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$
0.983142	0.0007	0.976619	0.0007
0.921714	0.0007	0.925441	0.0007
0.792045	0.0007	0.820101	0.0007
0.654010	0.0008	0.672540	0.0008
0.528444	0.0010	0.530301	0.0010
0.372348	0.0013	0.395401	0.0013
0.278710	0.0018	0.269746	0.0018
0.185513	0.0027	0.171751	0.0029
0.104001	0.0047	0.099161	0.0050
0.044346	0.0111	0.044346	0.0111
0.099161	0.0050	0.121447	0.0040
0.264222	0.0019	0.264222	0.0019
0.418359	0.0012	0.429950	0.0012
0.587480	0.0009	0.573934	0.0009
0.751923	0.0008	0.737398	0.0008
0.855315	0.0007	0.872952	0.0007
0.957812	0.0007	0.959863	0.0007
1.000000	0.0007	0.999016	0.0007

Table 5: Uncertainty of $u_{I^{0.5}/I_0^{0.5}}$ when $\alpha = 20°$

When $\alpha = 70°$:

$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$	$(I/I_0)^{0.5}$	uncertainty $u_{I^{0.5}/I_0^{0.5}}$
0.995953	0.0007	0.922699	0.0008
1.000000	0.0007	0.940044	0.0008
0.993517	0.0007	0.972979	0.0007
0.975466	0.0007	0.963804	0.0008
0.960446	0.0008	0.959604	0.0008
0.958762	0.0008	0.943475	0.0008
0.943475	0.0008	0.926194	0.0008
0.927937	0.0008	0.922699	0.0008
0.909473	0.0008	0.935738	0.0008
0.895149	0.0008	0.917431	0.0008
0.898752	0.0008	0.966315	0.0008
0.900547	0.0008	0.967150	0.0007
0.894247	0.0008	0.916550	0.0008
0.940044	0.0008	0.922699	0.0008
0.943475	0.0008	0.922699	0.0008
0.921823	0.0008	0.991075	0.0007
0.913903	0.0008	0.976294	0.0007
0.930544	0.0008	0.967985	0.0007

Table 6: Uncertainty of $u_{I^{0.5}/I_0^{0.5}}$ when $\alpha = 70°$

6 Conclusions and discussion

In this lab, we studied and experimented on the light polarization phenomenon and verify Malus' law, the way 1/2 and 1/4-wave plates work in optical systems and generation and detection of elliptically and circularly polarized light.

This effect can be visible since the light coming out of a polarization device is a change of the light brightness. It can be represented by the intensity of elctric flow:

$$I_{light} = I_{light,0} cos^2\theta$$

Since the amplitudes of the o-wave and the e-wave are both functions of α, the polarization state after passing through a 1/4-wave plate depends on the angle:

When $\alpha = 0$, the transmitted light is linearly polarized with the polarization axis parallel to the optical axis of the 1/4-wave plate;
When $\alpha = \pi/2$, the transmitted light is linearly polarized with the polarization axis perpendicular to the optical axis of the 1/4-wave plate;
When $\alpha = \pi/4$, the transmitted light is circularly polarized;
Otherwise, the transmitted light is elliptically polarized.

In this experiment, the error and inaccuracies mainly come from system errors. Moreover, the 1/4-wave plate we used seemed to have a little problem and is inaccurate. We didn't notice this problem until we were setting $\alpha = 45$. So, the measurement of $\alpha = 20$ might be inaccurate.

7 References

1. Qin Tian, Cao Jianjun, Yi Hankun, Wu Ziyou, Zhang Yifei, Yao Yuan, Mateusz Krzyzosiak