SJTU Global College

Physics Laboratory

(Vp241)

Laboratory Report

Excercise 4

Ploarization of Light

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[rev4.1]

1 Introduction

The objective of this exercise is to understand some properties of light, in particular to study the polarization phenomenon and verify Malus law, as well as to understand the way half- and quarter-wave plates work in optical systems. Generation and detection of elliptically and circularly polarized light will also be investigated.

2 Theoretical Background

Light is an electromagnetic wave in which the electric and magnetic fields oscillate perpendicular to the direction of propagation. This makes light a transverse wave. In natural light—emitted by typical sources—the electric field vectors fluctuate randomly in all directions within the plane perpendicular to the propagation direction. This randomness stems from the emission process itself. Such light is referred to as unpolarized. If the distribution of electric field directions is not uniform, the light is considered polarized.

The study of polarization has played a key role in the development of wave optics and has led to a wide range of applications, including optical metrology, crystallography, and stress analysis.

Polarization of Light

The electric field vector $\vec{E}$, often called the light vector in the context of visible electromagnetic waves, represents the time-varying electric field. Within the plane perpendicular to the direction of light propagation, this vector can oscillate in various directions. If the direction of oscillation remains fixed, the light is said to be linearly polarized, and the fixed direction is known as the polarization axis (see Figure 1).

If the electric field vector rotates around the propagation axis such that its tip traces a circle, the light is circularly polarized. If the tip traces an ellipse, the light is elliptically polarized (see Figure 2).

Natural light can be modeled as a statistical mixture of linearly polarized waves with equal amplitudes and random orientations. Light can also be partially polarized, meaning it contains both polarized and unpolarized components. The direction of the polarized component corresponds to the direction of maximum amplitude of the electric field.

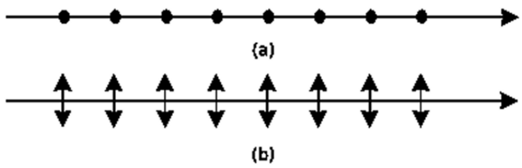

Figure 1: (a) Linearly polarized light with the polarization axis perpendicular to the page plane. (b) Linearly polarized light with the polarization axis parallel to the page plane.

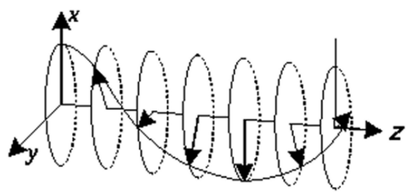

Figure 2: Elliptically polarized light propagating in the z direction. The light is polarized in the xy plane.

Polarizer

A polarizer is a device used to produce polarized light. It works based on the principle of dichroism, selectively absorbing light polarized in certain directions. Light polarized along the transmission axis of the polarizer passes through, while components in other directions are absorbed. As a result, unpolarized light becomes linearly polarized after passing through the polarizer.

The same device can also be used to analyze the polarization state of incoming light. In this case, it is referred to as an analyzer.

Malus' Law

One observable effect of polarization is the variation in light intensity after it passes through a polarizing system.

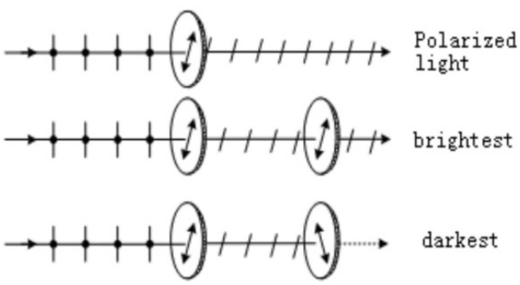

Figure 3: Change in the brightness of the light depends on the mutual orientation of the polarizer and the analyzer.

Consider two polarizers aligned such that their transmission axes form an angle θ (see Figure 3). The first acts as a polarizer, and the second as an analyzer. The intensity of the light transmitted through the analyzer is given by Malus' Law:

$$I = I_0 \cos^2 \theta, \tag{1}$$

where I_0 is the intensity of the light incident on the analyzer. This relationship, discovered by Étienne-Louis Malus in 1809, shows how the transmitted intensity depends on the angle between the polarizer and analyzer.

If the incoming light is partially or elliptically polarized, the minimum transmitted intensity will not be zero. If the intensity remains unchanged regardless of the analyzer's orientation, the light is either unpolarized or circularly polarized. Thus, a polarizer can be used to distinguish between different polarization states.

Generation of Elliptically and Circularly Polarized Light: Half-Wave and Quarter-Wave Plates

When linearly polarized light enters a birefringent crystal plate with its surface parallel to the optical axis, it splits into two components: an extraordinary wave (e-wave) aligned with the optical axis and an ordinary wave (o-wave) perpendicular to it. These two components travel at different speeds, resulting in an optical path difference:

$$\Delta = (n_e - n_o)d, \tag{2}$$

and a corresponding phase difference:

$$\delta = \frac{2\pi}{\lambda}(n_e - n_o)d, \tag{3}$$

where n_e and n_o are the refractive indices for the extraordinary and ordinary rays, d is the thickness of the plate, and λ is the wavelength of the light.

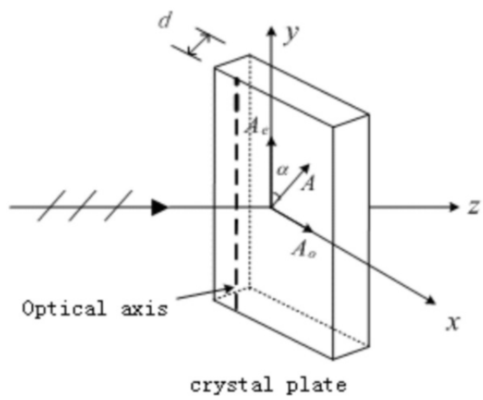

Figure 4: Linearly polarized light passing through a waveplate.

As the light propagates through the crystal, the electric field components can be written as:

$$E_x = A\cos\omega t,$$
$$E_y = A\cos(\omega t + \delta),$$

with $A_e = A\cos\alpha$, $A_o = A\sin\alpha$. Eliminating time yields the general equation of an ellipse:

$$\left(\frac{E_y}{A_o}\right)^2 + \left(\frac{E_x}{A_e}\right)^2 - 2\frac{E_x E_y}{A_e A_o}\cos\delta = \sin^2\delta. \tag{4}$$

Special cases include:

- If $\Delta = k\lambda$ (i.e., $\delta = 0$), the light remains linearly polarized. - If $\Delta = (2k+1)\frac{\lambda}{2}$ (i.e., $\delta = \pi$), the polarization axis rotates by 2α. This is the condition for a half-wave plate. - If $\Delta = (2k+1)\frac{\lambda}{4}$ (i.e., $\delta = \frac{\pi}{2}$), the light becomes elliptically polarized. This defines a quarter-wave plate.

If $A_e = A_o = A$, then:

$$E_x^2 + E_y^2 = A^2, \tag{5}$$

which describes a circle, indicating circular polarization.

The output polarization state depends on the angle α between the incident polarization and the optical axis:

- $\alpha = 0$: linearly polarized light, axis parallel to the optical axis.
- $\alpha = \frac{\pi}{2}$: linearly polarized light, axis perpendicular to the optical axis.
- $\alpha = \frac{\pi}{4}$: circularly polarized light.
- Other values: elliptically polarized light.

3 Measurement Setup and Procedure

Measurement Setup

- A linearly polarized light source is used as the initial beam.
- The optical components are arranged sequentially on an optical bench: a polarizer, a wave plate (half-wave or quarter-wave), an analyzer, and a photodetector.
- The polarizer sets the initial polarization direction of the light.

- The wave plate introduces a phase shift between orthogonal components of the electric field.
- The analyzer is used to measure the polarization state after modification by the wave plate.
- A photodetector measures the transmitted light intensity, which is proportional to the electric current I.
- Angular positions of the polarizer, wave plates, and analyzer are adjustable and measured with a precision of 1°.

Procedure

1. Malus' Law Verification

- Fix the polarizer and rotate the analyzer from 0° to 90° in 5° increments.
- Record the transmitted current I at each angle.
- Determine the maximum current I_0 for normalization.

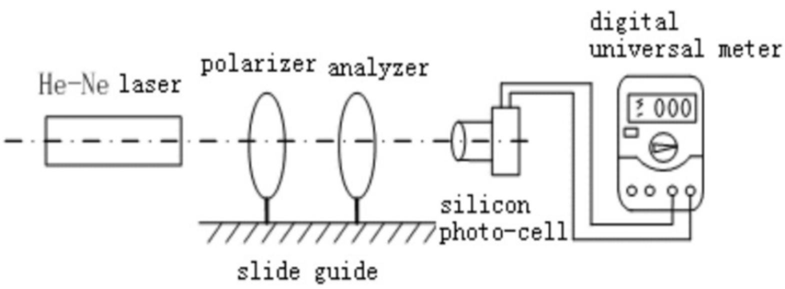

Figure 5: Experimental setup for a demonstration of Malus law

2. Half-Wave Plate Experiment

- Insert the half-wave plate between the polarizer and analyzer.
- Rotate the half-wave plate to angles from 0° to 90° in 10° steps.
- For each angle, rotate the analyzer to find the angle of minimum transmitted intensity and record it.

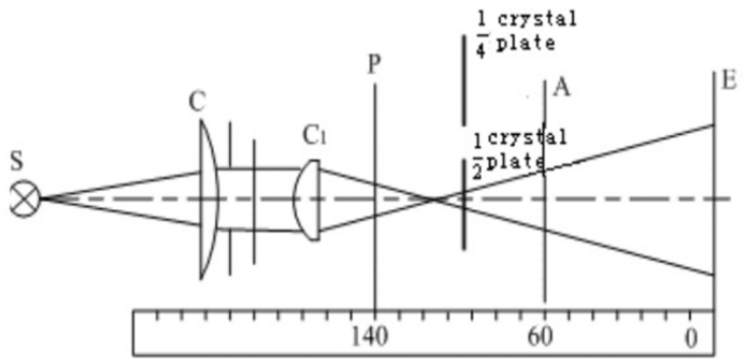

Figure 6: Experimental setup for the 1/2-wave plate

3. Quarter-Wave Plate Experiment

- Replace the half-wave plate with a quarter-wave plate.
- Set the quarter-wave plate to rotation angles of $0°, 20°, 45°, 70°$.
- For each setting, rotate the analyzer from 0° to 350° in 10° increments.
- Record the transmitted current I at each angle and determine the maximum I_0.

4 Results

Uncertainty of θ is 2°.

Maximum Electric Current $I_0\pm$ _____			
θ	$I\pm$ 0.001[mW]	θ	$I\pm$ 0.001[mW]
0°	1.672	50°	0.691
5°	1.660	55°	0.551
10°	1.622	60°	0.418
15°	1.560	65°	0.299
20°	1.476	70°	0.196
25°	1.373	75°	0.112
30°	1.254	80°	0.050
35°	1.122	85°	0.012
40°	0.981	90°	0.001
45°	0.837		

Table 1: TMeasurement data Malus' law demonstration.

Rotation angle of the 1/2-wave plate	Rotation angle of the analyzer [°] ± 2 [°]
initial	0
10°	22
20°	40
30°	60
40°	84
50°	100
60°	120
70°	146
80°	158
90°	178

Table 2: Measurement data for the 1/2-wave plate.

Rotation angle of 1/4-wave plate: 0°			
Maximum Electric Current I_0± 0.001[mW]			
θ	I± 0.001[mW]	θ	I± 0.001[mW]
0°	0.001	180°	0.002
10°	0.040	190°	0.042
20°	0.131	200°	0.140
30°	0.281	210°	0.286
40°	0.441	220°	0.447
50°	0.601	230°	0.606
60°	0.757	240°	0.758
70°	0.882	250°	0.891
80°	0.933	260°	0.935
90°	0.940	270°	0.939
100°	0.889	280°	0.891
110°	0.796	290°	0.797
120°	0.678	300°	0.679
130°	0.510	310°	0.512
140°	0.380	320°	0.381
150°	0.226	330°	0.225
160°	0.108	340°	0.108
170°	0.024	350°	0.024

Table 3: Measurement data for the 1/4-wave plate (rotation angle 0°).

Rotation angle of the 1/4-wave plate: 70°	
I [mW] ± 0.001[mW]	0.153, 0.957, 0.168, 1.099
θ [°] ± 2[°]	24, 100, 195, 296

Table 4: Measurement data for the 1/4-wave plate (rotation angle 70°).

Rotation angle of 1/4-wave plate: 20°			
Maximum Electric Current I_0 [mW] $\pm$ 0.001[mW]			
θ	I [mW] $\pm$ 0.001[mW]	θ	I [mW] $\pm$ 0.001[mW]
0°	0.225	180°	0.231
10°	0.346	190°	0.349
20°	0.447	200°	0.478
30°	0.604	210°	0.610
40°	0.718	220°	0.720
50°	0.782	230°	0.778
60°	0.842	240°	0.841
70°	0.856	250°	0.850
80°	0.793	260°	0.790
90°	0.709	270°	0.719
100°	0.596	280°	0.596
110°	0.468	290°	0.471
120°	0.361	300°	0.362
130°	0.247	310°	0.248
140°	0.247	320°	0.190
150°	0.176	330°	0.131
160°	0.129	340°	0.121
170°	0.164	350°	0.159

Table 5: Measurement data for the 1/4-wave plate (rotation angle 20°).

Rotation angle of 1/4-wave plate: 45° Maximum Electric Current I_0 [mW] $\pm$ 0.001[mW]			
θ	I [mW] $\pm$ 0.001[mW]	θ	I [mW] $\pm$ 0.001[mW]
0°	0.629	180°	0.631
10°	0.610	190°	0.612
20°	0.581	200°	0.590
30°	0.529	210°	0.533
40°	0.488	220°	0.491
50°	0.453	230°	0.473
60°	0.437	240°	0.437
70°	0.425	250°	0.427
80°	0.417	260°	0.419
90°	0.417	270°	0.417
100°	0.434	280°	0.433
110°	0.454	290°	0.454
120°	0.485	300°	0.490
130°	0.526	310°	0.533
140°	0.590	320°	0.597
150°	0.611	330°	0.619
160°	0.644	340°	0.651
170°	0.674	350°	0.677

Table 6: Measurement data for the 1/4-wave plate (rotation angle 45°).

5 Conclusions and discussion

A Signatured Datasheet

Uncertainty of θ is [2]°. $I = I_0 \cos^2\theta$

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170°

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Instructor's signature: 郭文慧

B Supplementary Materials

B.1 Code Used