Abbe School of Photonics | JENA

Friedrich-Schiller-Universität

Fundamentals of Experimental Optics

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03

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Contents

1 Introduction

Light is, in essence, electromagnetic radiation travelling in a vacuum at a speed of 299792458m/s. When light travels from one medium to another medium, a few interesting phenomena will be observed, such as reflection, dispersion, refraction and more. And from these phenomena, people developed a lot of fascinating applications in various fields.
In this project, we performed several experiments designed to explore several fundamental properties of light. Through these experiments, we measured data such as reflection angles, refraction angles and parallel shifts. And then, we identified, quantified and then analysed potential sources of errors.

2 Theory

2.1 Reflection

Reflection is a fundamental optical phenomenon and concept. It describes the behaviour of light striking on the surface of a medium and returning to the original medium.
Reflection obeys the law of reflection which states that the incident angle is equal to the reflective angle, as shown in the Figure 1.

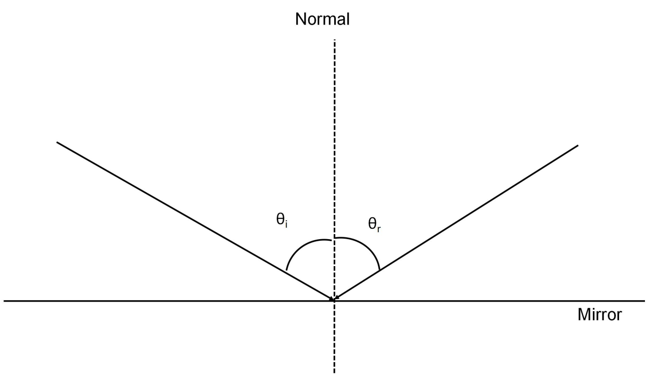

Figure 1: Reflection

$$\sin \theta_i = \sin \theta_r \tag{1}$$

2.2 Snell's Law

Snell's law is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass, or air. As shown in the Figure 2. [1]

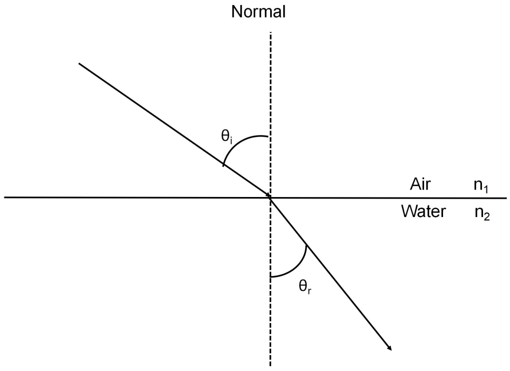

Figure 2: Refraction

The law states that, for a given pair of media, the ratio of the sines of angle of incidence θ_1 and angle of refraction θ_2 is equal to the ratio of the refractive indices $\frac{n_1}{n_2}$. [1]

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_2} \tag{2}$$

2.3 Parallel Shift

Parallel shift occurs when a ray propagates from a medium 1 to a rectangular medium 2 whose width is H with the angle of incidence θ_i and the angle of refraction θ_r. And then the ray travels back to the medium 1 with the second angle of incidence ϕ_i and the second angle of refraction ϕ_r. After this process, the incident ray will have a parallel shift d as shown in Figure 3.

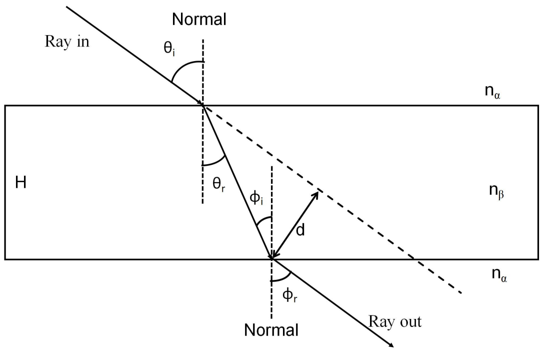

Figure 3: Parallel shift

According to Snell's Law, obviously we have θ_r=ϕ_i and θ_i=ϕ_r. Thus, Ray out is parallel to Ray in. And then we can derive out a relation between the Parallel shift d and θ_i, θ_r, H:

$$d = H\frac{\sin(\theta_i - \theta_r)}{\cos\theta_r} \tag{3}$$

2.4 Total Internal Reflection

Total internal reflection (TIR) is the phenomenon in which waves arriving at the interface (boundary) from one medium to another (e.g., from water to air) are not refracted into the second (”external”) medium, but completely reflected back into the first (”internal”) medium. It occurs when the second medium has a higher wave speed (i.e., lower refractive index) than the first, and the waves are incident at a sufficiently oblique angle on the interface. [2]

The sufficient oblique angle is called Critical Angle θ_c=θ_i, as shown in Figure 4. Here, the angle of refraction is ϕ_r=90°. And according to Snell's law, the Critical Angle can thus be expressed by:

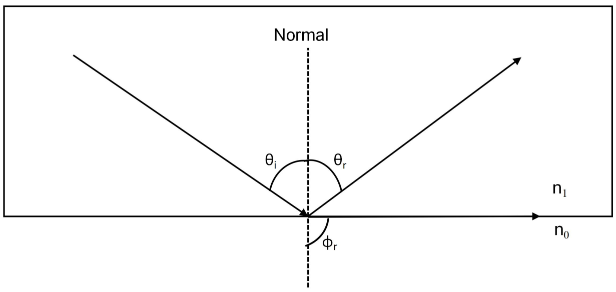

Figure 4: Total internal reflection

$$\theta_i = \theta_c = \arcsin\frac{n_0}{n_1} \tag{4}$$

Total internal reflection is applied in various fields. For example, optical fibre is based on total internal reflection. An optical fibre consists of a core with a higher refractive index and a cladding with a lower refractive index. According to the total internal reflection theory, rays in an optical fibre are always totally reflected, thus, the energy loss caused by refraction is nearly zero and rays can propagate further.

2.5 Beam Polarization

Polarization (also polarisation) is a property of transverse waves which specifies the geometrical orientation of the oscillations. In a transverse wave, the direction of the oscillation is perpendicular to the direction of motion of the wave. [3]

An electromagnetic wave such as light consists of a coupled oscillating electric field and magnetic field which are always perpendicular to each other; by convention, the "polarization" of electromagnetic waves refers to the direction of the electric field. In linear polarization, the fields oscillate in a single direction. In circular or elliptical polarization, the fields rotate at a constant rate in a plane as the wave travels, either in the right-hand or in the left-hand direction. [3]

Brewster's angle (also known as the polarization angle) is an angle of incidence at which light with a particular polarization is perfectly transmitted through a transparent dielectric surface, with no reflection. When unpolarized light is incident at this angle, the light that is reflected from the surface is therefore perfectly polarized. [4]
When a light strikes on an interface between two media with different refractive indices, some of it is usually reflected as shown in the Figure 5.

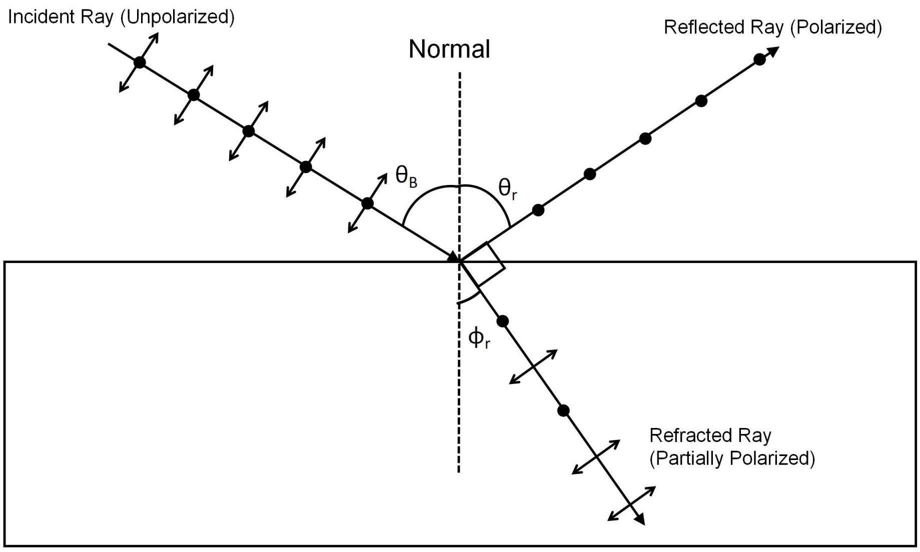

Figure 5: Brewster Angle

The light with the p polarization (electric field polarized in the same plane as the incident ray and the surface normal at the point of incidence) will not be reflected if the angle of incidence is: [4]

$$\theta_B = \arctan \frac{n_2}{n_1} \tag{5}$$

where n_1 is the refractive index of the initial medium through which the light propagates (the "incident medium"), and n_2 is the index of the other medium. This equation is known as Brewster's law, and the angle defined by it is Brewster's angle. [4]

2.6 Beam Propagation Through Prism and Prism Dispersion

An optical prism is a transparent optical element with flat, polished surfaces that are designed to refract light. At least one surface must be angled — elements with two parallel surfaces are not prisms. The most familiar type of optical prism is the triangular prism, which has a triangular base and rectangular sides. [5]

When light propagates through a prism, it undergoes multiple refractions. However, for the sake of simplification, let's consider a scenario with two refractions, as depicted in Figure 6. The ray in the figure is refracted twice, thus, we need Snell's Law to describe the propagation. According to Snell's Law, the angle of incidence and the angle of refraction is connected by the ratio of refractive indices. And refractive indices depend on frequency, thus a prism can disperse white light into its constituent spectral colors.

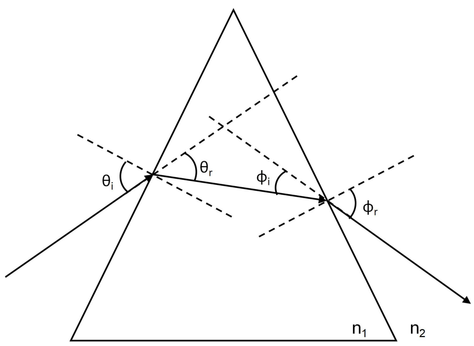

Figure 6: Prism

2.7 Beam Propagation Through Concave and Convex Lens

A concave lens is a diverging its thickness is thinner at the center than at the edges. When collimated rays undergo a concave lens, they diverge after passing through the lens. The light rays appear to originate from a single point on the object side of the lens. This point is called the focal point, and the distance from the lens to this point is the focal length. The focal length of a concave lens is negative. A typical beam propagation through a concave lens is shown in Figure 7

A convex lens is a converging lens. And its thickness is thicker at the center than at the edges. When collimated rays undergo a convex lens, they converge at a single point on the image side of the lens. This point is also called the focal point, and the distance from the lens to this point is the focal length. The focal length of a convex lens is positive. A typical beam propagation through a convex lens is shown in Figure 7

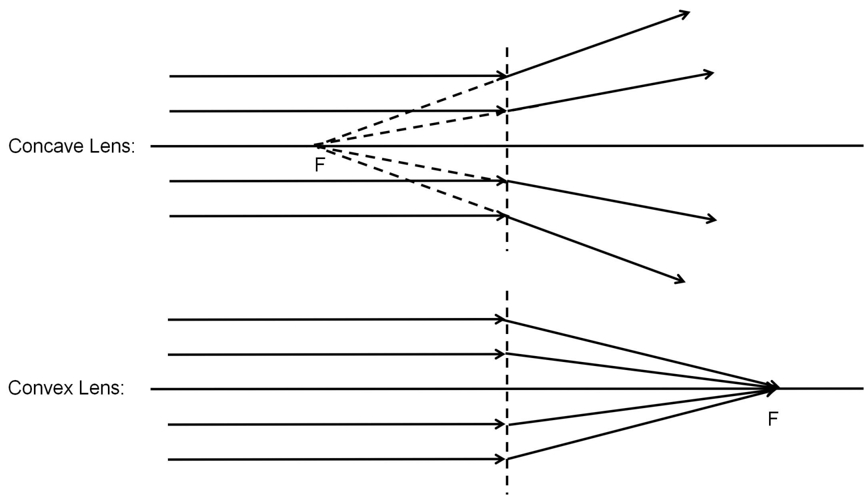

Figure 7: Beam Propagation through Concave and Convex Lens

2.8 Grating Dispersion

Grating dispersion is a phenomenon which describes that light is dispersed into different angles or positions based on its wavelength after undergoing a grating. It's because that a grating consists of periodical structures, and when light passes through these structures, it will be diffracted. Therefore, a grating is able to decompose the incident light into its constituent parts of different wavelength or frequencies. A typical beam propagation through a grating is shown in Figure 8.

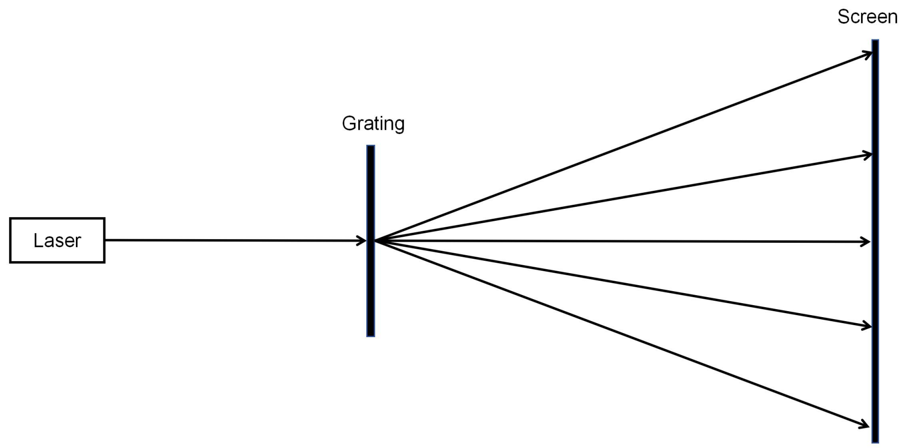

Figure 8: Grating Dispersion

2.9 Birefringence and Optical Activity

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. Birefringence is responsible for the phenomenon of double refraction whereby a ray of light, when incident upon a birefringent material, is split by polarization into two rays taking slightly different paths. [6]
The simplest type of birefringence is described as uniaxial, meaning that there is a single direction governing the optical anisotropy whereas all directions perpendicular to it (or at a given angle to it) are optically equivalent. Thus rotating the material around this axis does not change its optical behaviour. This special direction is known as the optic axis of the material. [6]
Light propagating parallel to the optic axis (whose polarization is always perpendicular to the optic axis) is governed by a refractive index no (for "ordinary") regardless of its specific polarization. For rays with any other propagation direction, there is one linear polarization that is perpendicular to the optic axis, and a ray with that polarization is called an ordinary ray and is governed by the same refractive index value no. For a ray propagating in the same direction but with a polarization perpendicular to that of the ordinary ray, the polarization direction will be partly in the direction of (parallel to) the optic axis, and this extraordinary ray will be governed by a different, direction-dependent refractive index. [6]
Because the index of refraction depends on the polarization when unpolarised light enters a uniaxial birefringent material, it is split into two beams travelling in different directions, one having the polarization of the ordinary ray and the other the polarization of the extraordinary ray. The ordinary ray will always experience a refractive index of no, whereas the refractive index of the extraordinary ray will be in between no and ne, depending on the ray direction as described by the index ellipsoid. [6]

3 Experimental Setup

3.1 Beam Propagation, Law of Reflection, and Snellius Law

3.1.1 Air-Metal Transition

This experimental setup consists of a laser, a protractor and a rectangular metal. and a ray from the laser is incident on the metal at the angle of incidence α and then reflected at the angle of reflection α', as shown in the Figure 9.

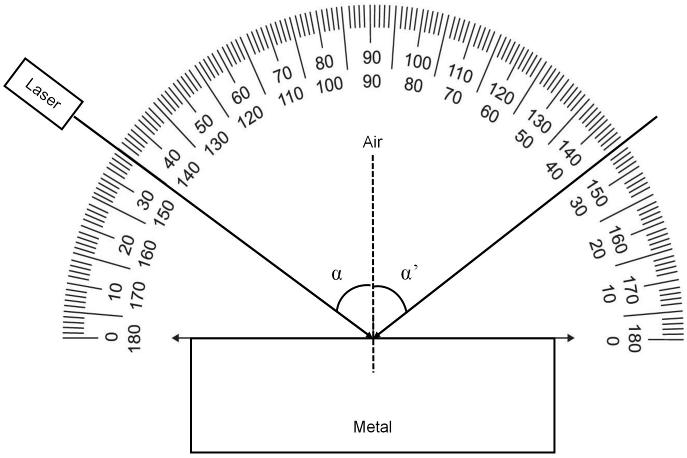

Figure 9: Air-Metal Transition

3.1.2 Air-Plexiglass Transition

The experimental setup in this section aims to investigate the behavior of light as it propagates through two interfaces between air and Plexiglass, as illustrated in Figure 10.

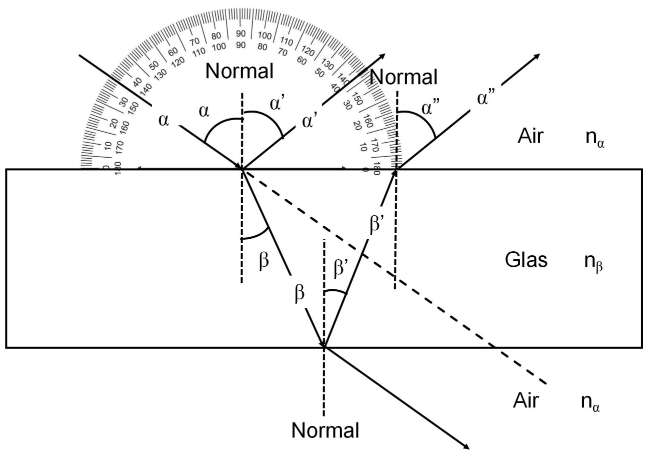

Figure 10: Air-Plexiglass Transition

3.1.3 Air-Water Transition

This experiment aims to calculate the refractive index of water according to angles of incidence and angles of refraction, as illustrated in Figure 11.

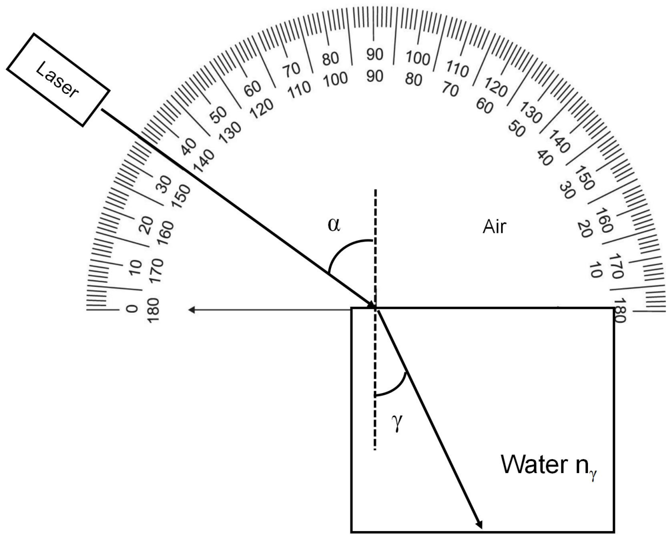

Figure 11: Air-Water Transition

3.1.4 Parallel Shift

This experimental setup is like the setup of the Air-Plexiglass Transition, butut this time we focus on the parallel shift between Ray α and Ray β'. Then we investigate the relation between the parallel shift and the angle of incidence and thickness of the plate, as illustrated in Figure 12. Given the thickness of slab d, angle of incidence α and angle of refraction β, the parallel shift b can be calculated using the following relation:

$$b = d\frac{\sin(\alpha - \beta)}{\cos\beta} \tag{6}$$

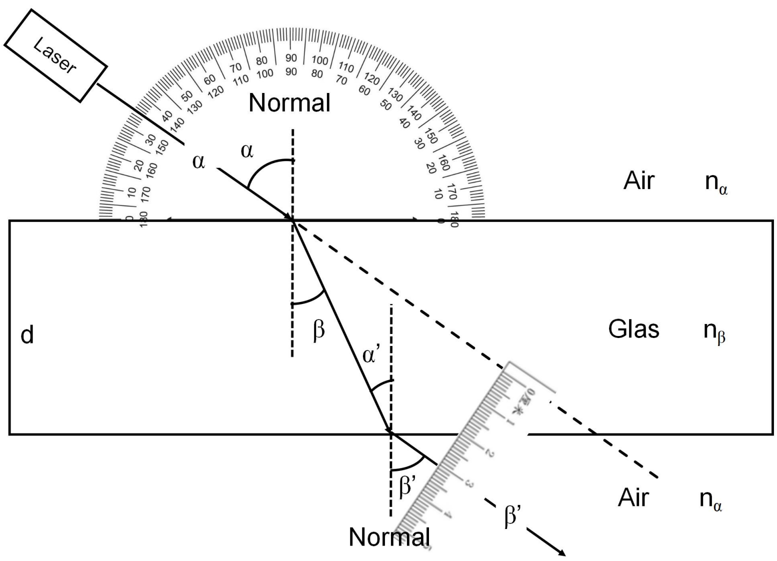

Figure 12: Parallel Shift Setup

3.1.5 Total Internal Reflection

This experiment is to measure the critical angle of total internal reflection in the plexiglass semi-arc and then calculate the refractive index of the plexiglass using the expression for total internal reflection. Thus the experimental setup is designed as illustrated in Figure 13.

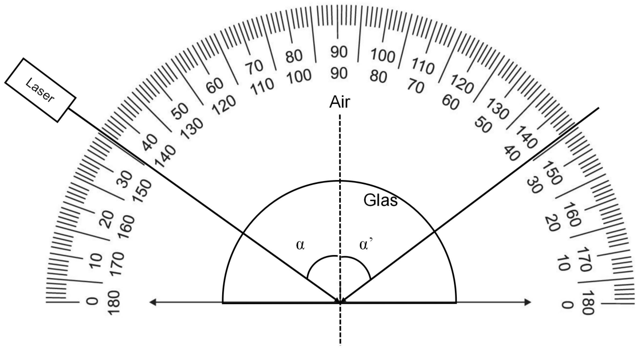

Figure 13: Total Internal Reflection setup

3.1.6 Brewster's Angle

This experiment is to measure Brewster's angle in the plexiglass semi-arc and then calculate the refractive index of the plexiglass using the expression about Brewster's Angle. Thus the experimental setup is designed as illustrated in Figure 14.

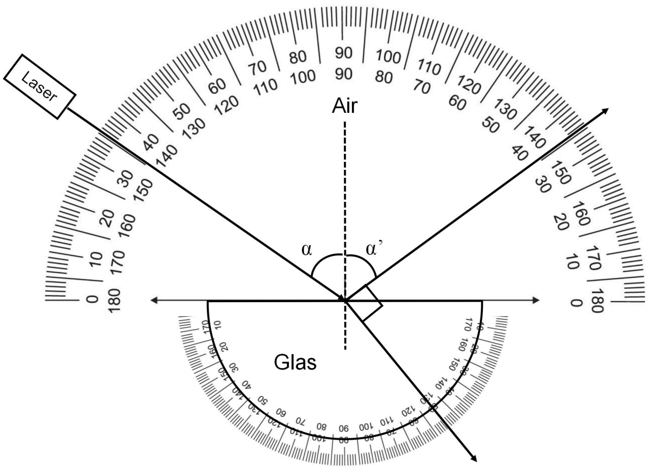

Figure 14: Brewster's Angle Setup

3.2 Propagation Through Prism and Prism Dispersion

The experiment of this part aims to observe the beam propagation in a prism and calculate the prism dispersion of a prism by using green and red lasers. Thus the setup of this experiment is as shown in Figure 15.

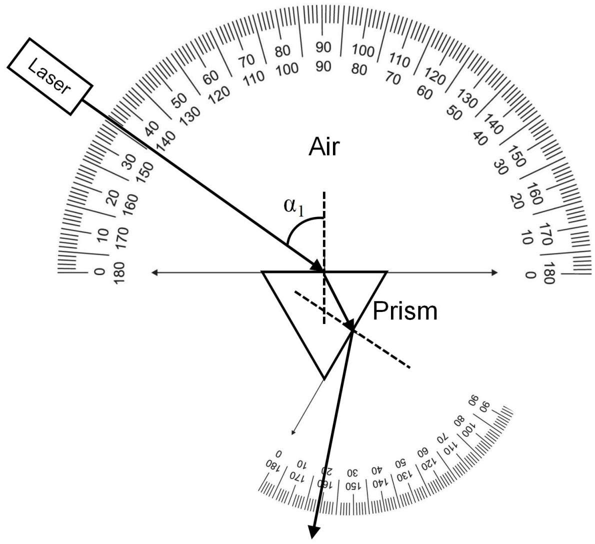

Figure 15: Setup for Prism Dispersion

The equation for calculating prism dispersion is:

$$dispersion = \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \tag{7}$$

3.3 Diffraction

This experiment is to measure grating dispersion using red and green lasers, as illustrated in Figure 16.

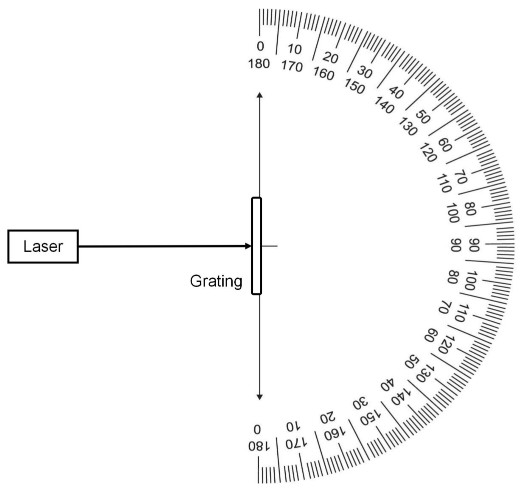

Figure 16: Diffraction

The equation for grating dispersion is:

$$dispersion = \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \tag{8}$$

3.4 Transmission Through Polarizers and Birefringent Crystals

This experiment uses two polarizers and a Birefringent crystal to explore the combination angles of each of them which minimizes the intensity of laser on the screen. The setup is as illustated in Figure 17.

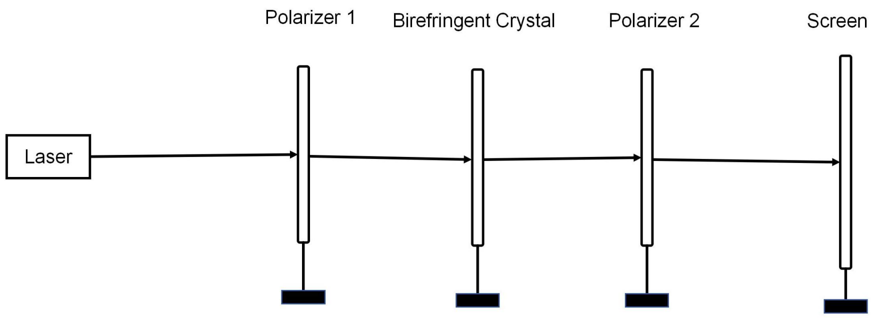

Figure 17: Transmission Through Polarizers and Birefringent Crystals

4 Results

4.1 Beam Propagation, Law of Reflection, and Snellius Law

4.1.1 Air-Metal Transition

The table 1 enlists the measured values for angle of incidence α and angle of refection α' when laser light is incident on air-metal interface.

$\alpha\,(^\circ)$	$\alpha'\,(^\circ)$	Uncertainty in $\alpha, \beta\,(^\circ)$
20	21	$\pm 0,5$
30	31	$\pm 0,5$
40	41	$\pm 0,5$
50	51,5	$\pm 0,5$
60	61	$\pm 0,5$
70	71	$\pm 0,5$

Table 1: Reflection at Air-Metal interface.

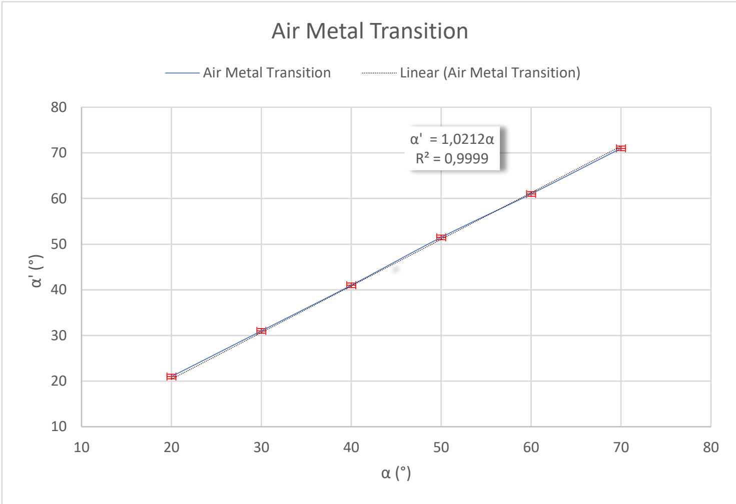

Figure 18: A graphical illustration of data adopted from Table 1. Error bars are shown in red.

4.1.2 Air-Plexiglass Transition

The table 2 enlists the measured values for angle of incidence α, angle of refection α', and angle of refraction β when laser light is incident on air-plexiglass interface. Refractive index for plexiglass n_{px} is calculated for each (α,β) using Eq. (2).

α (°)	α' (°)	β (°)	Uncertainty in α, β (°)	n_{px}
20	21	14	$\pm 0,5$	1,41
30	31	20,5	$\pm 0,5$	1,43
40	41	27	$\pm 0,5$	1,42
50	51,5	32,5	$\pm 0,5$	1,43
60	61	37	$\pm 0,5$	1,44
70	71	40,5	$\pm 0,5$	1,45

Table 2: Reflection and refraction at Air-Plexiglass interface.

Mean value of $n_{px} = 1,43$

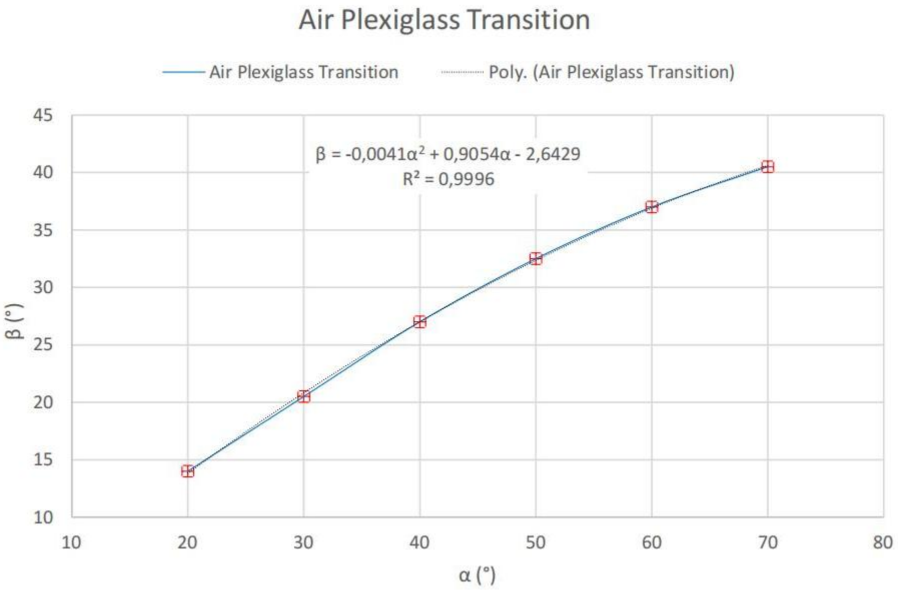

Figure 19: A graphical illustration of data adopted from Table 2. Error bars are shown in red.

4.1.3 Air-Water Transition

The table 20 enlists the measured values for angle of incidence α, and angle of refraction β when laser light is incident on air-water interface. Refractive index for water n_w is calculated for each (α,β) using Eq. (2).

$\alpha\,(^\circ)$	$\beta\,(^\circ)$	Uncertainty in $\alpha, \beta\,(^\circ)$	n_w
15	11,5	$\pm 0,5$	1,3
20	15	$\pm 0,5$	1,32
25	18,5	$\pm 0,5$	1,33
30	22,5	$\pm 0,5$	1,31
40	29	$\pm 0,5$	1,33

Table 3: Refraction at Air-Water interface.

Mean value of $n_w = \quad 1,318$

α (°)	β (°)	b_{measured} (mm)	$b_{\text{calculated}}$ (mm)	Uncertainty in α, β (°)	Uncertainty in b (mm)
20	14	6	6,3	$\pm 0,5$	$\pm 0,5$
30	20,5	9	10,31	$\pm 0,5$	$\pm 0,5$
40	27	16,5	14,77	$\pm 0,5$	$\pm 0,5$
50	32,5	22	20,86	$\pm 0,5$	$\pm 0,5$

Table 4: Parallel shift in Plexiglass slab.

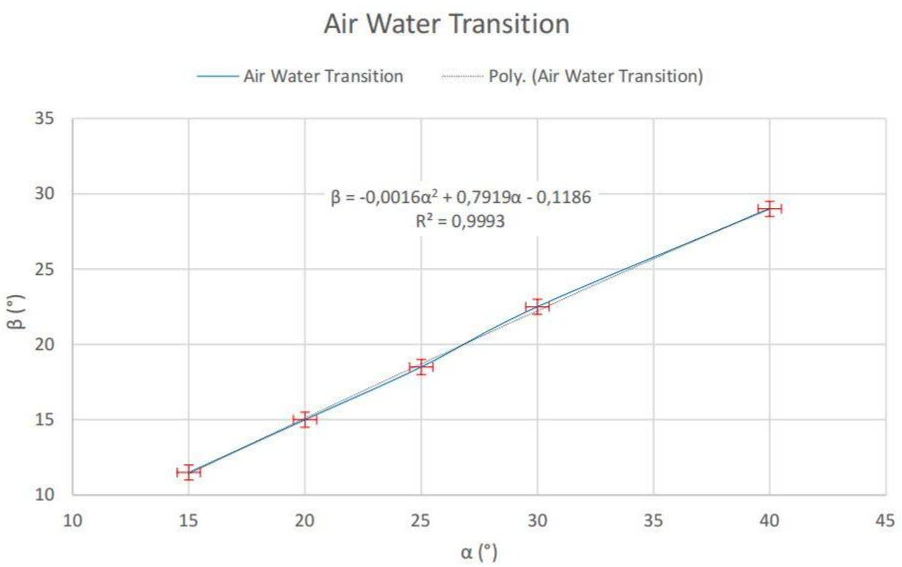

Figure 20: A graphical illustration of data adopted from Table 3. Error bars are shown in red.

4.1.4 Parallel Shift

The table 4 enlists the measured values for angle of incidence α, and angle of refraction β, and parallel shift $b_{measured}$ when laser light is incident on air-water interface. For reference, $b_{calculated}$ is also computed using Eq. (6). Error calculations

Figure 21: A graphical illustration of data adopted from Table 4. Error bars are shown in red.

4.1.5 Reflection with Plexiglass Arc Forms

4.1.6 Total Internal Reflection

Critical angle of total reflection:

$$n_\beta = \frac{1}{\sin \beta_\mathrm{c}} \tag{9}$$

β_c is measured to be $41.1 \pm 0.1°$. It follows from Eq. (9) that refractive index for the Plexiglass Arc is 1.52.

4.1.7 Brewster Angle

Brewster angle outside the Plexiglass Arc Forms:

$$n_\beta = \tan \alpha_\mathrm{Brew} \tag{10}$$

α_Brew was measured to be $56.5 \pm 0.1°$. Therefore, tha refractive index using Eq. (10) is found to be $1.51\pm$.

4.2 Propagation Through Prism and Prism Dispersion

4.2.1 Beam Propagation

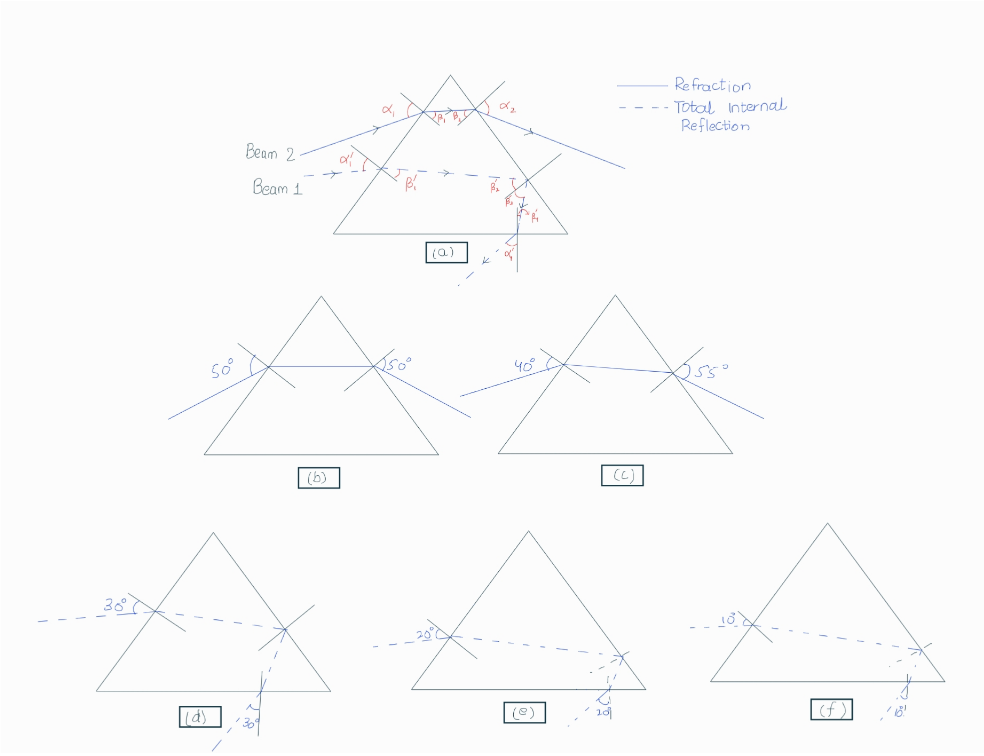

Figure 22: A sketch illustrating the refraction and total internal refraction through a prism. The angles are not to the scale.

Refractive index of the prism as a function of wavelength $n_\beta(\lambda)$ can be calculated by the angle of minimum inclination α_{min} using the following expression:

$$n_\beta(\lambda) = \frac{\sin\left(\frac{\alpha_{\text{min}}}{2} + \frac{\gamma}{2}\right)}{\sin\frac{\gamma}{2}} \tag{11}$$

γ is the angle of prism. For red laser,

$$n_\beta(633 \text{ nm}) = \frac{\sin\left(\frac{50^\circ}{2} + \frac{60^\circ}{2}\right)}{\sin\frac{60^\circ}{2}} = 1.63$$

For green laser,

$$n_\beta(532 \text{ nm}) = \frac{\sin\left(\frac{56.5^\circ}{2} + \frac{60^\circ}{2}\right)}{\sin\frac{60^\circ}{2}} = 1.70$$

4.2.2 Prism Dispersion

Using Eq.(7):

$$\begin{aligned} dispersion &= \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \\ &= \frac{\mid 50^\circ - 56.5^\circ \mid}{633 \text{ nm} - 532 \text{ nm}} \\ &= 6.4 \times 10^{-2^\circ} / \text{ nm} \end{aligned}$$

4.3 Diffraction

The Table 5 enlists the position of 1^{st} and 2^{nd} order diffraction pattern using two grating elements with grating period $N = 100$ and $N = 300$. Readings are measured for two light sources, i.e., green and red laser. incident normally on the grating elements.

		1st Order			2nd Order		
Laser	Grid	Θ_l°	Θ_r°	$\bar{\Theta}^\circ$	Θ_1°	Θ_r°	$\bar{\Theta}^\circ$
green	100	0	0	2	0	0	4.5
red	100	0	0	2.5	0	0	5
green	300	0	0	6	0	0	12.5
red	300	0	0	7	0	0	15.5

Table 5: Diffraction at 1^{st} and 2^{nd} order.

4.3.1 Dispersion at first order diffraction:

For $N = 100$:

$$\begin{aligned} dispersion &= \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \\ &= \frac{2.5^\circ - 2^\circ}{633 \text{ nm} - 532 \text{ nm}} \\ &= 4.95 \times 10^{-3^\circ} / \text{ nm} \end{aligned}$$

For $N = 300$:

$$\begin{aligned} dispersion &= \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \\ &= \frac{7^\circ - 6^\circ}{633 \text{ nm} - 532 \text{ nm}} \\ &= 9.9 \times 10^{-3^\circ} / \text{ nm} \end{aligned}$$

4.3.2 Dispersion at second order diffraction:

For $N = 100$:

$$\begin{aligned} dispersion &= \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \\ &= \frac{5^\circ - 4.5^\circ}{633 \text{ nm} - 532 \text{ nm}} \\ &= 4.95 \times 10^{-3^\circ} / \text{ nm} \end{aligned}$$

For $N = 300$:

$$\begin{aligned} dispersion &= \frac{\alpha_{red} - \alpha_{green}}{\lambda_{red} - \lambda_{green}} \\ &= \frac{15.5^\circ - 12.5^\circ}{633 \text{ nm} - 532 \text{ nm}} \\ &= 2.9 \times 10^{-2^\circ} / \text{ nm} \end{aligned}$$

4.4 Transmission Through Polarizers and Birefringent Crystals

The Table 6 present the birefringence of two crystals. Orientation of polarizer 1 $\alpha_{P_{linear_1}}$ and polarizer 2 $\alpha_{P_{linear_1}}$ with reference to the vertical axis has been measured for crystal 1 and crystal 2. Δa shows the relative positioning of both polarizers.

Crystal 1	$\alpha_{P_{linear_1}}$	$\alpha_{P_{linear_2}}$	Δa	Crystal 2	$\alpha_{P_{linear_1}}$	$\alpha_{P_{linear_2}}$	Δa
532 nm	90	60	30	532 nm	90	40	50
650 nm	90	30	60	650 nm	90	10	80

Table 6: Birefringence of two crystals.

5 Discussion

6 Conclusion

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