1. PRINCIPLES OF OPTICS

Tasks:

a) Determine the wavelength of a laser light source by using a diffraction grating.

b) Determine the index of refraction of an unknown material by measuring the angle of refraction (material → air incidence). Determine the critical incident angle of total internal reflection.

c) Determine the polarization (Brewster) angle (air → material incidence).

Introduction:

a) Diffraction grating

Diffraction (and interference) of light after passing through a diffraction grating is an important optical phenomenon that confirms the wave nature of light. A diffraction grating can be used to determine the wavelength of a monochromatic light source, or it can be used to separate the spectrum of an arbitrary light source into the individual spectral components (the operation of a monochromator).

As a monochromatic light beam passes the diffraction grating, as shown in Figure 1.1, the light diffracts and interferes with itself. This results in pronounced constructive interference peaks that are formed in well-defined directions. These interference peaks or *orders* are labeled by the index m. The *zeroth order* ($m = 0$) propagates in the same direction as the incident light beam, whereas the higher orders ($m > 0$) propagate at angles θ_m away from the incident direction, as shown in the figure. The angles θ_m depend on the wavelength of the light beam λ and the period of the diffraction grating P (distance between the grooves on the grating). They can be calculated according to Equation 1.1 (simplified for the case of perpendicular incidence).

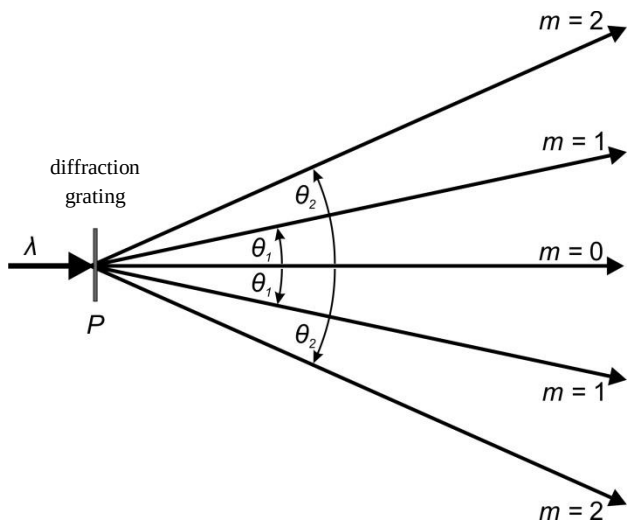

Figure 1.1: Interference orders forming at a diffraction grating.

$$\sin \theta_m = \frac{m \cdot \lambda}{P} \tag{1.1}$$

b) Refraction and reflection

The phenomenon of light refraction that occurs as the light passes from the medium with the index of refraction n_1 into the medium with the index of refraction n_2 can be described by the Snell law, given by Equation 1.2. In the equation, refractive indices are related to the sines of the angle of incidence θ_1 and the angle of refraction θ_2. The index of refraction is in general complex-valued in which case the imaginary part (the extinction coefficient k) holds information about light absorption in the medium. However, in the scope of our lab work, we will neglect the absorption and assume only real values for the index of refraction.

$$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2 \tag{1.2}$$

As the light passes from the medium with a *higher* index of refraction into the medium with a *lower* index of refraction ($n_1 > n_2$), for example from glass ($n_1 = 1.5$) into air ($n_2 = 1$), the effect of total internal reflection can occur if the incident angle θ_1 is high enough. The critical incident angle, that is the smallest incident angle at which total internal reflection occurs, can be calculated from the ratio of both indices of refraction (Equation 1.3).

$$\sin\theta_{1,crit} = \frac{n_2}{n_1} \tag{1.3}$$

Reflectance R and transmittance T can be determined by means of the Fresnel coefficients, which are different for the case of horizontally polarized (TE) and vertically polarized (TM) light (Equations 1.4).

$$R_{TE} = \left(\frac{n_1 \cdot \cos\theta_1 - n_2 \cdot \cos\theta_2}{n_1 \cdot \cos\theta_1 + n_2 \cdot \cos\theta_2}\right)^2 \qquad T = 1 - R \tag{1.4}$$
$$R_{TM} = \left(\frac{n_1 \cdot \cos\theta_2 - n_2 \cdot \cos\theta_1}{n_1 \cdot \cos\theta_2 + n_2 \cdot \cos\theta_1}\right)^2$$

If the light passes from the medium with a *lower* index of refraction into the medium with a *higher* index of refraction ($n_1 < n_2$), it turns out that R_{TE} monotonically increases with an increasing incident angle, whereas R_{TM} first drops to the minimal value of 0 and only then begins to increase. The incident angle at which $R_{TM} = 0$ is the so-called polarization or Brewster angle. It can be calculated from the ratio of both indices of refraction (Equation 1.5).

$$\tan\theta_{1,B} = \frac{n_2}{n_1} \tag{1.5}$$

Experimental procedure:

a) Determination of the wavelength of the laser light

The wavelength of the laser light will be determined from the interference pattern that forms as the light beam passes a diffraction grating. The principle of the measurement is shown in Figure 1.2.

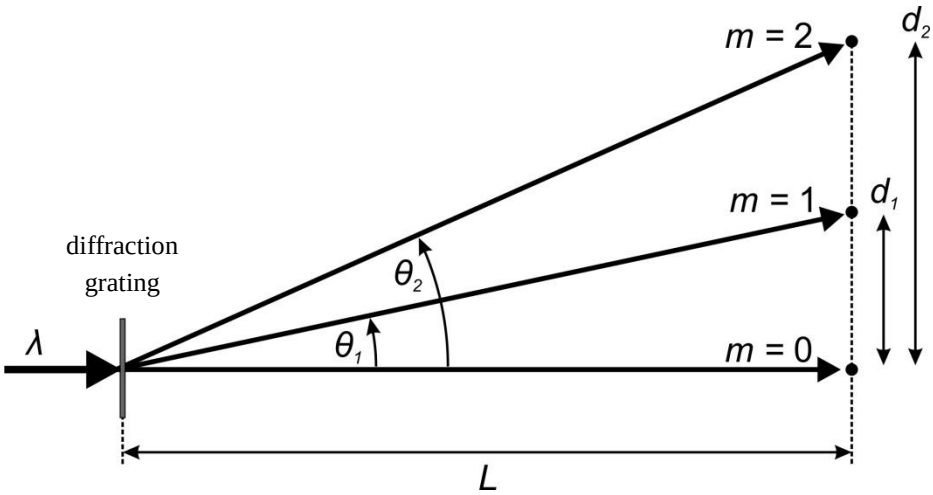

Figure 1.2: Measurement of the wavelength of the laser light.

Connect the laser to the DC power supply (**+6 V** output) and set the voltage to **6 V**. Put the diffraction grating in front of the laser into the slot (the density of the grating is 300 grooves per mm) and observe the bright dots (interference pattern) that form on the screen. For the first two dots (interference orders m = 1 and 2), measure the distance of each dot from the dot in the center of the screen (zeroth order, m = 0). Write down both distances (d_1 and d_2). The distance from the diffraction grating to the screen is L = 33 cm.

Calculate the angles of propagation θ_1 and θ_2 for both interference orders (*hint:* tangent function). Finally, using the equation of the diffraction grating (Equation 1.1), calculate the central wavelength of the laser light λ.

During the measurement, take special care that the interference pattern is fully symmetric! If not, try to rotate the grating a bit until sufficient symmetry is achieved.

Diffraction grating: density 300 grooves / mm → P = _____

d_1 = _____ θ_1 = _____ λ = _____

d_2 = _____ θ_2 = _____ λ = _____

b) Determination of the index of refraction and the critical angle of incidence

The index of refraction will be determined by measuring the angles of refraction as the light beam passes from the unknown material into air, as shown in Figure 1.3. Since the absorption in the material can be neglected (at the wavelength of the laser light), we will only determine the real part of the index of refraction.

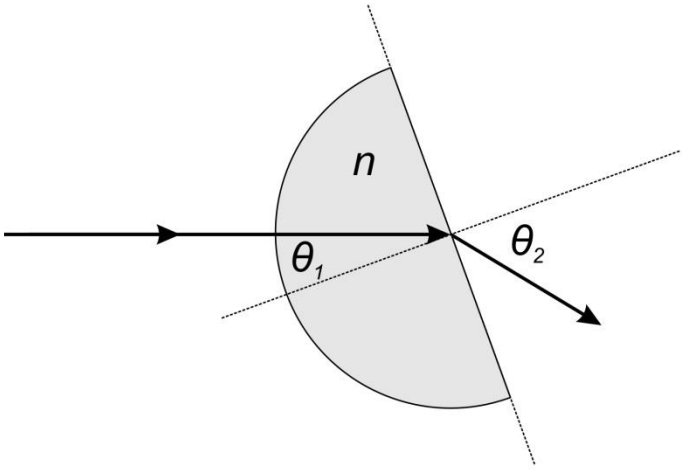

Figure 1.3: Measurement of the angle of refraction.

Set up the semi-circular prism so that the flat side is perpendicular to the laser beam and make sure that the laser beam enters the prism from the rounded side (as shown in Figure 1.3). Then, rotate the prism for $\theta_1 = 20\,°$ (this is now the angle of incidence) and observe how the light beam refracts as it passes out of the prism into air. Using the small screen, measure the angle of refraction θ_2 and finally calculate the index of refraction n according to the Snell law (Equation 1.2). Repeat the procedure for angles of incidence $\theta_1 = 30\,°$ and $40\,°$.

i) $\theta_1 = 20\,°$ θ_2 = _____ n = _____

ii) $\theta_1 = 30\,°$ θ_2 = _____ n = _____

iii) $\theta_1 = 40\,°$ θ_2 = _____ n = _____

Average of the results: $\bar{n}$ = _____

Continue rotating the prism until you reach the critical angle at which the transmitted light beam is propagating in parallel to the prism surface (angle of refraction $\theta_2 = 90\,°$). Measure the critical angle of incidence $\theta_{1,crit}$. Using this value, re-calculate the index of refraction by means of the Equation 1.3 and compare the result to the previous results.

$\theta_{1,crit}$ = _____ n = _____

c) Determination of the Brewster angle

The polarization (Brewster) angle of incidence will be determined by observing the reflected beam of a transverse-magnetic (TM) polarized light. TM polarized light will be achieved by means of a linear polarizer. The principle of the measurement is shown in Figure 1.4.

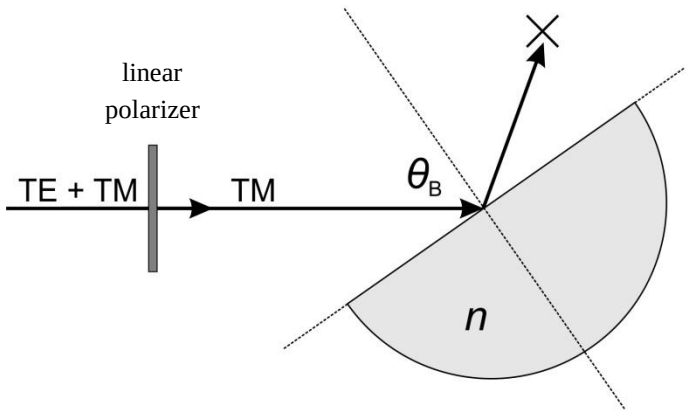

Figure 1.4: Determination of the Brewster angle.

Put the linear polarizer in front of the laser. The polarizer is rotated so that it only transmits the TM polarized light. Set up the semi-circular prism so that the light beam shines upon the flat surface, as shown in Figure 1.4. Then, rotate the prism for an angle θ and observe the reflected light beam. Find the angle of incidence at which you cannot see the reflected light – this is the Brewster angle of incidence θ_B.

Finally, calculate the Brewster angle by means of the Equation 1.5, using the average value of the index of refraction as determined under b. Compare the results

i) Measurement: $\theta_{B,\ measurement}$ = _____

ii) Calculation: $\theta_{B,\ calculation}$ = _____

Leave the prism rotated so that the angle of incidence matches the Brewster angle. Now, remove the liner polarizer so that the reflected light beam will become visible. Measure the angle between the *reflected* light beam and the *refracted* light beam.

$\Delta\theta$ = _____

Homework:

Assume light that shines from air (n_1 = 1) on top of the measured prism (n_2 as determined). For the three different angles of incidence θ_1 listed below, calculate:

- the angle of refraction θ_2
- the reflectance R_{TE} and transmittance T_{TE} for TE polarized light (using Equations 1.4)
- the reflectance R_{TM} and transmittance T_{TM} for TM polarized light (using Equations 1.4)

<u>Results:</u>

i) $\theta_1 = 0\,°$ θ_2 = _____ R_{TE} = _____ T_{TE} = _____

R_{TM} = _____ T_{TM} = _____

ii) $\theta_1 = 30\,°$ θ_2 = _____ R_{TE} = _____ T_{TE} = _____

R_{TM} = _____ T_{TM} = _____

iii) $\theta_1 = \theta_{B,\,calc.}$ θ_2 = _____ R_{TE} = _____ T_{TE} = _____

R_{TM} = _____ T_{TM} = _____