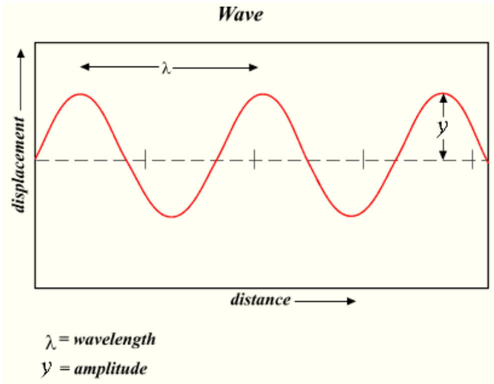
OPTICS 2
PHYSICAL OPTICS, WAVE OPTICS

1. Light as a wave

Light is an electromagnetic wave composed of oscillating electric and magnetic fields. These fields continually generate each other, as the wave propagates through space and oscillates in time.

The **frequency** of a light wave is determined by the period of the oscillations. The frequency does not normally change as the wave travels through different materials ("media"), but the speed of the wave depends on the medium.



The speed, frequency, and wavelength of a wave are related by the formula

$v = \lambda f$,

where

v is the speed,
λ is the **wavelength**, and
f is the frequency.

Because the frequency is fixed, a change in the wave's speed produces a change in its wavelength.

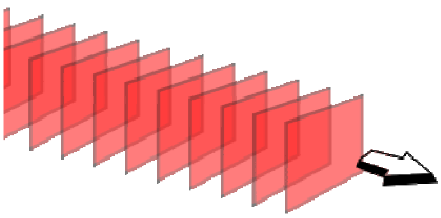
The **speed of light** in a medium is typically characterized by the **index of refraction, *n***, which is the ratio of the speed of light in vacuum, c, to the speed in the medium:

$n = c / v$.

The **speed of light in vacuum** is a constant, which is $c = 2.998 \cdot 10^8$ m/s.
(exactly $c = 299792458$ m/s)

Thus, a light ray with a wavelength of λ in a vacuum will have a wavelength of λ/n in a material with index of refraction n.

The **amplitude** of the light wave is related to the intensity of the light, which is related to the energy stored in the wave's electric and magnetic fields.

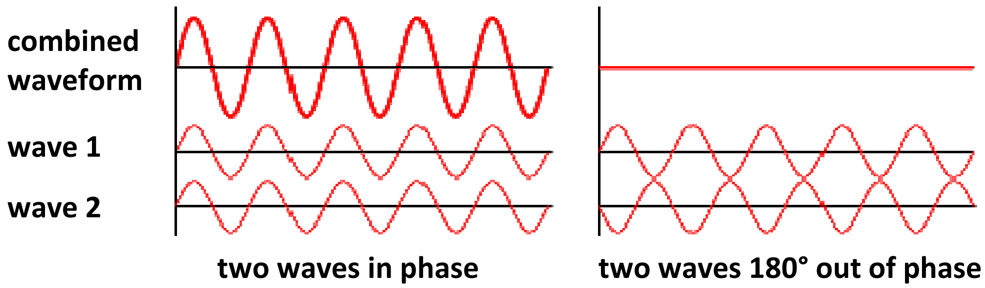


As a light wave travels through space, it oscillates in amplitude.
In this image, each maximum amplitude crest is marked with a plane to illustrate the wavefront.
The ray –used in geometrical optics– is the arrow perpendicular to these parallel surfaces.

Physical optics or wave optics builds on **Huygens's principle**, which states that every point on an advancing wavefront is the center of a new disturbance. When combined with the *superposition principle*, this explains how optical phenomena are manifested when there are multiple sources, or obstructions that are spaced at distances similar to the wavelength of the light.

Superposition and interference

The superposition principle can be used to predict the shape of interacting waveforms through the simple addition of the disturbances. This interaction of waves to produce a resulting pattern is generally termed "interference" and can result in a variety of outcomes.
If two waves of the *same wavelength and frequency* meet with a certain different phase shift the resulting wave will have the same wavelength and frequency but *the amplitude depends on the phase shift* between the two waves.
If the two waves are *in phase*, both the wave crests and wave troughs align. This results in *constructive interference* and an increase in the amplitude of the wave, which for light is associated with a brightening of the waveform in that location.
Alternatively, if the two waves of the same wavelength and frequency are *out of phase*, then the wave crests will align with wave troughs and vice-versa. This results in *destructive interference* and a decrease in the amplitude of the wave, which for light is associated with a dimming of the waveform at that location.



Since Huygens's principle states that every point of a wavefront is associated with the production of a new disturbance, it is possible for a wavefront to interfere with itself constructively or destructively at different locations producing bright and dark fringes in regular and predictable patterns.

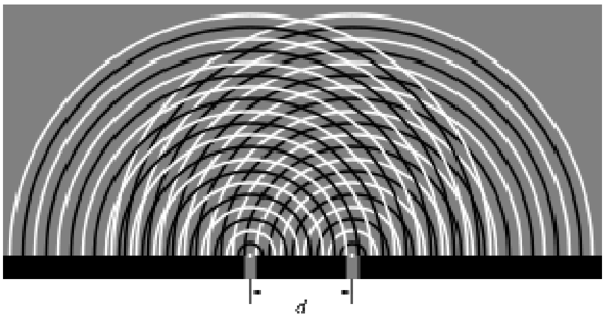
When oil or fuel is spilled,
colorful patterns are formed by thin-film interference.

Interferometry is the science of measuring these patterns, usually as a means of making precise determinations of distances or angular resolutions.

The *Michelson interferometer* was a famous instrument which used interference effects to accurately measure the speed of light.

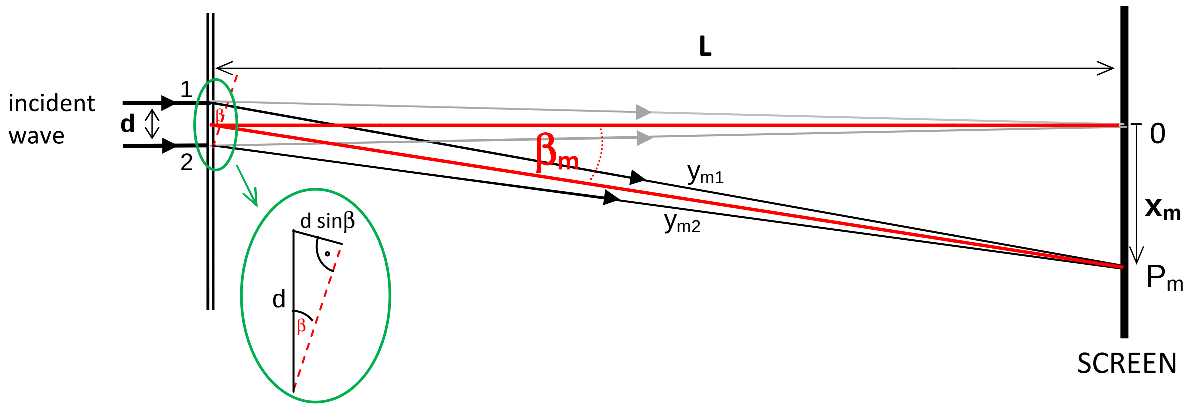
Diffraction

Diffraction is the process by which light interference is most commonly observed.



Diffraction on two slits separated by distance d.
The bright fringes occur along lines where black lines intersect with black lines and white lines intersect with white lines.
These fringes are separated by angle β and are numbered as order n.

The simplest physical models of diffraction use equations that describe the angular separation of light and dark fringes due to light of a particular wavelength (λ).



Light fringes appear when $m\,\lambda = d\,\sin\beta_m$

where d is the separation between two wavefront sources (e.g. two slits),

β_m is the angular separation between the central fringe and the mth order fringe (at the central maximum $m = 0$)

(The explanation for the above formula is that the phase of a wave at a given point P of the screen depends on the distance y between this point and the slit it travelled from. In case of a **coherent** light the incident wave at the two splits is in phase but at the screen there will be a phase difference $\Delta\varphi$ between the two waves arriving from the two splits owing to the path difference $\Delta y = y_1 - y_2$.

The relation between the path difference and the phase difference includes the wavelength λ:

$\Delta y = \lambda \cdot \Delta\varphi / 2\pi$.

As it can be seen from the figure: $\Delta y = d\,\sin\beta_m$.

Light fringes appear at constructive interference where the phase difference is $\Delta\varphi = m \cdot 2\pi$, so these are those points of the screen where $m\,\lambda = d\,\sin\beta_m$ holds.)

2. Polarization

Polarization is a general property of waves that describes the orientation of their oscillations. For transverse waves such as many electromagnetic waves, it describes the orientation of the oscillations in the plane perpendicular to the wave's direction of travel. The oscillations may be oriented in a single direction (linear polarization), or the oscillation direction may rotate as the wave travels (circular or elliptical polarization). Elliptically polarized waves can rotate rightward or leftward in the direction of travel (chirality).

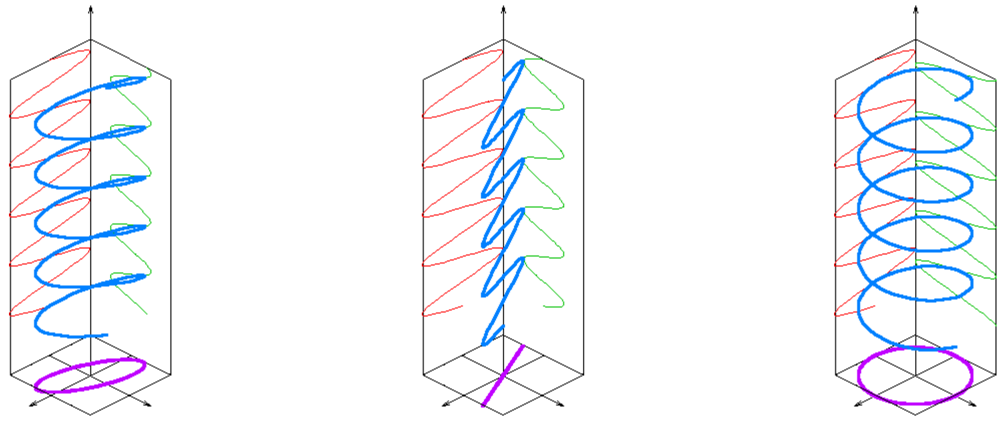


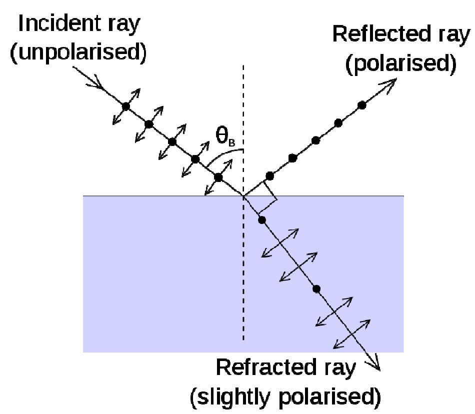
Figure: Evolution of the electric field vector (blue), with time (the vertical axes), at a particular point in space, along with its *x* (red/left) and *y* (green/right) components, and the path traced by the electric field vector in the *x* – *y* plane (purple).

There are media that have different indexes of refraction for different polarization modes; these are called *birefringent*. Media that reduce the amplitude of certain polarization modes are called *dichroic*. Devices that block nearly all of the radiation in one mode are known as *polarizing filters* or simply *polarizers*. By means of polarizers the natural elliptically polarized light can be transformed to linearly polarized light.

Brewster's angle[1]

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 Θ_B, the light that is reflected from the surface is therefore perfectly polarized.
At this angle the reflected and the refracted rays are perpendicular, so it is easy to show that

$$\mathrm{tg}\ \Theta_B = n \quad (n \text{ is the refractive index})$$

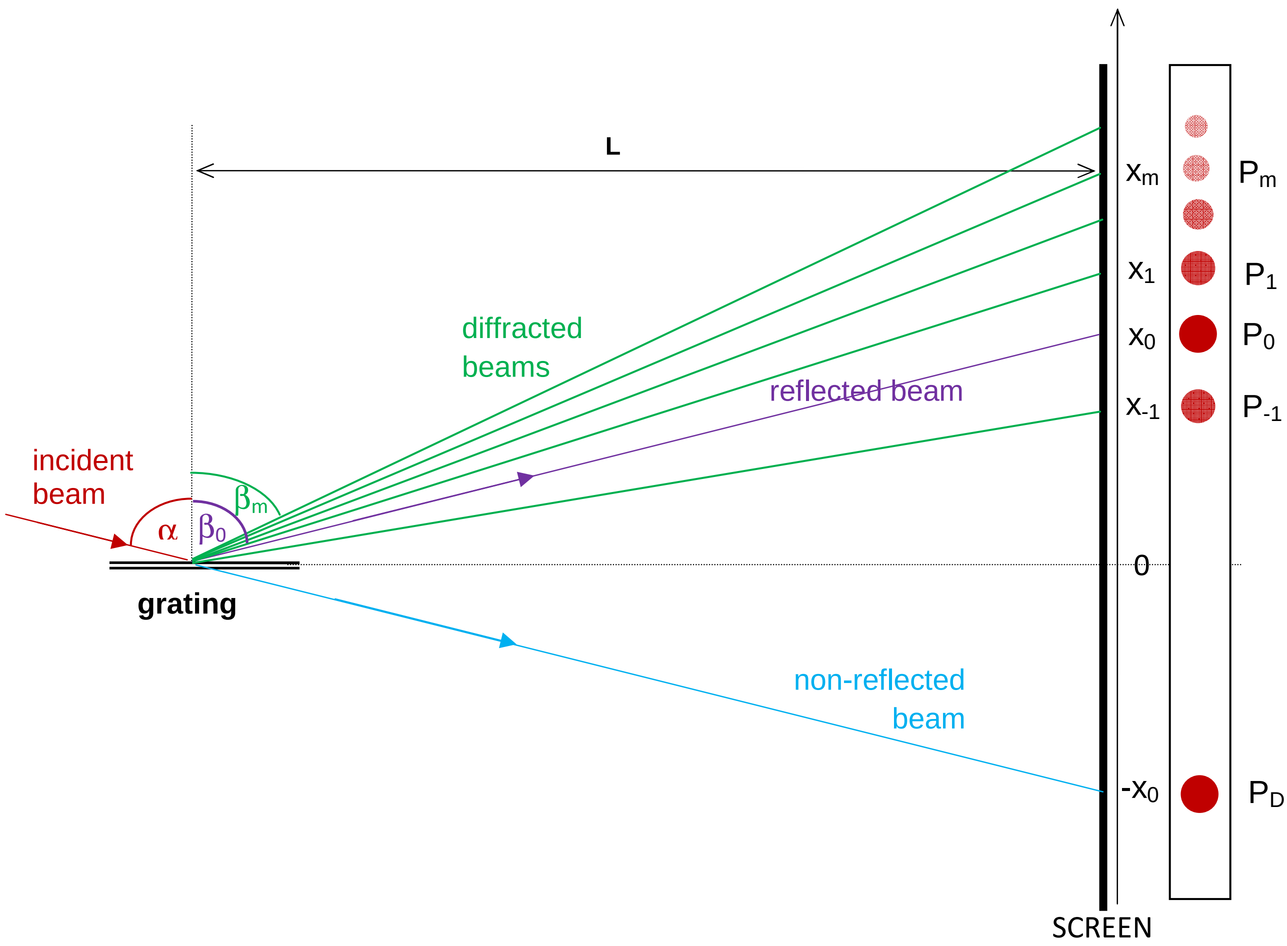


Optical rotation is the turning of the plane of linearly polarized light about the direction of motion as the light travels through certain materials. It occurs in solutions of chiral molecules such as sucrose (sugar), solids with rotated crystal planes such as quartz, and spin-polarized gases of atoms or molecules.

[1] https://en.wikipedia.org/wiki/Brewster's_angle

MEASUREMENTS

1. Measuring the wavelength of a laser diode using a metal ruler as a reflective diffraction grating



The pattern of the metal ruler splits (diffracts) the single laser beam into several beams travelling in different directions. If the path difference between the light from adjacent slits is equal to an integer multiple *m* of the wavelength, there is constructive interference. This condition for the grating is the so-called grating equation:

$$d\,(\sin\alpha - \sin\beta_m) = m \cdot \lambda$$

These directions (β_m) depend on the spacing of the grating (d), the incident angle (α) of the beam and the wavelength (λ) of the laser. The light that corresponds to the specular reflection is called the zero order (m = 0), so $\beta_0 = \alpha$.

From the above equation we get that $\sin\beta_m$ is a linear function of m :

$$\sin\beta_m = \sin\alpha - \frac{\lambda}{d} \cdot m$$

Plotting $\sin\beta_m$ vs. m gives a straight line with a slope of $-\lambda / d$.

Procedure

Tools: optical bench; laser; rotating disc; meal ruler; screen; mm paper.
The sketch of the experimental setup is shown in the figure above.
Adjust the metal ruler so that you see a clear diffraction image on the screen.
Measure *L*, the distance between the screen and the laser spot on the metal ruler.
Mark the spots of the diffracted laser beams on the mm paper on the screen.
Remove the ruler and mark the non-reflected beam also.

Evaluation

Find $x = 0$ as the midpoint between the non-reflected beam and the brightest diffracted beam (the reflected beam).
Read the values of the x_m distances according to the figure.
Calculate the values $\sin\beta_m$ from x_m and L for at least 6 decimals using the formula

$$\sin\beta_m = \frac{L}{\sqrt{L^2 + x_m{}^2}}$$

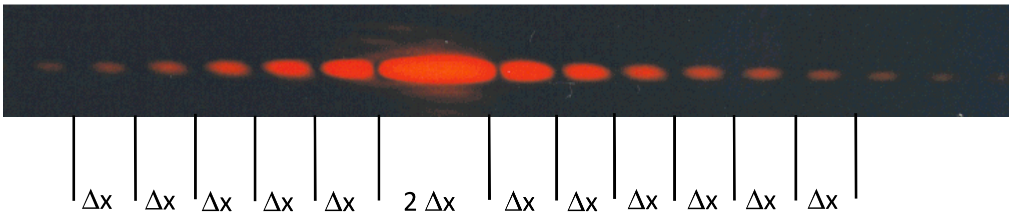
Plot $\sin\beta_m$ as a function of m.
Calculate the slope using the least squares method.
Calculate λ from the slope knowing that $d = 0.5$ mm.

2. Measuring the width of a hair by diffraction

As the width of a hair is commensurable with the wavelength of light the rays starting from the two "sides" of the hair interfere and a diffraction picture is obtained. Dark spots appear on the screen where the distance between two dark spots Δx depends on the width of the hair D:

$$\Delta x = \lambda \cdot L / D$$

where λ is the wavelength of the laser and
L is the distance between the hair and the screen.



Procedure

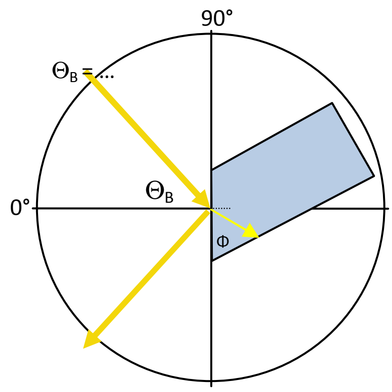
Tools: optical bench; laser; hair fiber in a slide + holder; screen.
Read the distance between the dark spots Δx,
and measure L, the distance between the hair and the screen.

Evaluation

Calculate the width of the hair (D) and compare it with the value determined with the lens.

3. Determining the refractive index of an unknown material by measuring Brewster's angle

Procedure



Tools: optical bench; halogen lamp; gaps; polarizer; rotating disc; prism; unknown material.
The experimental setup is similar to the one we used to measure the refractive index of the prism but a polarizer is also placed in front of the prism.
Calculate the Brewster's angle of the prism, and rotate the disc in that position.
Set the polarizer so that the intensity of the reflected ray should be minimal.
Remove the prism and place the unknown material on the rotating disc.
By rotating the disc find the angle where the reflected ray's intensity is minimal. Read this angle.

Evaluation
Calculate the refractive index of the unknown material.
What can it be?

4. Michelson interferometer

Demonstration.