IO2

Modul Optics

Refraction and Reflection

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1.1 Preliminary Questions

- What do we mean by the term reflection?
- What is the relationship between the angle of incidence and the angle of reflection?
- What is Snell's law?
- What do we mean by refraction/refraction?
- What does Fermat's principle state?
- What is geometrical optics and when is it valid?
- Are refraction and reflection phenomena that suggest a wave nature of light, i.e. is it helpful for these effects to think of light as a wave?
- What is meant by optically denser - or optically thinner media? How do the two terms differ from each other?
- What is total internal reflection and when does it occur?
- What is a virtual image, what is a real image?
- What is dispersion?
- What is the relationship between frequency and wavelength of light?
- What do we mean by phase or group velocity?
- Construct the optical path for a) a converging lens, b) a diverging lens, and c) a prism

1.2 Theory

1.2.1 Reflection and Refraction

In optics, reflection is the phenomenon of a change in the direction of propagation of electromagnetic radiation when it impinges on an interface between two media with different optical densities. Refraction is understood to be the effect in which electromagnetic radiation changes its direction of propagation or is deflected when it passes between media of different optical densities. A medium is said to be optically denser if electromagnetic radiation in it has a smaller propagation speed than in the reference medium (e.g. air or vacuum). This fact will be discussed in more detail in the next section. It is described by the so-called REFRACTION INDEX n. For vacuum, the refractive index is by definition exactly 1, for air $n = 1.0003$. For optically denser media, the refractive index is greater than one, e.g. for water $n = 1.33$, whereas the various types of glass usually have refractive indices between 1.5 and 2.

If the surface structures of the medium under consideration are small compared to the wavelength, the LAW OF REFLECTION applies. The reflected portion is reflected at an angle β to the perpendicular (cf. Fig. 1.1), which is equal to the angle α between the incident radiation and the perpendicular - angle of incidence is equal to angle of reflection.
However, part of the incident radiation passes the interface between the two media, but also undergoes a change in its direction of propagation. This is referred to as refraction. When passing into an optically denser medium, the light is always refracted toward the perpendicular.

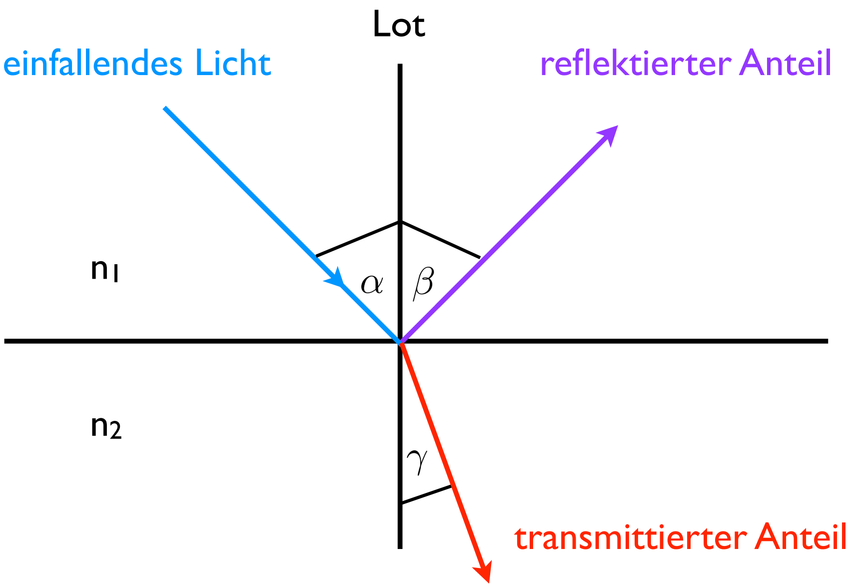

Figure 1.1: Here is a schematic representation of how incident light is reflected at the interface between two media of different optical densities. Furthermore, it can be seen from the sketch that there is also a transmitted contribution. However, this contribution also undergoes a change in the direction of propagation - it is refracted.

If the light would not be refracted, energy and momentum would not be preserved. Mathematically, this phenomenon can be described by the so-called SNELL'S LAW:

$$\frac{sin\ \alpha}{sin\ \gamma} = \frac{n_2}{n_1} = \frac{v_1}{v_2} \tag{1.1}$$

Here v denotes the phase velocity of the electromagnetic radiation in the respective medium, which will be discussed in more detail in the next section. From the equation above, one can derive an interesting special case in a very simple way. Obviously, it applies:

$$sin\ \alpha = sin\ \gamma \cdot \frac{n_2}{n_1} \tag{1.2}$$

Since the sine cannot be greater than one, this condition cannot be fulfilled for all angles. In this limiting case then applies:

$$\alpha_g = arcsin\ (sin\ \gamma \cdot \frac{n_2}{n_1}) \Rightarrow \gamma = arcsin\left(\frac{n_1}{n_2}\right)\ \text{bzw.}\ arcsin\ (1) \tag{1.3}$$

It can be seen that electromagnetic radiation in this limiting case can no longer penetrate the optical thinner medium - it is completely reflected, hence we speak of TOTAL REFLECTION.

1.2.2 Phase and Group Velocity

In the previous section, it was already mentioned that electromagnetic radiation propagates at different speeds in media of different optical densities. Ultimately, this is caused by the electrical and magnetic properties of the corresponding material, i.e. the permeability μ and the permittivity ε. In electrodynamics, the following relationship can be shown:

$$c_{Medium}^2 = \frac{1}{\varepsilon_0 \mu_0 \varepsilon \mu} \Rightarrow c_{Medium} = \frac{c_{Vakuum}}{\sqrt{\varepsilon\mu}} = \frac{c_{Vakuum}}{n} \tag{1.4}$$

It is important to note that in the case of transverse waves, i.e. waves in which the oscillation takes place perpendicular to the direction of propagation, two different velocities must be distinguished. If one considers a certain point of a wave or a certain phase of the wave, this point/these phases moves/move with the so-called PHASE SPEED v_{ph}. For the phase velocity, it applies in general:

$$v_{ph} = \lambda \cdot f = \frac{\omega}{k}, \tag{1.5}$$

where in this equation λ represents the wavelength and f the frequency of the considered waves. Alternatively, this relationship can be expressed by the angular frequency ω and the magnitude of the wave vector k. Further, we now consider a wave packet as shown in Figure 1.2 below. This wave packet propagates with the so-called GROUP SPEED, which is generally different from the phase velocity. It holds:

$$v_g = \frac{\partial \omega}{\partial k}. \tag{1.6}$$

Substituting equation 1.5 into equation 1.6, we obtain the general relationship between group velocity and phase velocity:

$$v_g = \frac{\partial \omega}{\partial k} = \frac{\partial (v_{ph} \cdot k)}{\partial k} = v_{ph} + k \cdot \frac{\partial v_{ph}}{\partial k} \tag{1.7}$$

If the phase velocity is not a function of the wave vector, the second term disappears and phase and group velocity are identical. Optical media in which this is the case are called NON-DISPERSIVE. For electromagnetic radiation, this is the case only in vacuum. Group velocity and phase velocity are both equal to the vacuum speed of light for electromagnetic radiation in vacuum. In other optical media, such as glass which is used in this experiment, this is not the case. Here, the phase velocity is a function of the wave vector. This phenomenon is called DISPERSION[1]. It can be observed experimentally very easily by letting light shine through a prism. White light, which is known to be composed of different wavelengths, is split into its different wavelengths - a spectrum is seen. In the case of refraction, one can show that only the phase velocity changes when passing into another medium, but not the group velocity. Furthermore, using equation 1.5, one can show that the wavelength changes during the transition into the medium, but not the frequency.

It should be mentioned here that the phase velocity of electromagnetic radiation can also be greater than the speed of light in vacuum. This is because the phase velocity cannot be used for the transfer of energy or information. The group velocity on the other hand can never be greater than the speed of light in vacuum.

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[1] In physics it is common to speak of dispersion, if a quantity depends on the frequency resp. the wave vector k

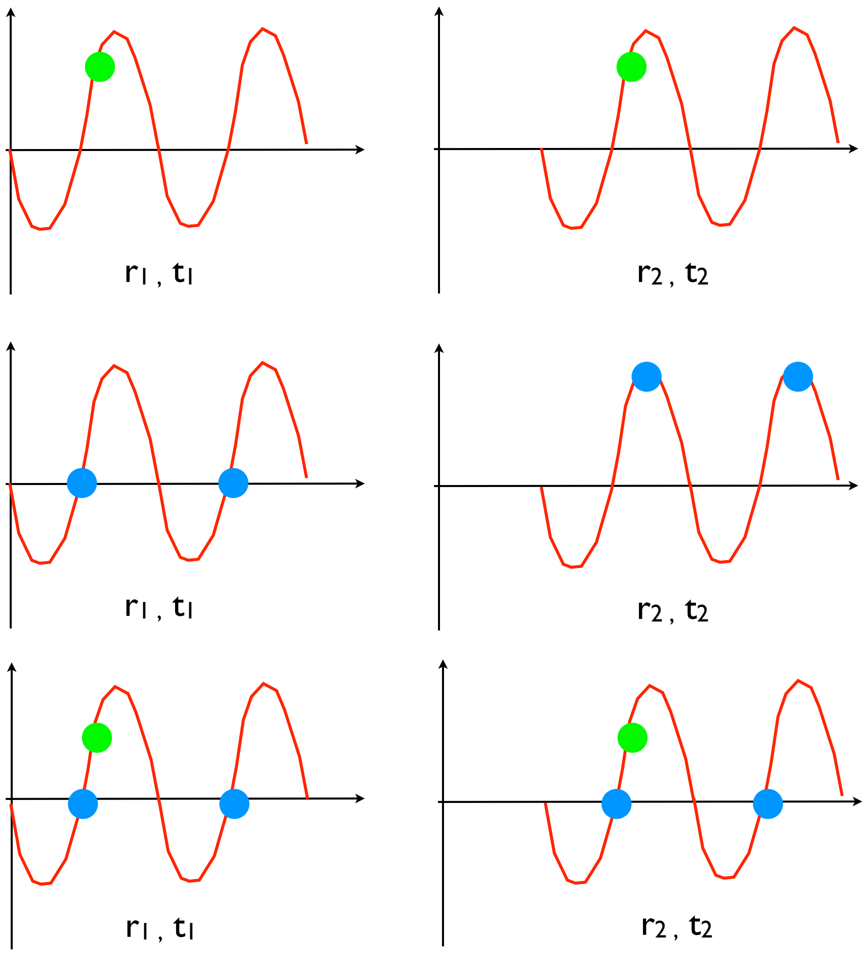

Figure 1.2: The upper row shows a wave train at two different times and places. The phase under consideration is marked with a green dot. This point is at time t_1 at point r_1 and now moves with the phase velocity, e.g. it is at time t_2 at point r_2. The second line shows a wave train, where a section is marked with the help of two blue points. This section moves with the group velocity from r_1 to r_2. Since in this example the group velocity is not equal to the phase velocity, the two blue points have different phases at time t_1 and at time t_2. In the last line, phase velocity and group velocity are identical.

1.3 Experiment

The setup of our experiment basically consists of a halogen lamp, which serves as the light source, and an observation screen with an angular scale, on which various glasses and mirrors can be attached. A lens is used to focus the light from the halogen lamp onto the corresponding glass or mirror. Incoming and outgoing light can now be observed and angles can be measured. The entire apparatus is mounted on an optical rail.

1.3.1 Equipment

1.3.2 Experimental Procedure

- Mount the halogen lamp, the observation screen including angular scale and the lens on the optical bench.

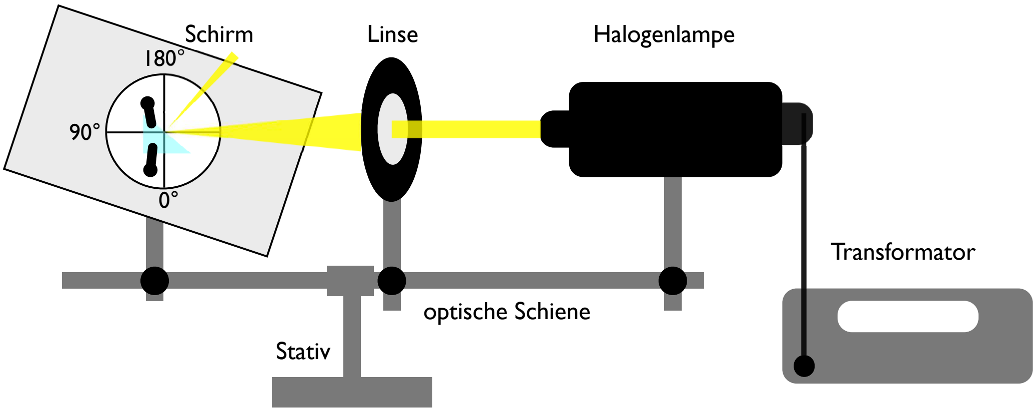

Figure 1.3: Schematic representation of the experimental setup. A halogen lamp, a lens and an observation screen with a angular scale are mounted on an optical rail. If the light of the lamp is focused with the help of the lens on the observation object, which can be fixed in the center of the screen, it is possible to observe the resulting beam path clearly. With the help of the scale of the screen it is now possible to measure the angles.

- Rotate the observation screen horizontally so that the 0° mark is parallel to the optical rail. Use the lens to focus the light of the lamp on the center of the observation screen, which is marked with a cross. Make sure that the incident light beam runs as far as possible along the 0° scale, as otherwise large systematic measurement errors can occur. If necessary, the height of the screen or the lens can be varied. There are two clamps on the screen, which are used to attach the lenses/mirrors to the screen. Estimate how accurately you have adjusted to zero, i.e.: How accurately can you measure the angle?
- Now, insert the flat mirror into the apparatus. Measure the emergent angle of the light for 20 different angles of incidence. The observation screen can be rotated for this purpose.
- Then, insert the concave mirror. Sketch the resulting beam path. Can you see a focal point? Does the observed image depend on the angle at which the light hits the mirror? Does the image depend on where the light hits the mirror, e.g. rather in the center or outside at the edge?
- Insert the image erecting prism (isosceles triangle). Find all configurations for which total internal reflection can be observed and sketch the ray path.
- Insert the second prism and sketch again the ray path for three different positions. When can dispersion be observed? Sketch the resulting spectrum. Which color of the spectrum is more strongly refracted, red or blue?
- Now, use the semicircular glass. Insert it into the apparatus with the flat side facing the lamp. For 20 different angles of incidence, measure the angle at which the light is refracted. It is advisable to use a ruler for this purpose.

Component	Number
Halogen lamp	1
Power supply	1
Lense	1
Screen with angular scale	1
Optical rail	1
Sleeves	3
Stand	1
Glass, mirrors and color aperture	9

- Finally, the round glass can be used - what do you observe?

1.4 Evaluation

- Calculate the quotient of the angle of incidence and angle of reflection for the experiment with the straight mirror. Then, calculate the mean value and the standard deviation from all the values obtained in this way. Can you confirm the law of reflection? How can any deviations be explained? Plot your results in a graph (measured values with error bars, error bars according to the estimated uncertainty, calculated mean uncertainty, add the calculated mean value as a straight line).
- For the experiment with the semicircular glass, Snell's law can be used to calculate the refractive index of the glass. Determine this refractive index, i.e. calculate n for all your measured values, determine the mean and standard deviation of your results and plot them in a graph.
- All ray paths and observations listed in subsection 1.3.2 are also to be subject of the protocol to be prepared - please ensure completeness.

Literature

- Demtröder Band 2 - *Elektrizität und Optik*, 6. Auflage: Abschnitt 8.4.2 - 8.4.6 und 9.2 - 9.5
- Demtröder Band 1 - Mechanik und Wärme, 6. Auflage: Abschnitt 11.9.7