

IU3

Modul Universal constants

Speed of Light

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Versuch IU3 - Speed of Light

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1.1 Preliminary Questions

- Explain the concept of transversal and longitudinal waves. Relate these two notions to light waves, sound waves and water waves.
- Calculate the time it takes for a light wave to travel over a 2 m long distance. Explain why a 20 MHz bandwidth oscilloscope cannot measure this time delay. How can this problem be solved ?
- What happens when crosses the surface between two media of different atomic densities (hence, two different refractive indexes).
- How do wavelength and frequency change when entering another optical medium?
- Which colour of light is bent stronger when refracted into a denser medium?

1.2 Theory

1.2.1 Basics

The velocity of light c_n in a medium depends on the refractive index n of that medium. The refractive index depends on the effective dielectric permittivity (ϵ_r) and magnetic permeability (μ_r) which can vary between different materials. As a consequence, it can be directly expressed as

$$c_n = \frac{c_0}{n} \quad (1.1)$$

where $c_0 = 2.998 \cdot 10^8 \text{m/s}$ is the propagation velocity of light in vacuum. Different velocities of light correspond to different propagation times along a given path length d . The propagation time (see Fig. 1.1) of light in a medium is

$$t_n = \frac{d}{c_n} \quad (1.2)$$

whereas in vacuum the propagation time is

$$t_0 = \frac{d}{c_0} \quad (1.3)$$

With the definition of a time delay

$$\Delta t = t_n - t_0 \quad (1.4)$$

and equations (1.2) and (1.3), the velocity of light in the medium is determined by the equation

$$c_n = \frac{c_0}{1 + \frac{\Delta t}{d}c_0} \quad (1.5)$$

By comparison with (1.1)

$$n = 1 + \frac{\Delta t}{d}c_0 \quad (1.6)$$

is obtained.

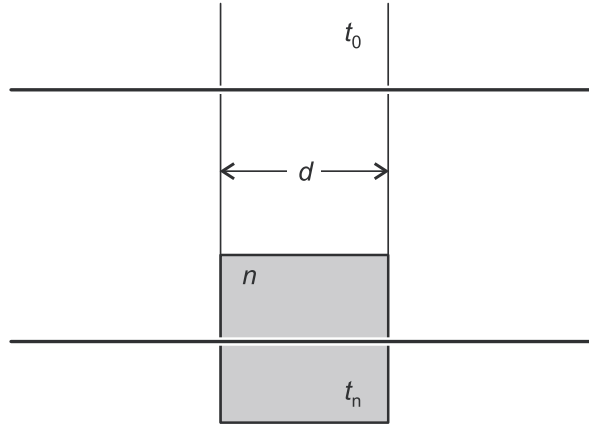


Figure 1.1: In a medium with refractive index n , light propagates slower than in a vacuum. This results in different transition times for a distance d .

1.2.2 Experimental measurement

In this experiment, the propagation time of light is measured by modulating the intensity of a light beam. The modulation frequency is

$$\Delta\phi = 2\pi\nu\Delta t = 2\pi\frac{\Delta t}{T}, \quad (1.7)$$

where T is its the period. The phase shift is measured with a receiver, which converts the light signal into an alternating voltage with the time behaviour

$$U = a \cdot \cos(2\pi\nu t - \Delta\phi). \quad (1.8)$$

A reference signal which oscillates synchronously with the intensity of the light transmitter is synchronized with the receiver signal by means of an electronic phase shifter. This serves as a time reference when the transmitter and receiver are separated by a fixed distance s . When a medium is inserted on the ray path, covering the partial path length d , this causes a change Δt in the propagation time of the light signal. This change can be measured as a phase shift $\Delta\phi$ between the reference and the receiver signal.

As a basic oscilloscope is used for determining the phase shift, the two signals is mixed (multiplied) electronically with a signal of the frequency $\nu' = 59.9\text{MHz}$, and the high frequency part of the mixed signal is suppressed. The receiver signal then has the form

$$U_1 = \frac{1}{2}a \cdot \cos(2\pi\nu_1 t - \Delta\phi) \quad (1.9)$$

with $\nu_1 = \nu - \nu'$. This signal can now be displayed (see Fig. 1.2) with a basic oscilloscope since the frequency ν_1 is 100 kHz which lies below the oscilloscope bandwidth. The phase shift $\Delta\phi$ is not changed by the mixing, but it corresponds to an *apparent change* Δt_1 of the lower frequency signal which has a period T_1 . From

$$\Delta\phi = 2\pi\frac{\Delta t_1}{T_1} \quad (1.10)$$

one gets

$$\Delta t = \Delta t_1 \frac{T}{T_1} = \frac{\Delta t_1}{T_1\nu}. \quad (1.11)$$

Combined with Eq. (1.5) and Eq. (1.6), one can finally express the velocity of light in the medium

$$c_n = \frac{c_0}{1 + \frac{c_0}{d\nu} \frac{\Delta t_1}{T_1}} \quad (1.12)$$

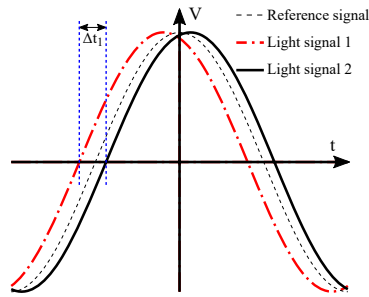


Figure 1.2: Principle of the delay measurement: a reference signal (dotted line) provides the time reference of the modulated light intensity. The detected light signals correspond to the two signals 1, dotted dashed, (resp. 2, full line) observed without (resp. with) a medium inserted on the light path. The apparent time delay Δt_1 induced by the medium corresponds to the delay between the zero crossings of the two signals.

and the refractive index

$$n = 1 + \frac{c_0}{dv} \frac{\Delta t_1}{T_1} \quad (1.13)$$

1.3 Experiment

1.3.1 Accessories

Component	Quantity
light transmitter and receiver	1
Lens $f = +150$ mm	1
Coaxial cable	2
saddle bases	3
Two channel oscilloscope	1
metal scale, 1 m	1
tube with 2 end windows	1
Acrylic glass block	1
prism table	1

1.3.2 Experimental Set-up and Adjustments

The experimental set-up is illustrated in Figs. 1.3 and 1.4.

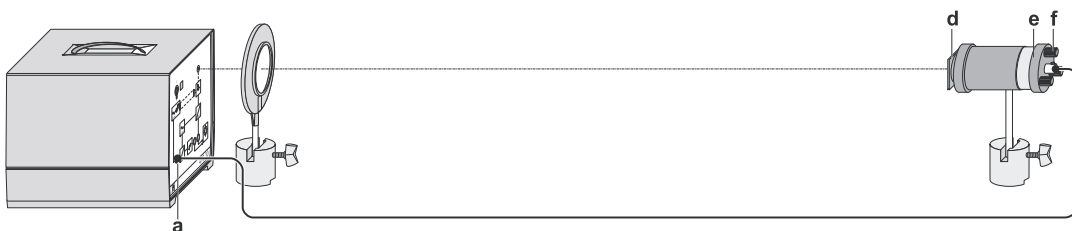


Figure 1.3: Set-up for the measurement of the propagation velocity of light in air.

- Set the light transmitter up at a distance of approx. 1.5 m from the receiver, connect it to the output (a) of the receiver, and switch the receiver on.

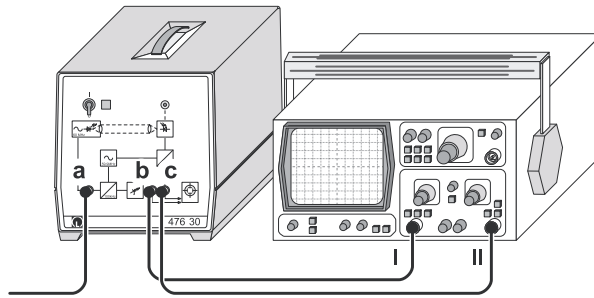


Figure 1.4: Connection of the oscilloscope for measuring the phase of the periodic light signal.

- Observe the red light patch of the light transmitter on the front plate of the receiver and displace the insert (e) relative to the condenser (d) so that the red light patch maintains approximately the same size for different distance between the transmitter and the receiver (collimation of the source).
- Place the lens on the ray path and centre it with respect to the light beam.
- Align the light transmitter and the lens so that the red light patch focuses on the entrance aperture of the receiver. If necessary, optimize the alignment of the light transmitter with the knurled screws (f).
- Connect the output (c) of the receiver to channel II of the oscilloscope. (Coupling channel II: AC, Trigger: channel II).
- Observe the receiver signal on the oscilloscope and optimize the alignment of the light transmitter and the lens so that the amplitude of the detected signal is maximal.

Velocity of Light in Air

- Set-up as seen in Fig. 1.3.

Velocity of Light in Acrylic Glass

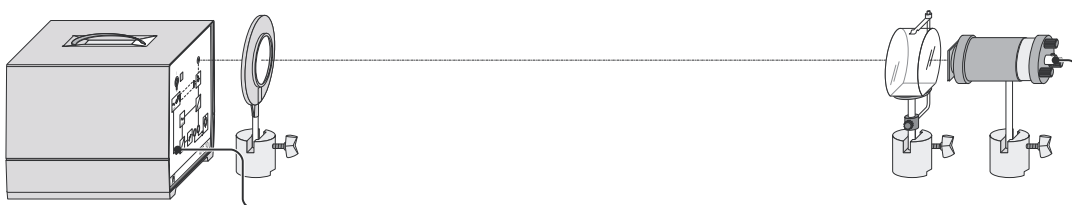


Figure 1.5: Set-up for the measurement of the velocity of light in acrylic glass.

- Mount the prism table in a saddle base, and clamp the acrylic glass block on the prism table with the metal holder. (see Fig. 1.5).

Velocity of Light in Water

- Place the tube between the transmitter and the lens (see Fig. 1.6). Ensure that the tube is horizontal and fill it carefully with water.

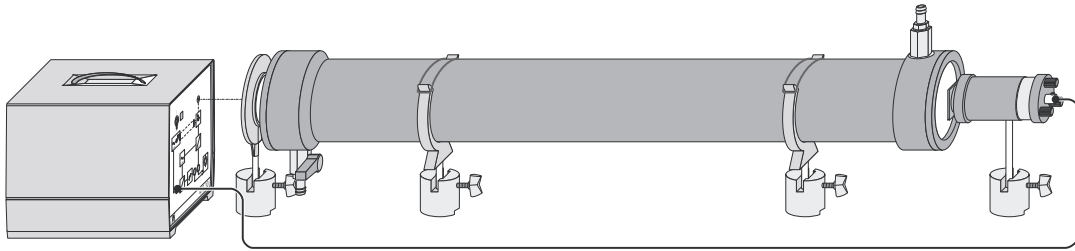


Figure 1.6: Set-up for the measurement of the velocity of light in water.

1.3.3 Measurements

A satisfactory accuracy of the result can only be obtained with thermal stability of the light transmitter and the receiver. Start the measurement only after the light transmitter and the receiver have been switched on for 15 minutes.

Synchronizing the Phases of the Reference and the Receiver Signal

- Connect the output (b) of the receiver to channel *I* of the oscilloscope and look at channel *I* (reference signal) and channel *II* (receiver signal) simultaneously. (Oscilloscope settings: Coupling channel *I* and *II*: AC, trigger: channel *I*).
- Adjust the vertical positions of channels *I* and *II* so that they are as symmetric as possible with respect to the horizontal centre line of the screen.
- For the sake of control adjust the vertical deflections with the fine adjustment control so that the maxima of both signals touch the same horizontal line.
- Adjust the two signals with the phase shifter ϕ so that they are in phase.
- Choose a suitable horizontal scale of the signals, and measure the period T_1 .

Velocity of Light in Air

- Observe a change in phase of the incoming wave at the oscilloscope, when modifying the distance between transmitter and receiver. The phase of the incoming wave should only change in one direction. If not, repeat the alignment procedure and take particular care that the light beam remains horizontal and centred with respect to the lens over the whole course of the transmitter.
- Measure the time delay between the reference signal and the light signal for different distances. Estimate the statistical uncertainty and systematic uncertainty for each measurement. You can begin your measurement with the greatest distance possible between transmitter and receiver. Work your way closer to the receiver in steps of 5 cm. This way, you should be able to do 15 measurements.

Velocity of Light in Acrylic Glass

- Choose arbitrary distance between transmitter and receiver. Match both signals at the zero crossing. Use a suitable time-scale.
- Mount the acrylic glass block directly in front of the transmitter (see Fig. 1.5)

- Measure the delay between the zero crossings and the *apparent change* Δt_1 (note: the delay in the time axis is tiny!).
- Repeat these measurements for 10 arbitrary distances and note their mean value of Δt_1 . Discuss why those values are all close to each other and why the absolute distance does not matter.

Velocity of Light in Water

- Put the tube into the ray path immediately in front of the light transmitter. Match both signal at the zero crossing. Use a suitable time-scale.
- Fill the tube with water.
- Measure the delay between the zero crossings and the *apparent change* Δt_1 .
- Repeat these measurements five times and compute the mean value of Δt_1 .

1.3.4 Tasks for Evaluation

- Convert all measurements of the apparent time changes in to real time changes. First, determine the conversion factor with the period to the modulation frequency (1.11).

Air

- Plot the measured propagation distances s as a function of the calculated real time delays. Make a linear fit through all your data points, including statistical error weights. What does the slope of the fit correspond to?
- Compare the measured value of speed of light in the air to the literature value (refractive index under typical condition of 1.003 ± 0.001). Precisely evaluate the different sources of error in your measurement.
- Calculate the refractive index of air.
- Calculate a full error estimation of the systematic error. The statistic error can be obtained from your fit program.

Glass and Water

- Calculate the velocity of light from the mean values of the propagation time difference and the refractive index. Use the literature value for the velocity of light in vacuum.
- Repeat the same calculations, this time by using the determined value for the velocity of light in air. What is your observation?
- Calculate a complete error estimation.

1.4 Literature

- D. Meschede, "*Gerthsen Physik*", Springer Verlag