

## Determining the velocity of light in various materials

### Objects of the experiments

- Determining the velocity of light and the refractive index for water.
- Determining the velocity of light and the refractive index for organic liquids.
- Determining the velocity of light and the refractive index for glass.

### Principles

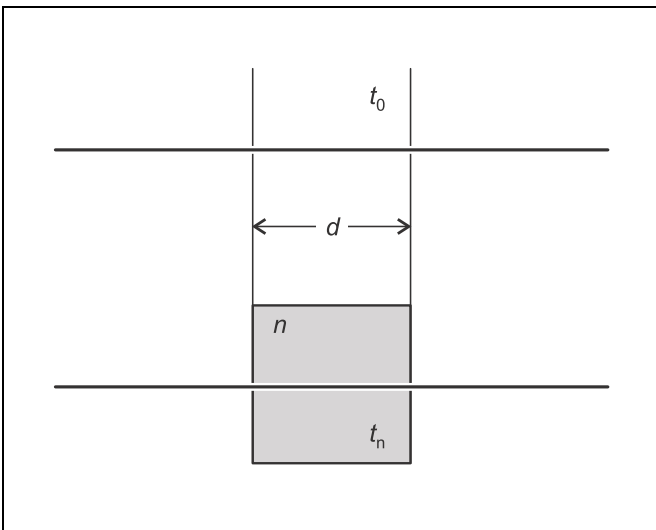


Fig. 1 In a medium with the refractive index  $n$  light propagates at a lower velocity than in vacuum. This leads to a change in the propagation time  $t$  of light along a path of length  $d$ .

The velocity of light  $c_n$  in a medium depends on the refractive index  $n$  of that medium. This material-dependent quantity is a measure for the optical density of the medium, and it relates the velocity of light in the medium to that in vacuum via

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

$$c_0 = 2.998 \cdot 10^8 \frac{m}{s}; \text{ velocity of light in vacuum}$$

Different velocities of light correspond to different propagation times along a certain path length  $d$ . The propagation time of light in a medium is

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

whereas in vacuum the propagation time is

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

(see Fig. 1). With the definition

$$\Delta t = t_n - t_0$$

and (II) and (III), the velocity of light in the medium is determined by the equation

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

By comparison with (I)

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

is obtained. The change of the velocity of light in the medium is measured in the experiment with a periodic light signal with the modulation frequency  $\nu = 60 \text{ MHz}$ . The propagation time difference  $\Delta t$  is observed as a phase shift

$$\Delta\varphi = 2\pi \cdot \nu \cdot \Delta t = 2\pi \cdot \frac{\Delta t}{T} \quad (VI)$$

$T$ : period

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

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

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 shift while the light transmitter and the receiver are at a distance  $s$  from each other in air (refractive index  $n = 1.003$  under standard conditions). If then a medium of sufficient optical density is put into the ray path covering the partial path length  $d$ , this causes a change  $\Delta t$  in the propagation time of the light signal. This change can be measured as a phase shift  $\Delta\varphi$  between the reference and the receiver signal.

Apparatus	
1 light transmitter and receiver . . . . .	476 30
1 lens, f = + 150 mm . . . . .	460 08
2 saddle bases . . . . .	300 11
1 two-channel oscilloscope 1004 . . . . .	575 221
1 metal scale, 1 m . . . . .	311 02
<i>velocity of light in water:</i>	
1 tube with 2 end windows . . . . .	47635
2 saddle bases . . . . .	300 11
distilled or demineralized water	
<i>velocity of light in organic liquids:</i>	
1 ethanol, denaturated, 1l . . . . .	671 972
1 glycerine, 99 %, 250 ml . . . . .	672 121
1 plate glass cell, 50×50×50 mm . . . . .	477 03
1 prism table . . . . .	460 25
1 saddle base . . . . .	300 11
<i>velocity of light in glass:</i>	
1 acrylic glass block . . . . .	476 34
1 prism table . . . . .	460 25
1 saddle base . . . . .	300 11

**Setup**

The experimental setup is illustrated in Figs. 2 and 3.

- 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.
  - Image the red light patch of the light transmitter on the front plate of the receiver and displace the insert (e) relative to the condensor (d) so that the red light patch is illuminated as evenly as possible.
  - Place the lens in the ray path.
  - Align the light transmitter and the lens so that the red light patch impinges 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.
- Oscilloscope settings:  
 Coupling channel II: AC  
 Trigger: channel II  
 Time base: 2 μs/DIV
- Observe the receiver signal on the oscilloscope and optimize the alignment of the light transmitter and the lens once more.

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

$$U_1 = \frac{1}{2} a \cdot \cos(2\pi \cdot \nu_1 \cdot t - \Delta\varphi) \tag{VIII}$$

with  $\nu_1 = \nu - \nu'$ .

This signal can be displayed with a simple oscilloscope since the frequency  $\nu_1$  is only 100 kHz. The phase shift  $\Delta\varphi$  is not changed by the mixing, but it corresponds to an *apparent change*  $\Delta t_1$  in the propagation time. The period  $T_1$  of the mixed signal is read from the oscilloscope. Then

$$\Delta\varphi = 2\pi \cdot \frac{\Delta t_1}{T_1} \tag{IX}$$

or

$$\Delta t = \Delta t_1 \cdot \frac{T}{T_1} = \frac{\Delta t_1}{T_1 \cdot \nu} \tag{X}$$

is obtained. Inserting in (IV) and (V) renders the velocity of light in the medium

$$c_n = \frac{c_0}{1 + \frac{c_0}{d \cdot \nu} \cdot \frac{\Delta t_1}{T_1}} \tag{XI}$$

and the refractive index

$$n = 1 + \frac{c_0}{d \cdot \nu} \cdot \frac{\Delta t_1}{T_1} \tag{XII}$$

**a) Velocity of light in water:**

- Clamp the tube holder in the a saddle base, put the tube with 2 end windows on the holder, and fix the tube with two elastic bands as shown in Fig. 4.
- Put a piece of tubing with a funnel on the hose connector on the bottom of the tube, and open the two stopcocks.
- Hold the funnel over the tube, and fill the tube with distilled water as bubble-free as possible.

*Remark:*

*The above stopcock should remain open to avoid changes in pressure inside the tube in the case of fluctuations of the temperature.*

**b) Velocity of light in organic liquids:**

- Mount the prism table in a saddle base, and clamp the plate glass cell on the prism table with the metal holder.
- Place the empty plate glass cell in the ray path immediately in front of the light transmitter.

**c) Velocity of light in glass:**

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

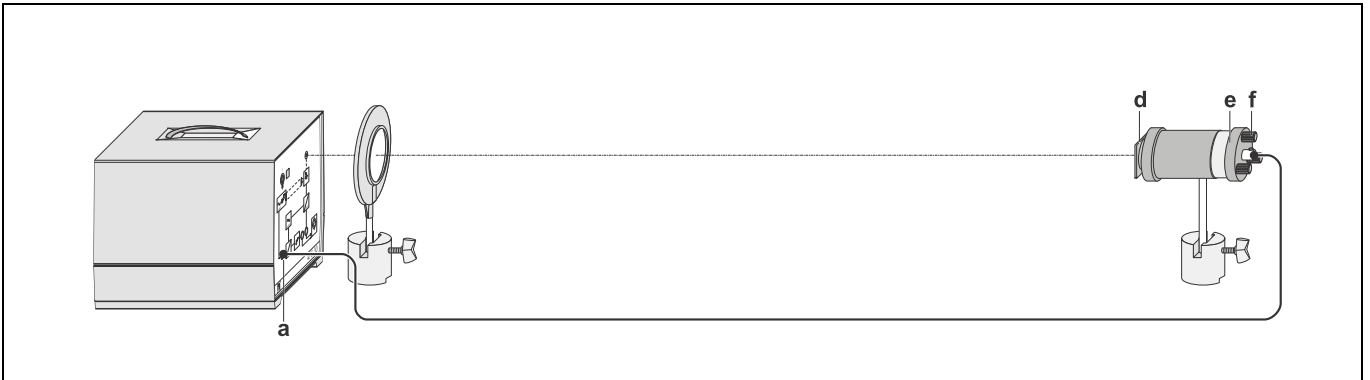


Fig. 2 Optical setup for determining the velocity of light.

**Carrying out the experiment**

*Remark:*

*A satisfactory accuracy of the results can only be achieved if the light transmitter and the receiver are thermally stable. Start the experiment only half an hour after switching on the light transmitter and the receiver.*

*Since the modulation frequency  $\nu = 60$  MHz is timed by a quartz, it need not be measured.*

**Synchronizing the phases of the reference and the receiver signal:**

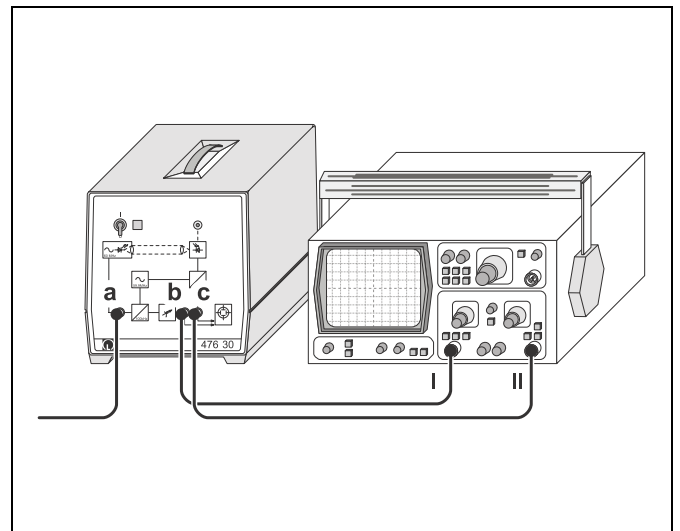
- Connect the output (b) of the receiver to channel I of the oscilloscope and look at channel I (reference signal) and channel II (receiver signal) simultaneously.

Oscilloscope settings:

Coupling channel I and II:	AC
Trigger:	channel I
Time base:	2 $\mu$ s/DIV

- 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  $\varphi$  so that they are in phase as exactly as possible.
- Choose a suitable horizontal position of the signals, and determine the period  $T_1$ .

Fig. 3 Connection of the oscilloscope for measuring the phase shift of the periodic light signal.



**a) Velocity of light in water:**

- Put the tube filled with water into the ray path immediately in front of the light transmitter.
- Set the time base 1  $\mu$ s/DIV, read the distance between the zero passages, and determine the *apparent change in propagation time*  $\Delta t_1$ .
- Repeat the measurement several times, and determine the mean value of the measured values  $\Delta t_1$ .

Fig. 4 Determining the velocity of light in water.

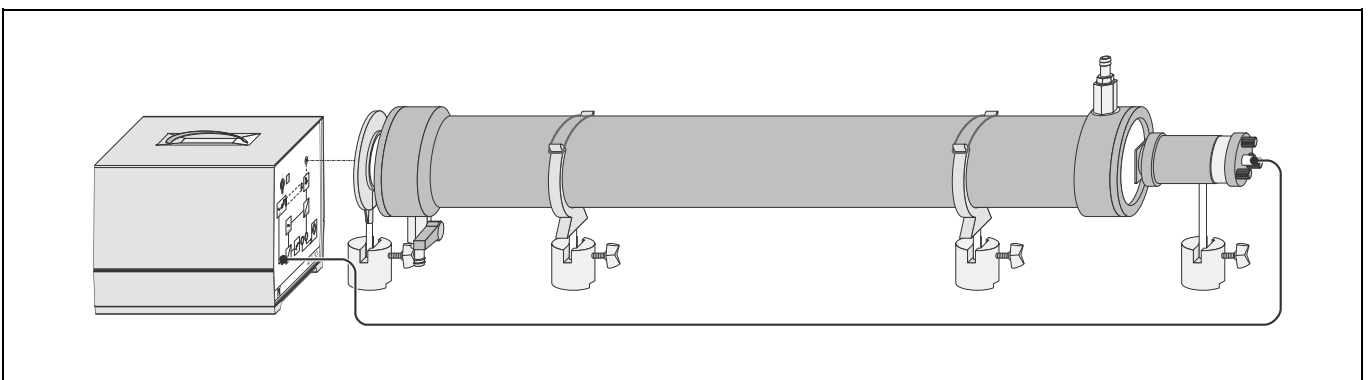




Fig. 5 Determining the velocity of light in organic liquids.

**b) Velocity of light in organic liquids:**

- In order to achieve an improved display of the phase shift, enlarge the section for both signals.

Oscilloscope settings:

Coupling channel I and II: AC  
Trigger: channel I

Automatic adjustment  
of the trigger threshold: off

Time base: 0.1  $\mu\text{s}/\text{DIV}$

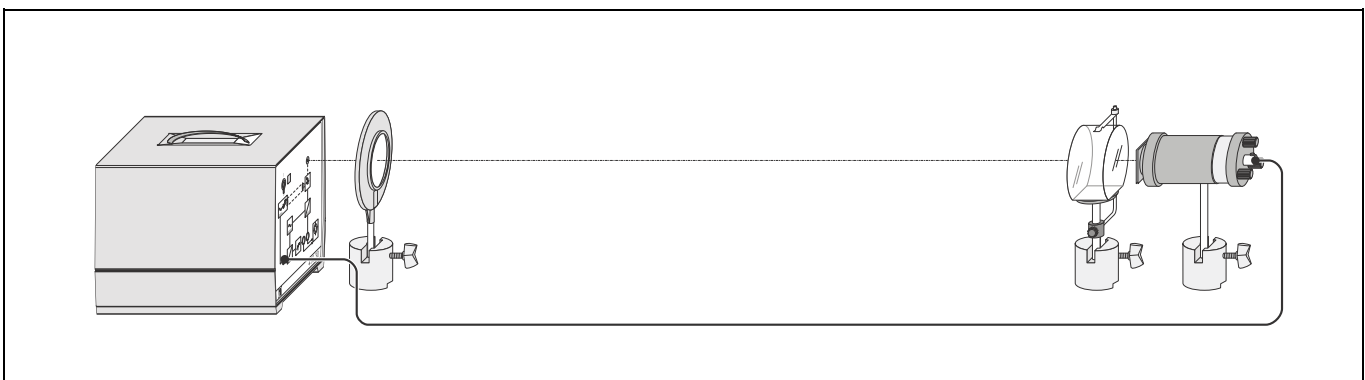
Amplitude: 0.1 mV/DIV

- Choose a suitable horizontal position of the signals (e.g. shift the zero passage to the centre of the screen).
- Fill the plate glass cell with ethanol, and observe the displacement of the signals.
- Read the distance between the zero passages, and determine the *apparent propagation time*  $\Delta t_1$ .
- Empty the plate glass cell, and adjust the signals with the phase shifter  $\varphi$  so that they are in phase again.
- Fill the plate glass cell with glycerine, and repeat the measurement.

**c) Velocity of light in acrylic glass:**

- Perform the measurement as described in section b) using the acrylic glass block instead of the plate glass cell.

Fig. 6 Determining the velocity of light in glass.



**Measuring example****a) Velocity of light in water:**

$$d = (100 \pm 1) \text{ cm}$$

$$\Delta t_1 = (0.70 \pm 0.05) \text{ DIV} \cdot 1 \text{ } \mu\text{s}/\text{DIV} = (0.70 \pm 0.05) \text{ } \mu\text{s}$$

$$T_1 = (4.90 \pm 0.05) \text{ DIV} \cdot 2 \text{ } \mu\text{s}/\text{DIV} = (9.8 \pm 0.1) \text{ } \mu\text{s}$$

**b) Velocity of light in organic liquids:**

The reference and the receiver signals for ethanol and glycerine look similar to those shown in Fig. 8.

*Ethanol:*

$$d = (5.0 \pm 0.1) \text{ cm}$$

$$\Delta t_1 = (0.3 \pm 0.1) \text{ DIV} \cdot 0.1 \text{ } \mu\text{s}/\text{DIV} = (0.03 \pm 0.01) \text{ } \mu\text{s}$$

$$T_1 = (4.90 \pm 0.05) \text{ DIV} \cdot 2 \text{ } \mu\text{s}/\text{DIV} = (9.8 \pm 0.1) \text{ } \mu\text{s}$$

*Glycerine:*

$$d = (5.0 \pm 0.1) \text{ cm}$$

$$\Delta t_1 = (0.4 \pm 0.1) \text{ DIV} \cdot 0.1 \text{ } \mu\text{s}/\text{DIV} = (0.04 \pm 0.01) \text{ } \mu\text{s}$$

$$T_1 = (4.90 \pm 0.05) \text{ DIV} \cdot 2 \text{ } \mu\text{s}/\text{DIV} = (9.8 \pm 0.1) \text{ } \mu\text{s}$$

**c) Velocity of light in acrylic glass:**

$$d = (5.0 \pm 0.1) \text{ cm}$$

$$\Delta t_1 = (0.6 \pm 0.1) \text{ DIV} \cdot 0.1 \text{ } \mu\text{s}/\text{DIV} = (0.06 \pm 0.01) \text{ } \mu\text{s}$$

$$T_1 = (4.90 \pm 0.05) \text{ DIV} \cdot 2 \text{ } \mu\text{s}/\text{DIV} = (9.8 \pm 0.1) \text{ } \mu\text{s}$$

**Evaluation****a) Velocity of light in water:**

The refractive index  $n$  of water can be determined with equation (XII):

$$n = 1.36 \pm 0.03$$

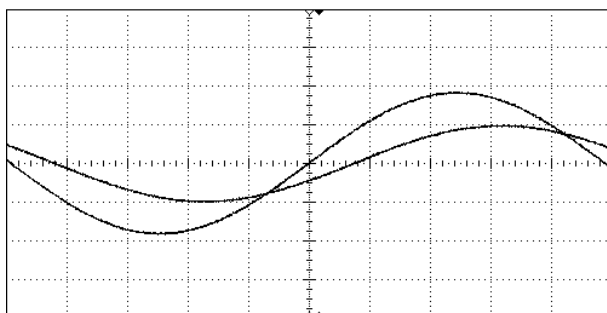
The velocity of light in water is calculated from the refractive index

$$c = (2.20 \pm 0.05) \cdot 10^8 \frac{\text{m}}{\text{s}}$$

*Value quoted in the literature:*

Refractive index of water:  $n = 1.333$

Fig. 7 Reference and receiver signal for water,  $d = 100 \text{ cm}$ , horizontal deflection  $1 \text{ } \mu\text{s}/\text{DIV}$ .

**b) Velocity of light in organic liquids:**

The refractive indices  $n$  of ethanol and glycerine can be determined with equation (XII):

$$\text{Ethanol: } n = 1.3 \pm 0.1$$

$$\text{Glycerine: } n = 1.4 \pm 0.1$$

The velocities of light in ethanol and glycerine are calculated from the refractive indices

$$\text{Ethanol: } c = (2.29 \pm 0.16) \cdot 10^8 \frac{\text{m}}{\text{s}}$$

$$\text{Glycerine: } c = (2.13 \pm 0.14) \cdot 10^8 \frac{\text{m}}{\text{s}}$$

*Values quoted in the literature:*

Refractive index of ethanol  $n = 1.36$

Refractive index of glycerine  $n = 1.47$

**c) Velocity of light in acrylic glass:**

The refractive index  $n$  of acrylic glass can be determined with equation (XII):

$$n = 1.6 \pm 0.1$$

The velocity of light in acrylic glass is calculated from the refractive index

$$c = (1.86 \pm 0.14) \cdot 10^8 \frac{\text{m}}{\text{s}}$$

*Value quoted in the literature:*

Refractive index of acrylic glass  $n = 1.5$

**Results**

If a light ray passes an optically dense medium, the propagation time of the light is changed. The change in propagation time manifests itself as a phase shift of a periodic light signal. From the phase shift the refractive index of the medium can be determined.

Fig. 8 Reference and receiver signal for acrylic glass,  $d = 5 \text{ cm}$ , horizontal deflection  $0.1 \text{ } \mu\text{s}/\text{DIV}$ .

