Notice: All measurements and calculated values must be presented with SI units with an appropriate number of significant digits. Uncertainties required only when explicitly asked for.

1.0 Introduction

Experiments with a laser distance meter (LDM)

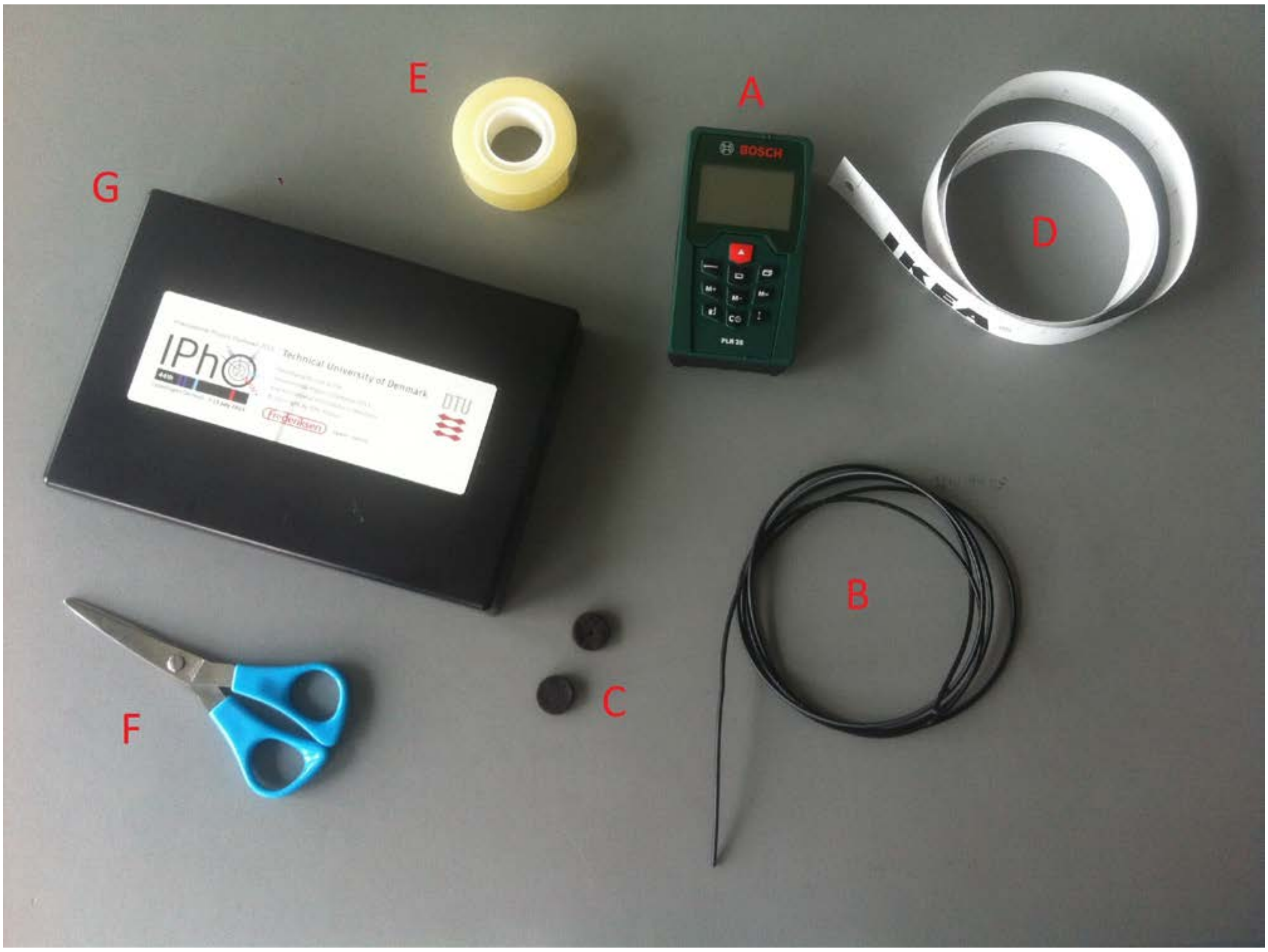

Figure 1.1 Equipment for the first experiments 1.1 and 1.2.

A: Laser distance meter

B: Fiber optic cable (approximately 1 m)

C: Self-adhesive black felt pads with hole

D: Tape measure

E: Tape

F: Scissors

G: Lid from the black box

A laser distance meter (LDM, see Fig. 1.2 and Fig. 1.3) consists of an emitter and a receiver. The emitter is a diode laser that emits a modulated laser beam, i.e. a laser beam for which the amplitude varies at a very high frequency. When the laser beam hits an object, light is reflected in all directions from the laser dot. Some of this light returns to the instrument's receiver which is situated immediately next to the emitter. The instrument's telescope optics is focused on the laser dot and receives the light returned from the laser dot. The electronics of the instrument measures the time difference in the modulation of the received light signal relative to the emitted light signal. The delay t in the modulation is exactly the time it takes for the light to travel from emitter to receiver. The measured time is then converted to a value

$$y = \frac{1}{2}ct + k$$

This value y is shown in the instrument's display. Here, $c = 2.998 \cdot 10^8 \mathrm{ms}^{-1}$ is the speed of light. The constant k depends on the instrument setting; on the instrument you can switch between measuring the distance either from the rear end or from the front end of the instrument. When the laser distance meter is turned on, the default setting is to measure from the rear. **This setting shall be maintained during all measurements.**

Due to parallax, the LDM cannot measure any distance shorter than 5 cm. The maximum distance that can be measured is around 25 m. The shape of the instrument is such that the rear side is perpendicular to the laser beam as well as the front side. When the instrument is lying on the table the polarization is vertical (perpendicular to the display)

The diode laser is of class 2 with power < 1 mW and wavelength 635 nm. Manifacturer uncertainty for measurements is +/- 2 mm.

Warning: The instrument's diode laser can damage your eyes. Do not look into the laser beam and do not shine it into other people's eyes!

Settings for LDM

The above calculation of the distance y of course assumes that the light has been travelling at speed c. At the level of accuracy in this experiment, there is no need to distinguish between the speed of light in vacuum and in air, since the refractive index for dry, atmospheric air at normal pressure and temperature is $1.000\,29 \approx 1.000$.

Figure 1.2 The unlabeled six buttons are irrelevant (they are used to calculate area and volume). The relevant buttons are:

A: On/off

B: Switch between measurement from the rear and the front of the instrument.

C: Indicator for measurement from the rear/front

D: Turn on laser/start measurement

E: Continuous measurement

F: Indicator for continuous measurement

Figure 1.3 The laser distance meter seen from the front end:

A: Receiver: Lens for the telescope focused on the laser dot

B: Emitter: Do not look into the laser beam!

1.1 Measurement with the laser distance meter

The instrument will perform a measurement when you press the button **D**, see Fig. 1.2.

1.1	Use the LDM to measure the distance H from the top of the table to the floor. Write down the uncertainty ΔH. Show with a sketch how you perform this measurement.	0.4

1.2 Experiment with the fiber optic cable

Figure 1.4 Diagram of a fiber optic cable.

You have been given a fiber optic cable of length approximately 1 m and diameter approximately 2 mm. The cable consists of two optical materials. The core (diameter approximately 1 mm) is made from a plastic with a high refractive index. The core is surrounded by a cladding made from a plastic with a slightly lower refractive index, and this is covered by a protective jacket of black plastic. Core and cladding serve as a wave guide for light shone into the cable, since the boundary between core and cladding will cause total reflection – and thereby prevent the light from leaving the core – as long as the angle of incidence is larger than the critical angle for total reflection. The light will therefore follow the core fiber, even if the cable bends, as long as it is not bent too much.

The LDM should now be set for continuous measurement (**E,** see Fig. 1.2), so that the display indication y updates approximately once per second. The LDM will automatically go into sleep mode after a few minutes. It can be reactivated by pushing the red start button.

Carefully and gently cover the lens of the receiver with one small, black felt pad (the other is a backup) with a hole of diameter 2 mm (see figure 1.3A). The adhesive side of the pad should be pressed softly against the lens. Insert a fiber optic cable of length x in the hole in the pad so that it touches the lens,

see Fig. 1.5.

Figure 1.5 (a) Felt pad and fiber optic cable. **(b)** Attaching the fiber optic cable.

The other end of the cable should be held against the emitter, so that it touches the glass in the middle of the laser beam. Now read off the y-value from the display. The supplied scissors should be used to cut the fiber optic cable into different lengths x.

Think <u>very</u> carefully before cutting the fiber optic cable, as you cannot get any more cable!!

Notice also that the LDM display might show a thermometer icon after a while in the continuous mode due to excessive heating of the electronics. If this happens, turn off the LDM for a while to cool off the instrument.

1.2a	Measure corresponding values of x and y. Set up a table with your measurements. Draw a graph showing y as a function of x.	1.8
1.2b	Use the graph to find the refractive index n_{co} for the material from which the core of the fiber optic cable is made. Calculate the speed of light v_{co} in the core of the fiber optic cable.	1.2

1.3 Laser distance meter at an angle from the vertical

In this part of the experiment you will need the equipment shown in Fig. 1.6.

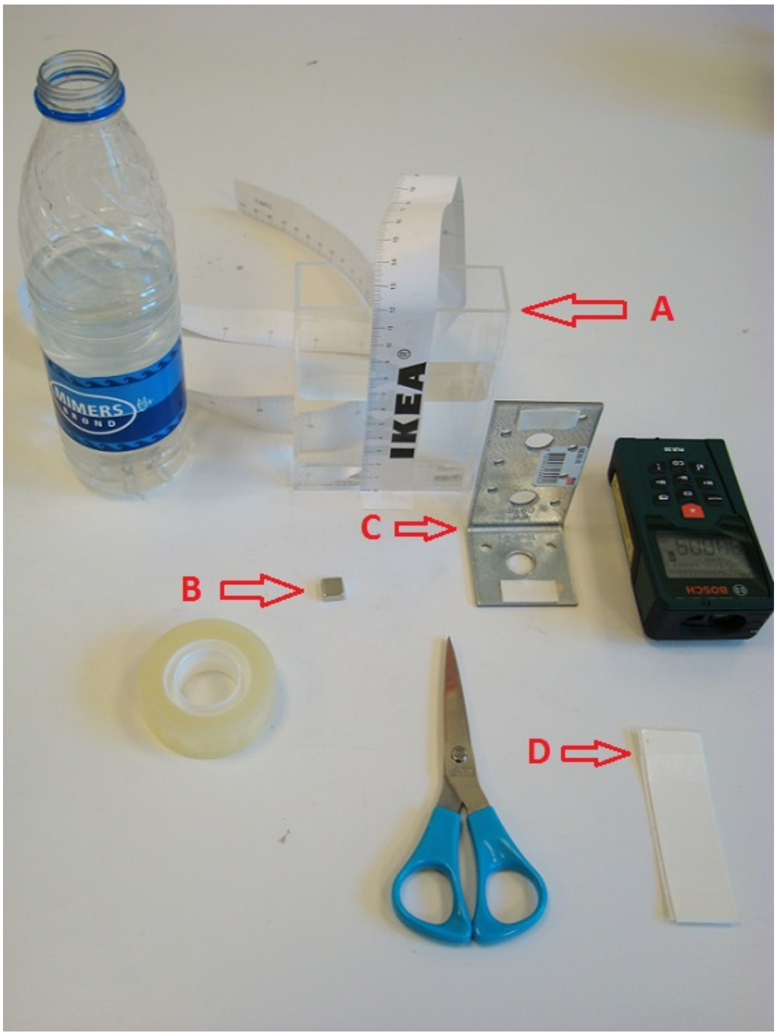

Figure 1.6 Equipment for experiment 1.3 shown in the figure:

A: Optical vessel with water and measuring tape

B: Magnet to secure the angle iron on top of the black box. (You find magnet placed on the angle iron).

C: Angle iron with self-adhesive foam pads

D: Self-adhesive foam pads

Remove the black felt pad from the lens. The LDM should now be placed in the following set-up: Place two self-adhesive foam pads on the angle iron, see **A** on Fig. 1.7.

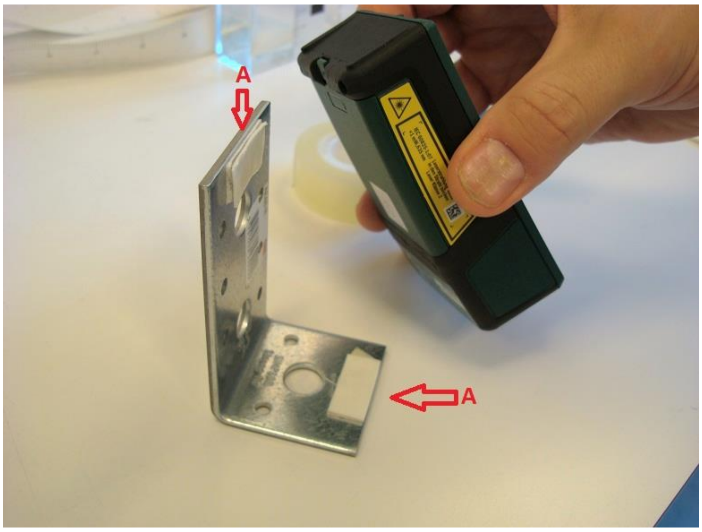

Figure 1.7 How to place the two self-adhesive foam pads on the angle iron.

The LDM should be carefully placed on the angle iron as shown in Fig. 1.8.

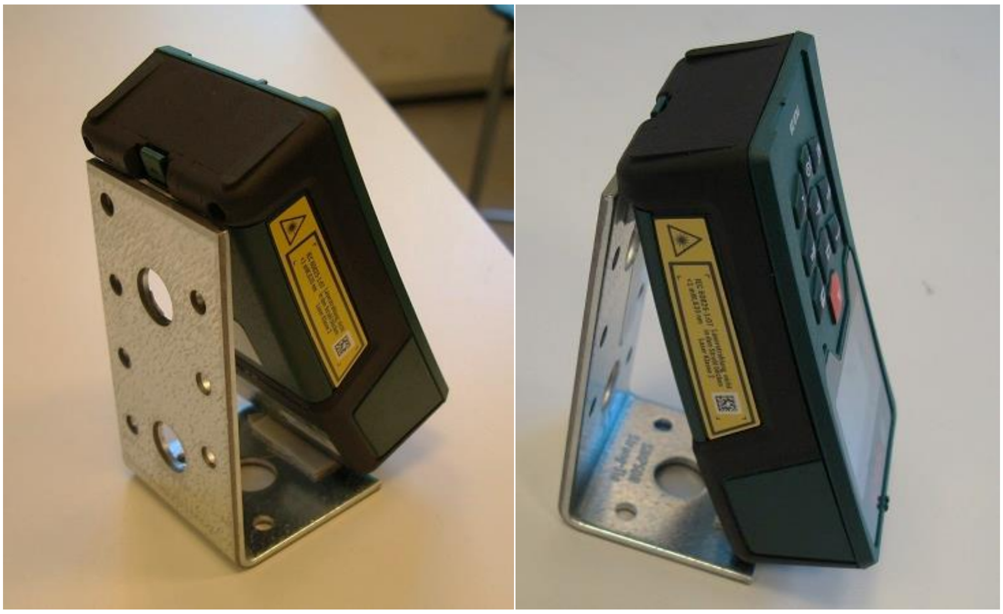

Figure 1.8 How to place the laser distance meter on the angle iron.

The angle iron with the LDM should be mounted on the black box as shown in Fig. 1.9. Secure the angle iron to the box with a magnet placed below inside the box. (The tiny magnet is found on the angle iron). It is important to mount the LDM exactly as in the photo, since the side of the box facing upwards slants by approximately 4 degrees. The laser beam should now be pointing unobstructedly downwards at an angle.

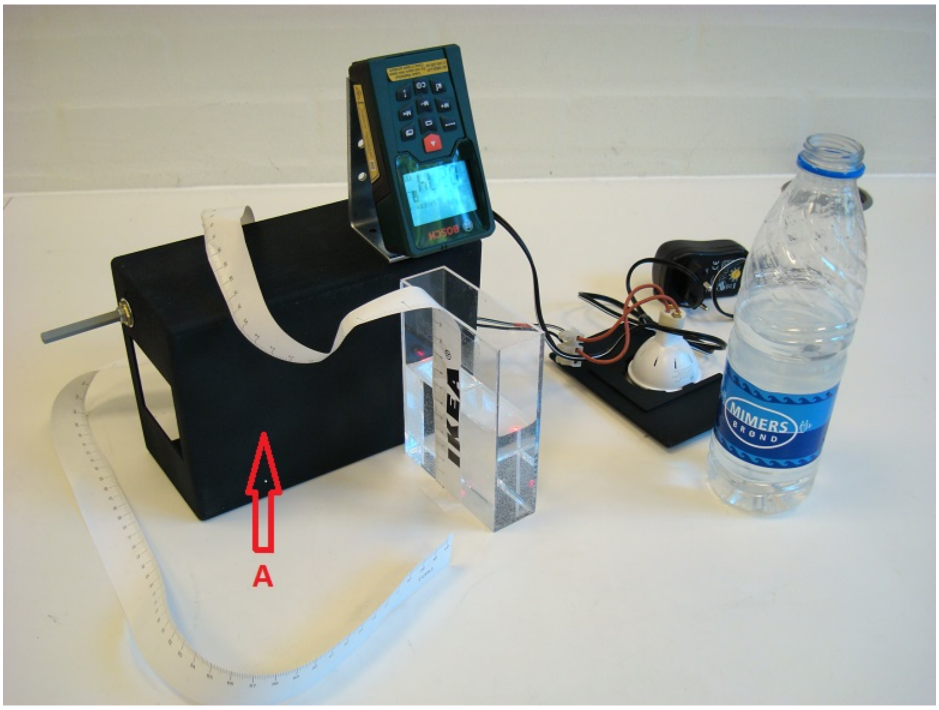

Figure 1.9 The experimental set-up. (The black box only serves as a support. The equipment behind the bottle is not used, though).

A: Important: The bottom of the black box must face forward as shown. The side that faces upwards is slanting approximately 4 degrees with respect to the horizontal plane. Make sure that the angle θ_1 is the same all the time

When the LDM is turned on and mounted as explained above, the laser beam will form an angle θ_1 with respect to the vertical direction. This angle, which must be the same throughout this experiment, must now be determined. The optical vessel is not needed here, so put it aside so far.

1.3a	Measure with the LDM the distance y_1 to the laser dot where the laser beam hits the table top. Then move the box with the LDM horizontally until the laser beam hits the floor. Measure the distance y_2 to the laser dot where the laser beam hits the floor. State the uncertainties.	0.2
1.3b	Calculate the angle θ_1 using only these measurements y_1, y_2 and H (from problem 1.1). Determine the uncertainty $\Delta\theta_1$.	0.4

1.4 Experiment with the optical vessel

Place the optical vessel so that the laser beam hits the bottom of the vessel approximately in the middle, see Fig. 1.10. Pour some water into the vessel. The depth of the water is x. Read off y on the display of the LDM.

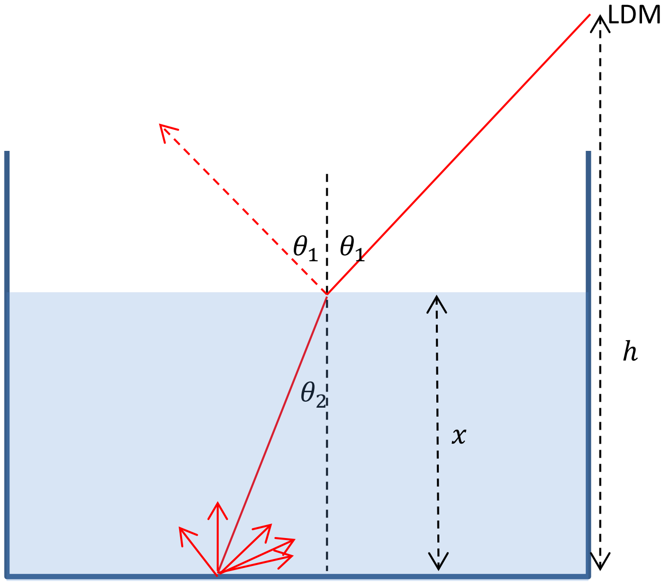

Figure 1.10 Diagram of laser beams in the optical vessel with water of depth x.

1.4a	Measure corresponding values of x and y. Set up a table with your measurements. Draw a graph of y as a function of x.	1.6
1.4b	Use equations to explain theoretically what the graph is expected to look like.	1.2
1.4c	Use the graph to determine the refractive index n_w for water.	1.2

2.0 Introduction

Equipment used for this experiment is displayed in Fig. 2.1.

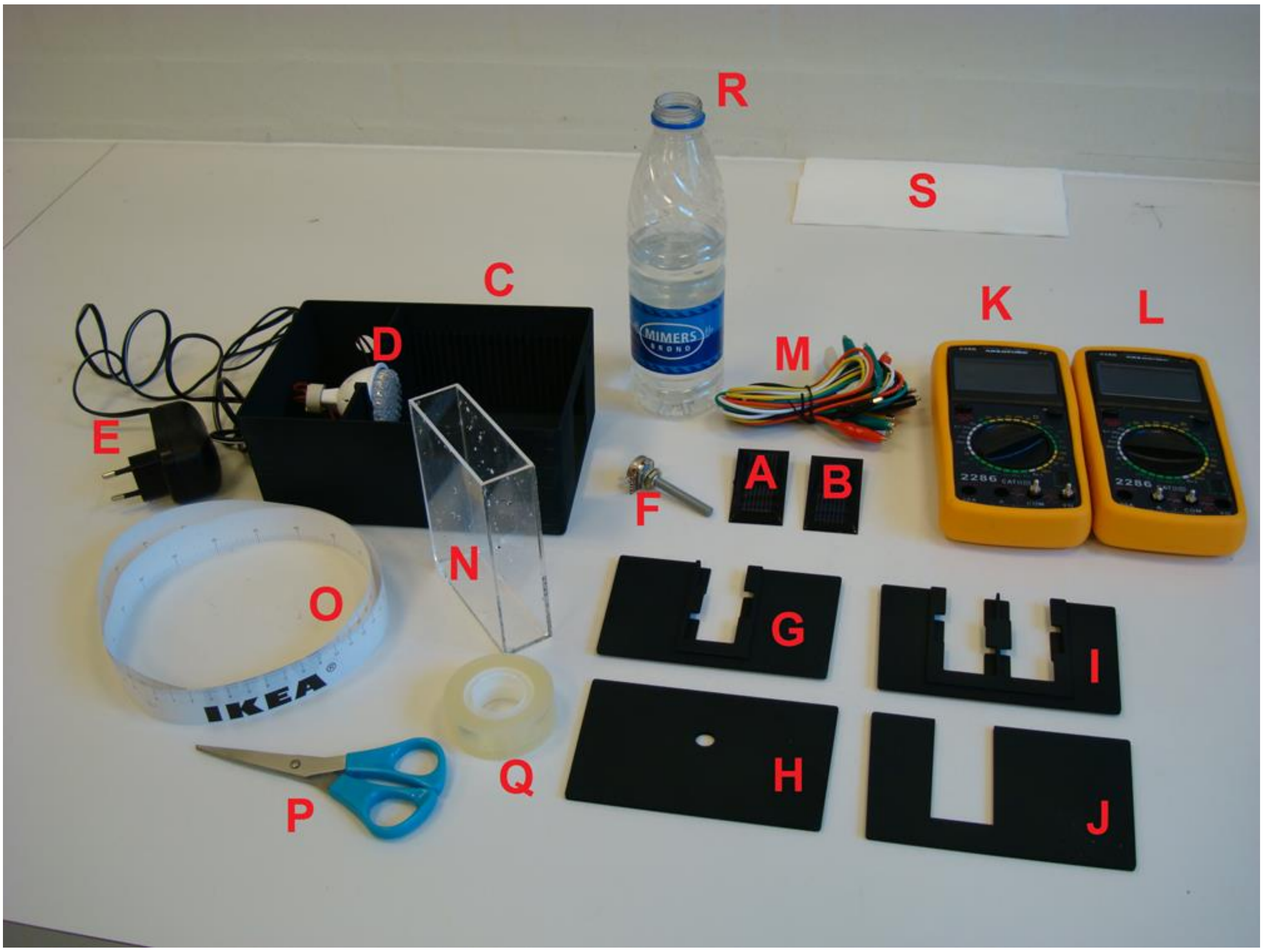

Figure 2.1 Equipment used for experiment E2.

List of equipment (see Fig. 2.1):

A: Solar cell

B: Solar cell

C: Box with slots for the mounting of light source, solar cells, etc.

D: LED-light source in holder

E: Power supply for light source D

F: Variable resistor

G: Holder for mounting single solar cell in the box C

H: Circular aperture for use in the box C

I: Holder for mounting two solar cells in the box C

J: Shielding plate for use in the box C

K: Digital multimeter

L: Digital multimeter

M: Wires with mini crocodile clips

N: Optical vessel (large cuvette)

O: Measuring tape

P: Scissors

Q: Tape

R: Water for filling the optical vessel N

S: Paper napkin for drying off excess water

T: Plastic cup for water from the optical vessel N (not shown in Fig. 2.1)

U: Plastic pipette (not shown in Fig. 2.1)

V: Lid for the box C (not shown in Fig. 2.1)

Data sheet: table of fundamental constants

Speed of light in vacuum	$c = 2.998 \times 10^{8}\ \mathrm{m\ s^{-1}}$
Elementary charge	$e = 1.602 \times 10^{-19}\ \mathrm{C}$
Boltzmann's constant	$k_{\mathrm{B}} = 1.381 \times 10^{-23}\ \mathrm{J\ K^{-1}}$

A solar cell transforms part of the electromagnetic energy in the incident light to electric energy by separating charges inside the solar cell. In this way an electric current can be generated. Experiment E2 intents to examine solar cells with the use of the supplied equipment. This equipment consists of a box with holders for light source and solar cells along with various plates and a lid. The variable resistor should be mounted in the box, see Fig. 2.2. One of the three terminals on the resistor has been removed, since only the two remaining terminals are to be used. Also supplied are wires with mini crocodile clips and two solar cells (labeled with a serial number and the letter A or B) with terminals on the back. The two solar cells are similar but can be slightly different. The two multimeters have been equipped with terminals for designated use as ammeter and voltmeter, respectively, see Fig. 2.3. Finally, the experiment will make use of an optical vessel together with some drinking water from the bottle.

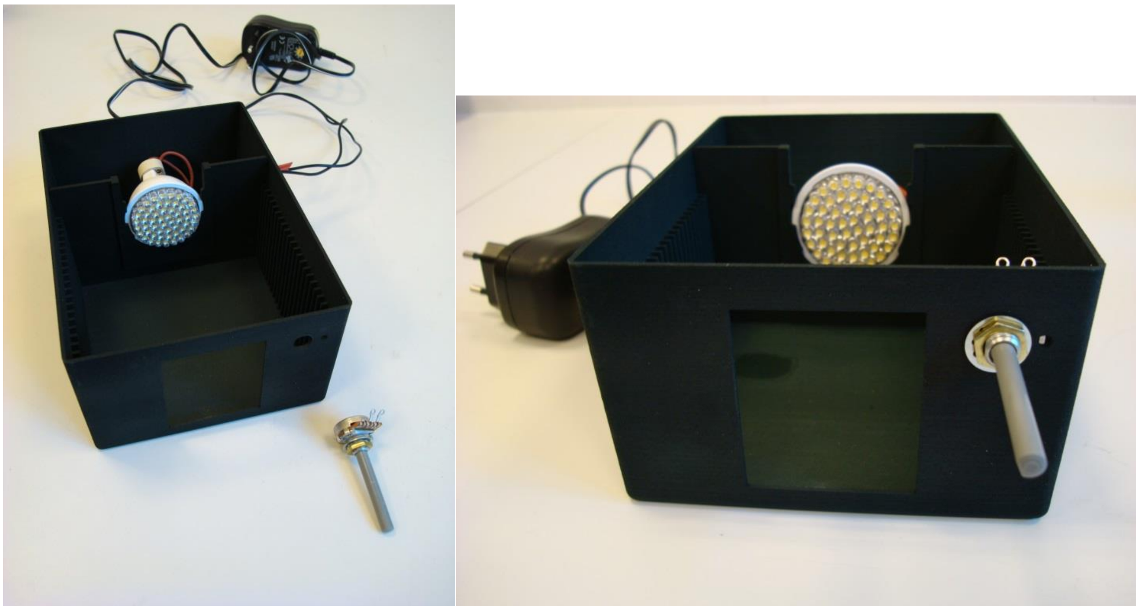

Figure 2.2 (a) Box with light source and resistor for mounting. **(b)** The resistor mounted in the box. Notice that the small pin on the resistor fits in the hole to the right of the shaft.

Figure 2.3 Multimeters equipped with terminals for use as ammeter **(left)** and voltmeter **(right)**, respectively. The instrument is turned on by pressing "POWER" in the top left corner. The instrument turns off automatically after a certain idle time. It can measure direct current and voltage (=) as well as alternating current and voltage (~). The internal resistance in the voltmeter is 10 MΩ regardless of the measuring range. The potential difference over the ammeter is 200 mV at full reading, regardless of the measuring range. In case of overflow the display will show "1", and you need to select a higher measuring range. The "HOLD" button (top right corner) should not be pushed, except if you want to freeze a measurement.

WARNING: ***Do not use the multimeter as an ohmmeter on the solar cells since the measuring current can damage them. When changing the measuring range on the multimeters, please turn the dial with caution. It can be unstable and may break. Check whether there is a number under the decimal point when measuring – if the dial is not fully in place, the multimeter will not measure, even if there are digits in the display.***

Notice: Do not change the voltage on the power supply. It must be 12 V throughout the experiment. (The power supply for the light source should be connected to the outlet (230 V ~) at your table.)

Notice: Uncertainty considerations are only expected when explicitly mentioned.

Notice: All measured and calculated values must be given in SI units.

Notice: For all measurements of currents and voltages in this experiment, the LED-light source is supposed to be on.

2.1 The dependence of the solar cell current on the distance to the light source

For this question you will measure the current, I, generated by the solar cell when in a circuit with the ammeter, and determine how it depends on the distance, r, to the light source. The light is produced *inside* the individual light diodes and r is therefore to be measured as shown in Fig. 2.4.

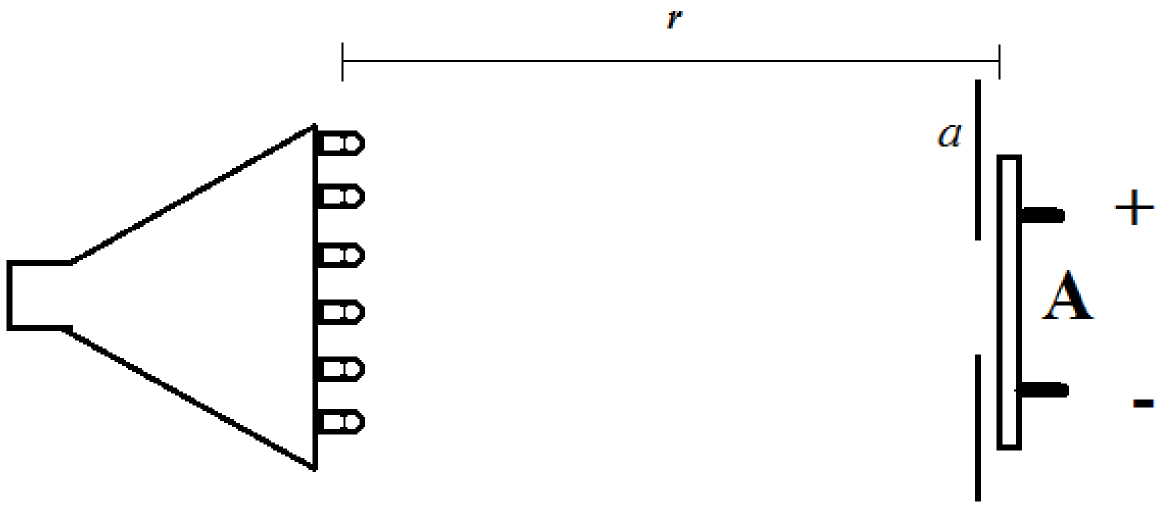

Figure 2.4 Top view of setup for question 2.1. Note the aperture *a* immediately in front of the solar cell A. The distance is measured from inside the light diode to the surface of the solar cell.

Do not change the measuring range on the ammeter in this experiment: the internal resistance of the ammeter depends on the measuring range and affects the current that can be drawn from the solar cell. State the serial numbers of the light source and of solar cell A on your answer sheet. Mount the light source in the U-shaped holder (the light source has a tight fit in the holder, so be patient when mounting it. Mount solar cell A in the single holder and place it together with the circular aperture immediately in front of the solar cell. The current I as a function of the distance r to the light source can, when r is not too small, be approximated by

$$I(r) = \frac{I_a}{1 + \frac{r^2}{a^2}}$$

where I_a and a are constants.

2.1a	Measure I as a function of r, and set up a table of your measurements.	1.0
2.1b	Determine the values of I_a and a by the use of a suitable graphical method.	1.0

2.2 Characteristic of the solar cell

Remove the circular aperture. Mount the variable resistor in the box as shown on Fig. 2.2. Place the light source in slot number 0, furthest away from the resistor. Mount solar cell A in the single holder *without the circular aperture* in slot number 10. Build a circuit as shown in Fig. 2.5, so that you can measure the characteristic of the solar cell, i.e. the terminal voltage U of the solar cell as a function of the current I in the circuit consisting of solar cell, resistor and ammeter.

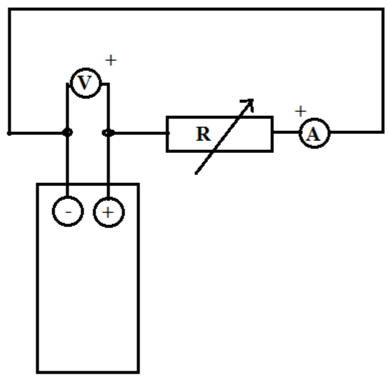

Figure 2.5 Electrical diagram for measuring the characteristic in question 2.2.

2.2a	Make a table of corresponding measurements of U and I.	0.6
2.2b	Graph voltage as function of current	0.8

2.3 Theoretical characteristic for the solar cell

For the solar cells in this experiment, the current as function of the voltage is given by the equation

$$I = I_{\max} - I_0 \left(\exp\left(\frac{eU}{\eta k_B T} \right) - 1 \right)$$

where the parameters $I_{\max}$, I_0 and η are constant at a given illumination. We take the temperature to be $T = 300$ K. The fundamental constants e and k_B are the elementary charge and Boltzmann's constant, respectively.

2.3a	Use the graph from question 2.2b to determine $I_{\max}$.	0.4

The parameter η can be assumed to lie in the interval from 1 to 4. For some values of the potential difference U, the formula can be approximated by

$$I \approx I_{\max} - I_0 \exp\left(\frac{eU}{\eta k_B T} \right)$$

2.3b	Estimate the range of values of U for which the mentioned approximation is good. Determine graphically the values of I_0 and η for your solar cell.	1.2

2.4 Maximum power for a solar cell

2.4a	The maximum power that the solar cell can deliver to the external circuit is denoted P_{max}. Determine P_{max} for your solar cell through a few, suitable measurements. (You may use some of your previous measurements from question 2.2).	0.5
2.4b	Estimate the optimal load resistance R_{opt}, i.e. the total external resistance when the solar cell delivers its maximum power to R_{opt}. State your result with uncertainty and illustrate your method with suitable calculations.	0.5

2.5 Comparing the solar cells

Mount both solar cells (A and B) in the double holder in slot number 15, see Fig. 2.6.

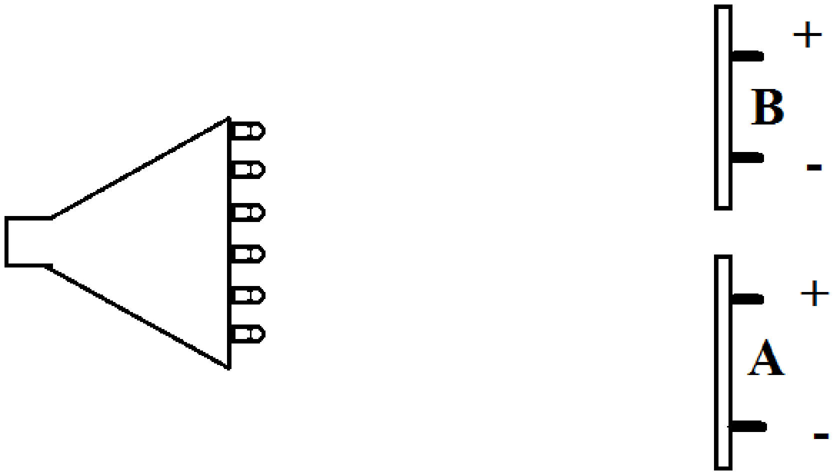

Figure 2.6 Top view of light source and solar cells in question 2.5.

2.5a	Measure, for the given illumination: - The maximum potential difference $U_A$that can be measured over solar cell A. - The maximum current I_A that can be measured through solar cell A. Do the same for solar cell B.	0.5
2.5b	Draw electrical diagrams for your circuits showing the wiring of the solar cells and the meters.	0.3

2.6 Couplings of the solar cells

The two solar cells can be connected in series in two different ways as shown in Fig. 2.7. There are also two different ways to connect them in parallel (not shown in the figure).

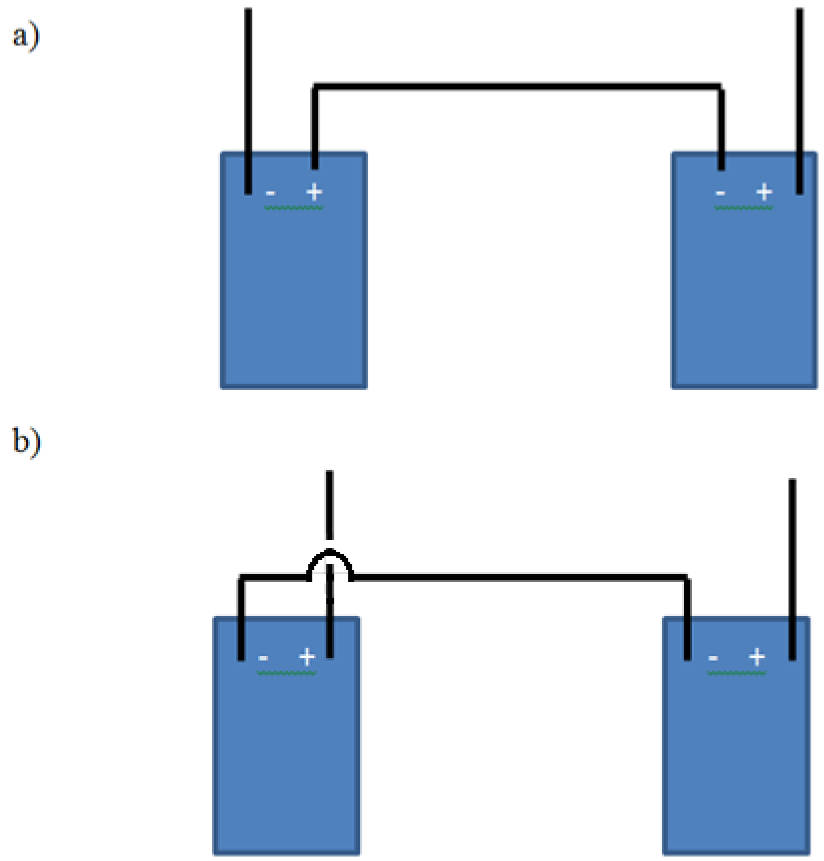

Figure 2.7 Two ways to connect the solar cells in series for question 2.6. The two ways to connect them in parallel are not shown.

2.6	Determine which of the four arrangements of the two solar cells yields the highest possible power in the external circuit when one of the solar cells is shielded with the shielding plate (J in Fig. 2.1). Hint: You can estimate the maximum power quite well by calculating it from the maximum voltage and maximum current measured from each configuration. Draw the corresponding electrical diagram.	1.0

2.7 The effect of the optical vessel (large cuvette) on the solar cell current

Mount the light source in the box and place solar cell A in the single holder with the circular aperture immediately in front, so that there is approximately 50 mm between the solar cell and the light source. Place the empty optical vessel immediately in front of the circular aperture as shown in Fig. 2.8.

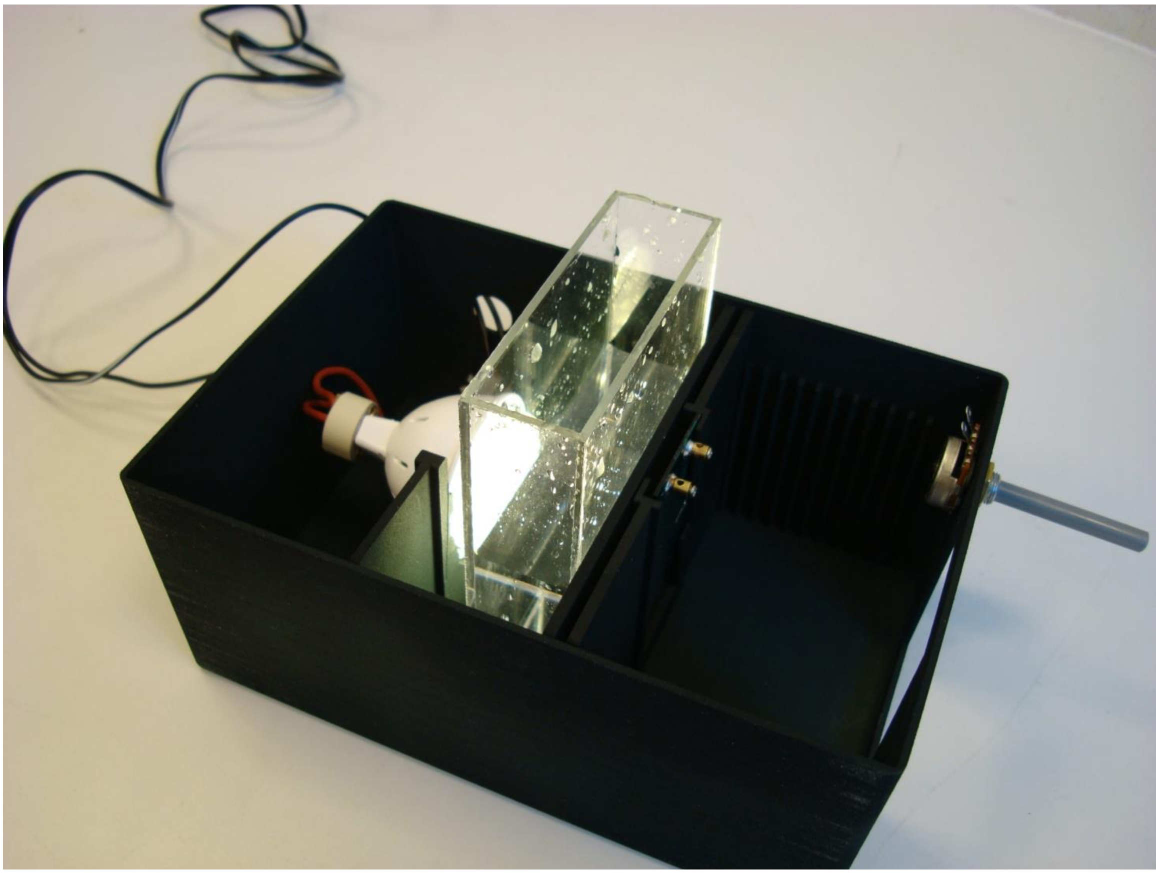

Figure 2.8 Experimental set-up for question 2.7.

2.7a	Measure the current *I*, now as a function of the height, *h*, of water in the vessel, see Fig. 2.8. Make a table of the measurements and draw a graph.	1.0
2.7b	Explain with only sketches and symbols why the graph looks the way it does.	1.0

Mount the light source in the box and place solar cell A in the single holder so that the distance between the solar cell and the light source is maximal. Place the circular aperture immediately in front of the solar cell.

2.7c	For this set-up do the following: - Measure the distance r_1 between the light source and the solar cell and the current I_1. - Place the empty vessel immediately in front of the circular aperture and measure the current I_2. - Fill up the vessel with water, almost to the top, and measure the current I_3.	0.6
2.7d	Use your measurements from 2.7c to find a value for the refractive index n_w for water. Illustrate your method with suitable sketches and equations. You may include additional measurements.	1.6