Universität Freiburg
Advanced physics lab, part 1
Holiday internship in the summer semester 2024

Experiment 2
Light runtimes

[redacted]
(Group 11)

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Tutor: [redacted]

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1 Goal of the experiment

The goal of this experiment is to measure the speed of light with light runtimes.

2 Experiment

2.1 Setup

The setup of the experiment is split into three parts, as shown in the lab book in the attachments in figure 12. The photo diode as detector is always connected to an oscilloscope with a coaxial cable. The laser in the first experiment is powered by a power supply set to 5 V. The chopper [1] used has 200 blades on its wheel. This setup is illustrated in figure 1.

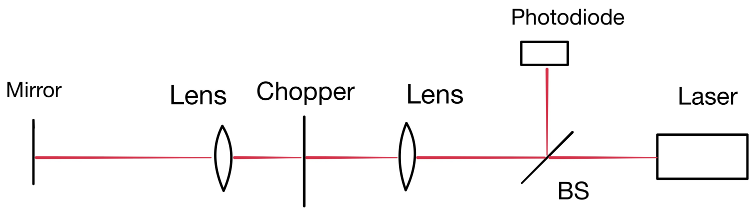


Figure 1: Setup with chopper

The pulse Laser is used for the second and third experiment. It has its own power adapter but needs always an external trigger signal, that is constantly set to $f = 50\,\mathrm{kHz}$, coming from a function generator set to a square wave function. These setups are illustrated in figure 2 and figure 3.

Figure 2: Setup with the Square wave function

Figure 3: Setup with the split beam

2.2 Execution

At first it is checked which devices are used for the experiments.

Then the real measurements start to determined the speed of light. Three measurements have been made:

1. The cw-laser beam goes through a beam splitter and after that through a chopper. Behind that are one ore multiple mirrors in some distance to bring the beam back. In the beam splitter the beam is directed into the photo diode. The signal from the diode is seen on the oscilloscope.
2. The pulsed laser is used with a square wave function trigger. The beam is send through the beam splitter on the mirrors and the way back into the diode. The function generator and the diode are connected to the oscilloscope and the time difference between them is measured.
3. The beam is split with the beam splitter into two ways with different lengths. The signals are again detected in the diode and the time difference between the resulting peaks is measured.

3 Evaluation and error analysis

3.1 Evaluation of used devices

The evaluation of the devices used is on the first page of the lab book in figure 12. In addition to that non of the amplifiers have been used because we had no beneficial effect with them as seen in figure 10 and figure 11 in the attechment.

The comparison of the photo diodes in figure 12 shows the time width of the raise and fall of the detected peak coming from the pulsed laser signal. For the Ixys and Osram diode the total width of the peaks are in the magnitude of microseconds. The width of the Thorlabs diode peak is in the magnitude of nanoseconds. Because of the much better time resolution the Thorlabs photo diode is used for all experiments. The uncertainty from the photo diode is expected to be very small compared to other factors. Because it is constant we can filter it out with a fit.

The error on the length measurements with the tape measure is always $a_d = 0.05\,\mathrm{cm}$ triangularly distributed and comes from the uncertainty of reading the scale. Therefore the uncertainty is

$$\Delta d = \frac{a_d}{\sqrt{6}} \approx 0.02\,\mathrm{cm}.$$

3.2 Chopper

With the values set and measured as shown in figure 12 the frequency of the chopper has an uncertainty of $\Delta f_0 \approx 1.2\,\mathrm{Hz}$ that comes from the fact that the frequency on the display varied around a few Hertz.

When the laser beam passes through the chopper but is blocked on the way back from the mirrors there is no signal visible on the oscilloscope. Then the speed of light is detected. With the fastest frequency possible and multiple distances behind the chopper the results look like this on the oscilloscope.

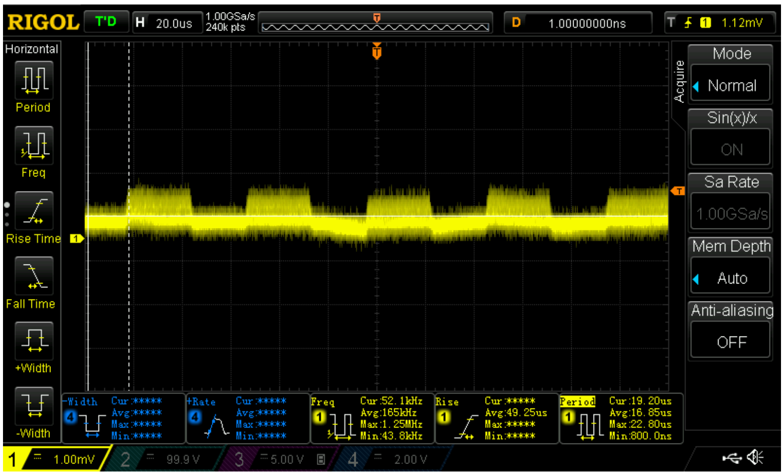


Figure 4: Signal from the photo diode Voltage V depending on the time t

The peaks in figure 4 show, that the light beam came through the same gap of the chopper on both ways. So the frequency or the traveled way is to small.

Because the speed of light is not detectable with this setup a low boundary can be set where the speed of light has to be faster. This is illustrated in figure 5. The speed is calculated by the formula

$$v = 2 \cdot d \cdot f = 2 \cdot d \cdot f_0 \cdot 200 \cdot 2$$

with 200 the amount of blades in the chopper wheel. The uncertainty is so small that it is not visible in the fit. It comes from the Gaussian error propagation and is calculated by

$$\Delta v = \sqrt{(800 \cdot f_0 \cdot \Delta d)^2 + (800 \cdot d \cdot \Delta f_0)^2}.$$

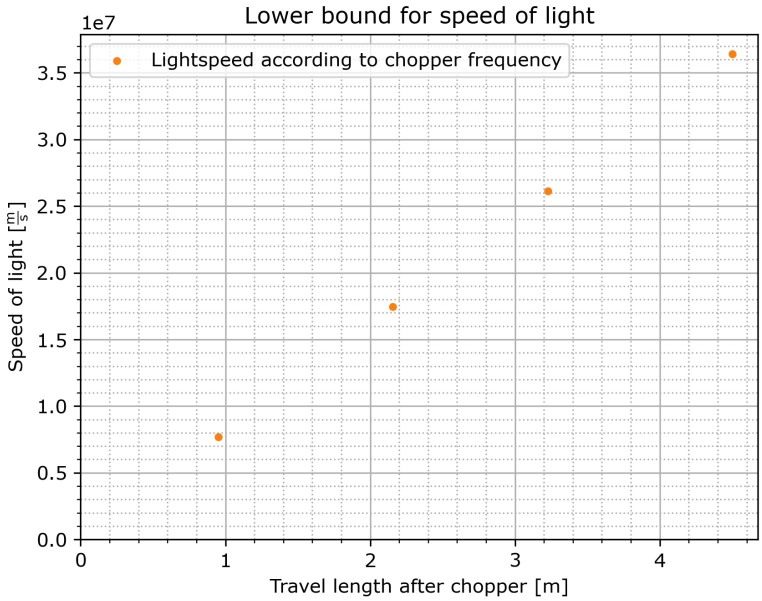


Figure 5: minimum of the speed of light depending on the length of the way

At the end it is possible to say that the speed of light measured with this method is

$$c \geq (36\,423 \pm 7)\,\mathrm{km/s}.$$

3.3 Square wave function

The pulsed laser used has a time delay [2] from the trigger input until the laser beam output of $\Delta t_l = (35 \pm 5)\,\mathrm{ns}$. This delay and the time the signal travels through the coaxial cables has a significant impact on the measurement. Because those values do not change between the different travel distances, they are systematical errors that are removed by fitting the data. Therefore those errors do not have to be quantified.

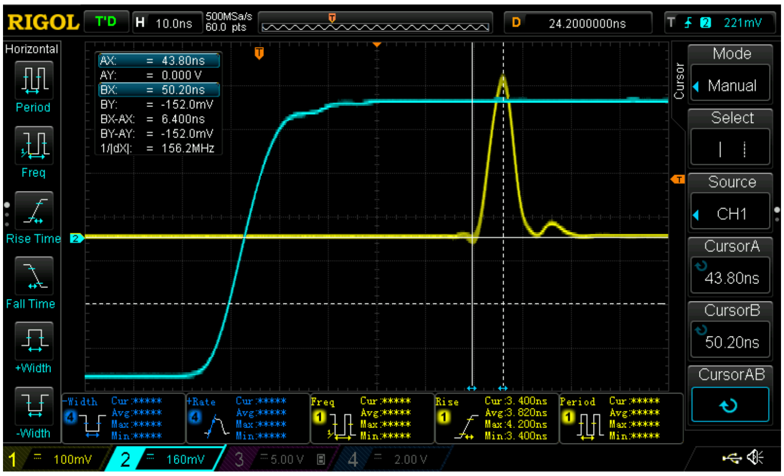


Figure 6: delay of the photo diode signal compared to the trigger function

In figure 6 the times when the peaks occur are measured on the oscilloscope. The measurement is taken from the begin of the raise or from 0 V to the peak. The value is then averaged and triangular distributed with the two boundaries measured as peak and zero point on the oscilloscope.

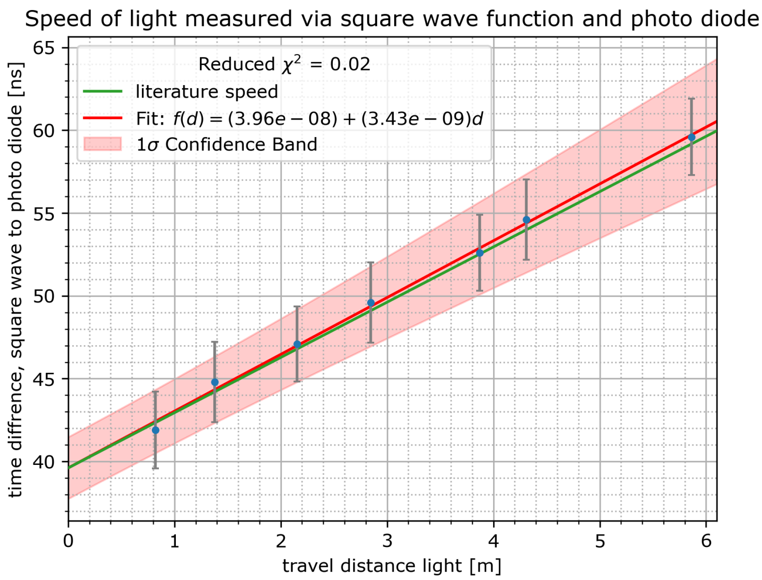


Figure 7: Minimum of the speed of light depending on the length of the way

In figure 7 the resulting data is plotted. The measured values are illustrated with error bars and a confidence band. The error comes mainly from the big selected interval on the oscilloscope where the data was collected.

According to this measurement the speed of light is

$$c = (291\,567 \pm 45\,829)\,\mathrm{km/s}.$$

It is calculated by the inverse of the fitted slope shown in red. The green line is the literature speed of light. The fit is quite fitting but the errors are way too big estimated. The reduced $\chi^2 = 0.02$ is extremely small. That means we estimated the errors to big. This is seen as well in the plot, because the error bars are way bigger than the difference between the fit and the real value.

3.4 Beam splitter

The difference in the distance between the two ways is $d_{diff} = 2 \cdot p_2 - 2 \cdot p_1$, where p_1 is the short path with d_1 and p_2 is the long path with d_2 (to d_4). The time difference between the detected peaks is $t_{diff} = t_2 - t_1$. The speed is then calculated to

$$v = \frac{d_{diff}}{t_{diff}}.$$

The uncertainties come through the Gaussian error propagation with

$$\Delta t_{diff} = \sqrt{(\Delta t_1)^2 + (\Delta t_1)^2}$$

and

$$\Delta d_{diff} = \sqrt{(2 \cdot \Delta p_2)^2 + (2 \cdot \Delta p_1)^2}.$$

Finally for the speed, the uncertainty is combined to

$$\Delta v = \sqrt{\left(\frac{\partial v}{\partial d_{diff}} \cdot \Delta d_{diff}\right)^2 + \left(\frac{\partial v}{\partial t_{diff}} \cdot \Delta t_{diff}\right)^2}.$$

The two peaks, each coming from one of the split ways are seen on the oscilloscope in figure 8.

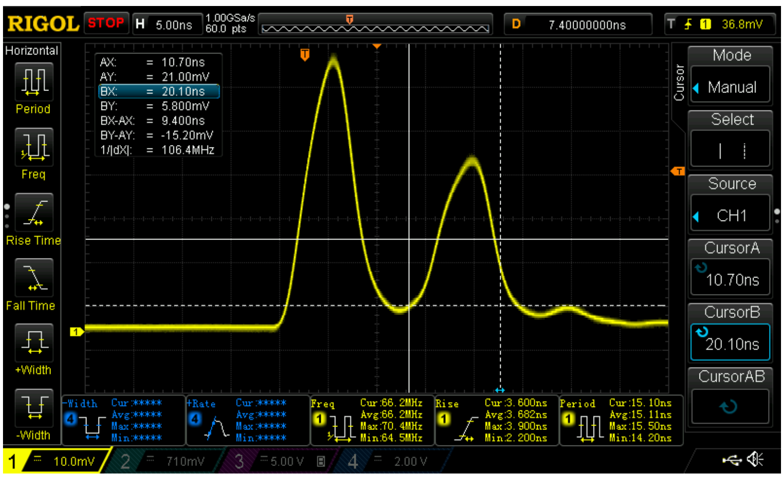


Figure 8: time delay between the peaks of the split laser beam

The measured values are plotted with their error bars and illustrated in figure 9. The speed of light is also calculated by the inverse of the slope of the red fit. The green line is the literature speed of light. The fit is fitting quite okay. The χ^2 value is high, but not that important with just five measurements. More important is that roughly two thirds of the points are on the fit, and the speed of light is determined quite neatly.

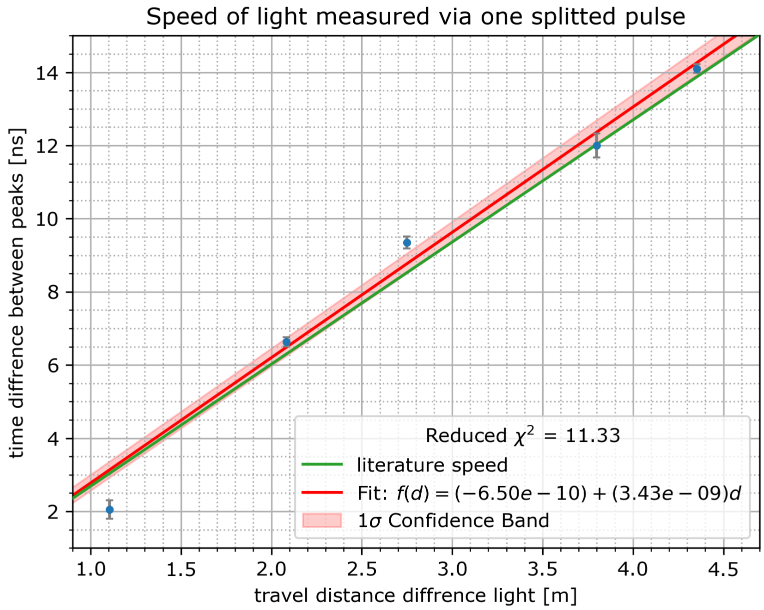


Figure 9

According to this measurement the speed of light is

$$c = (291\,955 \pm 5511)\,\mathrm{km/s}.$$

4 Discussion

4.1 Final results

With the Chopper setup the speed of light is

$$c \geq (36\,423 \pm 7)\,\mathrm{km/s}.$$

With the trigger setup the speed of light is

$$c = (291\,567 \pm 45\,829)\,\mathrm{km/s}.$$

With the beam splitter setup the speed of light is

$$c = (291\,955 \pm 5511)\,\mathrm{km/s}.$$

4.2 Comparison with expected results

The speed of light [3] is defined to the value

$$c_{lit} = 299\,792.458\,\text{km/s}.$$

4.2.1 Chopper

The measured value of c is smaller then the literature value. The measurement leads to

$$\frac{c}{c_{lit}} \approx 12\,\%$$

of the real value. The uncertainty is calculated by

$$\Delta\left(\frac{c}{c_{lit}}\right) = \frac{\Delta c}{c_{lit}} \approx 0\,\%.$$

It was not possible to get a better result, because the length of the way of the laser beam is limited by the size of the laser protection box in which the experiment was made. On top of that only four mirrors were available. This limits the possible length of the way as well. On top of that the chopper frequency was limited with 20 kHz. From figure 5 follows, that with a higher chopper frequency or a longer way, higher speeds can be measured. Therefore with an expanded setup the speed of light should be measurable.

4.2.2 Square wave function

The measurement leads to

$$\frac{c}{c_{lit}} \approx (97 \pm 15)\,\%$$

of the real value. The value itself is good but the uncertainty is very high as expected after the evaluation of figure 7.

With a t-test

$$t = \frac{|\,\hat{c} - c_{lit}\,|}{\Delta c} \approx 0.18$$

the measured value is compatible with the literature value.

4.2.3 Beam splitter

With a t-test

$$t = \frac{|\,\hat{c} - c_{lit}\,|}{\Delta c} \approx 1.4$$

the the measured value is again compatible with the real value. The t-test value is not so good as the value from the previous setup. This is because the uncertainty is very small and therefore the t-test is not so good although the measured value is better with this setup. The value itself is close to the speed of light with

$$\frac{c}{c_{lit}} \approx (97.4 \pm 1.8)\,\%$$

and the uncertainty is reasonable for this setup.

It was expected to get the best result with this setup, because there should be no error coming from the connection to the oscilloscope, because the difference is only in the split way of the laser beam. Maybe the result will get even more precise with longer ways the light has to travel. Furthermore, it could help to read the times of the peaks with an error at full width half maximum.

5 Attachment

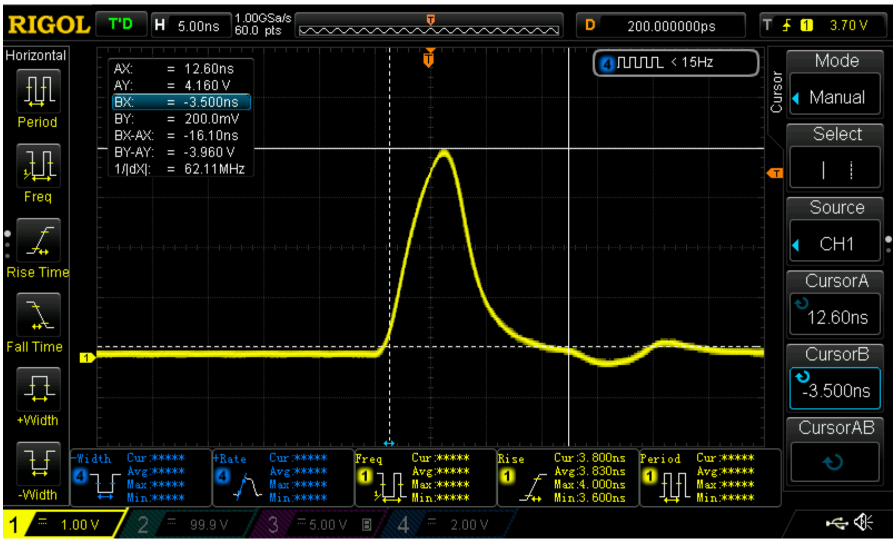


Figure 10: Thorlabs diode without amplifier

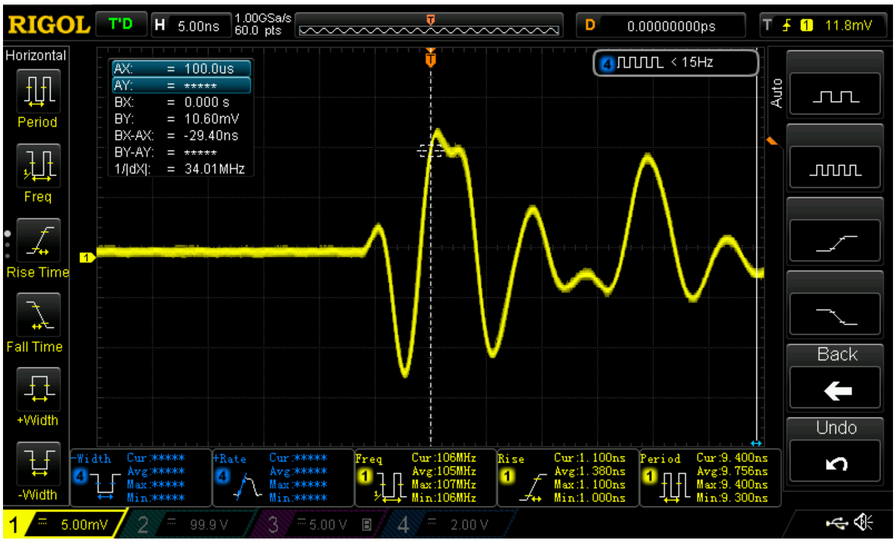
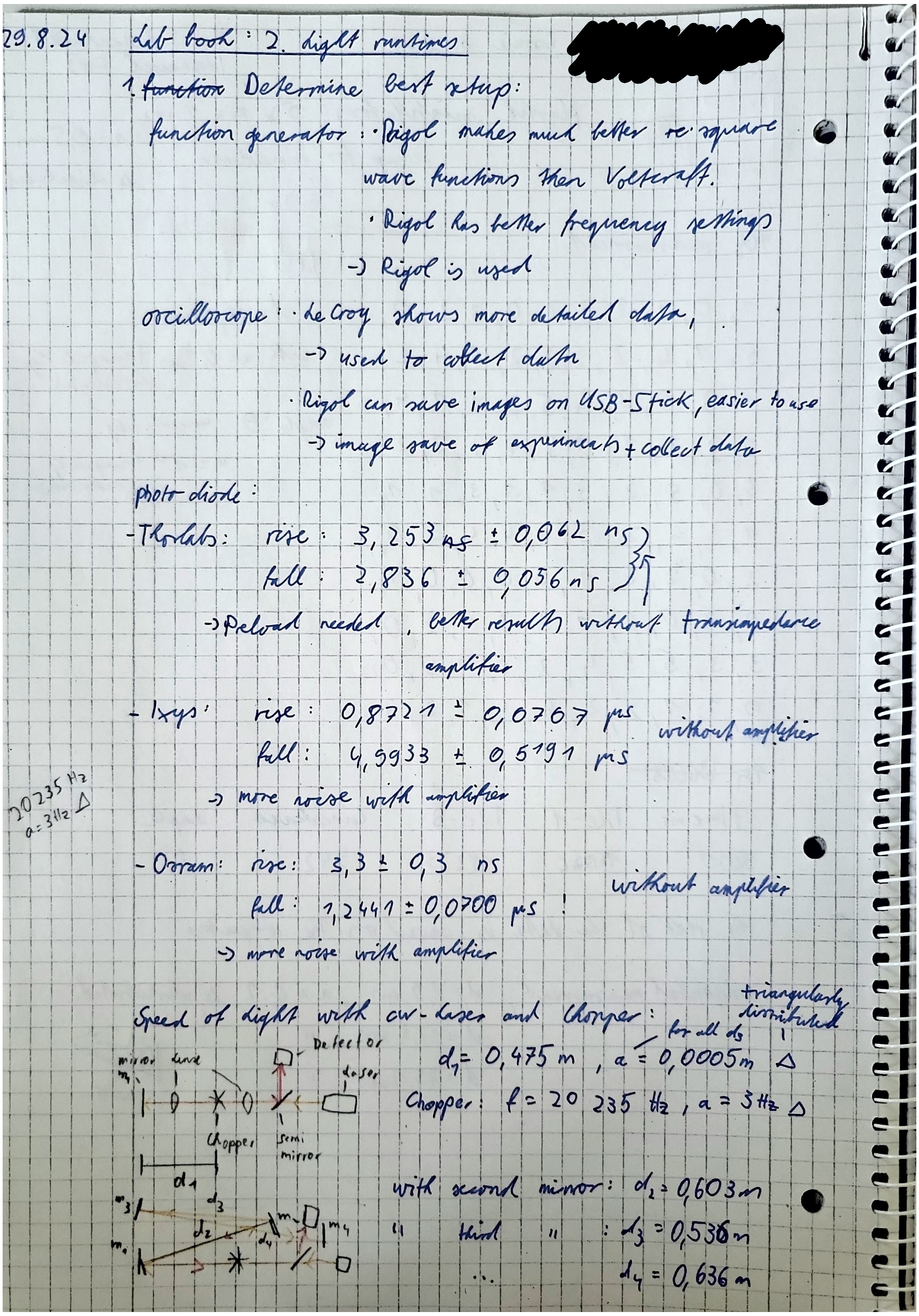


Figure 11: Thorlabs diode with amplifier

5.1 Lab book



29.8.24 Lab book: 2. Light runtimes [redacted]

1. ~~function~~ Determine best setup:

function generator: · Rigol makes much better re. square wave functions than Voltcraft.

· Rigol has better frequency settings

-> Rigol is used

oscilloscope: · LeCroy shows more detailed data,

-> used to collect data

· Rigol can save images on USB-Stick, easier to use

-> image save of experiments + collect data

photo diode:

- Thorlabs: rise: 3,253 ns ± 0,062 ns
  fall: 2,836 ± 0,056 ns

  -> Preload needed, better results without transimpedance amplifier

- Ixys: rise: 0,8721 ± 0,0707 µs
  fall: 4,9933 ± 0,5191 µs
  without amplifier

  -> more noise with amplifier

20235 Hz
a = 3 Hz △

- Osram: rise: 3,3 ± 0,3 ns
  fall: 1,2441 ± 0,0700 µs !
  without amplifier

  -> more noise with amplifier

Speed of light with cw-laser and Chopper:

mirror m_1, lense, Chopper, semi mirror, Detector, laser

d_1, d_2, d_3, d_4, m_1, m_2, m_3, m_4

$d_1 = 0,475$ m, a = 0,0005 m △ (for all ds, triangularly distributed)

Chopper: f = 20 235 Hz, a = 3 Hz △

with second mirror: $d_2 = 0,603$ m

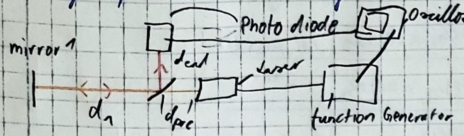
" third " : $d_3 = 0,536$ m

$d_4 = 0,636$ m

...

2

2. Lightspeed with through function generator pulsed Laser



$d1 = \cancel{60,7cm}$ 57,6cm

d_2 = 73,3 cm

d_3 = 73,2 cm

d_4 = 77,6 cm

d_{end} = 18,3 cm

d_{pre} = 4,5 cm

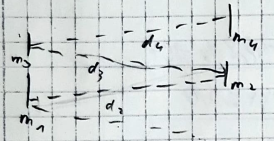
Laser trigger Delay: 35ns ± 5ns

(Triggered: -60,6 ns to -54,6 ns
measured: -3,6 ns to 3,2 ns)
↳ problems with cables

	$d_{pre} + d_1 + d_{end}$	$+ d_2$	$+ d_3$	$+ d_4$
triggered: (vs square current)	-2,8 ns to 7,2 ns	same	same	-65,4 to -55,8
measured: (laser peak)	43,8 ns to 50,2 ns	48,6 - 55,0 ns	53,6 - 60,0 ns	-4,0 to 2,0 ns

$a_{Oscilloscope}$ = 0,05 ns

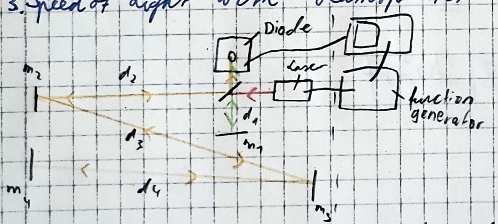
□ - distributed square



square wave voltage:
f = 50 000 kHz

measured with ~~Lecr~~ Rigol oscilloscope

3. Speed of light with beamsplitter



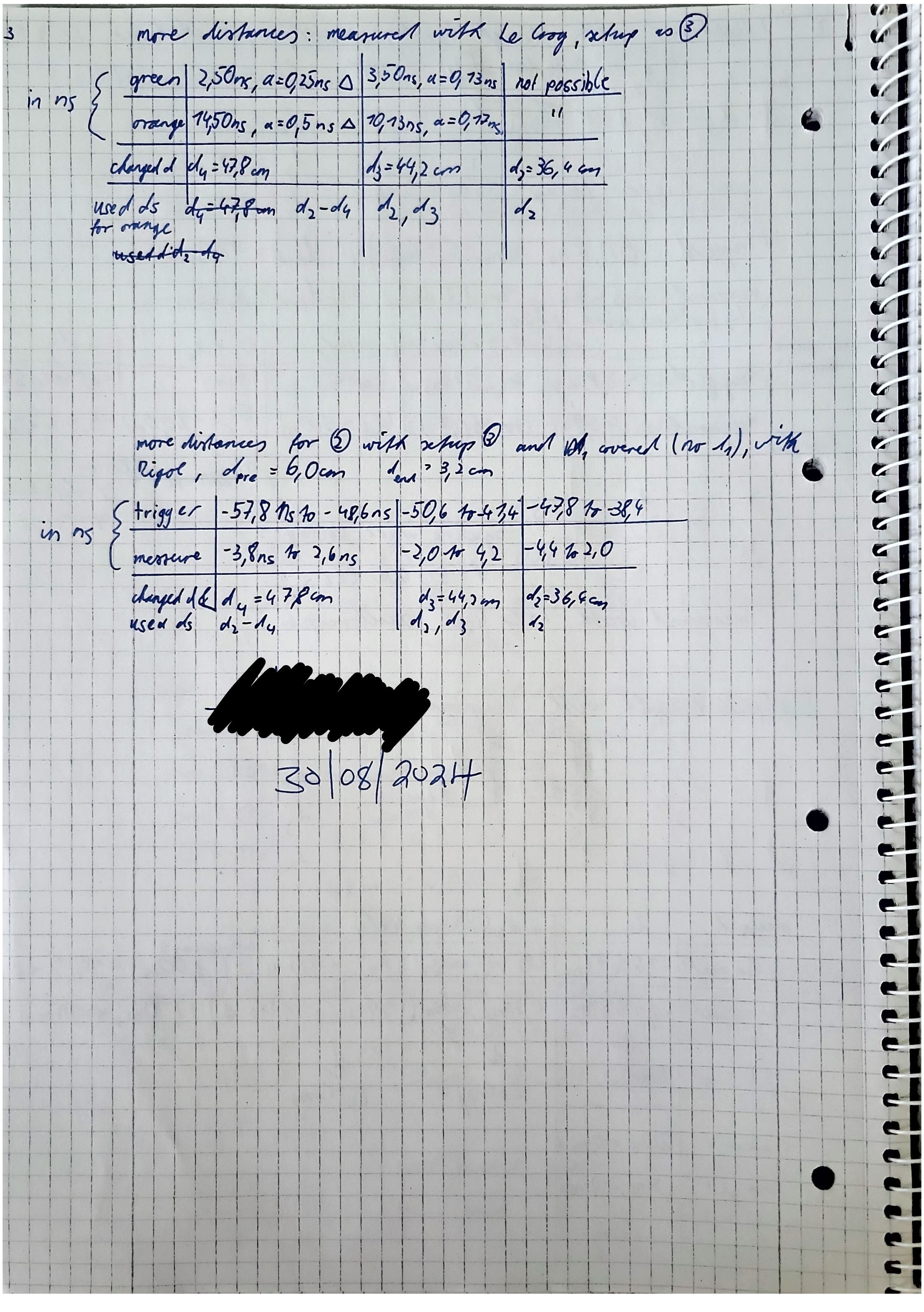
d_1 = 3,6 cm

d_2 = 58,9 cm

d_3 = 82,2 cm

d_4 = 80,7 cm

orange d	d_2	$+ d_3$	$+ d_4$	better settings →
green peak	-1,6 to 3,3 ns	2,85 ns, α = 0,15 ns Δ	(2,7 ns, α = 0,3 ns Δ)	3,00 ns, α = 0,15 ns Δ
orange peak	-1,1 to 3,8 ns	12,20 ns, α = 0,15 ns Δ	(17,0 ns, α = 0,3 ns Δ)	17,10 ns, α = 0,15 ns Δ
	↓ Rigol	↓ LeCroy	↓ Le Croy	
green "	0,20 ns, α = 0,4 ns Δ			
orange "	2,25 ns, α = 0,2 ns Δ			
	↓ Le Croy			



3

more distances: measured with Le Croy, setup as 3

in ns			
green	2,50ns, α=0,25ns Δ	3,50ns, α=0,13ns	not possible
orange	14,50ns, α=0,5ns Δ	10,13ns, α=0,17ns	"
changed d	d_4=47,8cm	d_3=44,2cm	d_2=36,4cm
used ds for orange	~~d_4=47,8cm~~ d_2-d_4	d_2, d_3	d_2

~~used d d_2 d_4~~

more distances for 2 with setup 3 and ~~[illegible]~~ covered (no d_1), with Rigol, d_{pre} = 6,0cm d_{end} = 3,2cm

in ns			
trigger	-57,8ns to -48,6ns	-50,6 to -41,4	-47,8 to -38,4
measure	-3,8ns to 2,6ns	-2,0 to 4,2	-4,4 to 2,0
changed ds	d_4=47,8cm	d_3=44,2cm	d_2=36,4cm
used ds	d_2-d_4	d_2, d_3	d_2

[redacted]

30/08/2024

Figure 12: Lab book

literature

[1] E. Optics. “Optischer chopper edmund optics.” (May 13, 2024), [Online]. Available: https://ilias.uni-freiburg.de/goto.php?target=file_3498705_download&client_id=unifreiburg (visited on 08/28/2024).

[2] Thorlabs. “Npl series of nanosecond pulsed lasers user guide.” (May 13, 2024), [Online]. Available: https://ilias.uni-freiburg.de/goto.php?target=file_3498711_download&client_id=unifreiburg (visited on 08/28/2024).

[3] S. Navas *et al.*, “Review of particle physics,” *Phys. Rev. D*, vol. 110, no. 3, p. 030 001, 2024. DOI: 10.1103/PhysRevD.110.030001.