Elaboration of experiment 42
lab course

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21st February 2005

Contents

1 Introduction

1.1 Topic of the experiment

In experiment 42 we dealed with microwaves. As these waves belong to the electromagnetic radiation, they behave simmilar to light waves. So they can be refracted, polarized, reflected and they can interferre. The experiment has been done by Christian Rewitz and Andreas Messer under supervision by Charles Gould on the 16.11.2004 at the university of Würzburg / Institute of Physics. The microwaves used in experiment have been generated by a Gunn-Diode. At the beginning we measured the angular dispersion of this microwave generator. Next we determined the focal length of a given wax lens. This was not easy because of standing waves created by reflections at the walls. After that we used the method of standing waves and then a Michelson interferrometer to quantify the wavelength of the microwaves. Then we examined the tunnel-effect of waves. This is much more easy using microwaves than using light because of the larger wavelength. Second last we looked into with polarization. At the end we used diffraction of microwaves to determine the lattice constant of a huge 'crystal'. This shows how waves (today x-rays) can be used to examine crystals or materials.

A problem during all measurements were the reflections of the microwaves at almost every object in the laboratory. Due to this fact, the error of the measured intensity was always estimated from the fluctuation of the meter gauge.

1.2 Theory

1.2.1 Maxwell equations and electromagnetic waves

The Maxwell equations cover anything about electrodynamics. They describe the behavior of electric and magnetic fields:

$$\begin{aligned} \nabla \cdot \vec{D} &= \rho & \qquad \nabla \cdot \vec{B} &= 0 \\ \nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} &= 0 & \qquad \nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} &= \vec{J} \end{aligned}$$

In vacuum ($D = \varepsilon_0 E$ and $B = \mu_0 H$) and with $\rho = 0$ and $\vec{J} = 0$ we get

$$\nabla \cdot \vec{E} = 0 \qquad (1.1)$$

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 \qquad (1.2)$$

$$\nabla \cdot \vec{B} = 0 \qquad (1.3)$$

$$\nabla \times \vec{B} - \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} = 0 \qquad (1.4)$$

Now combining the rotation of (1.2) with the time derivative of (1.4) and vice versa leads to

$$\begin{aligned}\nabla^2\vec{E}-\frac{1}{\mu_0\varepsilon_0}\frac{\partial^2}{\partial t^2}\vec{E} &= 0\\ \nabla^2\vec{B}-\frac{1}{\mu_0\varepsilon_0}\frac{\partial^2}{\partial t^2}\vec{B} &= 0\end{aligned}$$

These differential equations are called wave equations. They describe a wave propagating with velocity $c=1/\sqrt{\mu_0\varepsilon_0}$. One possible solution of the wave equation is an exponential function

$$\vec{E}\left(\vec{x},t\right)=\vec{E}_0\cdot e^{i\left(\vec{k}\vec{x}\mp ct\right)}$$

and a similar one for B field. The $\vec{k}$-vector describes the direction of propagation of the wave. The minus sign describes a wave propagating in direction of $\vec{k}$ and the positive sign stands for a propagation-direction opposite to $\vec{k}$. It can be shown from the Maxwell equations, that $\vec{E}$, $\vec{B}$ and $\vec{k}$ are perpendicular to each other.

1.2.2 The Gunn-Effect

To generate the microwaves in experiment, a Gunn-Diode oscillator was used. This semiconductor device utilizes the so called transferred-electron effect, where electrons move from a low energy conducting band to a higher energy conducting band, if the applied electrical field is strong enough. (Fig. 1.1) But in the higher energy band, the

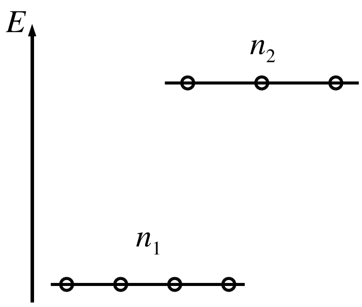

Figure 1.1: Gunn-Diode - different energy conducting bands in a semiconductor

mobility of the electrons is smaller than in the low energy band. This leads to a higher resistance of an area in the device, where many electrons are in the higher band and less in the lower. This implies a higher voltage drop at this area. (see Fig. 1.2) So the current near this aread rises, which leads again to a higher voltage drop. Now, the electric field is strong enough, to excite electrons near the area into the higher band, and so the area grows perpendicular to the direction of the current. Now there is an area with higher resistance reaching from one side of the device to the other. This causes an accumulation of negative charges in front of the area and a lack of negative charges

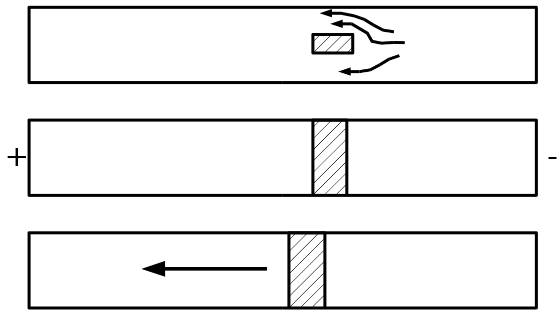

Figure 1.2: Gunn-Diode - Area of low mobility growing and moving (from [3, Chap. 11])

at the end of the area. The applied electrical field forces the charges to move towards the positive connection an so the area moves from one side to the other. When the area reaches the positive connection a current is induced into the circuit connected to the device. As the current and the potential are phase shifted, a wave is radiated.

For a more detailed information on this topic please refer to [3] or [4].

1.2.3 Basics on crystal structure and diffraction

Crystals are made of identical building blocks (e.g. atoms or molecules). These units are arranged as an array, which can described by the three fundamental translation vectors $\vec{a}$, $\vec{b}$ and $\vec{c}$ (from [2, chap. 1]). These vectors define the position of the building-blocks in respect to the next building blocks. Imagine a block at position $\vec{x}$, then the position of each block can calculated using (1.5).

$$\vec{x}' = \vec{x} + n_1\vec{a} + n_2\vec{b} + n_3\vec{c} \tag{1.5}$$

with n_1, n_2 and n_3 as arbitrary integers. This is shown in fig. 1.3. Planes within the crystals can be defined using equation (1.5). E.g. 100-plane refers to a plane which is parallel to $\vec{a}$

The regular placement of the building blocks can be used to determine the translation vectors: Incoming waves are diffracted at the blocks and inteferre with each other. So the intensity of the reflected ray depends on the angle of incidence of the incident ray (see fig. 1.4). Now the translation vectors can be calculated from the angles, where intensity maximas occur, and from the wavelength. For an interference maxima the dif ference of paths must be an even multiple of the wavelength.

$$2d\sin(\Theta) = n\lambda \tag{1.6}$$

This equation is also know as Bragg law ([2, chap. 2]). In experiment we used a cubic 'crystal', therefor all translationvectors are perpendicular and have the same length a. This length can now easily obtained using d and the examined plane

$$a = d \cdot \sqrt{n_1^2 + n_2^2 + n_3^2} \tag{1.7}$$

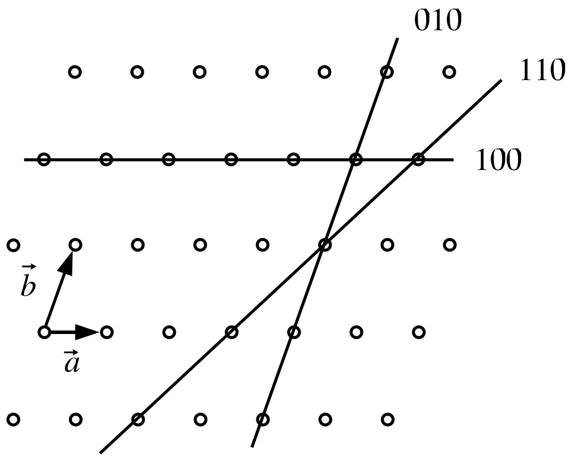

Figure 1.3: crystal - translationvectors of a crystal lattice. (only $\vec{a}$ and $\vec{b}$ shown)

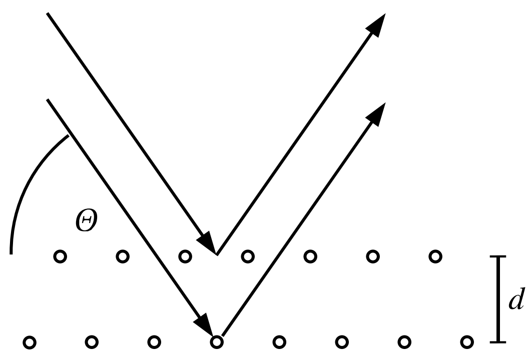

Figure 1.4: crystal - reflection and interference of waves at crystals

2 Measurements

2.1 Angular dispersion of the microwave emitter

2.1.1 Description

In this part of the experiment we examined the intensity of microwave radiation in dependence on the angle of the emitter. Figure 2.1 shows the configuration for this part of experiment . The detector was connected to a millivolt meter. The voltage

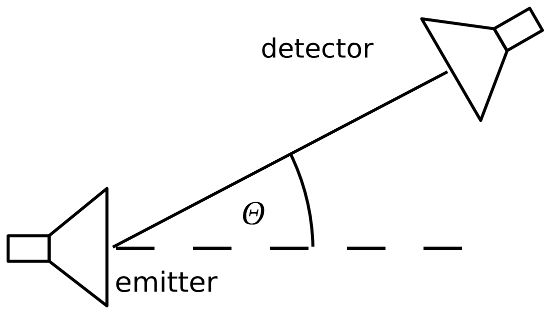

Figure 2.1: angular dispersion - schematic of experimental configuration

(proportional to intensity) has been measured for different angles.

2.1.2 Measured data

The distance between the emitter and the detector was

$$d = (50.0 \pm 1.0)\ \text{cm}$$

(measured with a ruler). The pairs of angle and measured voltages are shown in table 2.1. The maximum seems to be at zero degrees.

2.1.3 Evaluation

For further evaluation the voltage versus angle is plotted into a polar diagram. (fig 2.2) To find a function which can be fitted to the curve, I have plotted the data as a normal linear plot, which is not shown here. From this plot I supposed that a Gaussian distribution would match the measured values.

$$U = U_0 \cdot e^{-\left(\frac{\Theta}{a}\right)^2} \tag{2.1}$$

With the help of *gnuplot*[1] the following parameters have been determined:

$$\begin{aligned} U_0 &= (8.457 \pm 0.042)\ \text{mV} \\ a &= (19.05 \pm 0.11)^\circ \end{aligned}$$

The sum of squares of residuals was 0.031, so I think this is a good aproximation. To

[1]http://www.gnuplot.info

$\Theta/°$	U/mV
-30	0.80 ± 0.03
-20	2.80 ± 0.05
-10	6.4 ± 0.1
0	8.5 ± 0.1
10	6.4 ± 0.1
20	2.75 ± 0.05
30	0.76 ± 0.02
40	0.20 ± 0.02
50	0.058 ± 0.005
60	0.04 ± 0.03
70	0.016 ± 0.005
80	0.010 ± 0.005
90	0.008 ± 0.003

Table 2.1: angular dispersion - angles and measured voltages (error is estimated due to fluctuations of the voltmeter gauge)

get the the half-width angle, we can use equation (2.1) and the fitted parameters:

$$\begin{aligned} U_0/2 &= U_0 \cdot e^{-\left(\frac{\Theta}{a}\right)^2} \\ \Rightarrow \Theta_{1,2} &= \pm a \cdot \sqrt{\ln 2} \\ \Rightarrow \Delta\Theta_{1,2} &= \pm \Delta a \cdot \sqrt{\ln 2} \end{aligned}$$

Thus the half-width angle ($\phi = 2 \cdot \Theta$) is

$$\phi = (31.72 \pm 0.18)^\circ \,.$$

The deviation of the angle is very small, I suggest to small. One mistake is, that I have neglected the deviation of the angle (because I had no information about the precision of the goniometer).

As the half-width angle is very small, most of microwave intensity is emitted in forward direction.

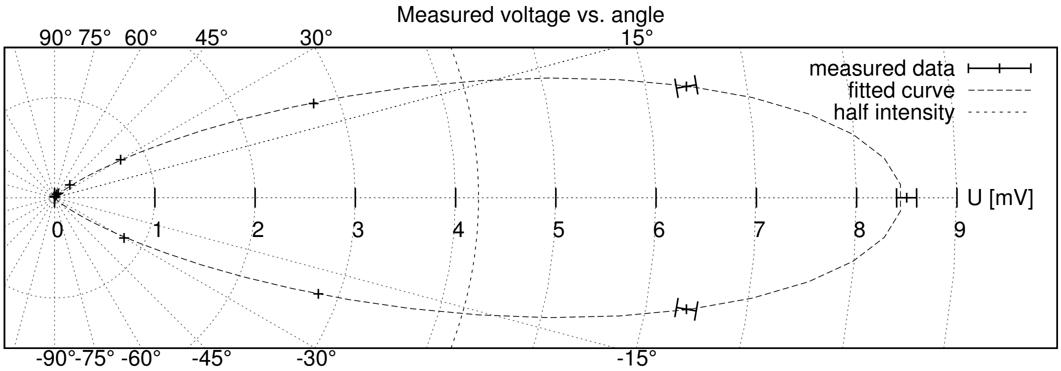

Figure 2.2: angular dispersion - polar diagram showing the measured intensity, a fitted Gaussian curve and a half intensity line.

2.2 Focal length of a wax lens

2.2.1 Description

For microwaves exist materials with different propagation speeds. So wax has a higher refraction indice than air for microwaves. This can be used to build a lens.

The task was to determine the focal length of a wax lens. As this lens follow the same law known from geometrical optics,

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{g}, \tag{2.2}$$

the focal length f can be calculated from the object distance g and the image distance b. For experiment the configuration shown in fig. 2.3 has been used.

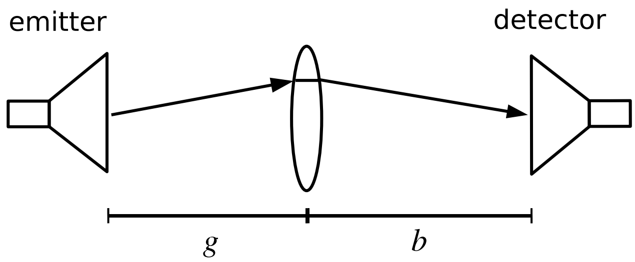

Figure 2.3: wax lens - configuration for determining the focal length

At first we tried to use the method described in the manual [1] to determine a (g, b)-pair. It turned out, that this method was not suitable because of standing waves created by reflection of microwaves at the walls. So we decided to use another way: We moved the detector until we got a maximum signal. Now we measured b. We have done this for different object distances g.

2.2.2 Measured data

The error of distances is estimated due to the fluctuations of signal intensities. Also it was not easy to determine the real location of the lens because of its big frame. The measured values are shown in table 2.2.

index	g/cm	b/cm
1	80 ± 1	61 ± 1
2	60 ± 1	79 ± 1
3	70 ± 1	62 ± 1
4	50 ± 1	66 ± 1

Table 2.2: wax lens - measured values

I omitted the measured data wich was obtained using the method of the manual because it is not needed (see appendix A).

2.2.3 Evaluation

Using (2.2) we get

$$\begin{aligned} f &= \frac{gb}{g+b} \\ \Delta f &= \pm\sqrt{\left(\frac{b}{g+b}\right)^4 (\Delta g)^2 + \left(\frac{g}{g+b}\right)^4 (\Delta b)^2} \end{aligned}$$

for focal lens and its error. Using this equations the focal lengths listed in table 2.3 are calculated.

index	f/cm
1	34.61 ± 0.37
2	34.10 ± 0.37
3	32.88 ± 0.36
4	28.45 ± 0.37

Table 2.3: wax lens - calculated focal lengths

Using the four focal lengths the mean value and standard deviation was calculated. So the focal length of the wax-lens is

$$f = (32.5 \pm 1.4)\ \text{cm}$$

2.2.4 Error analysis

The major error during measurement was made due to the standing waves created by reflection of the waves at the wall. We thought this leads to an error in the measured distances of about quarter the wavelength. Putting some diffracting material on the walls would help to get better results.

2.3 Determining the wavelength of microwaves

2.3.1 Description

We used two different methods to determine the wavelength. The first method uses standing waves (figure 2.4). Here a mirror reflects the wave and so a standing wave is

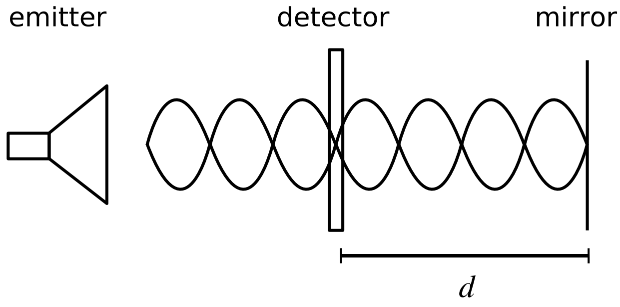

Figure 2.4: wavelength - configuration using standing waves

created. We move the detector in front of the mirror. Now while moving the detector away from the mirror, we counted the minima. The wavelength is calculated from the distance d and the number of minima.

Figure 2.4 shows the Michelson interferometer, which was the second method for determining the wavelength. Here the half-mirror splits the beam into two beams. One

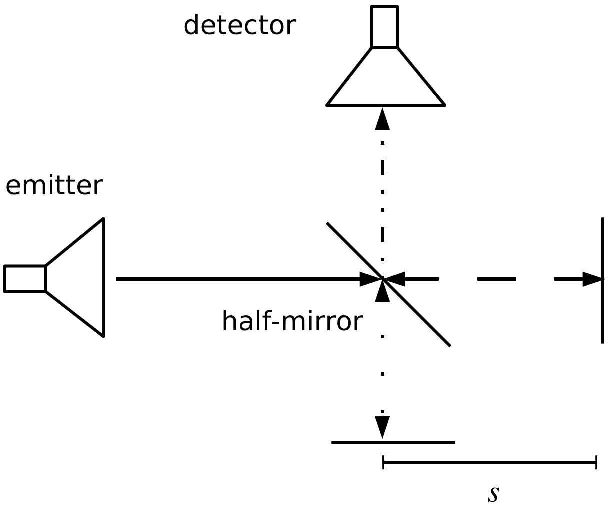

Figure 2.5: wavelength - configuration using Michelson interferometer

of the beams has to travel twice the path length s. The path length of the second path is unchangeable. After traveling their paths, the two beams are joined with the half-mirror, interfere and then hit the detector. If s is varied the difference between the paths is also changed which leads to a different phase difference and we can detect intensity maxima and minima. So when we move the mirror we can count the minima or maxima. Together with the difference of paths $\Delta s = s_1 - s_2$ the wavelength could calculated.

2.3.2 Measured data

We started our experiment with the standing wave. We used a different detector, which had the shape of a rod for this measurement. The distance d was measured using the ruler included in the bench. As we had also the problem of standing waves created by reflection of the wave at the wall we estimated the deviation of distance. We took three pairs of data (table 2.4).

index	count of minima	d/cm
1	30	55.0 ± 0.5
2	40	75 ± 1
3	50	95 ± 1

Table 2.4: wavelength - standing wave measured data

Using the Michelson interferometer we took also three measurement records (tab. 2.5). Here the distance was measured using a ruler with an deviation of ± 0.1 cm and we counted the maxima.

index	count of maxima	s_1/cm	s_2/cm
1	5	31.3 ± 0.1	23.5 ± 0.1
2	10	31.3 ± 0.1	15.8 ± 0.1
3	15	31.3 ± 0.1	8.0 ± 0.1

Table 2.5: wavelength - Michelson interferometer measured data

2.3.3 Evaluation

I start with the standing wave experiment. As we have a closed end reflection at the mirror we get

$$\begin{aligned} \lambda &= 2\frac{d}{\text{count}} \\ \Delta\lambda &= \pm 2\frac{\Delta d}{\text{count}} \end{aligned}$$

for wavelength and deviation. This leads to table 2.6. The mean value of the wavelength determined with the standing wave configuration is

$$\lambda = (3.739 \pm 0.039)\ \text{cm}.$$

index	λ/cm
1	3.667 ± 0.033
2	3.750 ± 0.050
3	3.800 ± 0.040

Table 2.6: wavelength - standing wave wavelengths

For the Michelson interferometer we have to look at the path differences. So

$$\begin{aligned}\lambda &= 2\frac{s_1 - s_2}{\text{count}} \\ \Delta\lambda &= \pm\frac{2}{\text{count}}\sqrt{(\Delta s_1)^2 + (\Delta s_2)^2}\end{aligned}$$

leads to the wavelength. Using the data of table 2.7 we obtain

index	$s_1 - s_2$/cm	λ/cm
1	7.80 ± 0.14	3.120 ± 0.056
2	15.50 ± 0.14	3.100 ± 0.028
3	23.30 ± 0.14	3.107 ± 0.019

Table 2.7: wavelength - michelson interferometer wavelength

$$\lambda = (3.1090 \pm 0.0059)\ \text{cm}$$

for the wavelength.

2.3.4 Error analysis

The deviation of both wavelenghts is very small but the difference between both wavelengths is greater than the sum of deviations. I think the result of the standing wave experiment is wrong. In table 2.6 the wavelength increases with increasing distance d. This seems to be a systematic error. Perhaps we have another standing wave created by reflections at the wall. So the wave length of the microwaves is

$$\lambda = (3.1090 \pm 0.0059)\ \text{cm}.$$

2.4 Total internal reflection and tunneling

2.4.1 Description

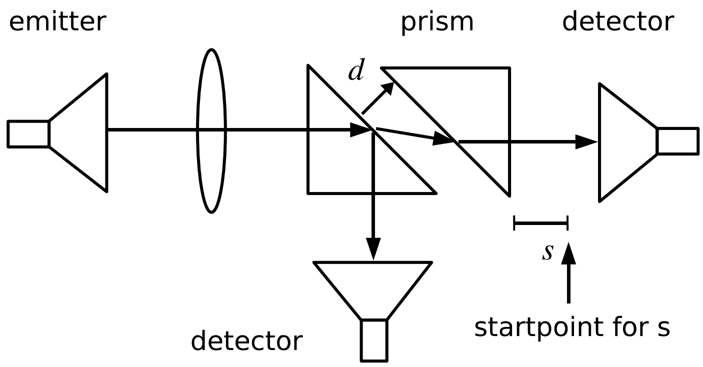

Figure 2.6: prisms - configuration

In this part of experiment we send microwaves to two prisms made of wax. The wave is focused with a lens into the first prism and hits a by 45 degrees rotated surface (see figure 2.6). Here the beam is reflected because the angle of incidence is greater than the limit for total internal reflection. When we move the second prism with its surface near the first prism, a part of the wave can travel through the slit to the second prism. Within the slit no electric or magnetic field can be measured - the field is 'imaginary'. We measured the intensity of the reflected and transmitted beam.

2.4.2 Measured data

At first we measured the intensity of the transmitted beam at different lengths s. Then we measured the intensity of the reflected beam for same s. Measured data is recorded in table 2.8. The deviation of the voltage was estimated while measuring.

2.4.3 Evaluation

For evalution I will omitt the deviation, because I don't need it for further discussion. At first we have to prepare the measured data. We calculate the real distance d between the two prisms

$$d_n = \frac{s[1] - s[n]}{\sqrt{2}}$$

and the relative intensities

$$R_n = \frac{U_r[n]}{U_r[13]} \text{ and } T_n \frac{U_t[n]}{U_t[1]}$$

(table 2.9) and plot the data. From table 2.8 we see, that the maximum intensity for

index	s/cm	U_t/mV	U_r/mV
1	15.5 ± 0.1	13.7 ± 0.1	0.00 ± 0.00
2	15.0 ± 0.1	16.5 ± 0.5	1.8 ± 0.1
3	14.5 ± 0.1	10.8 ± 0.3	4.5 ± 0.2
4	14.4 ± 0.1	9.2 ± 0.2	4.8 ± 0.2
5	14.3 ± 0.1	7.5 ± 0.2	5.50 ± 0.01
6	14.2 ± 0.1	6.2 ± 0.2	6.0 ± 0.2
7	14.1 ± 0.1	4.8 ± 0.2	6.1 ± 0.1
8	14.0 ± 0.1	4.3 ± 0.2	6.5 ± 0.1
9	13.5 ± 0.1	2.2 ± 0.1	8.5 ± 0.1
10	13.0 ± 0.1	2.1 ± 0.1	9.7 ± 0.1
11	12.0 ± 0.1	0.90 ± 0.05	10.3 ± 0.1
12	11.0 ± 0.1	0.47 ± 0.02	10.4 ± 0.1
13	10.0 ± 0.1	0.18 ± 0.05	11.8 ± 0.1

Table 2.8: prisms - measured data ($U_t \hat{=}$ transmitted, $U_r \hat{=}$ reflected)

transmission is not $U[1]$ but $U[2]$. Nevertheless I have chosen $U[1]$ as reference value because $U[2]$ seems to be a real wrong value.

Figure 2.7 shows the transmission coefficent plotted on a lin-log scale. The data points are on a line. To explain this, we have to look at the function describing a wave. At first the wave travels until it reaches the slit between the both prisms. Here it is total reflected. Using the Maxwell equations it can be shown, that within the slit a 'imaginary' wave exists. The amplitude of this wave decreases like an exponential function with increasing distance d from the prism.

$$\vec{E'} = \vec{E} \cdot e^{-a \cdot x}$$

When reaching the second prism near the first one, the imaginary wave is 'converted' into a real wave with the amplitude of the imaginary wave at distance d. This is a very graphic explanation of the complicated physical process. The straight line in figure 2.7 is a fitted exponential curve

$$T = e^{-a \cdot x}$$

with

$$a = (0.857 \pm 0.090)\ \text{cm}^{-1}$$

calculated by *gnuplot*. The reflected signal (figure 2.8) is the incoming signal minus the transmitted signal. Here

$$R = 1 - e^{-b \cdot x}$$

describes the curve. The parameter was calculated with *gnuplot* as

$$b = (0.769 \pm 0.032)\ \text{cm}^{-1}.$$

This experiment validates the theoretical asumption of wave propagation. Here its easy to show the tunnel-effect, because of the big wavelength of microwaves compared to lightwaves.

n (index)	d_n/cm	T_n	R_n
1	0.00	1.00	0.00
2	0.35	1.20	0.15
3	0.71	0.79	0.38
4	0.78	0.67	0.41
5	0.85	0.55	0.47
6	0.92	0.45	0.51
7	0.99	0.35	0.52
8	1.06	0.31	0.55
9	1.41	0.16	0.72
10	1.77	0.15	0.82
11	2.47	0.07	0.87
12	3.18	0.03	0.88
13	3.89	0.01	1.00

Table 2.9: prisms - reflection and transmission coefficients depending on distance

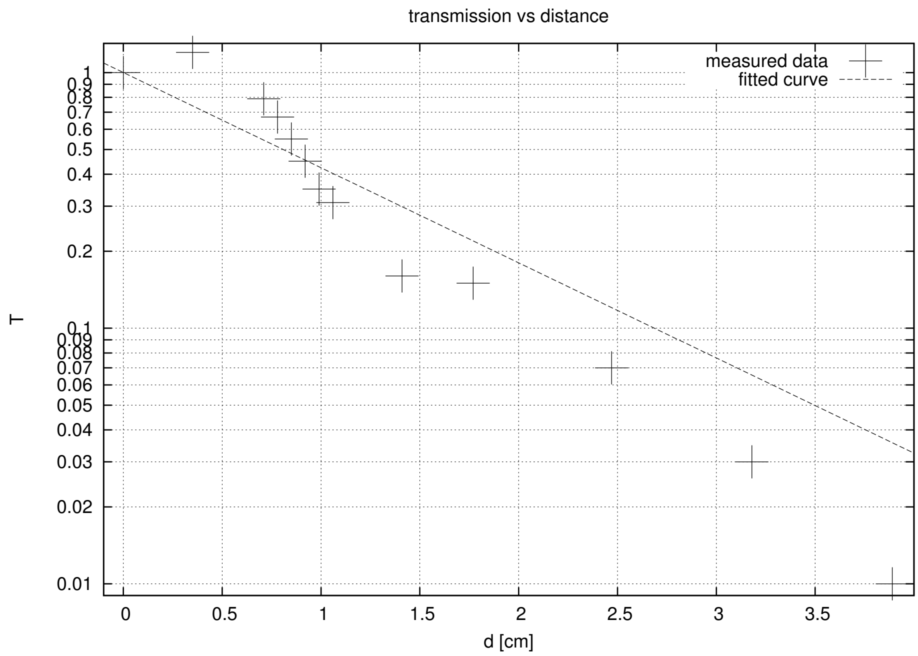

Figure 2.7: prism - transmission coefficent versus distance

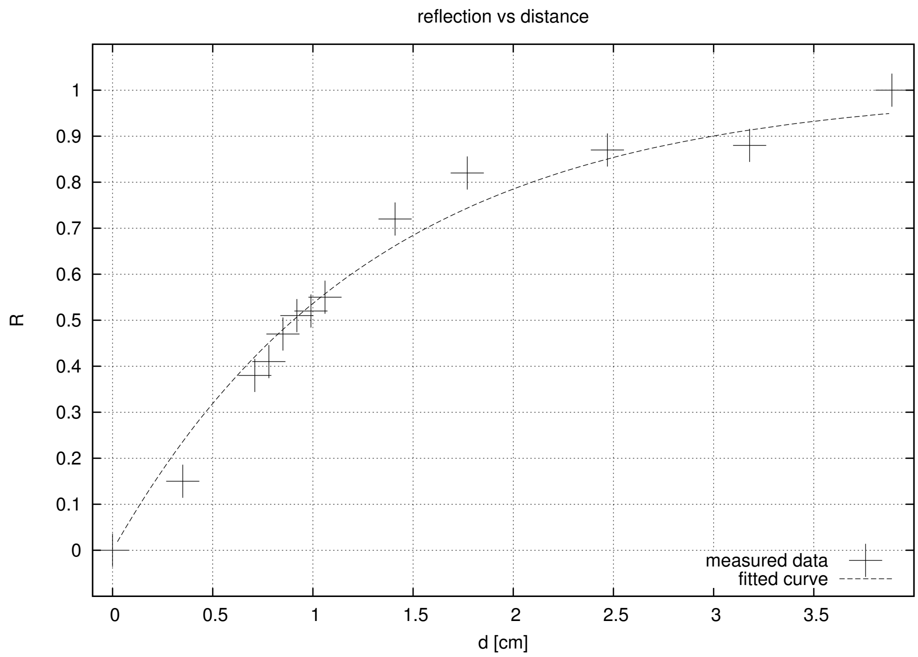

Figure 2.8: prism - reflection coefficent versus distance

2.5 Polarization of microwaves

2.5.1 Description

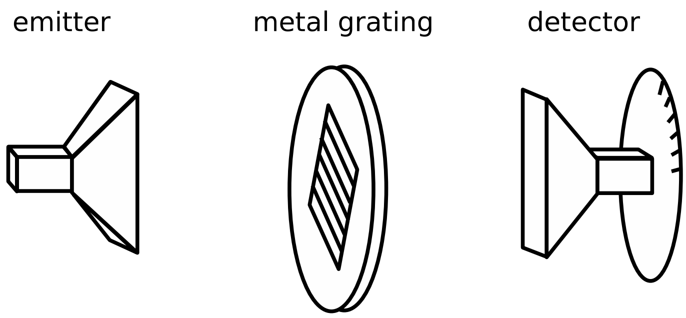

Figure 2.9: polarization - configuration for experiment

In this part of experiment we examined the polarization of the microwaves from the emitter. We used a detector which was mounted on a rotatable holder and a rotatable metal grating (figure 2.9).

2.5.2 Measured Data

At first we removed the metal grating. Now we rotated the detector until we had maximum signal. Now we inserted the metal grating such, that the slits were orientated horizontal. The signal only changes slightly. After rotating the grating by 45 degrees the intensity has decreased. Additional rotating by 45 degrees has lead to vertical oriented slits and a zero intensity.

For next measurements the detector was rotated by 90 degrees. We startet with the metal grating horizontally oriented. There was no signal. After rotating the grating by 45 degrees we get a signal which decreases with further rotating by 45 degrees (slits were vertical).

2.5.3 Evaluation

From the first part of experiment, we see that the detector detects only microwaves polarized in one direction. The metal grating polarizes/analyses the microwaves. The rods eleminate electrical fields, which are parallel to them ('short circuit'). So the microwaves must be linear and vertical polarized, because there was no signal with slits in vertical orientation. When the dector was perpendicular to the senders polarization, there was no signal with metal grating vertical (metal grating absorbs/reflects wave) and horizontal (wave can pass through grating, but detector ist perpendicular to polarization plane). With the grating at 45 degrees we had a signal because one part of the electrical field could pass through the grating and has a polarization, rotated by 45 degrees. This wave hits the detector, which has again a rotation by 45 degrees. So it can detect a part of this wave.

The magnetic field of the wave is always perpendicular to the electrical field.

2.6 Determining the lattice constant of a crystal using microwaves

2.6.1 Description

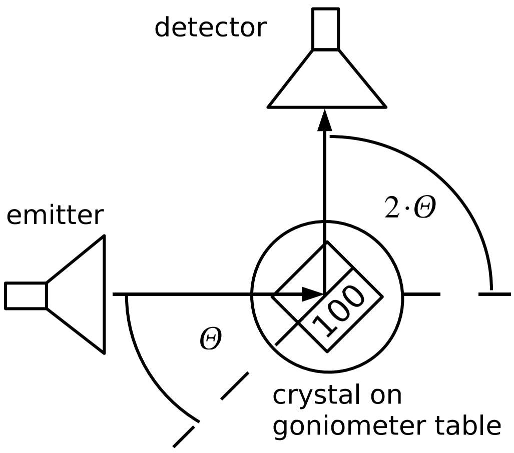

Figure 2.10: diffraction - experimental configuration

We want to determine the lattice constant of a cubic 'crystal' (it was made of styrofoam). For cubic crystals all translation-vectors are perpendicular and have the same length. Thus there is no difference for diffraction at 100, 010 or 001 plane.

The microwaves from the emitter were diffracted at the crystal and hit the detector. The intensity was measured for different angles of incidence (Θ). Then the lattice constant has been calculated using the angles of maxima of intensity, the wavelength and equations (1.6) and (1.7).

2.6.2 Measured data

We started our measurement with the 100 plane of the crystal. The deviation of Θ was neglected because there are bigger sources of errors like reflection at walls and bodys. The data of all examined planes is shown in table 2.10.

2.6.3 Evaluation

To calculate the lattice constant we have to determine the angles of maxima. The data has plotted into a diagramm and a *gnuplot* has drawn smooth curves through the datapoints. (figure 2.11, 2.12 and 2.13) From this curves the angles of maxima could be extracted. The boxes within the diagrams show the points of maxima. As the maximum of the smooth curve could be more right or more left, we can also extract an error from

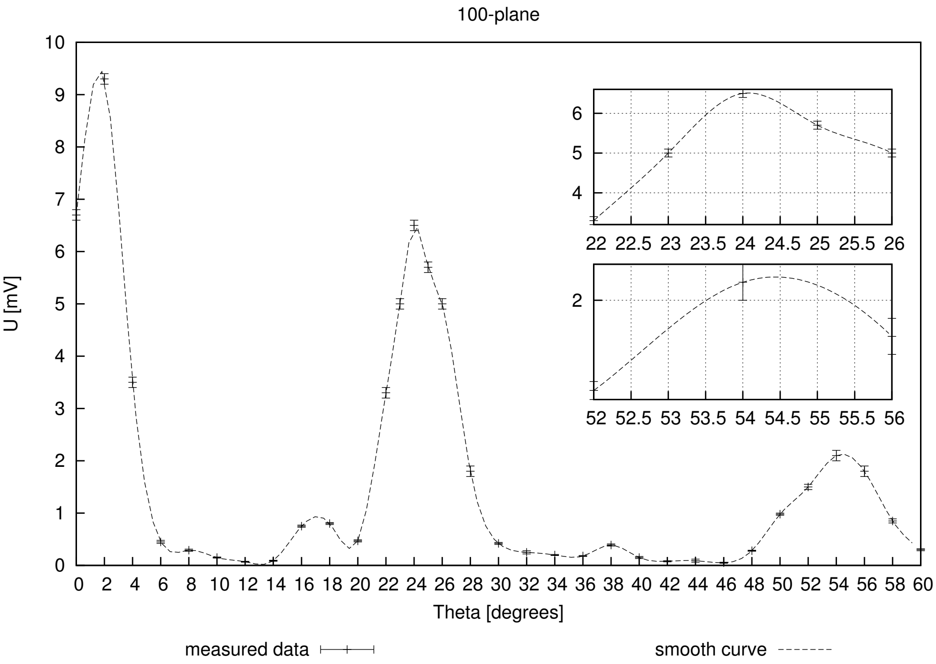

Figure 2.11: diffraction - 100 plane

the graph. For 100 plane I get

$$\begin{aligned} \Theta_1 &= (24.1 \pm 0.5)^\circ \qquad (n = 1) \\ \Theta_2 &= (54.4 \pm 0.5)^\circ \qquad (n = 2)\,, \end{aligned}$$

for 110 plane

$$\Theta_3 = (39.1 \pm 0.5)^\circ \qquad (n = 1)$$

and for 111 plane

$$\Theta_4 = (45.6 \pm 0.7)^\circ \qquad (n = 1)\,.$$

At the 111 plane someone might complain, that the greater maximum is located at about 35°. This maximum seems not to be the right one, as it leads to a lattice constant which is about 35% greater than the other ones. There is always a small maximum preceding the real maximum in graphs 2.11 and 2.12. In figure 2.13 the preceding maximum is greater than the real maximum. This might be caused by the geometry of the reflectors used in the crystal. Combining equation (1.6) and (1.7) leads to

$$\begin{aligned} a &= n \cdot \frac{\lambda \sqrt{n_1^2 + n_2^2 + n_3^2}}{2 \sin(\Theta)} \\ \Delta a &= \pm n \cdot \frac{\sqrt{n_1^2 + n_2^2 + n_3^2}}{2 \sin(\Theta)} \sqrt{(\Delta\lambda)^2 + (\lambda \cot(\Theta))^2 (\Delta\Theta)^2} \end{aligned}$$

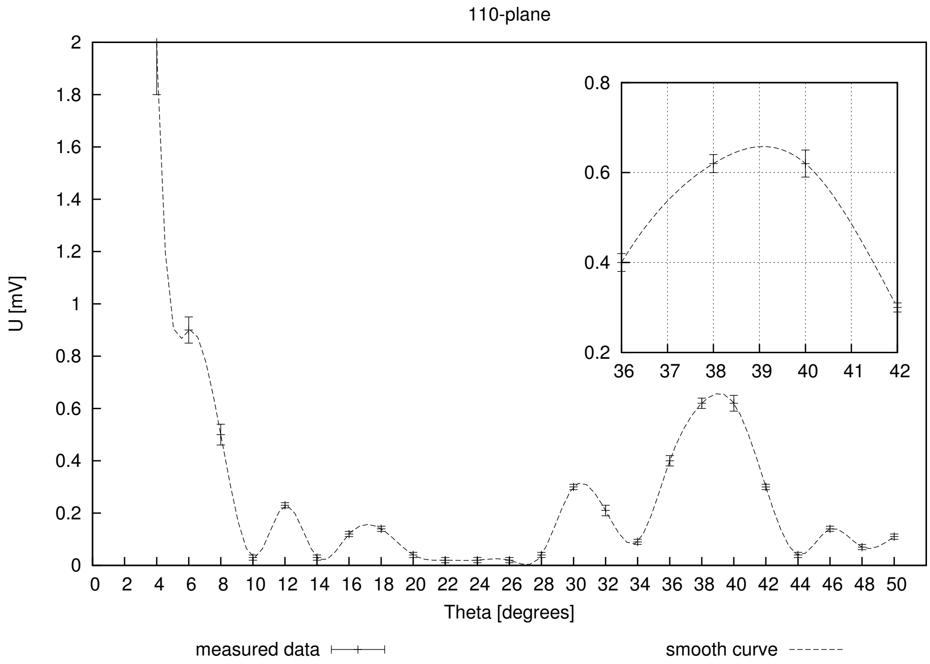

Figure 2.12: diffraction - 110 plane (without datapoints with $U \geq 2$ mV for better view)

where n describes the order of interference maximum and n_1, n_2 and n_3 describe the plane. Table 2.11 has been calculated using these equations. All lattice constants except the 110-plane one match within their deviation barriers. Nevertheless I will use all values to calculate a mean value because the error of the measured angle is not included in the deviation of the lattice constants. So the lattice constant of the crystal is

$$a = (3.721 \pm 0.079)\ \text{cm}.$$

2.6.4 Error analysis

Also at this experiment we had problems created by reflections of microwaves. As the intensity was very low even a moving experimenter influenced the meter gauge. This seems to be the most important source of measurement errors.

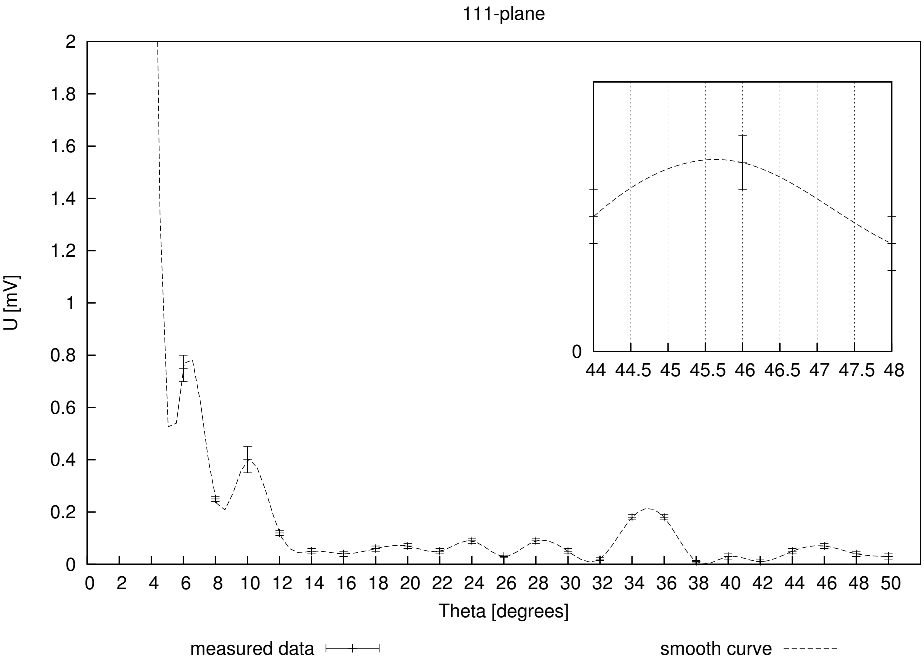

Figure 2.13: diffraction - 111 plane (without datapoints with $U \geq$ mV for better view)

$\Theta/°$	U_{100}/mV
0	6.7 ± 0.1
2	9.3 ± 0.1
4	3.5 ± 0.1
6	0.45 ± 0.03
8	0.29 ± 0.02
10	0.15 ± 0.01
12	0.07 ± 0.01
14	0.09 ± 0.01
16	0.75 ± 0.02
18	0.80 ± 0.02
20	0.47 ± 0.02
22	3.3 ± 0.1
23	5.0 ± 0.1
24	6.5 ± 0.1
25	5.7 ± 0.1
26	5.0 ± 0.1
28	1.8 ± 0.1
30	0.42 ± 0.02
32	0.25 ± 0.03
34	0.20 ± 0.01
36	0.18 ± 0.01
38	0.39 ± 0.02
40	0.15 ± 0.02
42	0.08 ± 0.01
44	0.09 ± 0.03
46	0.05 ± 0.01
48	0.28 ± 0.01
50	0.98 ± 0.02
52	1.50 ± 0.05
54	2.1 ± 0.1
56	1.8 ± 0.1
58	0.85 ± 0.04
60	0.30 ± 0.02

(a) 100-plane

$\Theta/°$	U_{110}/mV
0	9.8 ± 0.1
2	8.0 ± 0.1
4	2.0 ± 0.2
6	0.90 ± 0.05
8	0.50 ± 0.04
10	0.03 ± 0.01
12	0.23 ± 0.01
14	0.03 ± 0.01
16	0.12 ± 0.01
18	0.14 ± 0.01
20	0.04 ± 0.01
22	0.02 ± 0.01
24	0.02 ± 0.01
26	0.02 ± 0.01
28	0.04 ± 0.01
30	0.30 ± 0.01
32	0.21 ± 0.02
34	0.09 ± 0.01
36	0.40 ± 0.02
38	0.62 ± 0.02
40	0.62 ± 0.03
42	0.30 ± 0.01
44	0.04 ± 0.01
46	0.14 ± 0.01
48	0.07 ± 0.01
50	0.11 ± 0.01

(b) 110-plane

$\Theta/°$	U_{111}/mV
0	10.0 ± 0.1
2	19.8 ± 0.1
4	3.8 ± 0.1
6	0.75 ± 0.05
8	0.25 ± 0.01
10	0.40 ± 0.05
12	0.12 ± 0.01
14	0.05 ± 0.01
16	0.04 ± 0.01
18	0.06 ± 0.01
20	0.07 ± 0.01
22	0.05 ± 0.01
24	0.09 ± 0.01
26	0.030 ± 0.005
28	0.09 ± 0.01
30	0.05 ± 0.01
32	0.020 ± 0.005
34	0.18 ± 0.01
36	0.18 ± 0.01
38	0.010 ± 0.005
40	0.03 ± 0.01
42	0.01 ± 0.01
44	0.05 ± 0.01
46	0.07 ± 0.01
48	0.04 ± 0.01
50	0.03 ± 0.01

(c) 111-plane

Table 2.10: diffraction - measured data

index	a/cm	comment
1	3.807 ± 0.075	100 plane, $n = 1$
2	3.824 ± 0.025	100 plane, $n = 2$
3	3.486 ± 0.038	110 plane, $n = 1$
4	3.768 ± 0.045	111 plane, $n = 1$

Table 2.11: diffraction - calculated latice constants

2.7 Waveguiding

2.7.1 Description

The last part of experiment was about waveguiding. A metal tube was mounted at the wall and the ceilling. We put the emitter in front of one end of the tube and examined the signal at the other end.

2.7.2 Measurement

The wave travelled through the waveguide to the detector despite of the complicated trajectory of the wave guide. If we put a cap on one end of the wave guide we could not measure any signal with the detector. The wave also maintains its polarization while traveling through the waveguide.

2.7.3 Evaluation

The wave propagates in the wave guide. So even a complicated or long path doesn't balk the wave. The polarization stays unchanged within the waveguide.

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A Copies of measurement protocol

B Statement of autonomy

I assure with my sign, that I have created the present draft on my own without illegal help of other persons and that I have not used other than the specified sources.

loc., date   Andreas Messer