Day 2 March, 23

Franka Neumann
Nick Striebel

F85 Polarization optics

protocol + evaluation   In this part a laser with $\lambda =$

The goal of this part of the experiment is to understand the influence and usage of simple optic elements like polarizers, beam splitters and retarders.
The results/observations get cross-checked using the matrix-Jones-formalism

① Brewster angle

We start the experiment by reflecting the laser light using a glass plate. Doing this we search for the Brewster angle and analyse the effect of some other optical elements.

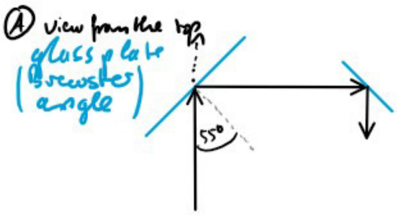
- First we approx. the Brewster-angle with $n_{glass} \approx 1.5$ and $n_{air} \approx 1$ so we get $\theta_B \approx 56°$.

To determine the Brewster angle we rotated around the approximated angle and measure the intensity of the reflected light that passes through a polarization filter that filters vertical polarized light.
Using the photo diod we search for the angle that has the lowest intensity. The angle can be fixed pricisly to get the minimum but it is hard to measure this angle good as there are no references on the elements on the table. This is why we give a very high error with $\theta_B^{exp} = (55 \pm 5)°$

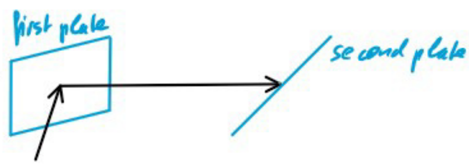
② Second glass plate

Fixing the first plate at the Brewster angle and reflect the light reflected at the first plate for a second time. The glass plates are arranged in such a way that they are perpendicular.
The result is as we expected. The beam complitly reflected (no transmission). This can be explained as the reflected light of the first plate is still perpendicular to the second one.
Doing the evalution we realize that not the plates but the planes of incidence should be perpendicular. This woud mean that the setup would look like in Ⓑ: The polarisation of the incoming light lays in the plane of incidence of the second plate ⇒ no light gets reflected

Ⓐ view from the top



Ⓑ side view



③ Polarizers

The first glass plate stays fixed and we use the reflected light to calibrate the polarizers. This means we have to find the polarization axis. This can be done using the reflection properties of the light at a surface: After the first plate fixed at the Brewster angle the polarization of the reflected light is vertically. Is the optical axis of the element under investigation vertical as-well all the light should be transmitted - Is the optical axis perpendicular to the polarisation all of the light is reflected/absorbed.

setup:

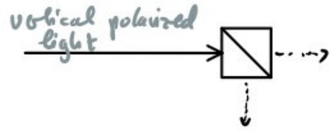
The following observations are done on two polarizers:
To get a minimum for the intensity the setting of the two polarizers were $(88 \pm 2)^\circ$ and $(89 \pm 1)^\circ$.

④ Beam splitters

In this part we figure out how the light that is reflected or passes the beam splitter is polarized and try to calibrate the types and induced polarizations of the beam splitters.
There are two BS available (one smaller cube / one larger)

small: the vertical polarized light is equally splitted in a transmitted and reflected part.

setup:

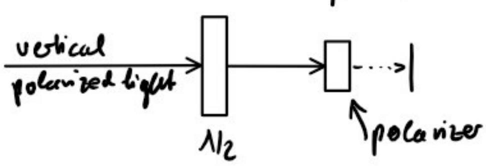


large: the BS nearly completly reflects the light (no transmission). So this is a PBS with with a horizontal optical axis.

⑤ $\lambda/2$ - waveplates

We setup a configuration to test waveplates and search for a position in which the $\lambda/2$-plate rotates the incident polarization by 90°.

setup:



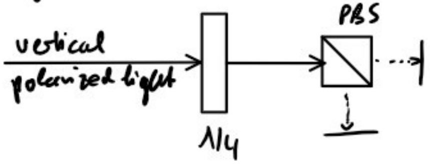
The axis of the polarizer is set to vertical with the previous results.
If the polarization of the beam is rotated by 90° nearly no light should be transmitted through the polarizer.
There are two $\lambda/2$ plates. The angles for 90° rotations are estimated with
a) $(5 \pm 2)^\circ$
b) $(-7 \pm 2)^\circ$

⑥ λ/4 - waveplates

Using the setup of ⑤ we search for a position in which the λ/4 - waveplate produces circular polarized light.

Instead of the polarizer we now use the PBS. If the light is circular polarized after the λ/4-plate the intensity of the transmitted and reflected light should be equal.

setup:



Again there are two plates.

The estimated settings for circular light are

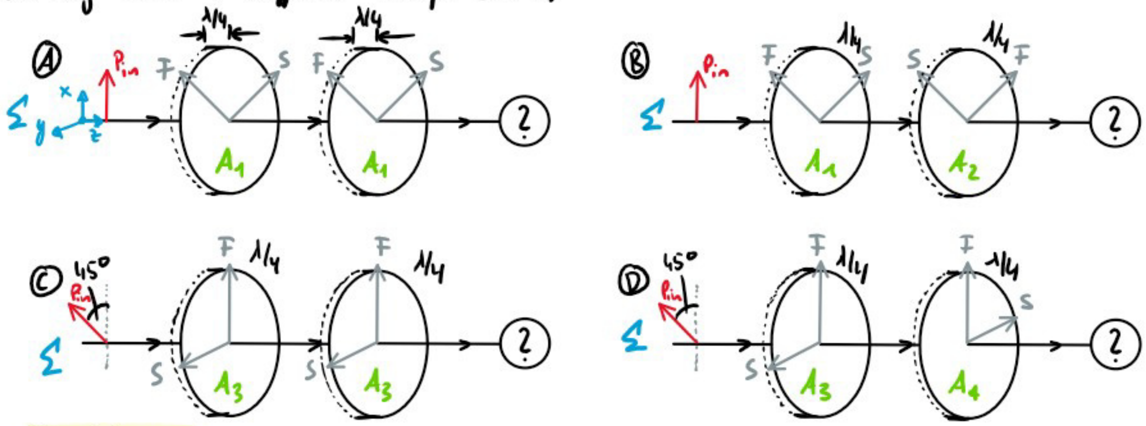
a) $(43 \pm 5)^\circ$

b) $(16 \pm 5)^\circ$

To get this value the photodiode was used to check for equal intensities. This measurement had high fluctuations. Therefor the errors are so high.

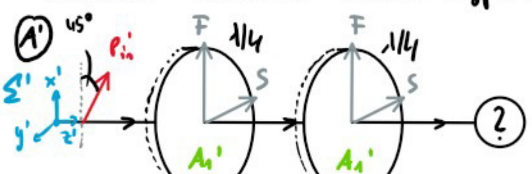
⑦ Operations of quater wave plates

Continuing working with λ/4 waveplates we analyse the effect of them working with 4 different setups (A-D)

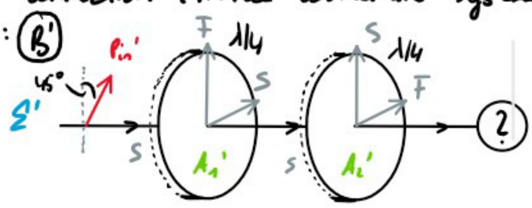


Expectations:

The first thing we recognize is that Ⓐ and Ⓒ are the same situations with the small difference that the beam direction is flipped:



This does not count for Ⓑ and Ⓓ. Rotating the second plate in Ⓒ does not change the symmetry of the plate, while in Ⓑ the flip leads to the result that the slow axis shows into the horizontal direction (in the coordinate system of the plates)



A/C/D With this preliminary considerations and the fact that $S\swarrow\!\uparrow F$ and $F\uparrow\!\nearrow S$ have the same effect due to symmetry we can view A, C and D as $\lambda/2$ - waveplates with incoming polarisation of $45°$.
In all three cases we expect that the polarization stays linear but gets rotated by $90°$.
The difference between A and C/D is that the beam direction is inverted so the $90°$ - rotations go in different directions.

B The two $\lambda/4$-plates cancel each other and only a phase shift of π will be introduced. However this is not observable.

Observations:

To check which polarization is at the end of the setup we again use a polarizer and a PBS

A The light is mainly horizontal polarized. The observation with the PBS shows that there might be a very small ellipse (this one comes from the fact, that the elements angles are not perfect (not everything is align with $90°$))

B Here the light is as expected still vertically polarized

C/D The result is the same as expected the polarization is rotated by $-90°$ (looking into beam direction to the left)

} again here might be a very thight ellipse

Jones formalism:

for A and B we do the calculus in A' and B'

A/A' $P_{in}' = \begin{pmatrix} 1 \\ -1 \end{pmatrix}$ $\quad A_1' = e^{i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$ $\quad \Rightarrow P'_{out} = e^{i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} e^{i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$

$P_{in} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$$= i\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = i\begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

The phase shift does not has an effect on the observation, so in Σ' the resulting polarisation is $P_{out}' = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$. In Σ this corresponds to $P_{out} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$.
So from the calculations we expect light polarized in horizontal direction.
This matches with our observation.

B/B' $P_{in}' = \begin{pmatrix} 1 \\ -1 \end{pmatrix}$ $\quad A_2' = R(\theta)\, A_1'\, R(-\theta)$ with $R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$ and $\theta = 90°$

$$\Rightarrow A_2' = e^{i\frac{\pi}{4}}\begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix}$$

$$\Rightarrow P_{out}' = i\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}\begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = i\begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = \begin{pmatrix} -1 \\ 1 \end{pmatrix}$$

This corresponds to $P_{out} = \begin{pmatrix} -1 \\ 0 \end{pmatrix}$. This is linear polarized light in horizontal direction, as we observed.

(C1D) As already mentioned: The flipping of the waveplate in (D) does not change the symmetry: $A_3 = A_4$. Instead of explicitly doing the calculations for the $\lambda/4$-waveplates we can handle the two plates as one $\lambda/2$-waveplate: $A_{C1D} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

This results in $P_{out} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 \\ 1 \end{pmatrix}}_{P_{in}} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}$

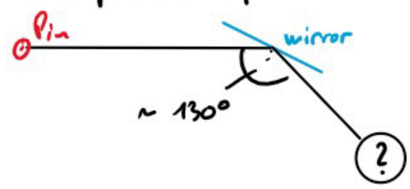
So in both cases the polarization gets rotated by 90°, as we observed.

Result: Observation, Expectation and Jones formalism agree with each other. (if we recognize that the exp. setup is not perfectly aligned)

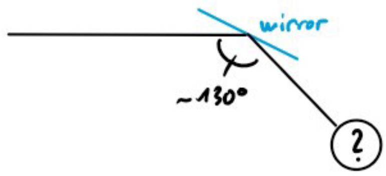
8) Reflecting linear polarized light using a mirror

We reflect linear polarized light on a mirror at a straight angle (>90°) and measure the polarization (A). After that the same is done again with a polarization perpendicular to the previous one (B).

(A) view from the top



(B) view from the top



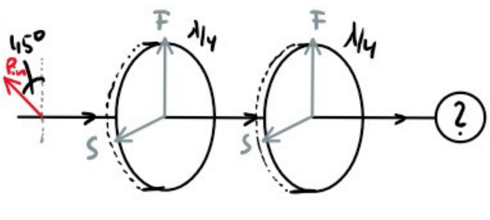
(A) P_{in}: vertical (0°), P_{out}: vertical (0°)

(B) P_{in}: horizontal (90°), P_{out}: horizontal (90° ± 20°)

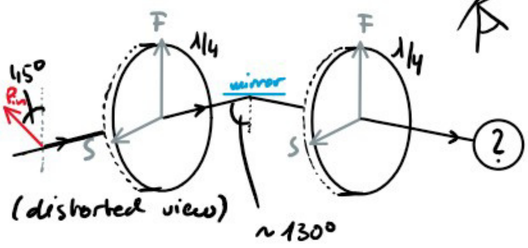
9) Quarter-wave-plates with mirror

We repeat the experiment of (7) with the wave plates oriented in such a way that there axes make an angle of 45° with the plane of polarization.
One time we measure the polarization without (A) and one time with a mirror (reflection > 90°) (B).

(A)



(B)



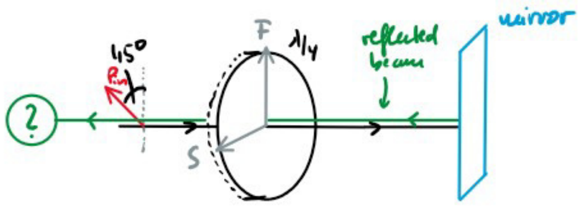
(A) The observation with already done in (7)(C)

(B) again we measure a thight ellipse but the polarization is mostly linear and rotated by ~20°.

(10) One quarter-wave-plate with parallel mirror

This time the mirror after the first $\lambda/4$-plate is perpendicular to the path of the light and we observe the polarization of the light that re-passed the $\lambda/4$-plate in the other direction

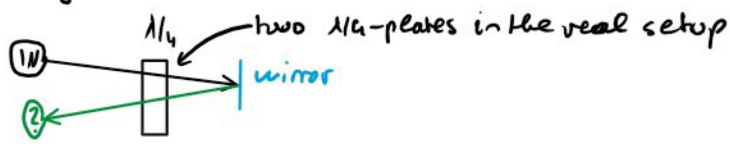
What we in theory want to measure is the following:



Unfortunately in such a setup the polarization of the reflected beam can not be measured. therefore the following setup is used:

So we setup the following (it introduces a small bias)

setup: top view:



Expectation a) If the incoming polarization is linear with $45°$ to the axes of the $\lambda/4$-plate the light is circular polarized after the $\lambda/4$ plate. The mirror changes the helicity of the polarisation. Going again through the $\lambda/4$-plate in the other direction and other helicity the same component gets slowed down again. So the polarisation in in total gets rotated by $90°$. The setup works like a $\lambda/2$-plate

b) If the incoming polarisation is circular the $\lambda/4$-plate "returns" linear polarized light. This polarization stays the same at the mirror. Going through the $\lambda/4$-plate again the polarization becomes linear again. But with inverted helicity.

Observations a) As expected incoming with $0°$ pol. ends up in $90°$ pol. (again a little bit elliptical)

b) The polarization stays circular.

Jones a) $P_{in} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$

after first pass $P_1 = e^{i\pi/4} \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = e^{i\frac{\pi}{4}} \begin{pmatrix} 1 \\ -i \end{pmatrix}$ (circular RH)

after mirror (change helicity): $P_2 = e^{i\frac{\pi}{4}} \begin{pmatrix} 1 \\ i \end{pmatrix}$ (circular LH)

after second pass $P_{out} = e^{i\frac{\pi}{4}} \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix} e^{i\frac{\pi}{4}} \begin{pmatrix} 1 \\ i \end{pmatrix} = i \begin{pmatrix} 1 \\ -1 \end{pmatrix}$

If we ignore the phase shift that is not observable this is the same result as we observed and ends up with $90°$ rotation.

b) $P_{in} = e^{i\pi/4}\begin{pmatrix}1\\ i\end{pmatrix}$

after first pass $P_1 = e^{i\frac{\pi}{4}}\begin{pmatrix}1 & 0\\ 0 & -i\end{pmatrix} e^{i\frac{\pi}{4}}\begin{pmatrix}1\\ i\end{pmatrix} = i\begin{pmatrix}1\\ 1\end{pmatrix}$

the mirror does nothing observable $P_2 = -i\begin{pmatrix}1\\ 1\end{pmatrix}$

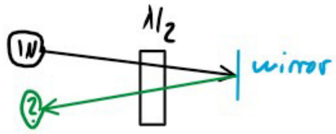
after second pass $P_{out} = e^{i\frac{\pi}{4}}\begin{pmatrix}1 & 0\\ 0 & -i\end{pmatrix}(-i)\begin{pmatrix}1\\ 1\end{pmatrix} = e^{i\frac{\pi}{4}}\begin{pmatrix}-i\\ -1\end{pmatrix}$

$\hat{=}\, e^{i\frac{\pi}{4}}\begin{pmatrix}1\\ -i\end{pmatrix}$

$\Rightarrow$ circular polarized with inverted helicity (as observed)

(11) Half-wave-plate with parallel mirror

Experiment (10) is repeated using a λ/2-waveplate.



Expectation (for linear polarised light only)

The first pass turns the pol. by 90°. The mirror again has no effect (beside a phase factor). Passing through the λ/2-plate again has the same effect as before, so in total a turn of 180°. This looks the same as 0°.

Observation The outcoming beam has a polarization with an angle of 5°. This prob. comes from the fact that the mirror is not perfectly perpendicular.

Jones $P_{in} = \begin{pmatrix}1\\ 1\end{pmatrix}$

after first pass $P_1 = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}1\\ 1\end{pmatrix} = \begin{pmatrix}1\\ -1\end{pmatrix}$

mirror does not have an observable effect

after second pass $P_2 = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}1\\ -1\end{pmatrix} = \begin{pmatrix}1\\ 1\end{pmatrix}$ $\Rightarrow$ as observed.

(12) Optical isolator

We observe the effect of the optical isolator on light of a white lamp and on the laser light.

In direction A only green light passes the filter. In direction B only red light passes the isolator. To see the isolation effect the element needs be used in direction A. This is confirmed experimental

	white lamp	laser
direction 1	green	light is blocked
direction 2	red/orange	light passes through

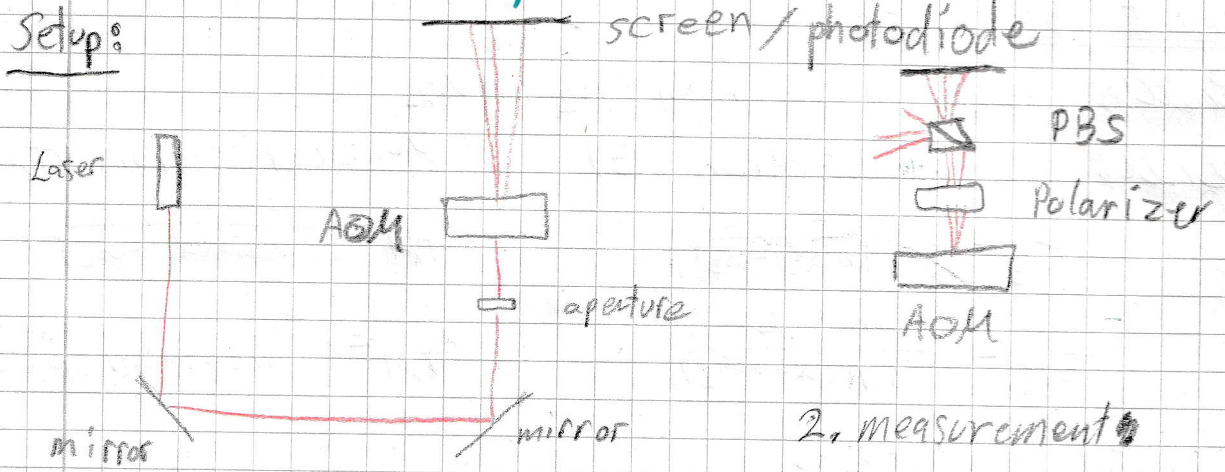
Discussion

This part of the lab is nearly qualitative. So there is no classical error discussion needed. However there are still some uncertenties doing the experiments.
First it should be mentioned that the photo-diod is very noisy. This makes the angle measurements very hard.
As mentioned before the observations are sometimes not as perfect as in the theory (small ellipse vs. perfect linear polarization). This is no surprise as for perfect results the optical elements themselves and their orientations need to be perfect.
All in all this part gives a good overview on optical elements. It is nice to see that the theoretical concepts are working in the lab.

Durchführung:

Part 3: Acousto-Optic Modulation

Setup:



3.1) **Measurement 1: Diffraction angle**

distance AOM-Screen: 41,5 ± 0,3 cm

frequency [MHz]	1st order distance	2nd order distance
95,0 ± 0,5	(7 ± 1) mm	(13 ± 1) mm
100,2 ± 0,5	(6,5 ± 1,0) mm	(13 ± 1) mm
105,0 ± 0,5		

new measurement with large screen on the wall
distance screen-AOM: d = (183,2 ± 0,5) cm
→ larger distances for smaller errors

VCO-level: internal

frequency [MHz]	d (first order) [cm]	d (2^{nd} order) [cm]
94,5 ± 0,5	2,7 ± 0,1	5,4 ± 0,1
102,0 ± 0,5	2,8 ± 0,1	5,7 ± 0,1
105,0 ± 0,5	3,0 ± 0,1	5,9 ± 0,1
110,0 ± 0,5	3,2 ± 0,1	6,2 ± 0,1
115,1 ± 0,5	3,3 ± 0,1	6,5 ± 0,1
120,0 ± 0,5	3,4 ± 0,1	6,7 ± 0,1
125,0 ± 0,5	3,5 ± 0,1	6,9 ± 0,1
129,8 ± 0,5	3,6 ± 0,1	7,2 ± 0,2
134 ± 1	3,8 ± 0,1	maximum not visible anymore

Measurement 2:

frequency [MHz]	1st ord.	~~2nd~~ 1st order
94,8 ± 0,3	1,90 ± 0,05 V	1,47 ± 0,02 V
100,2 ± 0,3	3,06 ± 0,05 V	1,88 ± 0,05 V
105,1 ± 0,3	1,64 ± 0,05 V	1,48 ± 0,02 V
110,2 ± 0,3	3,29 ± 0,05 V	2,56 ± 0,05 V
115,1 ± 0,2	4,67 ± 0,05 V	1,52 ± 0,05 V
120,2 ± 0,3	2,66 ± 0,05 V	0,85 ± 0,02 V
125,3 ± 0,6	3,07 ± 0,03 V	0,65 ± 0,08 V
130,1 ± 0,7	3,17 ± 0,05 V	0,595 ± 0,01 V
134,2 ± 0,7	3,10 ± 0,03 V	0,552 ± 0,01 V

Sometimes, the mean value of the maximum steadily dropped. The figures might be to large, if taken too soon.

Measurement 3: Power relation vs. sound amplitude

frequency: 111,5 ± 0,5 MHz

external VCO	signal amplitude	0 order	1st order
0,2V	1,60 ± 0,4 V	4,9V ± 0,1V	not detectable
0,4V	2,4 ± 0,1V	5,60V ± 0,2V	0,28 ± 0,02 * V
0,6V	14,0 ± 0,1V	5,43 ± 0,03V	0,66 ± 0,03 V
0,8V	28,0 ± 0,1V	3,76 ± 0,02V	1,26 ± 0,01 V
1,0V	34,4 ± 0,1V	2,79 ± 0,02V	1,28 ± 0,02 V
1,2V	38,4 ± 0,1V	2,10 ± 0,02V	1,31 ± 0,03V
1,4V	39,6 ± 0,1V	1,99 ± 0,02V	1,25 ± 0,03V
1,6V	40,8 ± 0,1V	1,95 ± 0,02V	1,28 ± 0,02V
1,8V	41,4 ± 0,2V	1,95 ± 0,02V	1,31 ± 0,02V

* visible light has probably a large impact (lamps)

2,0V	41,6 ± 0,1V	2,00 ± 0,02V	1,33 ± 0,02V

3.2) Two perpendicular AOMs

internal VCO level of second AOM not working

→ direct level 1,4V

Optic_Basics_AOM

March 29, 2021

[1]:
```
import numpy as np
import matplotlib.pyplot as plt
import scipy.constants as const
from scipy.optimize import curve_fit
```

0.0.1 Part 3.1 : Experiments with a single AOM

3.1.1. Diffraction angles The diffraction angles are calculated with:

$$\theta_i = arctan(\frac{x_i}{d}) \quad \Delta\theta_i = \sqrt{\left(\frac{\Delta x_i \cdot d}{x_i^2 + d^2}\right)^2 + \left(\frac{\Delta d \cdot x_i}{x_i^2 + d^2}\right)^2}$$

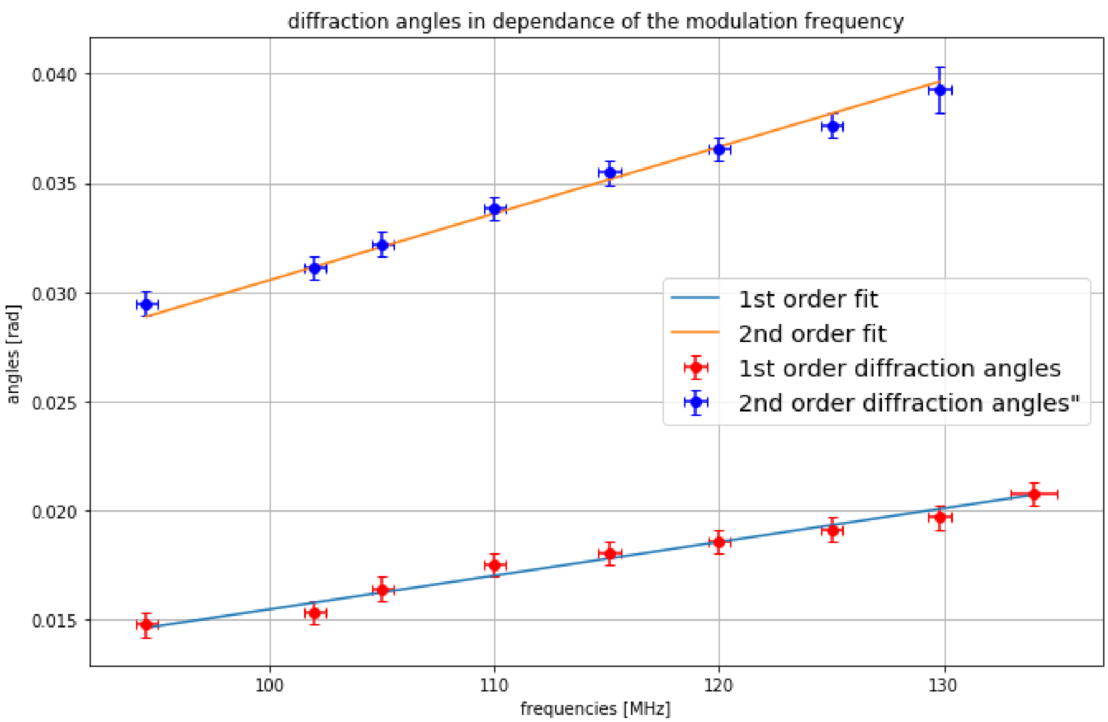
The resulting angles for the first and second order maximas are plotted vs. the frequency and fittet with a linear function (through zero).

[2]:
```
d = 183.2 #cm
deld = 0.5

x_1 = np.array([2.7, 2.8, 3.0, 3.2, 3.3, 3.4, 3.5, 3.6, 3.8]) #cm
delx_1 = np.ones(9)*0.1

x_2 = np.array([5.4, 5.7, 5.9, 6.2, 6.5, 6.7, 6.9, 7.2]) #cm
delx_2 = np.array([0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.2])

freq = np.array([94.5, 102.0, 105.0, 110.0, 115.1, 120.0, 125.0, 129.8, 134])
 ↪#MHz
delfreq = np.array([0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 1])
```

[3]:
```
theta1 = np.arctan(x_1/d)
deltheta1 = np.sqrt((delx_1*d/(x_1**2+d**2))**2 + (deld*x_1/(x_1**2+d**2)**2))

theta2 = np.arctan(x_2/d)
deltheta2 = np.sqrt((delx_2*d/(x_2**2+d**2))**2 + (deld*x_2/(x_2**2+d**2)**2))

def linear(x,a):
    return a*x

slope1, cov1 = curve_fit(linear, freq, theta1)
```

```
slope2, cov2 = curve_fit(linear, freq[:-1], theta2)


plt.figure(figsize=(11,7))
plt.errorbar(freq, theta1, xerr=delfreq, yerr=deltheta1, fmt='o',capsize=3,␣
 ↪label="1st order diffraction angles ", color = 'red')
plt.plot(freq, linear(freq, *slope1), label='1st order fit')
plt.errorbar(freq[:-1], theta2,xerr=delfreq[:-1], yerr=deltheta2, fmt='o',␣
 ↪capsize=3, label='2nd order diffraction angles"', color = 'blue')
plt.plot(freq[:-1], linear(freq[:-1], *slope2), label='2nd order fit')
plt.legend(fontsize='x-large')
plt.grid(True)
plt.xlabel('frequencies [MHz]')
plt.ylabel('angles [rad]')
plt.title('diffraction angles in dependance of the modulation frequency')
```

[3]: Text(0.5, 1.0, 'diffraction angles in dependance of the modulation frequency')



[4]:
```
print(np.round(slope1,7), '+-', np.round(np.sqrt(cov1),7), 'MHz^-1')
print(np.round(slope2,7), '+-', np.round(np.sqrt(cov2),7), 'MHz^-1')
```

```
[0.0001544] +- [[9.e-07]] MHz^-1
[0.0003054] +- [[1.2e-06]] MHz^-1
```

The fit gives the following result:

$$\frac{\theta_1}{f} = (154.4 \pm 0.9) \cdot 10^{-6} MHz^{-1}$$

$$\frac{\theta_2}{f} = (305.4 \pm 1.2) \cdot 10^{-6} MHz^{-1}$$

Sources of uncertainties: The folding rule sagged in the middle, making the distance from AOM to the screen harder to measure. The maxima themselves had a width of a couple millimeters, so finding the middle was tricky. For the higher frequencies especially the maxima also became fainter and hard to make out.

3.1.2 Determining the sound velocity For the diffraction, we have:

$$sin(\theta_{in}) + sin(\theta_{diff}) = \frac{m\lambda}{\lambda_s}$$

To approximate we assume, that the incident angle θ_{in} of the light beam hitting the AOM is much smaller than the diffraction angle and that $\theta_{diff} << 1$:

$$\theta_{diff} = \frac{m\lambda}{\lambda_s} = \frac{m\lambda f_s}{v_s}$$

$$\Rightarrow v_s = m\lambda \left(\frac{\theta}{f}\right)^{-1} \qquad \Delta v_s = v_s \cdot \frac{\Delta\frac{\theta}{f}}{\frac{\theta}{f}}$$

[5]:
```
wv = 632.8e-9
v_s1 = wv/(slope1*10**(-6))
v_s2 = 2*wv/(slope2*10**(-6))
dv_s1 = v_s1*np.sqrt(cov1)/slope1
dv_s2 = v_s2*np.sqrt(cov2)/slope2
print(v_s1, dv_s1, v_s2, dv_s2)
v_s = np.mean([v_s1, v_s2])
dv_s_stat = np.std([v_s1, v_s2], ddof=1)
dv_s = np.sqrt(dv_s1**2/4 + dv_s2**2/4)
print(v_s, dv_s_stat, dv_s)
```

```
[4098.82829694] [[23.42883797]] [4143.53437415] [[15.67676652]]
4121.18133554544 31.611970355699135 [[14.09495882]]
```

The resulting velocity of sound in the crystal is $v_{s,1} = (4099 \pm 23)\frac{m}{s}$ for the first order measurements and for the second order $v_{s,2} = (4144 \pm 16)\frac{m}{s}$. The mean is $v_s = (4121 \pm 32_{stat} \pm 14_{sys})$. The literature value is $4260\frac{m}{s}$. While in the right order of magnitude the experimental result differs by more than 3σ of this value, with both measurements being to small. Most likely the error estimate was to small. An error in the distance d between AOM and screen could have let to a systematic overestimation of the diffraction angle.

3.1.3 Sound wavelength and number of grating periods

We can calculate the wavelength with $\lambda_s = \frac{v_s}{f}$, using the average sound velocity. With $f_{min} = (94,5 \pm 0.5)MHz$ and $f_{max} = (134 \pm 1)MHz$ we find that the wavelength inside the crystal varies between $(30.8 \pm 0.3)\mu m$ and $(43.6 \pm 0.4)\mu m$. With a crystal length of $20mm$, that means the lights diffracts on ≈ 459 to ≈ 650 grating periods.

[6]:
```
lam_max = v_s/(94.5e6)
lam_min = v_s/(134e6)
dv_s_tot = np.sqrt(dv_s_stat**2 + dv_s**2)
dlam_max = lam_max * np.sqrt((dv_s_tot/v_s)**2 + (0.5/94.5)**2)
dlam_min = lam_min * np.sqrt((dv_s_tot/v_s)**2 + (1/134)**2)
print(lam_max, '+-',dlam_max, lam_min, '+-', dlam_min)
l_c = 20e-3
print(l_c/lam_max, l_c/lam_min)
```

```
4.3610384503126344e-05 +- [[4.3288714e-07]] 3.075508459362268e-05 +-
[[3.45536069e-07]]
458.60636698963845 650.2989754138789
```

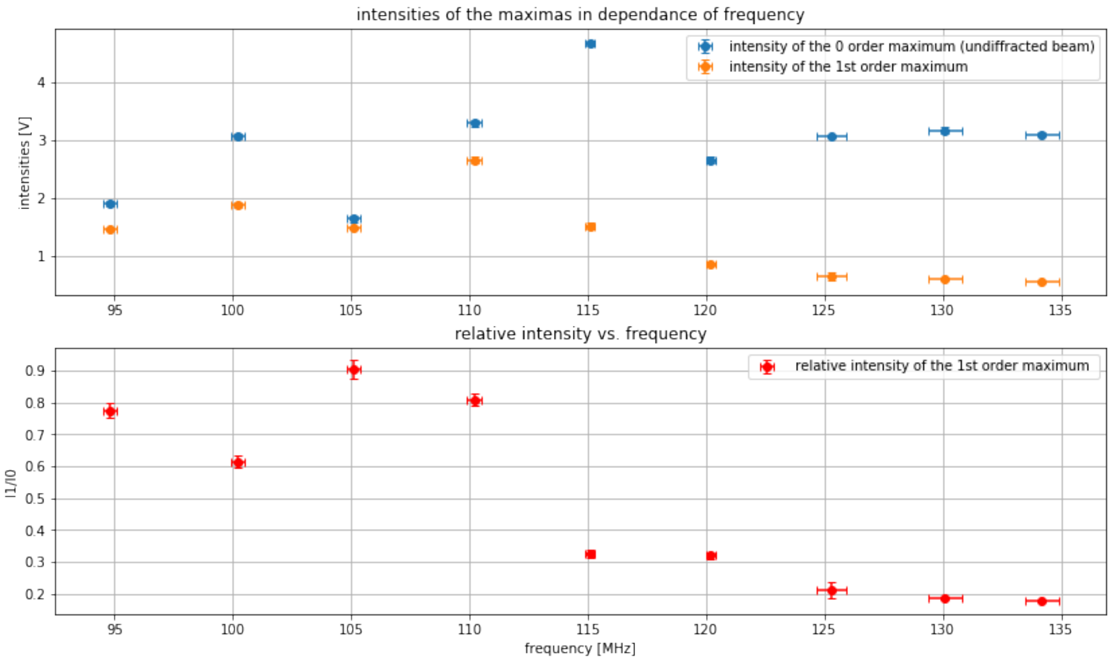
3.1.4 Sound Power

[7]:
```
f = np.array([94.8, 100.2, 105.1, 110.2, 115.1, 120.2, 125.3, 130.1, 134.2])␣
↪#MHz
df = np.array([0.3, 0.3, 0.3, 0.3, 0.2, 0.2, 0.6, 0.7, 0.7])

I0 = np.array([1.90, 3.06, 1.64, 3.29, 4.67, 2.66, 3.07, 3.17, 3.10]) #V
dI0 = np.array([0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.03, 0.05, 0.03])

I1 = np.array([1.47, 1.88, 1.48, 2.66, 1.52, 0.85, 0.65, 0.595, 0.552]) #V
dI1 = np.array([0.02, 0.05, 0.02, 0.05, 0.05, 0.02, 0.08, 0.01, 0.01])

rel = I1/I0
drel = rel*np.sqrt((dI0/I0)**2 + (dI1/I1)**2)
```

[8]:
```
plt.figure(figsize=(14,8))
plt.subplot(2, 1, 1)
plt.errorbar(f, I0, xerr=df, yerr=dI0, fmt='o',capsize=3, label="intensity of␣
↪the 0 order maximum (undiffracted beam)")
plt.errorbar(f, I1, xerr=df, yerr=dI1, fmt='o',capsize=3, label="intensity of␣
↪the 1st order maximum")
plt.legend()
plt.grid(True)
plt.ylabel('intensities [V]')
plt.title('intensities of the maximas in dependance of frequency')

plt.subplot(2, 1, 2)
plt.errorbar(f, rel, xerr=df, yerr=drel, fmt='o',capsize=3, label=" relative␣
↪intensity of the 1st order maximum ", color = 'red')
```

```
plt.legend(loc='upper right')
plt.grid(True)
plt.xlabel('frequency [MHz]')
plt.ylabel('I1/I0')
plt.title('relative intensity vs. frequency')
```

[8]: Text(0.5, 1.0, 'relative intensity vs. frequency')



The intensity measurements of the maximas (0 and 1st order) don't show a clear trend, especially in the first half of the data set. This is because the photodiode sometimes took a long time (> 1 minute) until the output stabilised and stopped dropping, which was only noticed in the middle of the measurements. Depending on the time when we noted down the value, the measurements can be to high by an arbitrary amount. For the next measurement series (power vs. amplitude) we set the frequency to $(111.5 \pm 0.5) MHz$ which was near the measured maximum for the first order intensity. However this was probably not the optimal frequency because of the error mentioned above.

We can calculate the relative intensity R of the maxima with the formula

$$R = \frac{I_1}{I_0} = sin^2 \left(\frac{\pi L}{\lambda cos\theta_B} \sqrt{\frac{M_2 I_s}{2}} \right)$$

where λ is the optical wavelength, L the interaction length, I_s the sound amplitude, $M_2 = 34.5 \cdot 10^{-15} \frac{s^3}{kg}$ a material constant and θ_B the Bragg angle. Because of $\theta_{in} + \theta_{diff} = 2\theta_B$ and our approximation $\theta_{diff} >> \theta_{in}$ we can calculate it using

$$\theta_B = \frac{1}{2} \frac{\lambda}{\lambda_s} = \frac{1}{2} \frac{\lambda f_s}{v_s}$$

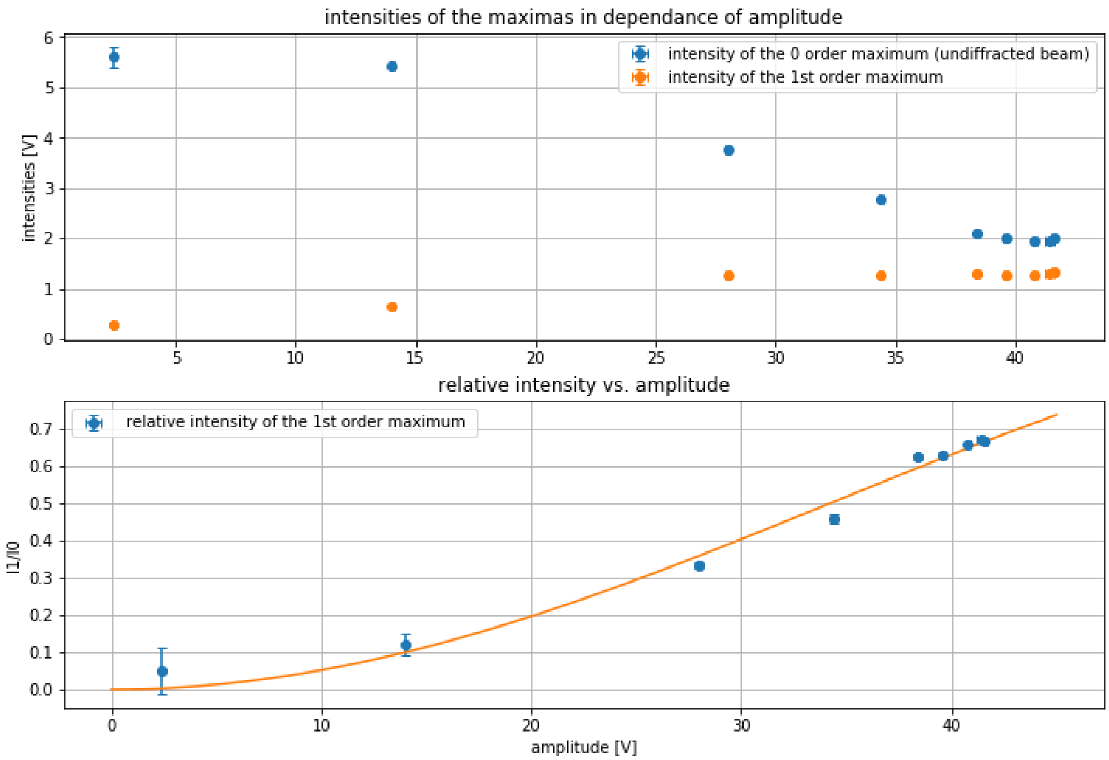
Because the sound intensity is proportional to the square of the amplitude, we can fit a sin^2-Funktion to the data points to determine R_{max}. For the maximal sound intensity follows:

$$I_s^{max} = \left(arcsin\left(\sqrt{R_{max}}\right)\frac{\lambda cos\theta_B}{\pi L}\right)^2 \frac{2}{M_2}$$

[14]:
```
amp = np.array([ 2.4, 14.0, 28.0, 34.4, 38.4, 39.6, 40.8, 41.4, 41.6])
damp = np.array([ 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.2, 0.1])

I0_2 = np.array([ 5.6, 5.43, 3.76, 2.79, 2.10, 1.99, 1.95, 1.95, 2.00])
dI0_2 = np.array([ 0.2, 0.03, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02])

I1_2 = np.array([ 0.28, 0.66, 1.26, 1.28, 1.31, 1.25, 1.28, 1.31, 1.33])
dI1_2 = np.array([ 0.02, 0.03, 0.01, 0.02, 0.03,0.03, 0.02, 0.02, 0.02])

rel_2 = I1_2/I0_2
drel_2 = rel*np.sqrt((dI0_2/I0_2)**2 + (dI1_2/I1_2)**2)



def sin_squared (x, a):
    return np.sin(a*x)**2

period, cov3 = curve_fit(sin_squared, amp, rel_2, p0=[0.03])
print(period, '+-', np.sqrt(cov3))
x_line = np.linspace(0, 45, 150)

plt.figure(figsize=(12,8))
plt.subplot(2, 1, 1)
plt.errorbar(amp, I0_2, xerr=damp, yerr=dI0_2,
             fmt='o',capsize=3, label="intensity of the 0 order maximum␣
 ↪(undiffracted beam)")
plt.errorbar(amp, I1_2, xerr=damp, yerr=dI1_2, fmt='o',capsize=3,␣
 ↪label="intensity of the 1st order maximum")
plt.legend()
plt.grid(True)
plt.ylabel('intensities [V]')
plt.title('intensities of the maximas in dependance of amplitude')

plt.subplot(2, 1, 2)
plt.errorbar(amp, rel_2, xerr=damp, yerr=drel_2, fmt='o',
             capsize=3, label=" relative intensity of the 1st order maximum ")
plt.plot(x_line, sin_squared(x_line, *period))
plt.legend(loc='upper left')
plt.grid(True)
plt.xlabel('amplitude [V]')
plt.ylabel('I1/I0')
plt.title('relative intensity vs. amplitude')
```

```
[0.02294435] +- [[0.00028895]]
```

[14]:
```
Text(0.5, 1.0, 'relative intensity vs. amplitude')
```



With the fit function, we can see that the maximal amplitude allowed by the AOM modulator is still within the first quarter period. Therefore the maximum amplitude is at the maximum allowed VCO level input (2V), which translates to $(41.6 \pm 0.1)V$ amplitude at the AOM.

[15]:
```
f_s =111.5e6
df_s = 0.5e6
theta_B = 0.5 * wv * f_s/v_s
dtheta_B = theta_B*np.sqrt((df_s/f_s)**2+(dv_s/v_s))
L=20e-3
M2 = 34.5e-15

a= period[0]
R_max = sin_squared(41.6, a)
dR_max = 2*np.sin(a*41.6)*np.cos(a*41.6)*np.sqrt((np.sqrt(cov3)*41.6)**2+(0.
 ↪1*a)**2)
print('R_max =', R_max, '+-', dR_max)

I_s_max = (np.arcsin(np.sqrt(R_max))*wv*np.cos(theta_B)/np.pi/L)**2*2/M2
dI_s_max = 2/M2*(wv/np.pi/L)**2 \
```

```
*np.sqrt((np.arcsin(np.sqrt(R_max))*np.cos(theta_B)**2*dR_max/np.
↪sqrt(R_max-R_max**2))**2
                                        +(np.arcsin(np.sqrt(R_max))**2*2*np.
↪cos(theta_B)*np.sin(theta_B)*dtheta_B)**2)
print('I_s,max=',I_s_max, '+-', dI_s_max, 'kg/s^3')

h = 3e-3
P_s = I_s_max*h*L
dP_s = P_s*dI_s_max/I_s_max
print('Sound power P_s =', P_s, '+-', dP_s, 'W')
```

```
R_max = 0.6658824027233838 +- [[0.01154413]]
I_s,max= 5356.616043879039 +- [[137.35173427]] kg/s^3
Sound power P_s = 0.32139696263274237 +- [[0.0082411]] W
```

The maximum relative intensity is $R_{max} = 0.666 \pm 0.012$, the resulting maximal sound intensity $I_s^{max} = (5357 \pm 137)\frac{kg}{s^3}$. To find out the sound power at optimal deflection efficiency, we have to multiply the intensity with the cross-sectional area of the crystal:

$$P_s^{opt} = I_s^{max} \cdot L \cdot h = (0.321 \pm 0.008)W$$

.

3.1.5 Factors for the optimum working frequency The optimum working frequency depends on a number of things in the experimental setup, such as the wavelength of the laser λ, the material of the crystal (and therefore the refraction indices and sound velocity) and it's size (length).

Discussion for Part 3.1 In the first part we used the diffraction angles to determine the sound velocity. Our result was within approximately 4σ of the real value. Reasons for this might be an underestimation of the error size and systematic errors like the distance between AOM and screen, which impacted all measurement points. The maximas were blurry and the middle had to be estimated by eyesight. There was also an approximation error made, as we assumed $\theta_{in} = 0$, even though that can't be the case, when we have a diffraction pattern. To improve, one could find a way to measure the incident angle, or use a setup with Bragg diffraction, where $\theta_{in} = \theta_{diff} = \theta_B$ holds true.
The sound wavelength was calculated to be between $(30.8 \pm 0.3)\mu m$ and $(43.6 \pm 0.4)\mu m$, corresponding to ≈ 459 to ≈ 650 grating periods.

The other part proved to be more problematic, because the photodiode needed a long adjustement time until it gave a constant measurement. Because of this, we probably used the wrong frequency for the variation of amplitude, and the resulting sound power $P_s^{opt} = (0.321 \pm 0.008)W$ was only optimized for amplitude. To increase the accuracy of this part it might be better to use a different photodiode or take more time for the adjustement (which necessitates increasing the time frame for the FP experiment or reducing the workload).The fit of the squared sine function has also proven to be quite unstable with weird results for a different initialization parameter. As the relation between appplied VCO level voltage and amplitude was not linear it would have been better to decrease the stepsize for the lower values.

[ ]:

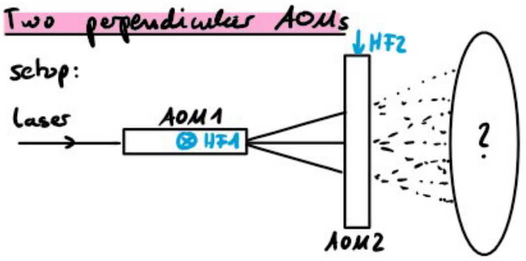
Day 2 March, 23
Franka Neumann
Nick Striebel

F87 Acousto-Optic Modulation (6.2.2 Two AOMS)

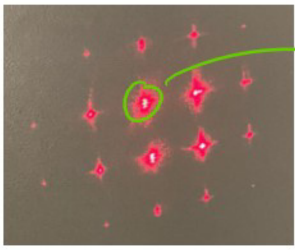
protocol + evaluation

Two perpendicular AOMs

setup:



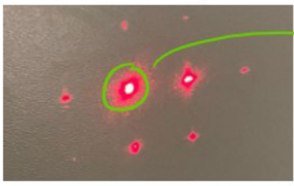
1. The observation pattern looks like the following. The properties are managed intern in the VCO of the AOM



main maximum

(like a 2D version)

2. If we change the offset voltages it changes the intensity of the first and second orders. The higher the voltage the higher the intensitys.
For too low voltage the effect is not working



- The next parts of the experiments would be done with a function gen. connected to the phase shifting box input. The phase shifting box is not working so we directly connect each AOM to a function generator.

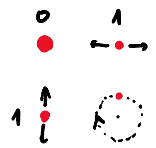
1. starting with modulating the sound amplitudes we observe the same as before. The intensity varies

2. with the sound amplitudes fixed the frequencies can be modulated:
In general periodic input waves are forcing a periodic appearing of the orders of grade one and higher. For sine and triangle the maximas are changing there intensity smoothly (for the sine this effect is in theory more smoothly but for us it is hard to distinguish between the sine and triangle waveform)

3. Another observation: for sine and triangle the maximas are moving closer to the center as they get a higher intensity.
Next we observe the patterns at different relative phase differences between the output-channels (0°, 90°, 180°).
We observe a systematic phase shift of the function generators, unfortunately this shift is different every time.

However we still can see that the phase shift in the wave results in a phase shift in the appearing

4. Coming from the previous observations we take a closer look at the 0th, 1st, 2nd rows and columns for each phase difference. First we have to mention that we could not see the 2nd orders.
To draw a circle on the $(\pm 1, \pm 1)$ order we used two sine waves with $90°$ phase difference

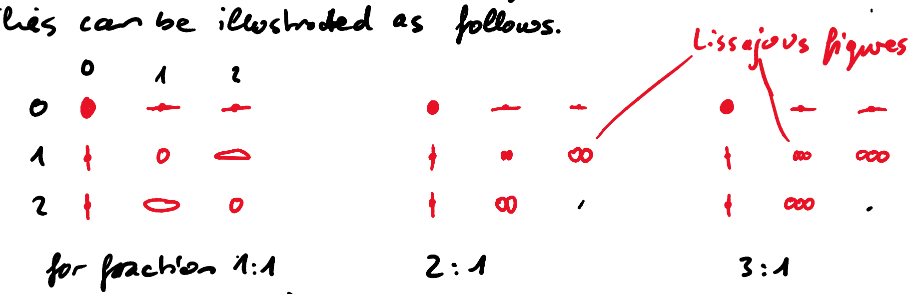


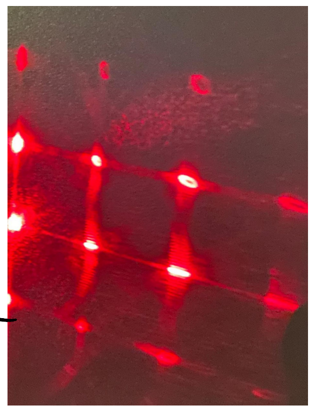
5. The effects are independent of the polarization state of the light, because the modulation happens via sound waves. However the principle is the same: Circular polarized light can be described as the addition of two perpendicular linear polarizations with a phaseshift of $\pi/2$.
For the diffraction pattern we have two perpendicular AOMs, with a sound wave modulation with a $90°$ phase shift. The result is a maximum in the shape of a circle

6. The analogue to the phase-shifting box would be the use of the Pockels cell. Both can be used to create different phaseshifts. One in the light polarization, one in the sound wave modulation.

- As the last experiment the frequencies and phases can be changed individually:

1.ll. The frequency of one AOM gets modulated twice, threetimes,... as fast as the other one:
If the frequency is exactly two, three,... time the other the behaviour follows an order. If the fraction is not exactly the behaviour does not seem to follow an order but it is hard to say.
This can be illustrated as follows.





3. The different frequencies can be compared to light travelling through a birefringent crystal with a slow and fast axis. In this case the polarization vector also draws a Lissajous figure

4. A laser has a very sharp peak in the wavelength spectrum. The variance is small. Regular light has a broader spectrum. Additionally the coherence time and length of a laser is much larger.

5. The coherence time and length are defined as the time and distance in which the light keeps its polarization state and the phase difference within the beam are small enough, that the light can form a stable interference pattern. For perfectly monochromatic light, the coherence length is infinite. For lasers it can be of the order of kilometers, for sunlight of the order of micrometers.