Gaussian beam optics

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Contents

1 Einleitung

1.1 Dies ist eine Überschrift zweiten Ranges

in diesem Versuch soll das Intensitätsprofil von Gaußschen Strahlen vermessen und die Auswirkungen von optischen Elementen untersucht werden

Genereller Versuchsaufbau mit Skizze

2 Measuring the power of the laser

In the first part we measured the power of the laser itself. First, we put a photodiode with internal resistance 100kΩ after the first passive reflector and measured the voltage $U = (1.2 \pm 0.1)V$. Then we turned the laser off and measured again at the same position to eliminate the background light (the windows were covered by curtains). We measured $U_b = (1.2 \pm 0.1)mV$ using the 10kΩ photodiode.

add answer, fehlerrechnung, make sure to say we incoroprated the fact that the diode resistances were different and add sktech of experimental set up, answer all questions page 11

Though we used a voltmeter, but an Oscilloscope with a known measuring resistance R_m can just as well be used. With the measured voltage V_m one can conclude the photocurrent $I_p = V_m \cdot R_m$. To ensure an accurate measurement, we would want $R_m >> R_i$ since

$\frac{1}{R_{total}} = \frac{1}{R_m} + \frac{1}{R_i}$

and for sufficiently large R_i: $\frac{1}{R_{total}} \approx \frac{1}{R_m} \rightarrow R_{total} = R_m$

Calculating the power from the voltage When the beam hits the diode, the multimeter detects a voltage U. For photodiodes, the relation between the power and light current ist given by

$$P = \frac{hfI}{e\eta} \tag{1}$$

Here, $h = 6.62607015 * 10^{-34} Js$ is the planck constant, $e = 1.602176634 * 10^{-19} C$ the charge of an electron, I is the current and $\eta = 0.75$ the quantum efficiency of the photodiode. We can replace the frequency f in the formula by the corresponding wavelength $\lambda = 632.8nm$ of the laser using $c = \lambda f$, with the vacuum speed of light $c = 299792458 \frac{m}{s}$. Using ohm's law $U = R \cdot I$ we eliminate the current I and obtain

$$P = \frac{hcU}{\lambda R e \eta} \tag{2}$$

Wie Formeln nummerieren? Quellenverzeichnis! https://de.wikipedia.org/wiki/Quantenausbeute

The resistance R can be read from the photodiode. In the experiment we used two diodes, mainly diode 1 with $R = 10k\Omega$. Diode 2 has $R = 100k\Omega$. Thus by plugging the respective values in, we can calculate:

$$P_{Laser} = \frac{6.62607015*10^{-34} \cdot 299792458 \cdot 1.2}{632.8 \cdot 10^{-9} \cdot 1.602176634*10^{-19} \cdot 0.75 \cdot 100000} = 3.13 * 10^{-5}$$

$$\Delta P_{Laser} = \pm \frac{6.62607015*10^{-34} \cdot 299792458 \cdot 0.1}{632.8 \cdot 10^{-9} \cdot 1.602176634*10^{-19} \cdot 0.75 \cdot 10^{5}} = \pm 0.27 * 10^{-5}$$

$$P_{Background} = \frac{6.62607015*10^{-34} \cdot 299792458 \cdot 1.2*10^{-3}}{632.8 \cdot 10^{-9} \cdot 1.602176634*10^{-19} \cdot 0.75 \cdot 10^{4}} = 0.03 * 10^{-5}$$

$$\Delta P_{Background} = \pm \frac{6.62607015*10^{-34} \cdot 299792458 \cdot 0.1}{632.8 \cdot 10^{-9} \cdot 1.602176634*10^{-19} \cdot 0.75 \cdot 10^{5}} = \pm 0.27 * 10^{-7}$$

Thus by subtraction we can determine the power of the laser without any background influence as

$$P_{Laser}^{'} = 3.13 * 10^{-5} - 0.03 * 10^{-5} = 3.10 * 10^{-5} \pm 0.27 * 10^{-5}$$

Since the background power is outside of the measurement error of the laser power measurement, we cannot ignore the background power, however the difference is so low that one can safely expect results to not change much in a dimmed and normally lit room. A lit room, however, allows for more accurate measurements since observation of scales and thus of measurements becomes easier to the human eye and there are fewer risks of bumping into instruments or the table, thus reducing the chance of misallignments and accidentally influencing measurements. Fehlerquellen: Lichtstrahl hat Diode nicht perfekt fokussiert, verluste?

3 Coupling the optical fibre cables

After determining the power of the laser we coupled the fibre optic cables into the coupler in the optical path. First, we coupled the multimode cable and adjusted the optical elements such that the conduction was optimized. By variating the angles a little we tried to see different modes on a piece of paper, put behind the cable. Unlike our expectations we could not identify them, instead the dot on the paper disappeared, because too few light was conducted through the cable. We could however see on the paper a dot with a small dark hole in it's center, just like the shape of a donut mode. It is also possible that the small hole was a dust crumb on the lens whatsoever. Unfortunately it was not possible to take a picture of the dot which shows more than a diffuse point, because the mobile phone cameras could not work with the light conditions.

Now we measured the voltage from the photodiode behind the cables. Therefor we focused the beam into the photodiode, using another lens. For the multimode cable we measured a maximum voltage of $U = 209mV$, but the value fluctuated a lot (about 20mV just from touching the table). After coupling the single mode cable we measured $U = (106 \pm 5)mV$. This is less than for the multimode cable, which makes sense because there is only one mode lead through the single mode cable. With the resistance of the used photodiode, $R = 10k\Omega$, we can calculate the percentage of the power lead through the cable:

The corrected laser power translates to a corrected voltage value for the Laser of

$U'_{Laser} = 1.19 \pm 0.11V$

$U_{single-mode} = (106 \pm 5)mV \qquad U_{multi-mode} = (209 \pm 20)mV$

$\eta_{single-mode} = \frac{106}{1.19*10^3} = 8.93\% \qquad \eta_{single-mode} = \frac{209}{1.19*10^3} = 17.61\%$

$\Delta\eta_{sinlge-mode} = \pm 8.93\% \cdot (\frac{5}{106} + \frac{0.11}{1.19}) = \pm 1.25\%$

$\Delta\eta_{single-mode} = \pm 17.61\% \cdot (\frac{20}{209} + \frac{0.11}{1.19}) = \pm 3.32\%$

$\rightarrow \eta_{single-mode} = 8.93 \pm 1.25\% \qquad \Delta\eta_{sinlge-mode} = 17.61 \pm 3.32\%$

As expected, the multi mode cable has a higher efficiency since it allows for more modes to be transmitted. The measured efficiency was highly dependent on the sensitive alignment of the laser. This is especially true for the single mode photodiode since it has a smaller lens diameter. We can therefore expect that energy has been lost due to imperfect alignment and other various smaller inefficiencies, such as optical instruments heating up. The influence of dust particles on the lens of the photodiode is also noteworthy as a factor that further lowers efficiency. During the experiment it had a significant impact on the observed laser projection. Fehlerquellen: -kabel Beschädigt: keine perfekte Leitung durch kabel, Fehler aus TV1

4 Measuring the beam profile

In this experiment we measured the intensity of the laser light that is emitted by the fibre. We cut off some of the beam with a razor blade to see how much voltage is still measured by the photodiode. Thereby we obtained a profile of the beam cross section. After that we put a lens ($f = 100mm$) behind the fibre end so that the beam was focused at the focal point. We measured the profile of the beam at different positions between the two lenses (the second lens ($f = 50mm$) focuses the beam into the photodiode). Near the focal point of the first lens, where the waist of the gaussian beam lies, we measured three times. To eliminate influences from ambient light, we normalized the voltage signal with the other photodiode.

The total power the photodiode is detecting depends on the position of the razor blade x and is given by:

$$P(x) = \int_x^\infty \mathrm{d}x' I_0 \mathrm{e}^{-\frac{2(x'-x_0)^2}{\omega^2}}. \tag{3}$$

Beantworten: Welches Brechungsindexprofil müßte eine Glasfaser aufweisen, damit die Faser eine ideale Gauß-Mode führt?

Measuring the cross section profile without focusing the beam To calculate the beam radius $\omega(z)$ we fitted the data of our measurement a (see annex) Anhang hinzufügen to the power integral. In order to do this we calculated the power from the voltage using eq.
Formelnummerierung

The first two measurements of the series with $Distancerazorblade - fibreend = 8.3cm$ seemed to fall out of line. When doing the fit, the curve (red dashed) also looked inappropiate. Presumably we measured these points too early, namely not at the point right before the power falls off (i.e. the maximum). Therefore we decided to leave them out of the fitting, which lead to a much better result (see figure). which figure number? The resulting parameters from the fitting are:

For $Distancerazorblade - fibreend = 11.0cm$ the waist is negative, which is impossible and therefore we left this value out in the calculation of the average waist. Since this measurement series was taken at the furthest point from the beam origin, we assume that generally the influence of error sources are much higher than for measurements taken close to the beam origin.

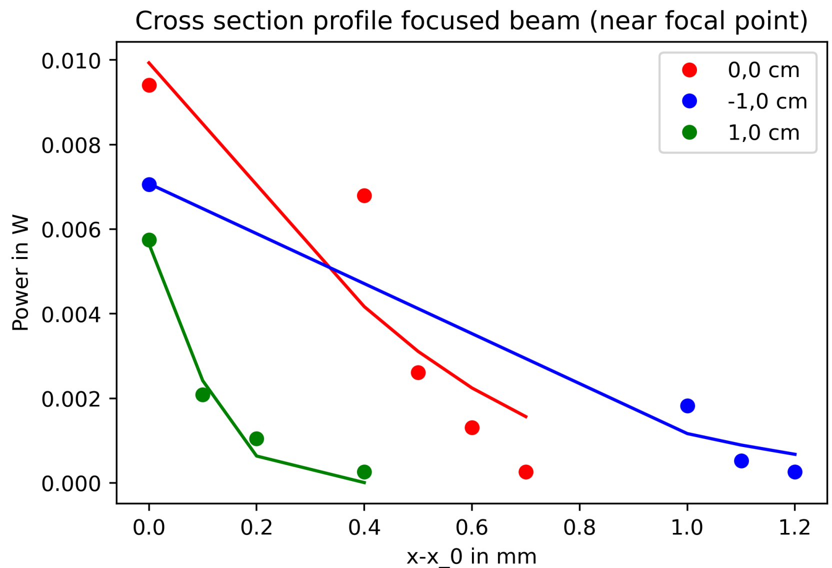
include parameters of csv datei a;Interpretation! Ziel war, ω zu bestimmen.;alle zahlenwerte;messungenauigkeiten;Fehlerquelle: streuendes licht; Am Ende Prüfen ob im Pythoncode die richtigen formeln benutzt wurden, outputs von pythoncode einfügen und diskutieren

Measuring the cross section profile with lens ($f = 100mm$) We measured the beam profile using the razor blade technique at seven distances from the lens. Three measurements were taken near the focal point because here we expected the waist ω_0, i.e. the minimum of the beam radius $\omega(z)$. They are related by the equation:

$$\omega(z) = \omega_0 \sqrt{1 + \frac{z^2}{z_R^2}}, \tag{4}$$

The razorblade positions z from which we measured the beam profile are $-(7.0 \pm 0.2)cm$, $-(4.0 \pm 0.2)cm$, $-(1.0 \pm 0.2)cm$, $(0.0 \pm 0.2)cm$, $(1.0 \pm 0.2)cm$, $(4.3 \pm 0.2)cm$ and $(7.0 \pm 0.2)cm$, where $z = 0$ is the focal point. For better clearness we plotted the data near focal point in an extra plot. The plots show the calculated powers (eq.) from the measuring data along with the corresponding Fit to the part a: cross section profile of collimated beam.png

Figure 1: cross section profile of collimated beam



gaussian integral (eq.). From the fit we obtained I_0 and $\omega(z)$.:

formelnummerierung und Daten aus pythoncode einfügen The value $\omega(7cm) =$ ... is negative and therefore illogical. Therefore we left it out from further calculations. Again this measurement series was taken from the furthest point from the fibre end, so we assume generally higher influence from error sources of any kind

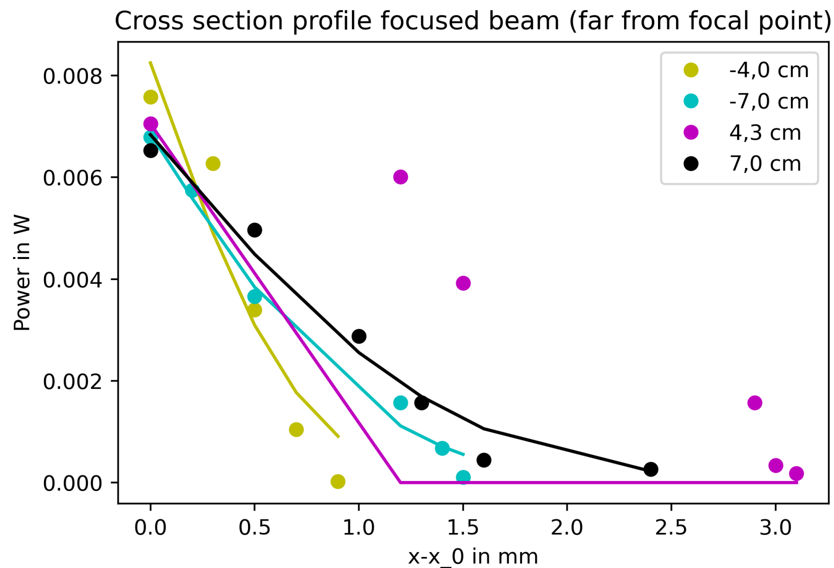
We fitted the values $\omega(z)$ to eq. $\omega(z) = \omega_0\sqrt{1+\frac{z^2}{z_R^2}}$ and eventually obtained the waist ω_0 and rayleigh length z_R as fit parameters: include results

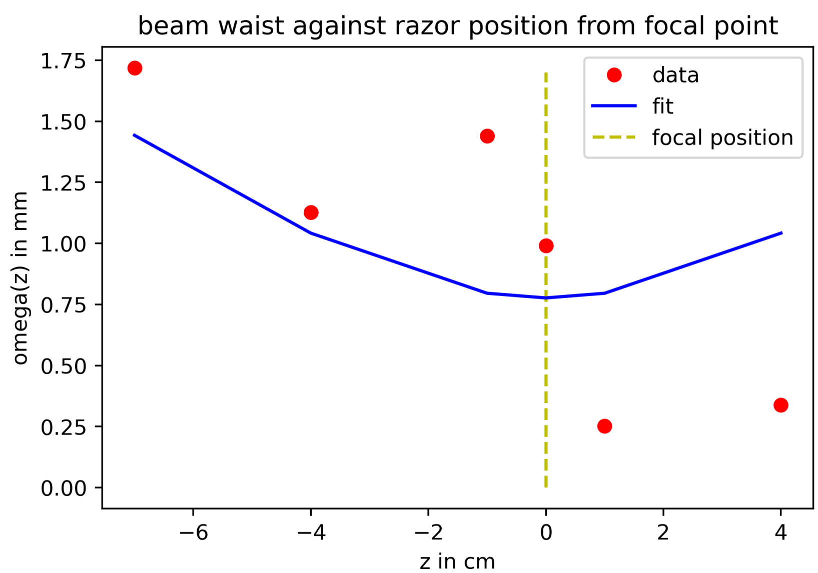
where

$$z_R = \frac{\pi\omega_0^2 n}{\lambda} \tag{5}$$

is the rayleigh length, at which the beam radius is $\sqrt{2}\omega_0$. In our case, $n = 1$ is the refraction index of the medium (air) and the wavelength of the laser is $\lambda = 632.8nm$.

Again, we fitted the measurement series for each razor-lens-distance z to the power integral and obtained the local $\omega(z)$. Then we fitted these together with the corresponding z to eq. [] nummerierung. From that we obtained the waist $\omega_0 = \ldots$ The resulting rayleigh length is zR ...





Wie müssen Sie eine plankonvexe Linse in diesem Fall orientieren, wenn Sie den Einfluß von Linsenfehlern möglichst gering halten wollen?

Beschreibung Plot: Messdaten: Messungenauigkeiten Ursachen: -At the focal point the multimeter display showed strong fluctuations

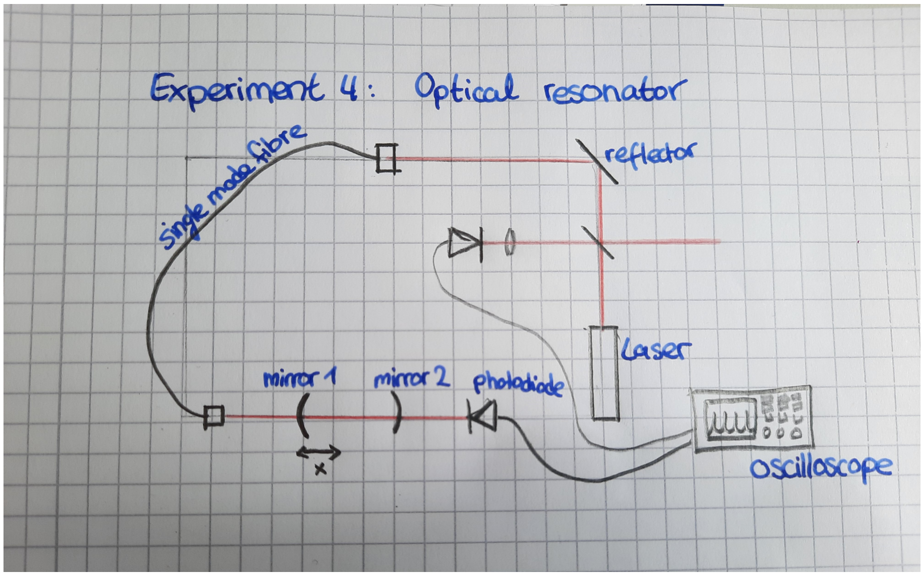


Figure 2: Experiment 4: Optical resonator

5 Optical resonator

In the last part we constructed an optical resonator and detected the periodic signal of the beam that went through it with an oscilloscope. To do this we focused the beam on a lens 1 ($f = 100mm$). Then we focused that on the movable reflector 1 with radius $r = 50mm$. In a distance $L = r$ (confocal arrangement) behind it we then positioned reflector 2 (same radius). The distance between lens 1 and reflector 1 is at first 50mm, so that the focal point of lens 1 lies exactly in the center of the optical resonator. At last we focused the beam into the center of a lens 2 and then into the photodiode with $R = 100k\Omega$ (such that the signal is stronger), which we connected to the oscilloscope.

Determining the transmission of the two reflectors The mirrors of the Fabry-Perot-interferometer both let some of the incoming beam intensity pass and reflect some. A small amount might also be absorbed by the material of the mirror. The transmitted amplitude $E_t$of the interferometer is given by:

$$E_t = E_{in} \cdot \frac{T}{1 - Re^{i\varphi}} \tag{6}$$

Here, E_{in} is the incoming amplitude of the light. The intensity I_t of the light is then proportional to E_t^2. In general, the intensity is given by the power divided by the area A ($I = \frac{P}{A}$). The electric power is proportional to the voltage ($P = UI$), where I is the current. In total we obtain the relation:

$$|I_t| \propto |E_t|^2 \propto U^2 \tag{7}$$

The transmittivity is then defined as the intensity of the transmitted light divided by the intensity of the incoming light:

$$T = \frac{I_t I_{in}}{=} \frac{U_t^2}{U_{in}^2} \tag{8}$$

The opposite of the transmissivity T is the reflectivity R, if we assume that no light is absorbed by the mirrors they fulfil $R+T=1$. The total transmittivity can be calculated from the transmittivities of the single mirrors by $T = \sqrt{T_1 T_2}$, and analogously $R = \sqrt{R_1 R_2}$. Having the reflectivity, we can calculate the finesse F, a measurement for the quality of the resonator:

$$F = \frac{\pi\sqrt{R}}{1-R} \tag{9}$$

We measured the following:
$U_b = (29 \pm 1)mV$ voltage with both mirrors $U_1 = (55 \pm 1)mV$ Spiegel voltage with first mirror $U_2 = (46 \pm 1)mV$ voltage with second mirror $U_o = (472 \pm 1)mV$ voltage without mirrors

From that we obtain

Fehler der Finesse einfügen, Messfehler vielleicht erhöhen, Tabelle fixen

Pythoncode einbringen Bestimmen Sie zuerst die Transmission der Spiegel für die vorhandene Wellenlänge. Welche Reflektivität R und Finesse F sind zu erwarten Welcher Resonatorkonfiguration entspricht diese Anordnung? Welchen Strahlparameter w0 der Gaußschen Moden erwartenSie für das Lichtfeld im Resonator? Wie groß sollte der Abstand der Linse vom Einkoppelspiegel sein? Zunächst: Was erwarten Sie für eine Transmissionsfunktion für einen Resonator, der aus Planspiegeln aufgebaut wird und auf den eine monochromatische Lichtwelle trifft? Wie erklären Sie sich das Auftreten von mehr als einem Transmissionsmaximum bei dem gerade aufgebauten Resonator?
In einer Periode sollten jetzt nur noch zwei beinahe identische Transmissionsmaxima sichtbar sein. Warum? Drucken Sie das Oszilloskopbild aus. Schätzen Sie das Verhältnis des freien Spektralbereichs zur Linienbreite ab, welche Finesse ergibt sich auf diese Weise?

From the signal detected by the oszilloscope 3 we can also determine the Finesse F. The full width at half maximum $\Delta\omega_{FWHM}$ and the free spectral range $\Delta\omega_{FSR}$, which is the distance of two peaks, are related by

$$\Delta\omega_{FWHM} = \frac{\Delta\omega_{FSR}}{F} \tag{10}$$

Using the cursors, we see that the full width at half maximum is $\Delta\omega_{FWHM} = 3 \pm 1$ units of the oszilloscope pattern. For the free spectral range we see that it is $\Delta\omega_{FSR} = 10 \pm 1$ units wide. Therefore we get a Finesse:
$F_{fig} = 3.3333333333333335 \pm 1.11665284679121$

das ist sehr schlecht und weicht stark von der Finesse ab...

The next figure 4 shows the oscilloscope signal of one single peak:

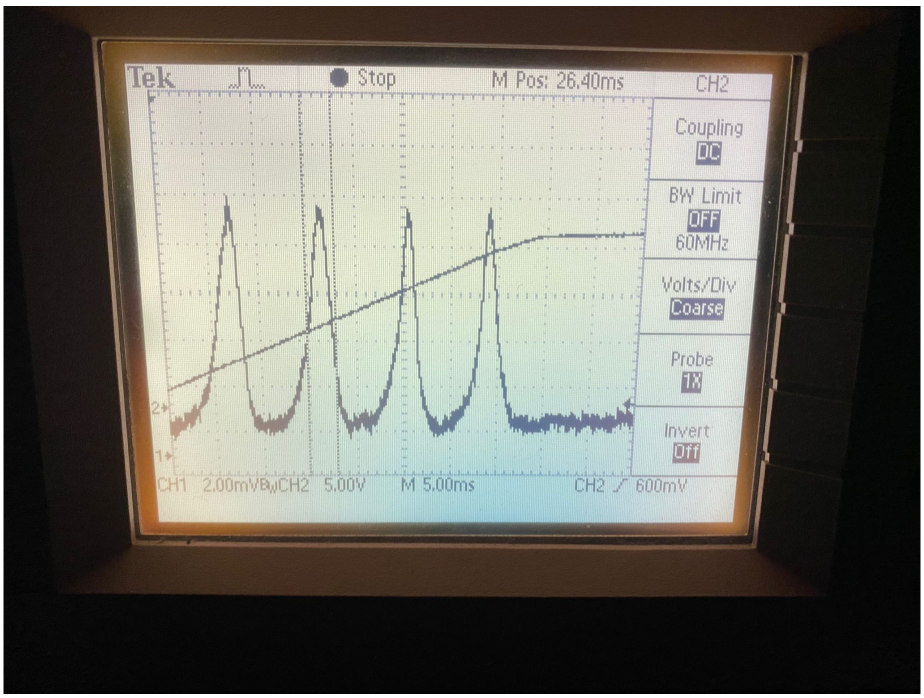


Figure 3: Osz1

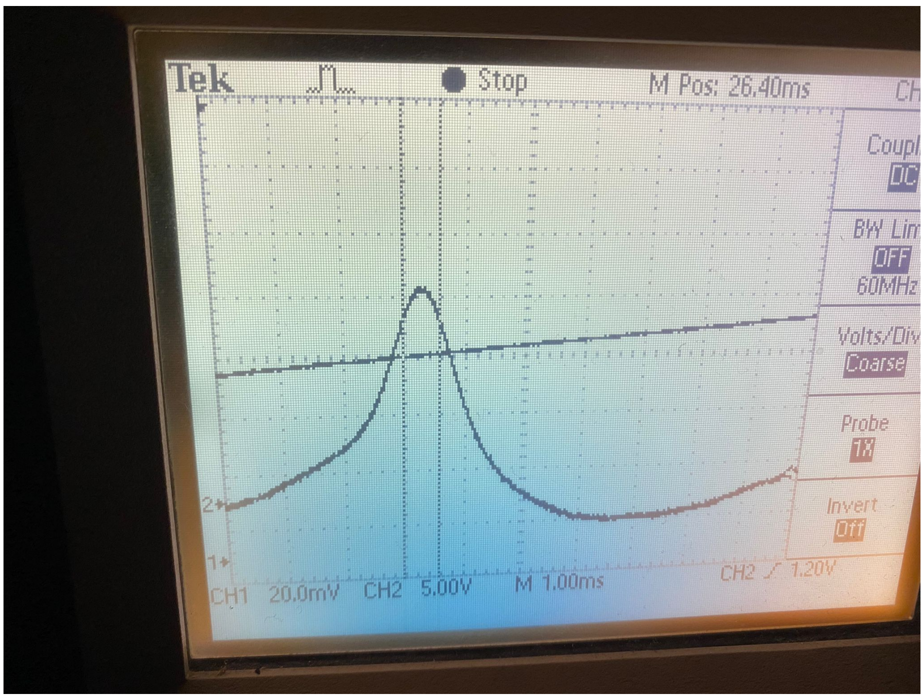


Figure 4: Osz3

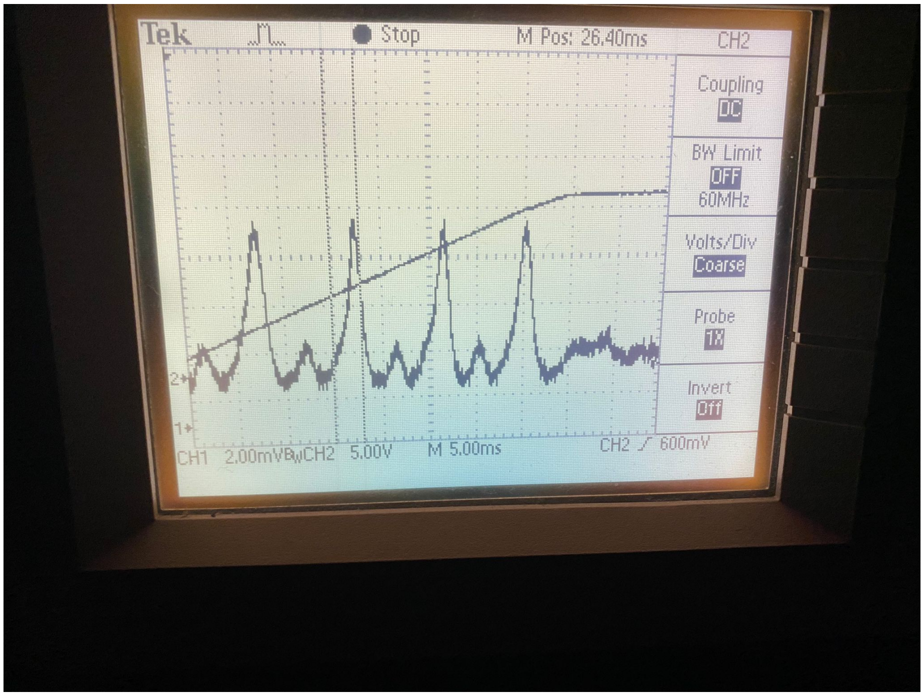


Figure 5: Eigenmodenlaser

In the following figure 5 we observe that between the peaks of the modes there are smaller modes which presumably depict the eigenmodes of the laser: Macht das Sinn? Warum sind nicht die Bilder unter den Beschreibungen? und Annex wird komplett ignoriert...

6 Annex

Annex noch besser beschriften, Wikipediaquelle

6.1 Measurements

```
#Abstand Linse-Diode:6cm;Abstand Linse-Faserausgang in cm;Fehler Schraubenpositionen;Fehler
#6cm;15.5;0.1;1
#Abstand Rasierklinge-Linse: 7.2cm (Fehler 0.2cm)
Position Schraube;6.0;8.0;12.1;12.5;12.7;12.9;13.1;14
normierte Spannung in mV;41;39;33;27;20;12;7;1
#Abstand Rasierklinge-Linse: 4.5 cm
Position Schraube;0;0.8;1;1.2;1.5;1.7;2;2.5
normierte Spannung in mV;40;30;25;18;10;6;3;0
#Abstand Rasierklinge-Linse:10.5cm
```

```
Position Schraube;4.8;6.5;6.8;7;7.2;8.1
normierte Spannung in mV;40;32;20;13;8;1
```

```
Abstand Linse 1-Faserausgang in cm; Abstand beide Linsen in cm; Abstand Linse-Photodiode in
4; 32.5; 5;
Abstand Rasierklinge-Linse 1: 10 cm
Position Schraube; 5.2; 5.6; 5.7; 5.8; 5.9;
normierte Spannung in mV; 36; 26; 10; 5; 1;
Abstand Rasierklinge-Linse 1: 9 cm
Position Schraube; 5.5; 6.5; 6.6; 6.7;
normierte Spannung in mV; 27; 7; 2; 1;
Abstand Rasierklinge-Linse 1: 11 cm
Position Schraube; 2.2; 2.3; 2.4; 2.6;
normierte Spannung in mV; 22; 8; 4; 1;
Abstand Rasierklinge-Linse 1: 6 cm
Position Schraube; 5.2; 5.5; 5.7; 5.9; 6.1;
normierte Spannung in mV; 29; 24; 13; 4; 0.1;
Abstand Rasierklinge-Linse 1: 3 cm
Position Schraube; 13.5; 13.7; 14; 14.7; 14.9; 15;
normierte Spannung in mV; 26; 22; 14; 6; 2.6; 0.4;
Abstand Rasierklinge-Linse 1: 14.3 cm
Position Schraube; 12.5; 13.7; 14; 15.4; 15.5; 15.6;
normierte Spannung in mV; 27; 23; 15; 6; 1.3; 0.7;
Abstand Rasierklinge-Linse 1: 17 cm
Position Schraube; 9.4; 9.9; 10.4; 10.7; 11; 11.8
normierte Spannung in mV; 25; 19; 11; 6; 1.7; 1;
```

6.2 Pythoncode

matrizenoptik.py

```
# -*- coding: utf-8 -*-
"""
Created on Thu Jun  9 22:27:53 2022

@author: corin
"""

import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from scipy.optimize import curve_fit
import scipy.integrate as integrate
from functools import partial #https://stackoverflow.com/questions/61675014/integral-with-va
```

```
csv_path_a = r"C:/Users/corin/Gausssche-Strahlenoptik/Strahlprofil_a.csv"
csv_path_b = r"C:/Users/corin/Gausssche-Strahlenoptik/Strahlprofil_b.csv" # Vielleicht Teil

a_72 = pd.read_csv(csv_path_a, delimiter=";", header=None, skiprows=3, nrows=2, usecols=[1,2
a_45 = pd.read_csv(csv_path_a, delimiter=";", header=None, skiprows=6, nrows=2, usecols=[1,2
a_105 = pd.read_csv(csv_path_a, delimiter=";", header=None, skiprows=9, nrows=2, usecols=[1,
data_a = [a_45, a_72, a_105]

h = 6.62607015*10**(-34)
c = 299792458
wvl = 632.8*10**(-9)
e = 1.602176634*10**(-19)
distLS = 15.5 #Distance lens-fibre end (Source of laser beam)
Rd = 10**4 #Resistance of the photodiode in ohm

#normalized micrometer positions:
x72 = a_72.values[0]-a_72.values[0][0]
x72new = a_72.values[0]-a_72.values[0][2]
x45 = a_45.values[0]-a_45.values[0][0]
x105 = a_105.values[0]-a_105.values[0][0]

maxints = []
omegas = []

def P(U, R):
    return (h*c*U)/(wvl*R*e*0.75)

def gaussint(x, I0, w):
    inner = lambda xp: np.exp((-2*xp**2)/(w**2))
    #inteqrate.quad kann keine Integrationsgrenzen als Variablen haben, darum komplizierter
    integral = np.array(list(map(partial(integrate.quad, inner, b=np.inf), x)))[:,0]
    return I0*integral

def rayleigh(w):
    return (np.pi*w**2)/wvl

plt.plot(x72, P(a_72.values[1], Rd), 'ro', label="8,3 +- 0,2cm")
plt.plot(x45, P(a_45.values[1], Rd), 'bo', label="11,0 +- 0,2 cm")
plt.plot(x105, P(a_105.values[1], Rd), 'go', label="5,0 +- 0,2 cm")

#8,3cm fit
popt, cov = curve_fit(gaussint, x72, P(a_72.values[1], Rd))
maxintensity, omega = popt
plt.plot(x72, gaussint(x72, maxintensity, omega), 'r--') #Die ersten beiden Werte sind schle
popt, cov = curve_fit(gaussint, x72new[2:], P((a_72.values[1]), Rd)[2:])
```

```
maxintensity, omega = popt
maxints.append(maxintensity)
omegas.append(omega)
plt.plot(x72[2:], gaussint(x72new[2:], maxintensity, omega), 'r')
print("8,3cm:\n", "I_0:", maxintensity, "Strahltaille:", omega)

#11cm fit
popt, cov = curve_fit(gaussint, x45, P(a_45.values[1], Rd))
maxintensity, omega = popt
#maxints.append(maxintensity)
#omegas.append(omega)
plt.plot(x45, gaussint(x45, maxintensity, omega), 'b')
print("11cm:\n", "I_0:", maxintensity, "Strahltaille:", omega)

#5,0cm fit
popt, cov = curve_fit(gaussint, x105, P(a_105.values[1], Rd))
maxintensity, omega = popt
maxints.append(maxintensity)
omegas.append(omega)
plt.plot(x105, gaussint(x105, maxintensity, omega), 'g')
print("5,0cm:\n", "I_0:", maxintensity, "Strahltaille:", omega)

plt.xlabel("x-x_0 in mm (normalized micrometer position)")
plt.ylabel("power in mW") #Milli weil die Spannungen in mV angegeben sind
plt.legend(title="Distance razor blade - fibre end")
plt.title("cross section profile of collimated beam")
plt.savefig("part a: cross section profile of collimated beam.png", dpi=400)

print("waist: (", np.mean(omegas), "+-", np.std(omegas), ") mm")
rays = [rayleigh(i)/10**6 for i in omegas] #10**6 weil millimeter umrechnen
print("rayleigh length: (", np.mean(rays), "+-", np.std(rays), ") mm")

#Muss noch y-Werte in Lichtleistungen umrechnen (und ylabel anpassen!)
#Aufgaben Seite 14 und 15
#Fehler bei 8,3 cm: Wahrscheinlich nicht als ersten Wert die stelle gewählt, an der die Rasi
#gerade noch so nicht in den strahl hineinragt, sondern schon früher gemessen (rasierklinge
#Offset durch Hintergrundhelligkeit abziehen: wurde gemacht durch normalisierte spannung
# 11,0 cm : omega negativ... wahrscheinlich zu große entfernung von kabelausgang, sodass feh

# -*- coding: utf-8 -*-
"""
Created on Sat Jun 11 00:53:58 2022

@author: corin
"""
```

```
# Task: d bestimmen Sie aus dem Verlauf von w(z) den
#Waist w0 dieses Strahls mithilfe eines Fit-Programms. Dabei passen Sie die Funktion von w(z
#nach Gl. (11) an die gemessenen Werte w1(z1), w2(z2),... an. Die Position des waist z0 ist
#ein unbekannter Parameter, welcher gleichzeitig angepasst werden muss. Bestimmen Sie aus
#dem Waist w0 auch die Rayleigh-Länge zR

import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from scipy.optimize import curve_fit
import scipy.integrate as integrate
from functools import partial

csv_path_b = r"C:/Users/corin/Gausssche-Strahlenoptik/Strahlprofil_b.csv"

b_10 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=3, nrows=2, usecols=[1,2
b_9 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=6, nrows=2, usecols=[1,2,
b_11 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=9, nrows=2, usecols=[1,2
b_6 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=12, nrows=2, usecols=[1,2
b_3 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=15, nrows=2, usecols=[1,2
b_14 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=18, nrows=2, usecols=[1,
b_17 = pd.read_csv(csv_path_b, delimiter=";", header=None, skiprows=21, nrows=2, usecols=[1,
data = [b_3, b_6, b_9, b_10, b_11, b_14, b_17]

Rd = 10*10**3
#f = 100 #mm

maxints=[]
omegas=[]
zvals=[0,-1,1,-4,-7, 4]
#zvals=[10**(-6)*i for i in zvals]
zvals.sort()
localwaists=[]

def P(U, R):
    h = 6.62607015*10**(-34)
    c = 299792458
    wvl = 632.8*10**(-9)
    e = 1.602176634*10**(-19)
    return (h*c*U)/(wvl*R*e*0.75)

def localwaist(z, omega_0, rayleigh):
    #rayleigh = np.pi*(omega_0**2)/(632.8*10**(-9)
    return omega_0*np.sqrt(1+(z**2)/(rayleigh**2))

#lokaler Strahlradius bestimmen
```

```
def gaussint(x, I0, w):
    inner = lambda xp: np.exp((-2*xp**2)/(w**2))
    #inteqrate.quad kann keine Integrationsgrenzen als Variablen haben, darum komplizierter
    integral = np.array(list(map(partial(integrate.quad, inner, b=np.inf), x)))[:,0]
    return I0*integral

for d in data:
    popt, cov = curve_fit(gaussint, d.values[0]-d.values[0][0] , P(d.values[1], Rd))
    maxintensity, omega = popt
    maxints.append(maxintensity)
    omegas.append(omega)
    print("I_0:", maxintensity, "Strahltaille:", omega)

#nahe z=0
#indizierung von maxints und omegas potentielle fehlerquelle
plt.plot(b_10.values[0]-b_10.values[0][0], P(b_10.values[1], Rd), 'ro', label="0,0 cm")
plt.plot(b_9.values[0]-b_9.values[0][0], P(b_9.values[1], Rd), 'bo', label="-1,0 cm")
plt.plot(b_11.values[0]-b_11.values[0][0], P(b_11.values[1], Rd), 'go', label="1,0 cm")
plt.legend()
plt.plot(b_10.values[0]-b_10.values[0][0], gaussint(b_10.values[0]-b_10.values[0][0], maxint
plt.plot(b_9.values[0]-b_9.values[0][0], gaussint(b_9.values[0]-b_9.values[0][0], maxints[2]
plt.plot(b_11.values[0]-b_11.values[0][0], gaussint(b_11.values[0]-b_11.values[0][0], maxint
plt.xlabel("x-x_0 in mm")
plt.ylabel("Power in W")
plt.title("Cross section profile focused beam (near focal point)")
plt.savefig("Cross section profile focused beam (near focal point).png", dpi=400)
plt.clf()
#große z
plt.plot(b_6.values[0]-b_6.values[0][0], P(b_6.values[1], Rd), 'yo', label="-4,0 cm")
plt.plot(b_3.values[0]-b_3.values[0][0], P(b_3.values[1], Rd), 'co', label="-7,0 cm")
plt.plot(b_14.values[0]-b_14.values[0][0], P(b_14.values[1], Rd), 'mo', label="4,3 cm")
plt.plot(b_17.values[0]-b_17.values[0][0], P(b_17.values[1], Rd), 'ko', label="7,0 cm")
plt.legend()
plt.plot(b_6.values[0]-b_6.values[0][0], gaussint(b_6.values[0]-b_6.values[0][0], maxints[1]
plt.plot(b_3.values[0]-b_3.values[0][0], gaussint(b_3.values[0]-b_3.values[0][0], maxints[0]
plt.plot(b_14.values[0]-b_14.values[0][0], gaussint(b_14.values[0]-b_14.values[0][0], maxint
plt.plot(b_17.values[0]-b_17.values[0][0], gaussint(b_17.values[0]-b_17.values[0][0], maxint
plt.xlabel("x-x_0 in mm")
plt.ylabel("Power in W")
plt.title("Cross section profile focused beam (far from focal point)")
plt.savefig("Cross section profile focused beam (far from focal point).png", dpi=400)
plt.clf()
#
##waist bestimmen
##Fehlerquelle: Mehr Messungen wären nötig
#Fehlerquellen aus H3 Notes
```

```
## b_17 liefert negativen waist ??? Vielleicht am ungenausten weil am weitesten von Quelle w
# dran denken 14,3 cm
popt, err = curve_fit(localwaist, zvals, omegas[:6], absolute_sigma="True") #fitted localwai
waist, zR = popt
plt.plot(zvals, omegas[:6], 'ro', label="data")
for i in zvals:
    localwaists.append(localwaist(i, waist, zR)) #nur weil plt.plot(zvals, localwaist(zvals)
plt.plot(zvals, localwaists, 'b', label = "fit")
plt.vlines(0, 0, 1.7, 'y', '--', label="focal position")
plt.xlabel("z in cm")
plt.ylabel("omega(z) in mm")
plt.legend()
title = "beam waist against razor position from focal point"
plt.title(title)
plt.savefig("beam waist against razor position from focal point.png", dpi=400)

print("waist: (", waist, "+-", np.sqrt(err[0,0]), ") mm")
print("rayleigh length: (", zR, "+-", np.sqrt(err[1,1]), ") mm")
# standardabweichung größer als  eigentlicher wert bei rayleigh length
#waist mit 0.8 mm wahrscheinlich zu groß, weit über dem gemessenen minimum (siehe figure let
```

Optical$_r esonator.py$