Characterization of a Gaussian shaped laser beam

Aim: To learn how to characterize a Gaussian beam and to calculate the position and size of a beam waist.

Literature: This manual + sections 7.5 and 7.6 from Laser Physics by Milonni and Eberly.

Prerequisites: Basic knowledge about Gaussian beam propagation and familiarity with the $ABCD$-matrix approach.

Laboratory work in the course
Laser Physics C, 7.5 ECTS

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1 Introduction

There are several occasions where knowledge of the beam spot size and waist location is of interest. For instance, when coupling a beam into a cavity or an optical fiber these parameters need to be accurately measured. The spot size of the beam is also of importance when you are considering different detector sizes or when a beam needs to be focused by a lens.

There are several techniques to determine the size of the beam waist and its location. In this laboratory exercise you will familiarize yourself with one of them, the razor blade technique. Due to its simple setup it is frequently used whenever Gaussian shaped beams need to be characterized.

2 Theory

2.1 Characterization of a beam with a Gaussian intensity profile

The intensity profile of a Gaussian beam in the \((x, y)\)-plane while propagating in the \(z\) direction (schematically depicted in Fig. 1) is given by,

\[
I(x, y, z) = \frac{2P_0}{\pi w(z)^2} \exp \left[ -\frac{2(x^2 + y^2)}{w(z)^2} \right],
\]

where \(P_0\) is the power of the beam given by the double integral,

\[
P_0 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y) \, dx \, dy
\]

and \(w(z)\) is the beam radius as a function of coordinate \(z\) given by

\[
w(z) = w_0 \sqrt{1 + \frac{z^2}{z_0^2}},
\]

where \(w_0\) is the minimum spot size obtained at the beam waist and \(z_0 = \pi w_0^2 / \lambda\) is the Rayleigh range, defined as the distance from the beam waist where \(w(z_0) = w_0\sqrt{2}\) [1] and \(\lambda\) is the wavelength of the light.

The divergence angle of the beam, \(\theta\), is defined as \(\partial w / \partial z|_{z \to \infty} = w_0 / z_0 = \lambda / (\pi w_0)\).

\[\text{Figure 1} \quad \text{The radial spot size, } w(z), \text{ of a Gaussian beam along with the Gaussian beam parameters: beam waist } w_0, \text{ Rayleigh range } z_0 \text{ and divergence angle } \theta.\]
2.2 Determining the beam spot size by the razor blade technique

The razor blade technique is a simple technique used for characterization of laser beams. It provides a direct way to calculate the minimum spot size \( w_0 \) and the location of the beam waist. By knowledge of these, the beam size can be assessed at any other position. In the following section a short description of how to apply this technique follows.

Assume that the laser beam is directed at a detector whose active area is bigger than the spot size of the laser at that position. Now if we cover a part of the beam by a razor blade, the power impinging on the detector is given by the covered power, \( P_c \), subtracted from the total power, \( P_0 \):

\[
P(x) = P_0 - P_c = \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dx' I(x', y, z) - \int_{-\infty}^{x} dx' I(x', y, z)
\]

\[
= \int_{-\infty}^{\infty} dy \int_{x}^{\infty} dx' I(x', y, z) = \frac{2P_0}{\pi w(z)^2} \int_{x}^{\infty} dx' \exp \left[ -\frac{2(x'^2 + y^2)}{w(z)^2} \right]
\]

\[
= \frac{P_0}{2} \left[ 1 - \text{erf} \left( \frac{x\sqrt{2}}{w(z)} \right) \right],
\]

where \( \text{erf}(x) \) is the error function to which no analytical solution exists and the solution is usually calculated numerically. From Eq. (4) one can define the width of the beam as the distance from the center of the beam where the intensity has dropped by a factor \( e^2 \) [1]. In Fig. 2(a) the normalized intensity distribution of a partly blocked Gaussian shaped beam is shown. In Fig. 2(b), a schematic illustration of the normalized power \( (P/P_0) \) as a function of razor blade position is shown. In this example the width of the beam has been set to 2 mm.

![Figure 2](image)

**Figure 2** – Panel (a): The intensity, \( I \), normalized to the maximum intensity, \( I_0 \), as a function of \((x, y)\). The width of the beam, \( w \), is set to 2 mm and the shift, \( x_0 \), is set to zero. The razor blade is cutting less than half of the beam. Panel (b): The power, \( P \), normalized to the total power, \( P_0 \), as a function of razor blade position for the same beam.

In order to make an accurate curve fit to the experimental data an arbitrary shift along the \( x \)-axis is often introduced to Eq. (4) [3], so that
By fitting Eq. (5) to the measured data, it is possible to obtain the radius of the beam, \( w(z) \), at a certain distance, \( z \). In order to determine the complete beam profile a series of measurements needs to be made where the beam radius, \( w(z) \), is calculated for several positions, \( z \).

3 Tasks

3.1 Characterization of the distributed feedback (DFB) laser threshold current and power response

Your first task is to determine the threshold current and the power response of a DFB laser emitting light at a wavelength around 1560 nm by making a plot of the intensity as a function of current. The data sheet for this particular laser is provided as an attachment. The laser is connected to a collimator which provides a collimated beam over a long distance.

First, set the temperature to 20°C and the laser current to 70 mA. Connect the laser output to the collimator and direct the beam on the power meter which is placed more than 1 m away from the collimator. Try to maximize the power on the power meter by aligning the beam. This should give you a power around 15 mW. Turn the current down to 0 mA, where you are sure that no lasing takes place. Slowly increase the current in steps of 5 mA and note the power corresponding to each current step. Plot the power as a function of current in Fig. 3. Find the corresponding current for the lasing threshold and show it on the figure.

![Figure 3](image_url)

Figure 3 – Power as a function of current.

When this is done, choose a suitable working current for the laser. You should avoid being too close to the threshold, where the power can show excess fluctuations, but you need also not to be at the highest power.
3.2 Characterization of the beam shape from the collimator

!!! The razor blade is sharp !!!

Your second task is to determine the shape of the beam coming from the collimator. Follow the procedure outlined below.

1. Align the collimator and power meter so that the power meter measures all of the power emitted by the laser.

2. Familiarize yourself with the translation stage where the razor blade is mounted, make sure that you understand how many turns are required in order to move the blade by 1 mm. Avoid dripping blood on the optical table.

3. Turn the razor blade back to its starting position and place the blade at a distance of 5 cm from the collimator. Make sure that the razor blade is perpendicular to the beam. Be careful not to block the light with the razor blade.

4. Start measuring the power while moving the blade in increments of 0.25 mm. Write down the power values in Tab. 1, until there is no longer any decrease in the measurement power.

5. Move the blade to the next position indicated in the Tab. 1, and repeat the process.

6. When you have completed all the measurement points, fit Eq. (5) to your data sets using the program supplied by the supervisor. You will get a beam radius, $w(z)$, for each particular distance, $z$, from the collimator. Fill the last row of the table with the corresponding beam radius values and plot the results in Fig. 4.

Table 1 - Power after the collimator for different razor blade positions, $x$, and different distances from the collimator, $z$.

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</tbody>
</table>
To make a curve fit to the experimental data the beam waist position from the collimator, $d_0$, is often introduced to Eq. (3) yielding

$$w(z) = w_0 \sqrt{1 + \frac{(z - d_0)^2}{z_0^2}}. \quad (6)$$

Now, using the program supplied by the supervisor, fit Eq. (6) to your data set for the beam radius. Fill in the parameters of the Gaussian beam in the table below. Find the relations for calculating the divergence angle of the beam and the wavelength of the laser from the values obtained from the fit. Fill them in the corresponding fields and note the relation that you used as well. Does the calculated wavelength match with the specified wavelength of the laser?

| Beam waist position $d_0$ [mm]: | .................................................. |
| Beam waist radius $w_0$ [mm]: | .................................................. |
| Rayleigh range $z_0$ [mm]: | .................................................. |
| Calculated divergence angle $\theta_0$ [rad]: | .................................................. |
| Calculated wavelength of the laser $\lambda$ [nm]: | .................................................. |

### 3.3 Calculate lens position relative to the collimator

Imagine that you need to place a detector at a distance of 75 cm from the collimator. To ensure that you have maximum power impinging on the detector it is necessary for you to focus the beam at this distance from the collimator. To accomplish this you have purchased a lens ($f = 250$ mm), which is to be placed after the collimator. A schematical view of the beam propagation in the system is shown in Fig. 5.
Figure 5 – Schematical view of the beam propagation in the system. \(d_1\) is the distance from the collimator to the lens, \(f\) is the focal length of the lens, \(f = 250\,\text{mm}\), \(d_2\) is the distance from the lens to the second beam waist, \(w_0\) is the beam waist radius after the collimator, and \(\theta_0\) is the divergence angle of the beam for the first beam waist. \(w'_0\) is the beam waist radius after the lens. The distance \(d_1 + d_2\) should be 750 mm.

3.3.1 The \(ABCD\) law for Gaussian beams

A Gaussian beam can, at any position, be characterized by a \(q\)-parameter, given by

\[
\frac{1}{q(z)} = \frac{1}{R(z)} + \frac{i\lambda}{\pi w^2(z)},
\]

where \(R(z)\) is the radius of curvature of the Gaussian beam wavefront which is defined as \(R(z) = z[1 + z_0^2/z^2]\). The \(q\)-parameter at one position, \(q_f\), can be related to that at another position, \(q_i\), by

\[
q_f = \frac{A q_i + B}{C q_i + D},
\]

in which \(A\), \(B\), \(C\), and \(D\) are the elements of the \(ABCD\) matrix for the propagation of light.

If we examine the Fig. 5 closely we see that the beam propagation consists of three parts: (i) free space propagation a distance \(d_1\), (ii) propagation through a thin lens, and (iii) free space propagation a distance \(d_2\). The \(ABCD\) matrix for the propagation of light through this system (starting from the second beam waist, passing through the lens and ending in the first beam waist) can then be written as,

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
1 & d_2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
-1/f & 1
\end{bmatrix} \begin{bmatrix}
1 & d_1 - d_0 \\
0 & 1
\end{bmatrix}
= \begin{bmatrix}
1 - \frac{d_2}{f} & d_1 - d_0 + d_2 - \frac{(d_1 - d_0)d_2}{f} \\
-\frac{1}{f} & 1 - \frac{d_2 - d_0}{f}
\end{bmatrix},
\]

which gives the expressions for the \(ABCD\) coefficients,
The light at a beam waist will have a purely imaginary \( q \)-parameter since \( R \to \infty \). The \( q \)-parameter for the first beam waist, \( q_i \), will then be given by
\[
q_i = -\frac{i\pi w_0^2}{\lambda} = -iz_0. \tag{14}
\]
The same condition is applicable to the second beam waist, i.e.
\[
q_f = -\frac{i\pi w_0'^2}{\lambda} = -iz'_0. \tag{15}
\]
Inserting Eq. (14) and Eq. (15) into Eq. (8) and multiplying the expression by the complex conjugate of the denominator gives
\[
-iz'_0 = \frac{Aq_i + B}{Cq_i + D} = \frac{(-iAz_0 + B)(iCz_0 + D)}{(-iCz_0 + D)(iCz_0 + D)} = \frac{BD + ACz_0^2}{D^2 + C^2z_0^2} + i\frac{z_0(BC - AD)}{D^2 + C^2z_0^2}. \tag{16}
\]
By equalizing the imaginary and real parts we obtain two equations,
\[
\text{Re}[q_f] = 0 \implies BD + ACz_0^2 = 0, \tag{17}
\]
and
\[
\text{Im}[q_f] = -z'_0 \implies z_0(AD - BC) - z'_0(D^2 + C^2z_0^2) = 0. \tag{18}
\]
Your task is, as previously stated, to calculate where to place the lens if the location of the beam waist is to be 750 mm from the collimator \((d_1 + d_2 = 750 \text{ mm})\). In order to do this, insert Eqs. (10)-(13) as well as the condition \(d_1 + d_2 = 750 \text{ mm}\) into Eq. (17) and solve for \(d_1\).
Estimated lens position after the collimator, $d_1$ [mm]: .................

In addition, Eq. (18) gives an expression for $z'_0$ according to,

$$z'_0 = \frac{f^2 z_0}{(d_1 - d_0 - f)^2 + z_0^2}.$$  \hspace{1cm} (19)

Use this expression to estimate the beam waist radius after the lens, $w'_0$.

Estimated beam waist radius, $w'_0$ [mm]: ..........................

3.4 Measure the beam shape profile after the lens

1. Align the collimator, lens and power meter so that maximum power is obtained.

2. Turn the razor blade to its starting position and place the blade at a distance of 5 cm from the lens. Make sure that the razor blade is perpendicular to the beam. Be careful not to block the light with the razor blade.

3. Start measuring the power while moving the blade in increments of 0.25 mm. Write down the power values in Tab. 1, until there is no longer any decrease in the measurement power.

4. Move the blade to the next position indicated in the Tab. 2, and repeat the process.

5. When you have completed all the the measurements, fit Eq. (5) to your data sets using the program supplied by the supervisor. You will get a beam radius, $w(z)$, for each particular distance, $z$, from the collimator. Fill the last row of the table with the corresponding beam radius values and plot the results in Fig. 6. Using the program supplied by the supervisor, fit Eq. (6) to your data set for the beam radius. Fill in the parameters of the Gaussian beam in the table below. Calculate the divergence angle of the beam and the wavelength of the laser using the values obtained from the new measurement and write it in the corresponding fields. Does the wavelength match with the specified value and the result from the previous measurement?

Beam waist position from the lens $d_2$ [mm]: ......................

Beam waist radius $w'_0$ [mm]: ..................................

Rayleigh range $z'_0$ [mm]: ....................................

Calculated divergence angle $\theta'_0$ [rad]: .........................

Calculated wavelength of the laser $\lambda$ [nm]: ......................

8
Table 2 – Power after the lens for different razor blade positions, $x$, and different locations, $z$.

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Figure 6 – Beam radius, $w$, as a function of distance to the collimator.

References


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NEL Laser Diodes

NLK1C5EAAA

1530-1565 nm DFB laser diode in a butterfly-type 14 pin package with thermo-electric cooler. Pigtail fiber is connectorized with an FC/PC connector.

FEATURES
* Wavelength Range 1530 - 1565 nm, ITU-T grid wavelength
* Fiber Output Power 10mW

ABSOLUTE MAXIMUM RATINGS($T_{sub}=25\text{deg.C}$)

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<td>V</td>
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ELECTRICAL/OPTICAL CHARACTERISTICS($T_{sub}=25\text{deg.C}$)

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<td>Dark current(PD)</td>
<td>$I_{(0)}$</td>
<td>CW, $V_{DR}=5V$</td>
<td>100</td>
<td></td>
<td></td>
<td>nA</td>
</tr>
<tr>
<td>Tracking error</td>
<td>$E_R$</td>
<td>$I_{R(E)}=\text{constant}$</td>
<td>-0.5</td>
<td></td>
<td>+0.5</td>
<td>dB</td>
</tr>
<tr>
<td>Cooling capacity</td>
<td>$\Delta T_{PE}$</td>
<td>$\phi_e=10mW, T_{case}=70\text{deg}$</td>
<td>45</td>
<td></td>
<td></td>
<td>deg.</td>
</tr>
<tr>
<td>Peltier current</td>
<td>$I_{PE}$</td>
<td>$T_{case}=-5$ to 70deg.</td>
<td>1</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Peltier voltage</td>
<td>$V_{PE}$</td>
<td>$T_{case}=-5$ to 70deg.</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Thermistor resistance*</td>
<td>$R$</td>
<td>$T_{sub}=25\text{deg}.$</td>
<td>10</td>
<td></td>
<td></td>
<td>k$\Omega$</td>
</tr>
<tr>
<td>Isolation*</td>
<td>$I_s$</td>
<td>$T_{sub}=25\text{deg}.$</td>
<td>30</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

$\Delta T=|T_{case}-T_{sub}|$

* Data is not attached.

WARNING

If you plan to use these products in equipment which could endanger lives in the event of a product failure, please consult an NEL engineer before usage. Improper application of these products may endanger life. To avoid possible injury, make certain these products are used in a redundant configuration.

1 These products are subject to export regulations and restrictions set force by the Japanese Government.
2 NTT Electronics Corporation reserves the right to make changes in design, specification or related information at any time without prior notice.
3 The characteristics which are not specified in the data sheet are not guaranteed.
4 The characteristics under the different operation conditions from the ones specified in the data sheet are not guaran...