05 Monomode fibre

[Version 21.2.2019]

Nanophotonics and Metrology Laboratory

Institute of Microengineering,

School of Engineering,

École Polytechnique Fédéderale de Lausanne,

EPFL-STI-IMT-NAM

ELG 237

Station 11

CH-1015 Lausanne

Web : http://nam.epfl.ch

Contact person: Dr. Toralf SCHARF,
Phone: +41 21 6954286
E-mail : toralf.scharf@epfl.ch

Contents

1 Objective and overview

The practical work should introduce the following subjects to you:

- Determine the numerical apertures of optical fibres
- Inject light into different fibres with one or more guided modes
- Compare the injection efficiency for different situations

To get this done you need to read the reference document provided and you should be able to answer the questions under Appendix A of this document.

2 Safety Issues

In this experiments laser sources and low power electrical equipment are used. The laser is of class II. Class II: low-power visible lasers that emit a radiant power below 1 mW. The concept is that the human aversion reaction to bright light will protect a person. Only limited controls are specified. (http://www.osha.gov, Laser Hazards)
The laser is safe because the blink reflex of the eye will limit the exposure to less than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Intentional suppression of the blink reflex could lead to eye injury. In our experiment the laser sources are collimated and should be handled with care. A strongly divergent beam will not be focussed on the eyes retina and represents often no danger. Collimated beams will lead to small focus spots onto the retina special care is needed. ***Do not stare into a collimated beam!***
The electrical equipment used in the experiments is based on USB power (5V, 0.5 A, 2.5 W) and not subjected to any particular security issues. Nevertheless you should **not produce short circuits** on the printed circuit board (PCB) or to the computers USB connection to avoid damage to the material. Make proper use of screwdrivers. Do not force any mechanical parts.

3 Background

Camera

In our experiment we use a pixilated camera. The pixels are arranged in a regular array that is produced at very high precision. The camera chip has 1600 x 1200 pixels and is 4.536mm x 3.416mm wide and large respectively. Pixel pitch is 2.835 micron in both directions (square). We can safely assume that there is no deviation of pixel position.

Fibres

Optical fibres guide light in a confined geometry, the—so called—waveguide geometry. It is based on total internal reflection at the boundary between the core (the inner part) and the cladding (See Fig. 1). Total internal reflection happens when the refractive index of the core is larger than the refractive index of the cladding and the angle of incidence is large.

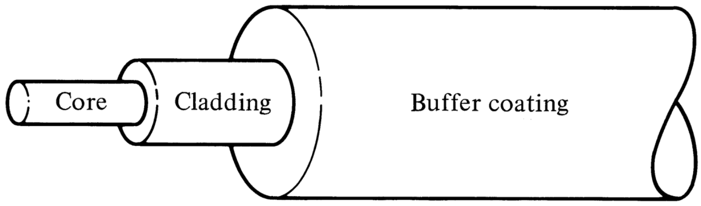


Figure 1 Light is guided inside the high refractive index zone by total internal reflection. The angles are chosen to have total internal reflection at the boundaries. (G.Keiser: Optical Fiber communications, 3rd ed., ,McGrawHill, 2000)

Optical fibres have a multiple shell complex construction with the **core**, the **cladding**, and another protection cover, the **jacket.**
Different fibres are used for different applications. For illumination, a large amount of light has to be transmitted and larger fibres are used. These fibres have a large core, which support several modes. They are called multimode fibres. For optical communication, the information content is important and thin fibres are used. These fibres support only one mode. They are called monomode fibres.
Monomode fibres have core diameters in the range of **3-10 micrometers** (depending on wavelength) and **multimode** fibres have core diameters **larger than 20 micrometers up to several millimetres**

Here are selection criteria to choose an optical fibre adapted to a given application

- Does one need multimode or monomode fibres? Will the fibre be used for information transmission (monomode) or light distribution and collection (multimode)?
- Do the spectral transmission characteristics and the wavelengths range fit the applications (Visible – near infrared – infrared)? This is particular important because of the limited choice of materials to create the high and low index configurations.
- What material should be used and what are the mechanical constrains? Different glass material or hollow fibres (IR) have different stiffness and cannot be used under all circumstances.
- What jacket material has to be used and to protect from the environmental conditions. (Outdoor – indoor)?

Figure 2. Optical fibres on a roll (only core and cladding) and with jacket and connectors as used in patchcord cables (right). (Images web)

Numerical aperture

For fibre coupling there is therefore a limit of the incident angle α_{max} below which light can be injected. For larger incident angles, the light injected into the fibre is not propagated because the reflection at the core/cladding interface is not total and light will be lost. This maximum angle α_{max} is called **acceptance angle.**

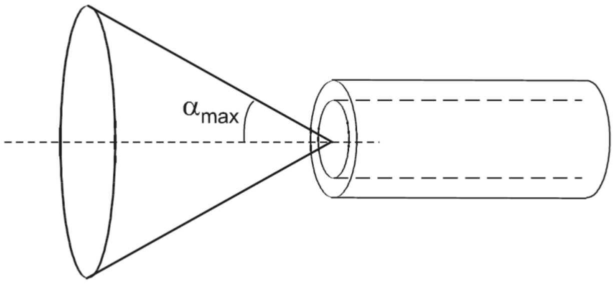


Figure 3. Acceptance angle of optical fibres. If light within this cone is injectied it will be guided. If light with larger angles is sent onto the fibre entrance it cannot be guided.

The acceptance angle of an optical fibre depends on the refractive indices of the core and the cladding materials. Considering the geometry in the Fig. 3, one can relate the maximum acceptance angle to the numerical aperture NA. The following relations hold when the fibre is in air:

$$\mathrm{NA} = \sin\alpha_{max} = n_1 \sin\alpha_c = \sqrt{n_1^2 - n_2^2} \qquad \text{Eq. 1}$$

Here n_1 and n_2 are the refractive index of the core and of the cladding, respectively. For small refractive index differences Eq. 1 can be approximated by

$$\mathrm{NA} \approx n_1\sqrt{2\Delta} \text{ with } \Delta = \frac{n_1 - n_2}{n_1} \qquad \text{Eq. 2}$$

Example:

Assume we have a fractional refractive index difference of Δ=0.005 and light is coming from air. The core refractive index is n_1=1.5. One finds:

$$\mathrm{NA} \approx n_1\sqrt{2\cdot 0.005} = 0.15$$

The corresponding angle of acceptance is

$$\alpha_{max} = \sin^{-1}(\mathrm{NA}) = \sin^{-1}(0.15) = 8.6°$$

If one would immerse such a fibre in water the angle of acceptance (but not the NA!) would change because of the different refractive index of the environment (n=1.33). One would find:

$$\alpha_{max} = \frac{1}{n_{water}}\sin^{-1}(\mathrm{NA}) = \frac{1}{1.33}\sin^{-1}(0.15) = 6.5°$$

The table below summarizes the acceptance angle of the most common types of optical fibre.

Fibre Type (Core/Clad)	Numerical Aperture	Full Acceptance Angle °	F#
Silica/Silica	**0.12**	**13.8**	**4.2**
Silica/Silica	0.22	25.4	2.3
Silica/Plastic	0.39	46.0	1.3
Silica/Plastic	0.48	57.4	1.0
Borosilicate Glass	0.56	68.1	0.9
Plastic (PMMA)	0.55	66.7	0.9

Mode profile and mode field diameter

Monomode fibres show a particular intensity distribution over the fibre diameter. Very often this can be approximated with a Gaussian beam profile.

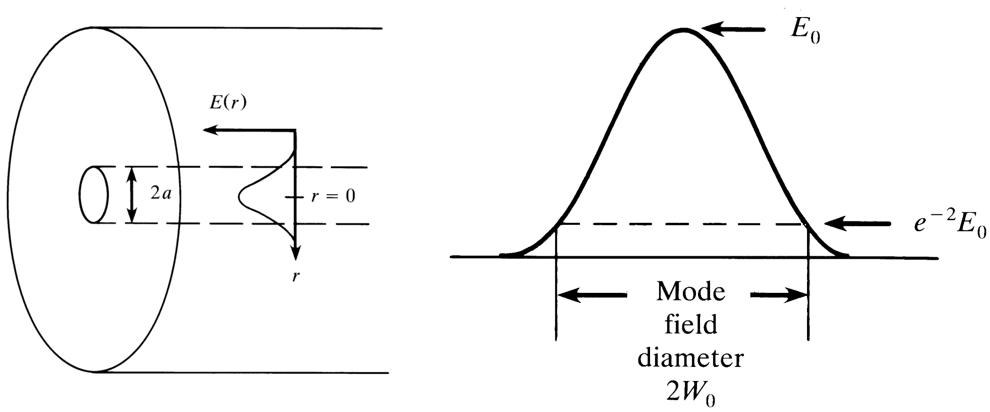


Figure 4. Typical appearance of intensity profiles in monomode fibers.The electrical field amplitude can be modelled by a Gaussian beam profile having a diameter $2W_0$. The mode field diameter is a value that is taken at $1/e^2$ of the maximum value of the electrical field. (G.Keiser: Optical Fiber communications, 3rd ed., McGrawHill, 2000)

The mode field diameter depends on the refractive index, the wavelength and the refractive index difference between cladding and core and discribes the area where most of the intenisty is found.
Under certain circumstances several modes can propagate into an optical fibre. These modes show polarization dependence and each of it has a particular field distribution. The figure below shows examples for a circular waveguide, hence a fibre. The appearance of modes can be calculated exactly (Gauss Hermite polynoms) and is a function of size, wavelength, geometry and refractive indices distribution in the waveguide. The nomenclature is done with numbers that count the zeros in the intensity. For example, the mode LP_{01} has no zeros. LP_{02} has a radial ring with vanishing amplitude. LP_{11} has zero amplitude along an axial direction.

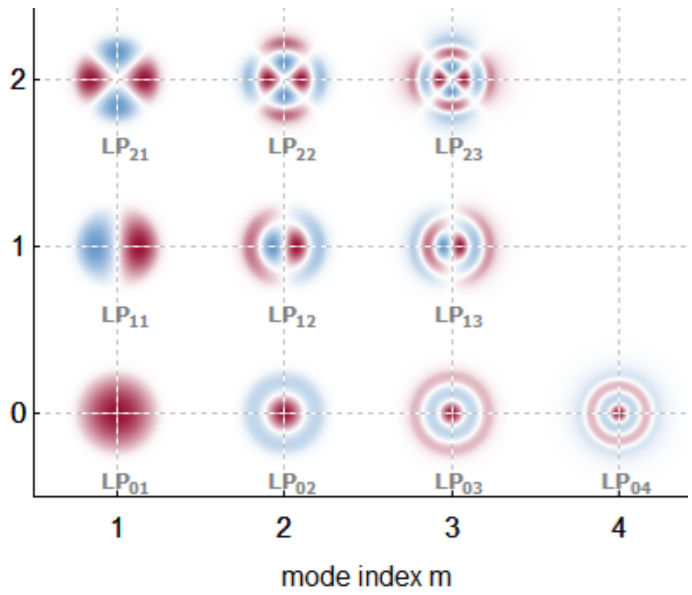


Figure 5. Intensity distribution and polarization states for various modes. (http://www.rp-photonics.com/waveguides.html)

V parameter

Mode characteristics are classified with the **normalized frequency**, V that is defined by:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^{\,2} - n_2^{\,2}} = \frac{2\pi a}{\lambda}\mathrm{NA} \qquad \text{Eq. 3}$$

where a is the radius of the core, λ is the optical free space wavelength, n_1 and n_2 are the refractive indices of the core and the cladding, respectively. **Single mode operation** is possible (monomode fibre) when:

$$V \le 2.405 \qquad \text{Eq. 4}$$

The detailed analysis leads to rather complex equations and depends on the type of fibre (step index, gradient...) that is used. The mode number increases each time the mode field diameter of a new mode has enough space to propagate in the fibre. This can be achieved **by reducing the wavelength or increasing the fibre diameter** for a given situation. **The basic mode is LP_{01} and new modes appear when V > 2.4 (LP11), 3.8 (LP21), 5.1 (LP31), 5.5...**

Example:

For NA = 0.14 and a = 3 micron (radius) one finds

at 0.633 micron wavelength:

$$V = \frac{2\pi a}{\lambda}\mathrm{NA} = 2\pi\frac{3}{0.633}0.14 = 4.16$$

at 1.55 micron wavelength:

$$V = \frac{2\pi a}{\lambda}\mathrm{NA} = 2\pi\frac{3}{1.5}0.14 = 1.759$$

A fibre with a radius of 3 micrometer has a normalized frequency of *V=1.76* at a wavelength of 1.5 micrometer. This fibre is single-mode for all wavelengths greater than λ_{min}, the wavelength for which V<2.4. One finds

$$\lambda_{min} = \frac{2\pi a}{V} NA = 2\pi \frac{3}{2.405} 0.14\ [\mu m] = 1.1\ \mu m$$

For wavelengths smaller than λ_{min}, several modes can propagate.

When *V* is large for instance in a **multi-mode fibre** the total number of modes *M* supported is approximately given by:

$$M \approx \frac{V^2}{2} \qquad \text{(many modes)} \qquad \text{Eq. 5}$$

Example:

How many modes M can propagate in a step index fibre of 50 micron diameter (r = 25 micron) with Δ=0.03 ? Take the core index of refraction n_1=1.5 and assume a free space operation wavelength of 0.633 micron.

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^{\ 2} - n_2^{\ 2}} = \frac{2\pi a n_1}{\lambda}\sqrt{2\Delta} = \frac{2\pi \cdot 25 \cdot 1.5}{0.633}\sqrt{2 \cdot 0.03} = 91$$

$$M \approx \frac{V^2}{2} = \frac{8282}{2} = 4140$$

Bending radius

Optical fibres are fragile. One of the critical issues with handling fibres is bending. The amount of bending a fibre can be subjected is limited by the integrity of the fibre, it can break, and the waveguiding condition, light is lost if the reflection angle is not total bending radius should be greater than ten times the outer diameter (OD) of the fibre cable. A 3-mm cable should not have bends with radius smaller than 30 mm.

Fibre connectors

Figure 6. A variaty of fibre connector exist (left). We will use here SMA connectors (middle) typical for multimode fibres and FPC connectors often used for monomode fibres. (images WEB)

Fibres have to be connected with each other. There is a multitude of fibre connectors. The ones for monomode fibres have to deliver accurate positioning well below the fibre core diameter (below 10 micron). Multimode fibres with diameters of several 100 micron are easier to connect. There are more than 30 different types of connectors. The main criteria to select a connector are: The type of fibres (monomode or multimode), the permitted coupling losses and the compatibility with the installation.
For monomode fibres higher positioning precision is required and FC connectors are used. The FC - Ferrule Connector (Fibre Channel) - has a screw of 2.5 mm diameter (IEC 61754-13). These connectors exist in two versions: PC and APC. The PC and APC connectors are not compatible. We use FC-PC connectors that were developed for datacom, telecom and measurement equipment.

Monomode fibres

Monomode fibres are designed to transport information. They have special transmission properties. The basic idea is to propagate only 1 mode (in a simplified picture one ray) in the fibre by reducing the radius of its core. For monomode fibres, the core radius is different for each wavelength. In our case, the core diameter is 4.3 micron (mode field diameter MFD). An image and a table of specifications of the monomode fibre used here are given below (source Thorlabs.)

Figure 7. Monomode fibre patchcord cable with FC connector. The core diameter is only several microns for monomode fibres. The jacket is yellow and the fibres have FC connectors. (images Thorlabs)

We use two different models: Single Mode Fibre Patch Cable, 2 m, 633 nm, FC/PC, P1-630A-FC-2, Single Mode Fibre Patch Cable, 2 m, 1.55 micron, P1-SMF28E-FC-2

#	P1-630A-FC	P1-SMF28E-FC-2
Fibre Type	SM600	SMF-28e+
Operation Wavelength	633 nm	1260-1625 nm
Mode Field Diameter (MFD)[a]	**4.3 µm @ 633 nm**	**10.5 ± 0.5 µm @ 1550 nm**
Cladding Diameter	125 ± 1 µm	125 ± 0.7 µm
Coating Diameter	245 ± 5 µm	245 ± 5 µm
Cut-off Wavelength	550 ± 50 nm	<1260 nm
Attenuation (Max)	≤15 dB/km @ 633 nm	0.20 dB/km @ 1550 nm
NA	0.10 - 0.14	0.14

Protective Jacketing	Ø3 mm, Yellow	Ø3 mm, **Yellow**
Insertion Loss	<2.0 dB Loss (Connector to Connector) @ 633 nm	<0.3 dB Loss (Connector to Connector) at 1550 nm
Length	2 m (for items ending in -2)	2 m

The light in a monomode fibre is homogenous and propagates within the numerical aperture NA. A skew ray experiment makes no sense because there is virtually only one ray that is propagating. At the exit, a particular intensity modulation can be found. At different positions after the fibre a uniform disc of light can be observed. The diameters at certain distance from the fibre exit are given by the numerical aperture.

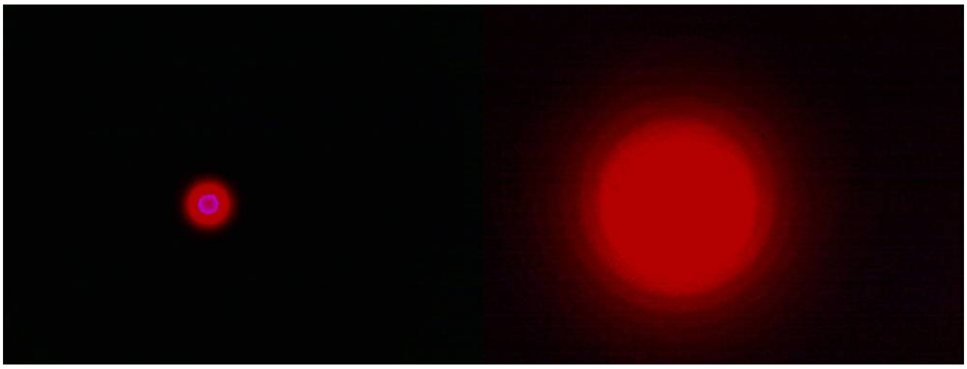


Figure 8: Light spot recorder at different positions after the fibre. Left close to the fibre exit. Right: further away from the fibre exit

Evaluation of the light distribution at different distances can be used to obtain the numerical aperture of the fibre.

Sources

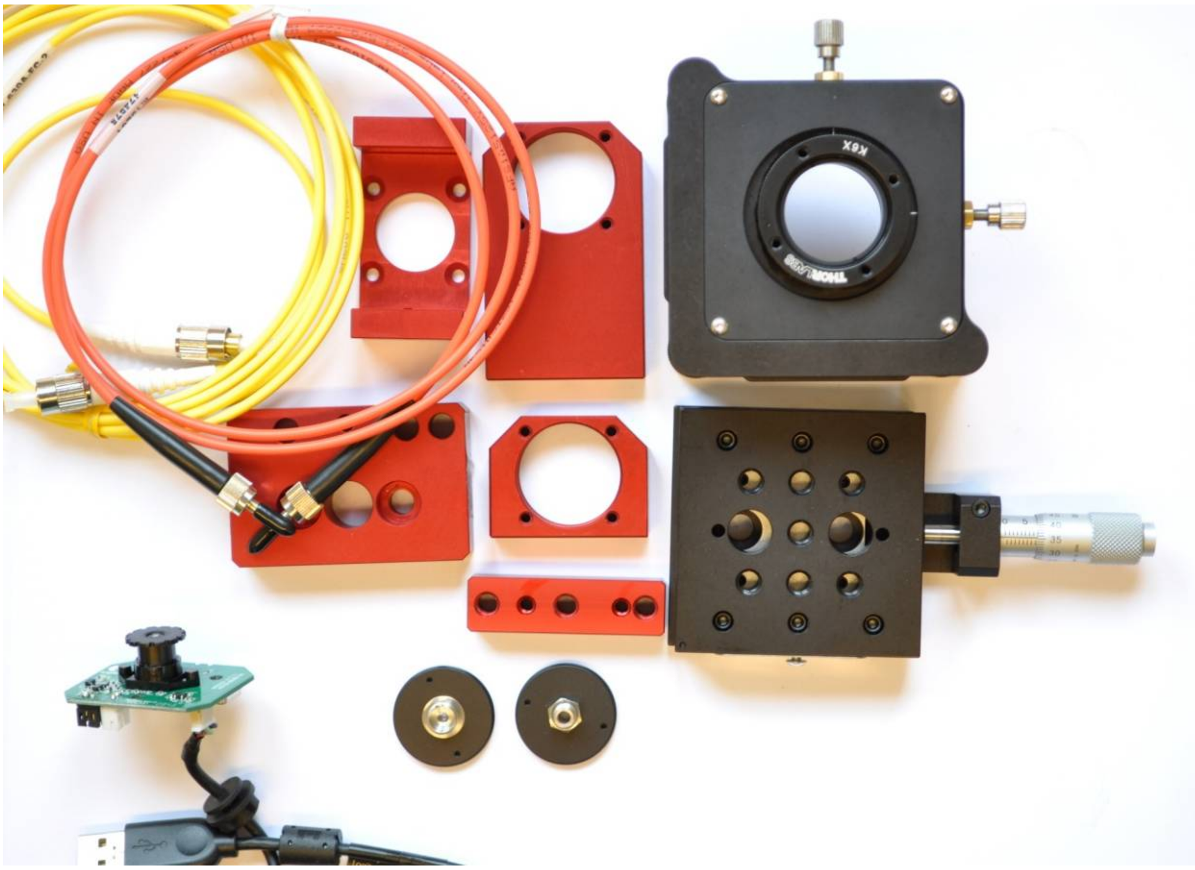
To test the light injection for different sources we are using the halogen lamp, the LED and the laser. Characteristics are given in an earlier description. (TP on Sources). Fibres are only several micrometer wide and this has to be compared to the minimum spot size of the sources. To recall the figure below shows the minimum spot size achieved on the detector.

Figure 9. Minimum focus spot as obtained for different sources. The laser could be focused on a very small spot. The field of view is the whole camera chip and 4.536mm x 3.416mm.

4 Setup and equipment

4.1 Materials

- A CMOS camera (1600x1200 pixels, color, pixel size 2.835 um) C600 from Logitech
- Three different light sources (Halogen, LED, laserdiode) USB driven
- Sheet polarizer
- Objective lens Logitech C600
- Planconvex lens diameter 9 mm, f=12 mm
- Monomode (633 nm) optical fibre (yellow patchcord) P1-630A-FC
- Monomode (1550 nm) optical fibre (yellow patchcord) P1-SMF28E-FC-2



The fibres have to be mounted in a stage with the discs adapter shown below. (FC/PC (Thorlabs part SM1FC))

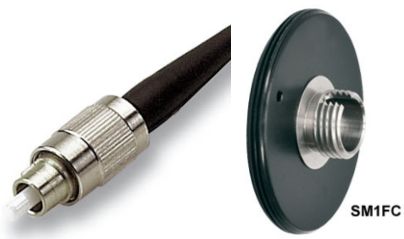


Figure 10: Connector and adapter disc to be used with FC PC connectors.

4.2. Monomode optical fibre injection and mode profiles

The detailed photos below give you precise indication how to mount the setup.

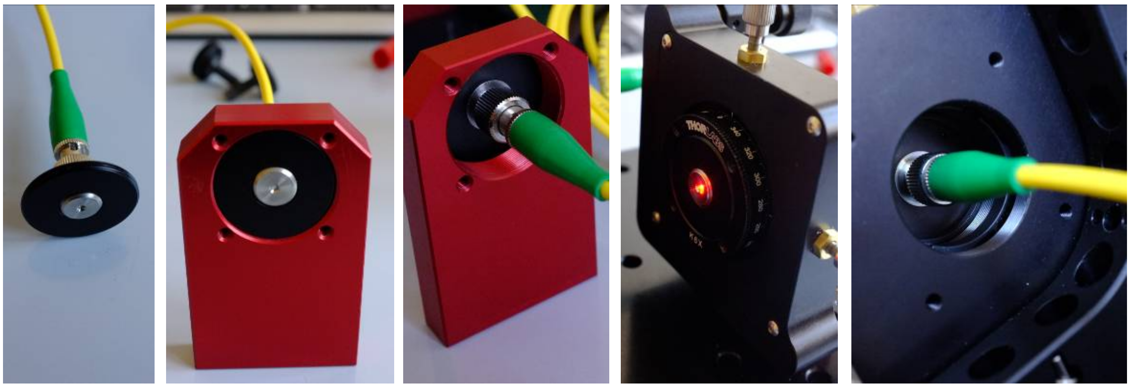


Figure 11: Details of the fibre connector assemblies for monomode patch cords.

NOTE: Mount the fibres with the greatest care to prevent from small bending radius and TORSION. It is sometimes adapted to rotate the holder and not the fibre to prevent from torsion. Use the right connectors. Do not touch the fibre ends.

The camera is used without objective and without IR filter to allow short distances between fibre exit and camera chip.

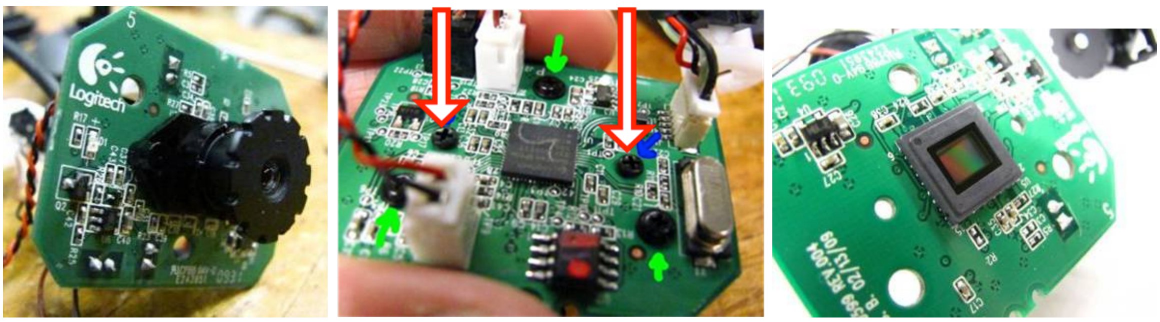


Figure 12. Camera PCB with objective. The red-white arrows show the screws to take off the objective. The PCB with the naked sensor has to be used.

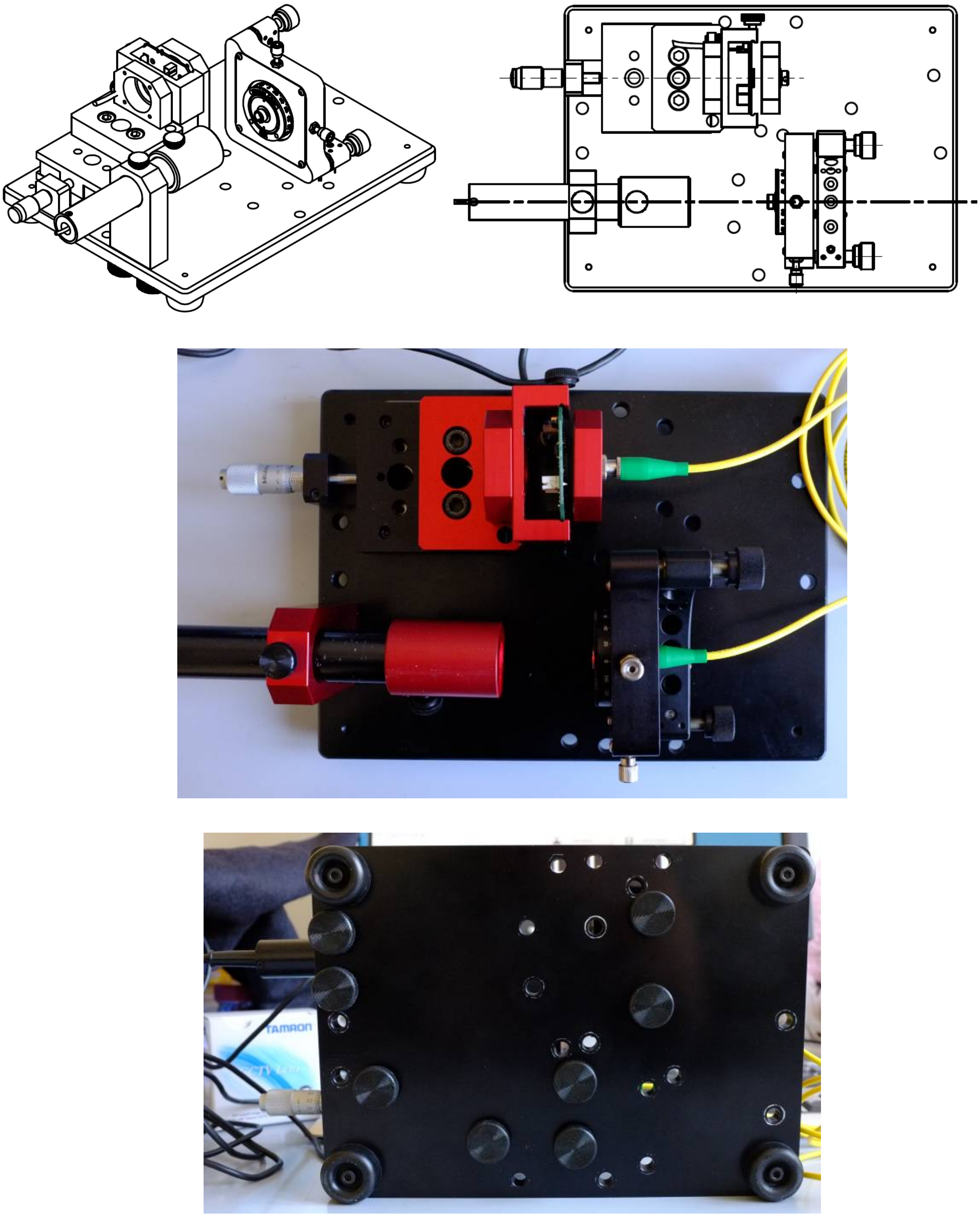


Figure 13. Top and back side of the board.

As discussed above, when a monodmode fibre designed for a long wavelength is used at shorter wavelength several modes appear. The first experiment consists in showing the appearance of such modes.

- Mount the setup with the monomode fibre designed for 1.5 micron wavelength (yellow patchcord **P1-SMF28E-FC-2**)
- Handle the fibres with care and use the **FC connectors**!!!
- Use the **laser** as source
- Chose a high intensity by rotating the cap

- Focus on the fibre entrance
- Adjust the laser focusing to inject light into the fibre (focusing and x-y stage alignment)
- **Switch off** the camera control LED
- Set the exposure conditions to automatic
- Adjust the distance camera – fibre exit distance and adjust the camera position in height to find light at the exit
- Observe the images and the camera and try to obtain the best coupling.
- Adjust and fix the exposure conditions (not automatic anymore)
- Cover the setup with the black tissue to prevent straylight as shown below.

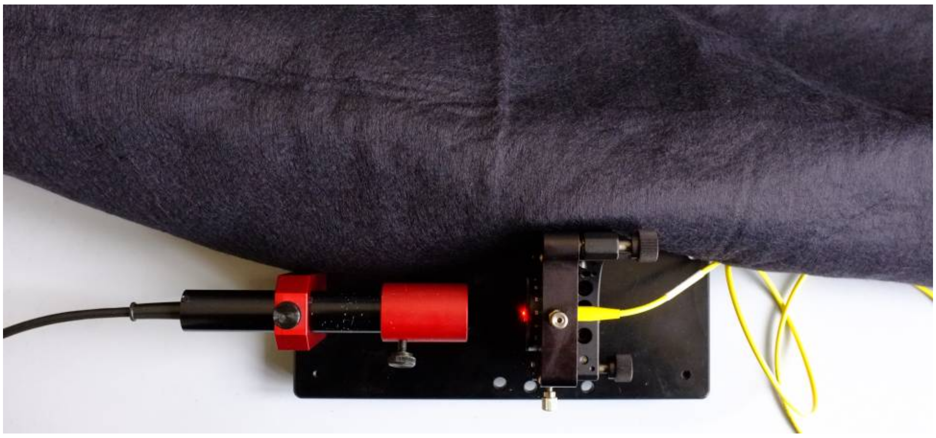


Figure 14. Cover half of the setup to prevent from ambient and stray light.

To find different mode profiles you need to adjust the setup and get access to all possible parameters. Below are a few examples of adjustment possibilities you have.

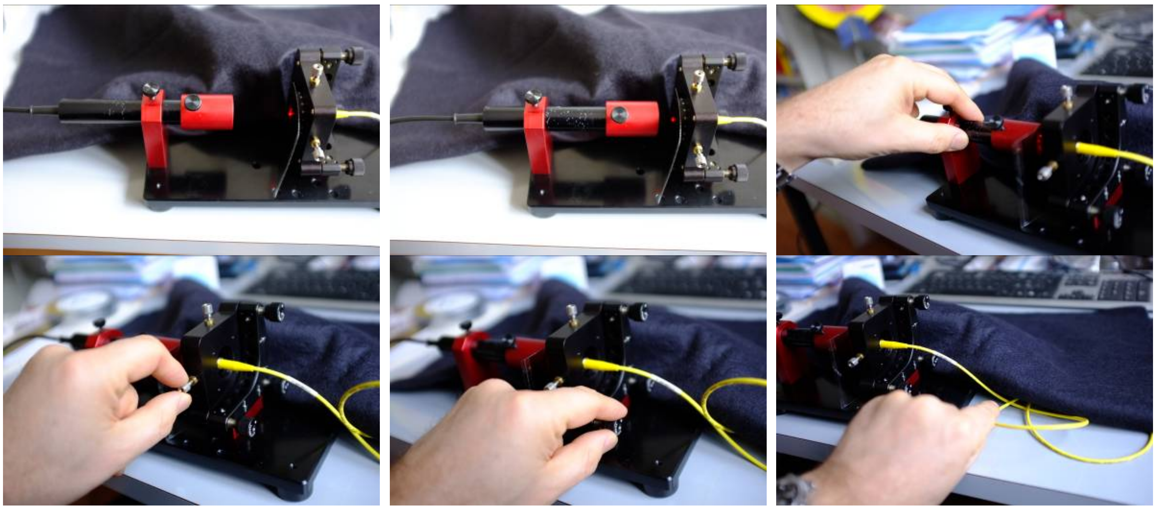


Figure 15: Adjustments to find different modes: Change the source position, focus at different planes, use the 6 axis stage and touch the fibre cable.

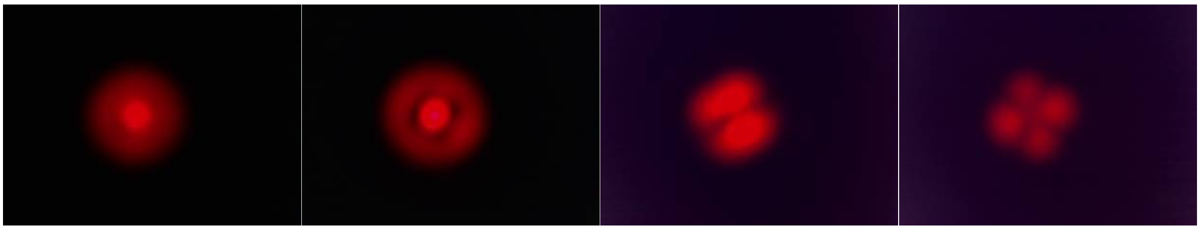


Figure 16: Example of mode profiles. For all these profiles different focussing and exposure conditions were used!

Polarization dependence

Different modes have different polarizations. In simplified description modes are linealy polarized with different direction of polarization. One can see this

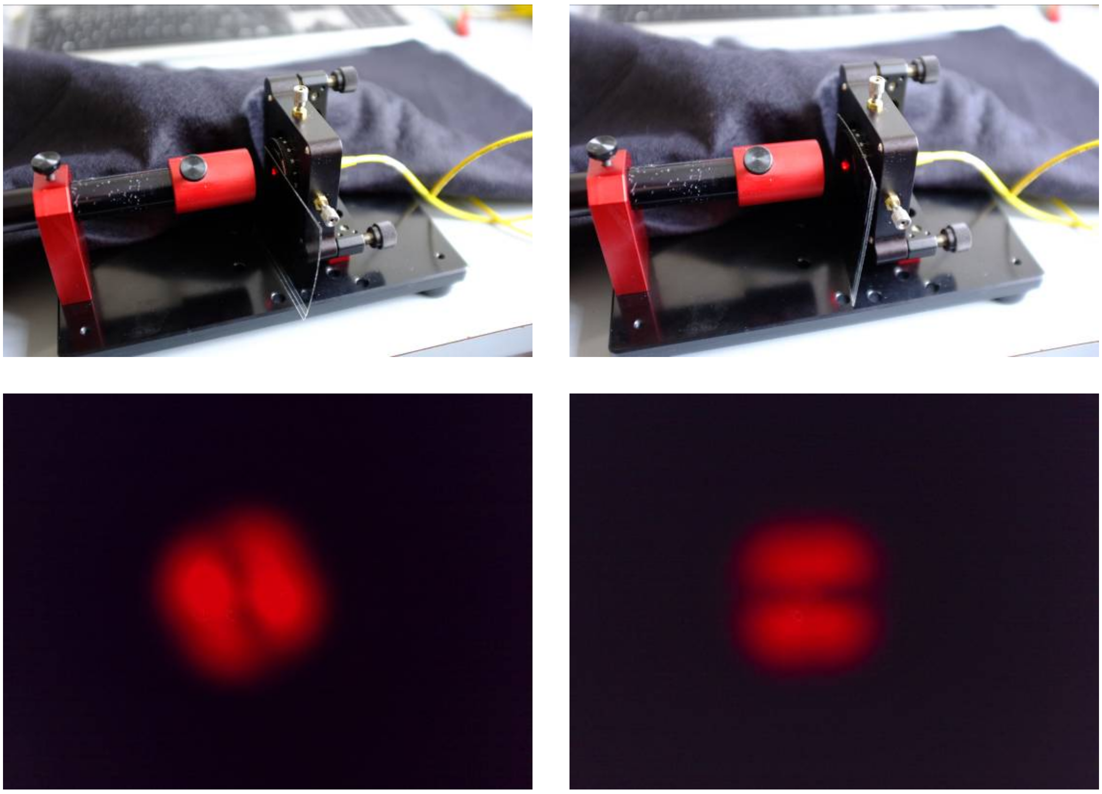


Figure 17: Top: Injection with two different orientations of the polarization direction. Bottom: Mode intensity distribution for two different polarizer positions. Note: the initial polarization direction has to be set at 45° to get equal intensity of the mode profiles.

To be done for the report: Present at least three images with intensity distributions that present different mode profiles similar to the ones shown in the examples above (Figure 16). Play with different adjustments to get the highest contrast of the images and prevent saturation. Show two images for different polarization states, when the polarizer is rotated by 90°. (Rotate the polarizer –do not rotate the lens cap or the laser!). Interpret your result.

4.3. Numerical aperture measurement

Monomode fibres have a very small fibre core allowing only one mode to propagate. This mode has an intensity profile similar to a Gaussian beam profile and it will be visible at the fibre exit. The NA of the fibre can be determined by observing the intensity profile at different distances after the fibre. Mount the monomode fibre for 633 nm: **P1-630A-FC**. Record images for different distances of the camera from the fibre exit using the linear stage.

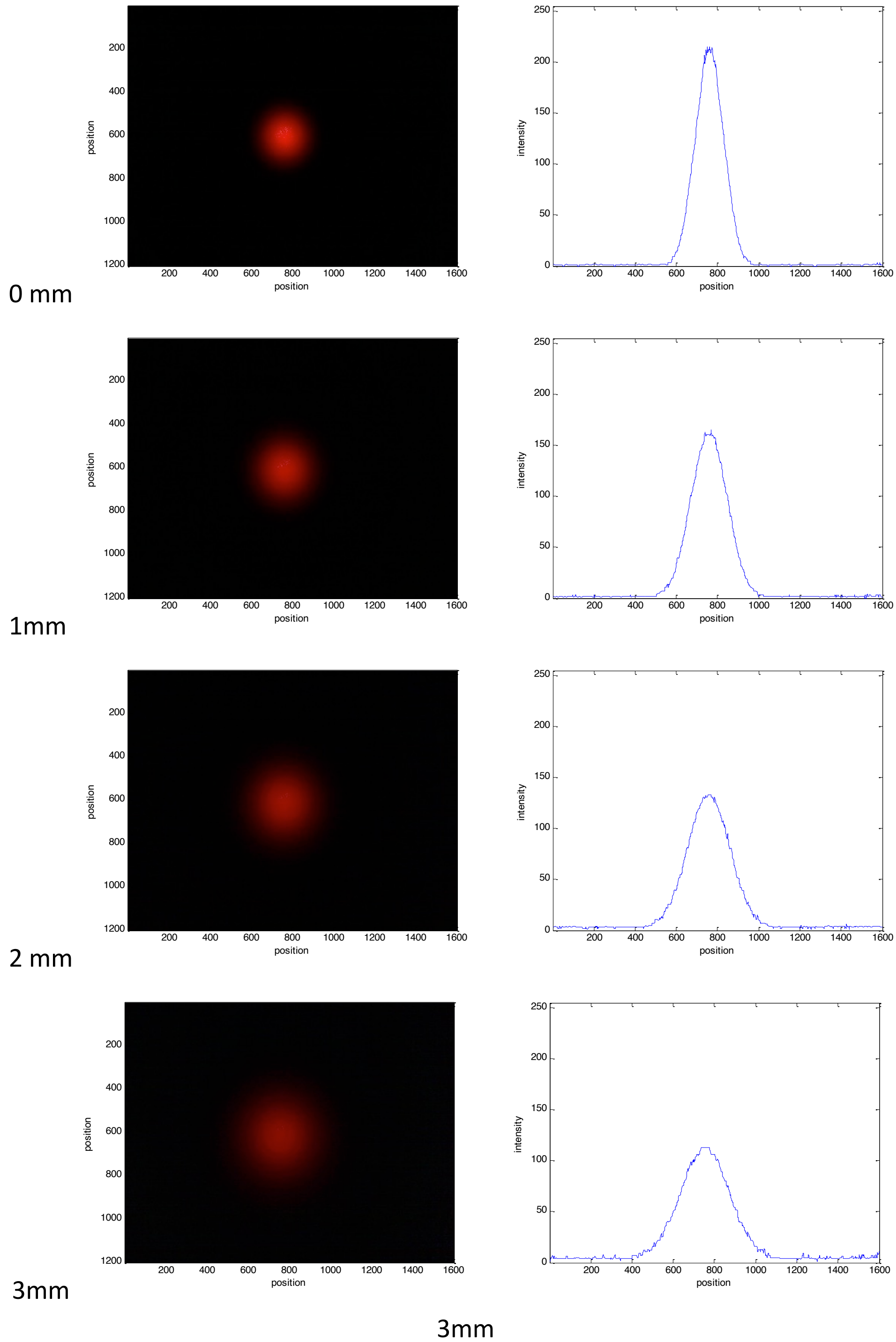


Figure 18. Different intensities and profiles after the fibre exit. The diameter can be measured by using the width of the curve at the bottom.

NOTE: The linear stage moves 500 micron at one full turn of the micrometer screw!

The matlab script (FWHM_line_red.m) will help you to make the evaluation.

```
% close images
fclose ('all');
% Read image 1
I_1 = imread('picture 91.jpg');
% select a channel (here red)
Red_1 = I_1(:,:,1);
% format conversion
Red_1 = double(Red_1);
%visiualize the image to define region of interest
imagesc(Red_1)
xlabel('position')
ylabel('position')
% select a line of interest ROI (1 x 1600), center of peak
Line = Red_1(605:605,1:1600);
%plot a single line
figure
plot(Line)
xlabel('position')
ylabel('intensity')
axis([1 1600 0 255])
```

To be done for the report. Present three example photos for different positions of the spot after the fibre exit. Show line plots of the intensity profile for these images. Make a table with full width at the bottom values for a minimum of 5 measurements. Calculate the numerical aperture value for the monomode fibre. Make an error calculation. Interpret your result.

4.4 Coupling for different numerical apertures.

Injection should be done for the monomode fibre and laser at two different configurations.

Low numerical aperture case.

If the source is far away from the fibre input the image on the fibre input has a low numerical aperture (brightness conservation).

- Use the monomode fibre **P1-630A-FC** (yellow cable) with the FCPC connectors
- Use the laser diode as source and the planoconvex lens.
- Set the source at 75 mm back side holder-source distance as shown below.

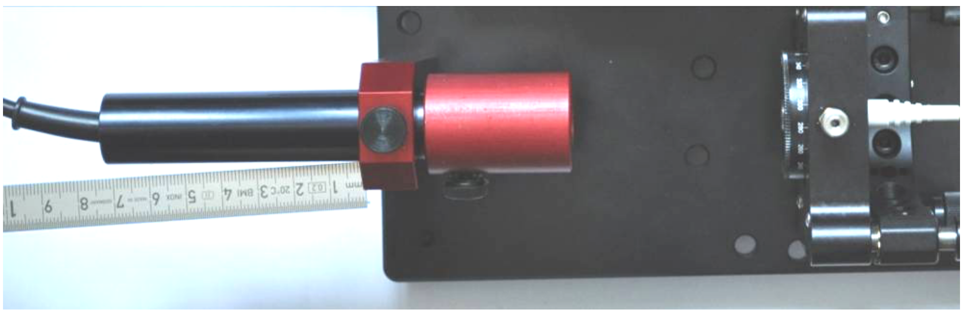


Figure 19 Position of the laser source to achieve low NA focalisation.

- Adjust the camera position in height
- Put the detector camera close to the fibre output with the linear stage
- Rotate the lens cap to adjust the intensity, chose a the **HIGHEST** intensity
- Focus with the lens in the plane of the fibre entrance
- Move the fibre input with the x-y adjustment of the 6-axis stage to find the optimal coupling position
- Adjust positions and focus to **maximize coupling**
- Adjust the exposure conditions (gain and exposure) and fix them (no automatic, **no saturation**)
- Take one or several images

High numerical aperture case.

Now we look at the second measurement with high NA. The lens has to be close to the fibre entrance.

- Set the source at 45 mm back side holder-source distance as shown below.

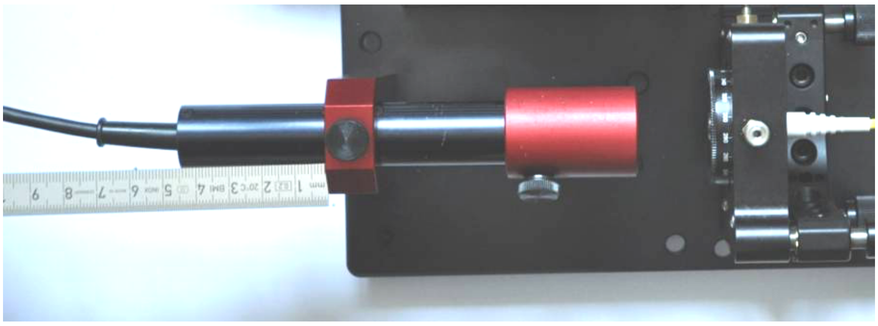
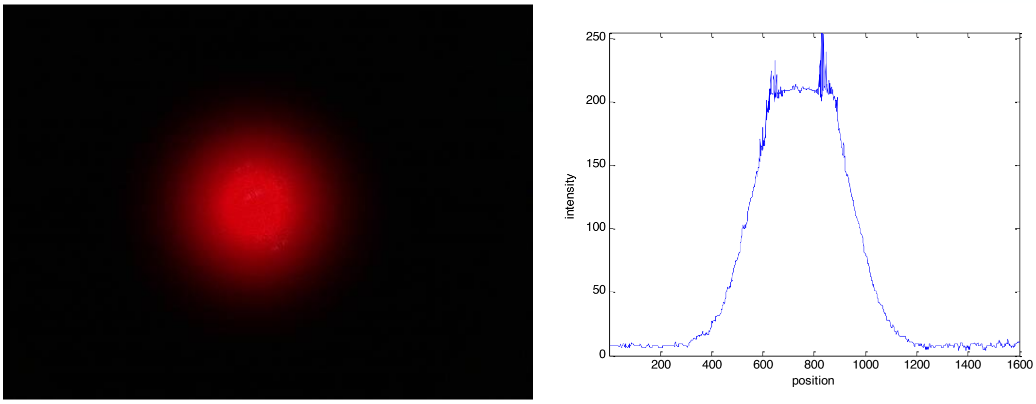
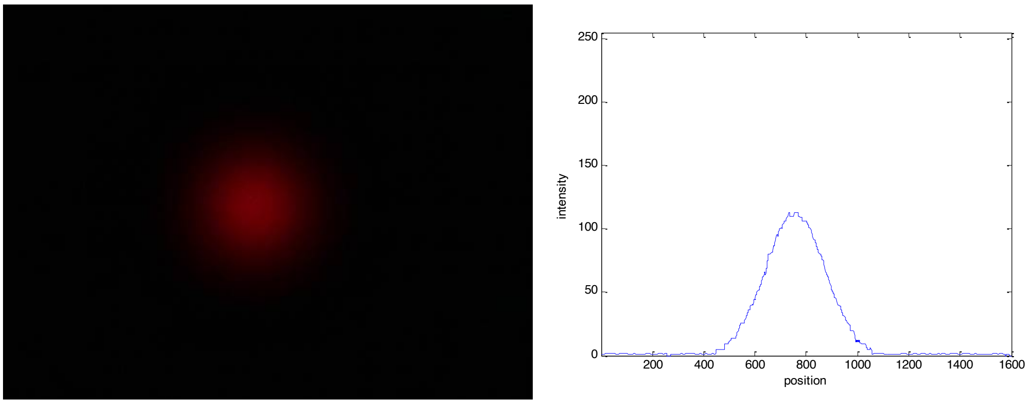


Figure 20: The position with 45 mm creates a much shorter distance between the fibre entrance and the lens. The numerical aperture in this case can be approximated by calculating with the lens diameter and the distance between lens and fibre entrance.

- Focus with the lens in the plane of the fibre entrance, use a sheet of paper to visualize the focus spot if needed
- Rotate the lens cap to adjust the intensity, chose the **HIGHEST** intensity
- Move the fibre intput with the x-y adjustment of the 6-axis stage to find the optimal coupling position
- Adjust positions and focus to **maximize coupling**
- **DO NOT TOUCH the exposure conditions**
- Take one or several images
- **Switch off the light and take an image without light (dark noise evaluation!) but with exactly the same exposure conditions.**



first



second

Figure 21. Two spots on the camera and the corresponding line profiles for laser illumination and different NA at the entrance.

To be done for the report. Show the two images and line plots. Evaluate which coupling is more efficient (for High NA or low NA) by comparing the data taken at the same exposure conditions. Which value is larger. Measure the distance between lens cap and fibre entrance to calculate the NA for both situations (NA = D/(2Z), D lens diameter 9mm, Z distance lens fibre entrance).Give a short explanation of the result.

4.5. Monomode fibre coupling for different sources

We want to compare the coupling for different sources into a monomode fibre. Proceed as follow:

- Move the camera close to the fibre exit and cover the camera part with the black tissue to prevent straylight
- Mount the laser and try to find the maximum coupling. You can choose a position of the laser tube as you wish
- Choose a convenient position of the camera to have well centred images
- Set the camera on automatic exposure to find the fibre exit
- **Maximize the coupling!!** Do not forget that you can rotate the lens cap to increase power values
- **Switch to manual exposure**
- Take an image and record the exposure data
- Continue with the LED and the Halogen source

- Take images and record the exposure data

Examples are given in the figure below. The exposure data together with the recorded intensity reveal the difference of coupling efficiency.

HINT: You can copy an **active window** under windows with by pressing ALTGR and PRTSC at the same moment.

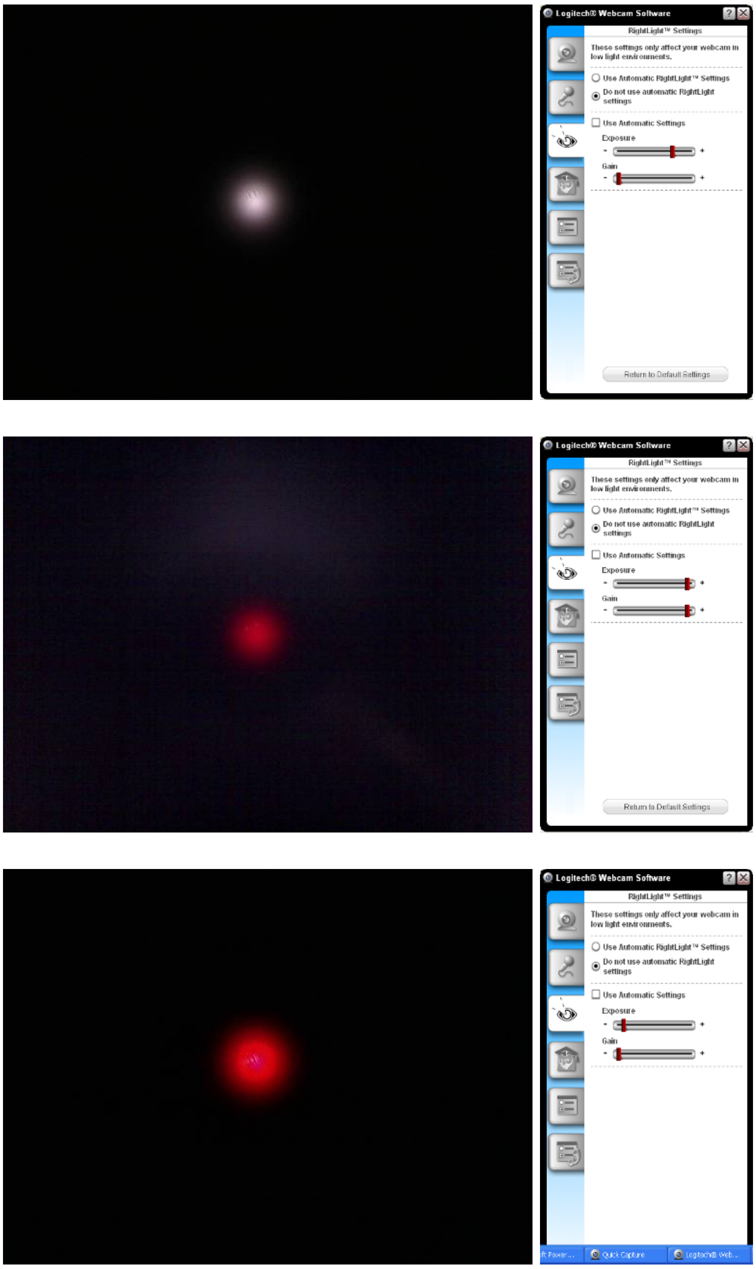


Figure 22: Example images of the light output of the monomode fibre for three different sources. Top : Halogen lamp, middle LED and bottom laser. Please take care that the images are well centred and no saturation appears.

To be done for the report: Show sample images for light spots on the camera for each source. Give the exposure conditions for each source **(screenshot of the settings window).** . Why is it so difficult to couple light from LED and halogen source? Give a short explanation.

5. Summary of tasks of the experimental work

4.2 Monomode optical fiber injection and mode profiles (40 min)

Present at least **three images** with intensity distributions that present different mode profiles similar to the ones shown in the examples above (Figure 16). Play with different adjustments to get the highest contrast of the images and prevent saturation. Show **two images** for different polarization states, when the polarizer is rotated by 90°. (Rotate the polarizer – do not rotate the lens cap or the laser!). Interpret your result.

4.3 Numerical aperture measurement (30 min)

Present **three example photos** for different positions of the spot after the fibre exit. Show **line plots** of the intensity profile for these images. Make a table with full width at the bottom values for a minimum of 5 measurements. Calculate the numerical aperture value for the monomode fibre. Make an error calculation. Interpret your result.

4.4 Coupling for different numerical apertures (30 min)

Show the two images and line plots. Evaluate which coupling is more efficient (for High NA or low NA) by comparing the data taken at the same exposure conditions. Which value is larger. Measure the distance between lens cap and fibre entrance to calculate the NA for both situations (NA = D/(2Z), D lens diameter 9mm, Z distance lens fibre entrance).Give a short explanation of the result.

4.5. Monomode fibre coupling for different sources (20 min)

Show sample images for light spots on the camera for each source (**3 images**). Give the exposure conditions for each source (screenshot of the settings window). Why is it so difficult to couple light from LED and halogen source? Give a short explanation.

Do not forget the feedback at the end!