04 Multimode fibre

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1 Objective and overview

The practical work introduces the following subjects:

- Measure the maximum injection angle with skewed rays
- Determine the numerical apertures of a multimode optical fibre
- Compare the injection efficiency for different illumination conditions

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 pixelated 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 than a critical value.

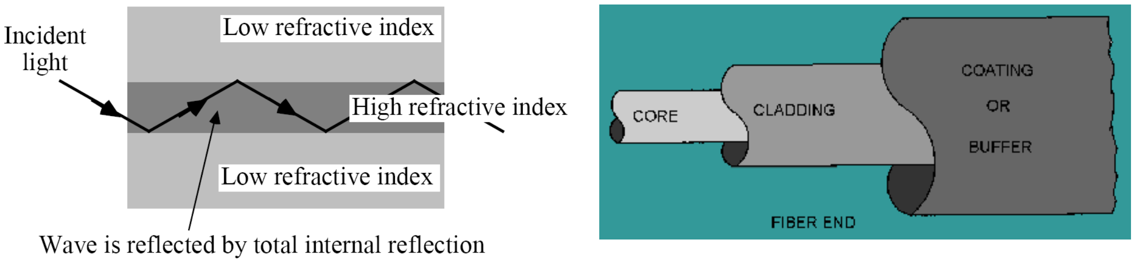


Figure 1 The light is guided inside the high refractive index zone by total internal reflection. The angles are chosen to have total internal reflection at the boundaries.

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 fibres with large cores or fibre bundles are used. These fibres have a large core and support several so called modes. Therefore they are called multimode fibres. For optical communication, the information content is important and fibres with thin cores are used. These fibres support only one mode (for a certain wavelengths range). They are called monomode fibres.
Monomode fibres have core diameters in the range of **3-10 micrometres** (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)?

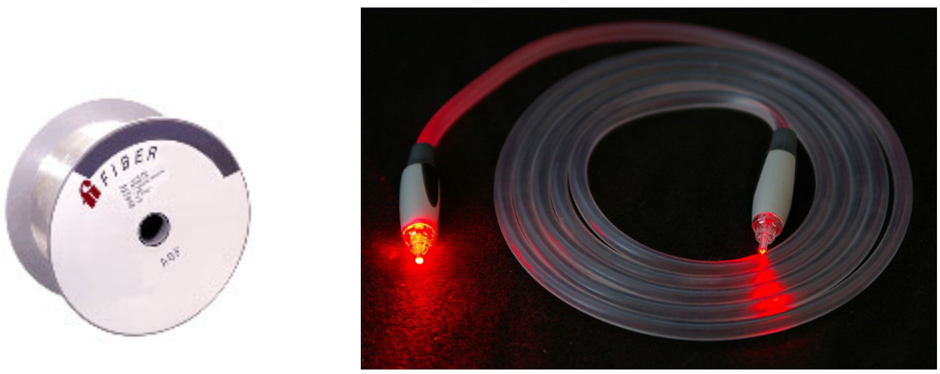


Figure 2. An optical fibres on a roll (left, only core and cladding) and with jacket and connectors as used in patchcord cables (right).

Acceptance angle

In the geometric approximation of optics, light propagates as rays. We consider a **step index fibre** (Fig. 3) that has two well separated refracted indices n_1 (core) and n_2 (cladding) where $n_1>n_2$. The light from a source is incident on the entrance facet of the fibre with different angle α. The rays are refracted at the entrance interface and propagate in the core until they reach the core/cladding interface. When the angle between the ray and the interface is small, light is reflected inside the core. When the angle between the ray and the interface is large, part of the light is lost from the core.

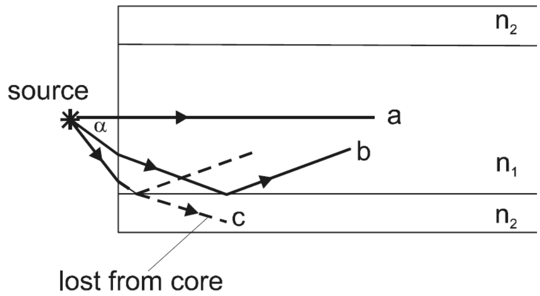


Figure 3. Step index fibre coupling geometry. Rays (a) and (b) are guided because their internal angles of propagation are smaller that the total internal reflection angle. In case (c) the internal angle is large and the ray will be lost from the core. Notice the light refraction at the entrance facet which has to be considered for detailed calculations.

For fibre coupling there is therefore a limit of the incident angle $\boldsymbol{\alpha_{max}}$ 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 $\boldsymbol{\alpha_{max}}$ is called **acceptance angle.**

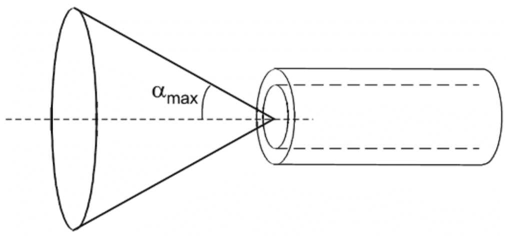


Figure 4. Acceptance angle of optical fibres. Light within this cone is guided be the fibre. Light outside of this cone is not guided.

The acceptance angle of an optical fibre depends on the refractive indices of its core and its cladding materials. The table below shows the acceptance angle of the most common types of optical fibres.

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

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 wave guiding 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.
Below is a table of minimal bending radius for single-core fibres. The bending radius of multicore fibres, such as fibre bundles and fibre cables, is further limited by sheath material, fibre quantity, and length.

Fibre Core Size (µM)	Continuous Bend Radius (mm)	Momentary Bend Radius (mm)
50	31	12.5
100	35	14
200	61	25
400	120	48
600	165	66
1000	275	110
1500	413	165

Fibre connectors

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 (below10 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.

Figure 5. A sample of existing fibre connectors (left). We use SMA connectors (middle) for multimode fibres and FPC connectors (right) for monomode fibres. (images WEB)

In the practical work we use SMA 905 - Sub Miniature A – connectors for multimode fibres. These connectors have a screw-type connection with a 3.14 mm winding and are used for industrial lasers, for military applications and for spectroscopy. If one looks at the connector tip, he can see the fibre facet.
For monomode fibres higher positioning precision is required. 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.

Multimode fibres

In our experiment we use multimode fibres with a diameter of 105 µm, a numerical aperture of NA = 0.22 in a1-m long SMA-SMA Fibre Patch Cable. (Product code - M15L01, Thorlabs). An image is shown below.

Figure 6 Fibre with SMA couplers as used in our experiment. The multimode fibre has a orange jacket and SMA couplers.(images Thorlabs)

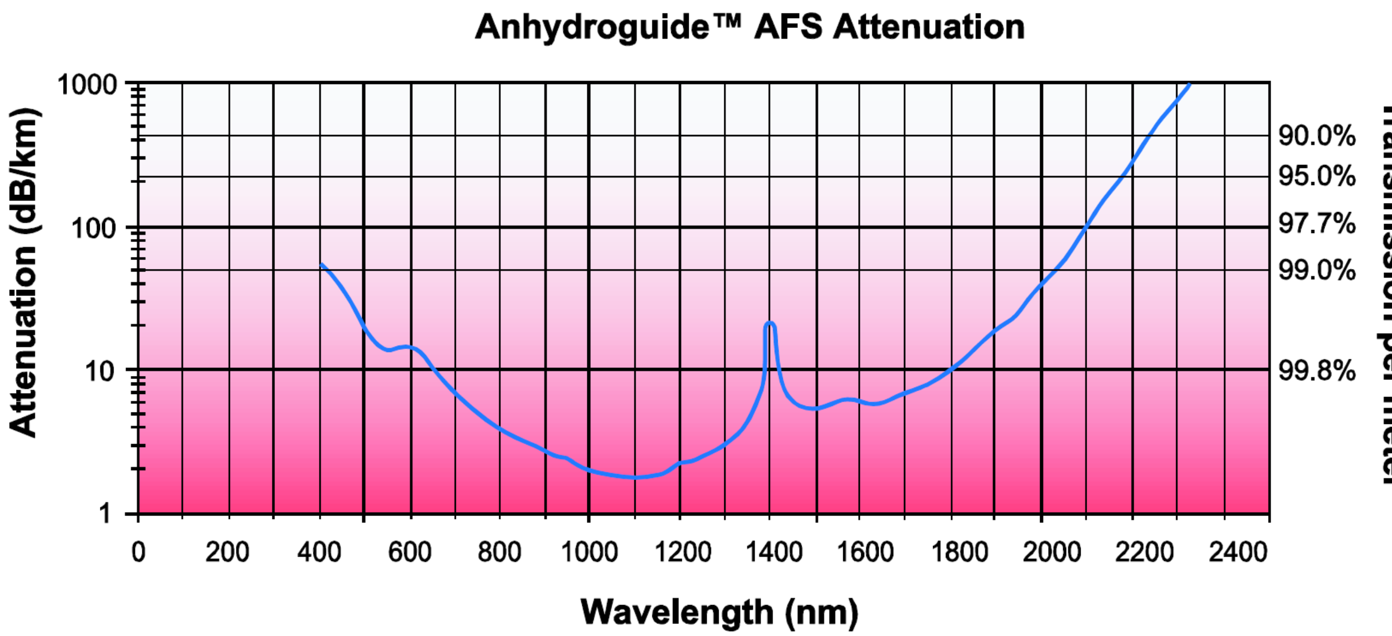


Figure 7. Attenuation of the fibre. Left scale in dB per kilometre (logarithmic) and right is the transmission per meter. (images Thorlabs)

When a collimated beam is incident onto a multimode fibre at a given angle, smaller than the NA of the fibre, particular patterns from skewed ray propagation appear. The reason is that the rays are propagating with a limited angular spectra. Some of the information of the entrance angle is preserved. The figure below illustrates the propagation of skewed rays. A ray injected is reflected at the core and propagates through the fibre without changing the angle θ_m. After a multitude of reflections, a ring-like light pattern is formed at the fiber exit.

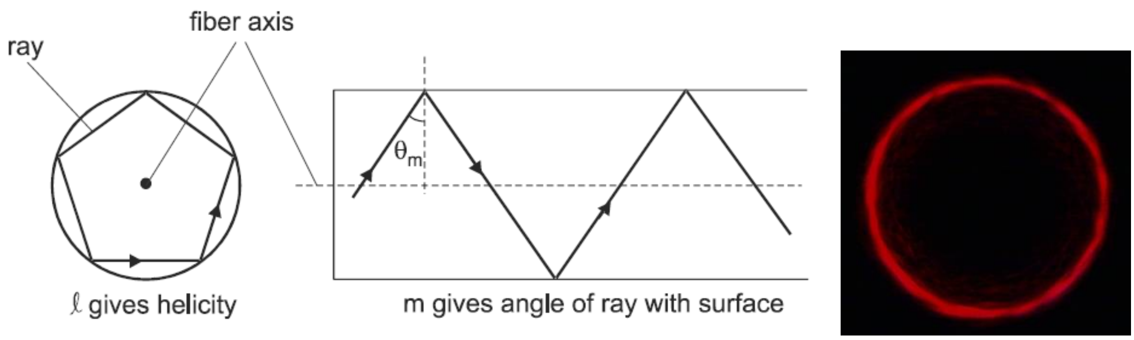


Figure 8: Transverse (left) and longitudinal view (Middle) of the path followed by a skew ray in the core of a multimode fibre. At the exit, a ring-like light pattern is observed (right).

By varying the angle between the collimated laser beam and the fibre, the maximum angle of injection and hence the NA of the fibre can be measured.

NOTE: The cladding might partially guide the light especially if the surrounding media is air. The effect of having light guiding in the cladding results in to large value for the maximum angle and wrong NA values.

Sources

To test the light injection, we use the halogen lamp, the LED and the laser sources, whose characteristics are given in one of the precedent lecture on sources. The size of the fibres and its numerical aperture determine the injection efficiency and might be smaller or larger than the minimum spot size achieved with the sources. To recall, the figure below shows the minimum spot size achieved on the detector.

Figure 11. Minimum focus spot obtained using different light sources. The laser can be focused on a very small spot. The LED has a larger size and the chip is visible. The halogen lamp is biggest. The field of view is 4.536mm x 3.416mm.

Fibre coupling

To understand the main light coupling issues, we take the example of point source.

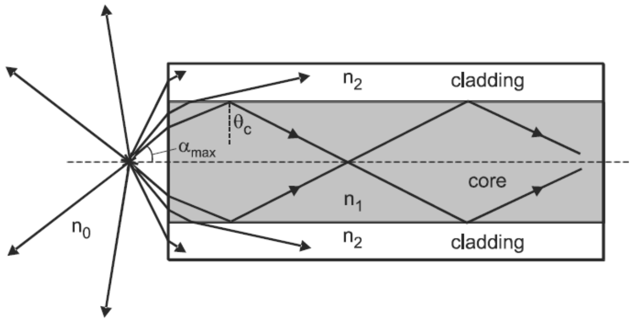


Figure 12. Geometry of the points source to fibre coupling.

We want to calculate the maximum coupling efficiency. In such a geometry, we compare the surface and solid angle values of the source and the fibre. Assume the fibre has an acceptance angle α. The solid angle for this acceptance angle is

$$\Omega = 2\pi(1-\cos\alpha) \tag{1}$$

which can be written as

$$\Omega = 2\pi\left(1-\sqrt{1-\sin^2\alpha}\right) \tag{2}$$

And with the equation for the numerical aperture

$$\mathrm{NA} = n_0 \sin\alpha \tag{3}$$

One finds

$$\Omega = 2\pi\left(1-\sqrt{1-(\mathrm{NA}/n_0)^2}\right) \tag{4}$$

Assuming that NA/n_o is small (i.e. <0.3), the equation can be approximated by

$$\Omega \approx 2\pi\frac{1}{2}\left(\frac{\mathrm{NA}}{n_0}\right)^2 = \pi\frac{\mathrm{NA}^2}{n_0^2} \tag{5}$$

The power of the source P_s is emitted in the whole space, that is, over a solid angle of 4π. The fibre accepts light only in a solid angle Ω. The surface of the source plays no role because it is a point source and only the ratio of the solid angle has to be considered. One can relate the injected power P_{in} with the source power P_s by the equation

$$\frac{P_{in}}{P_s} = \left(\frac{\Omega}{4\pi}\right) \tag{6}$$

which is the maximal injection efficiency η_c. Rewriting, we obtain

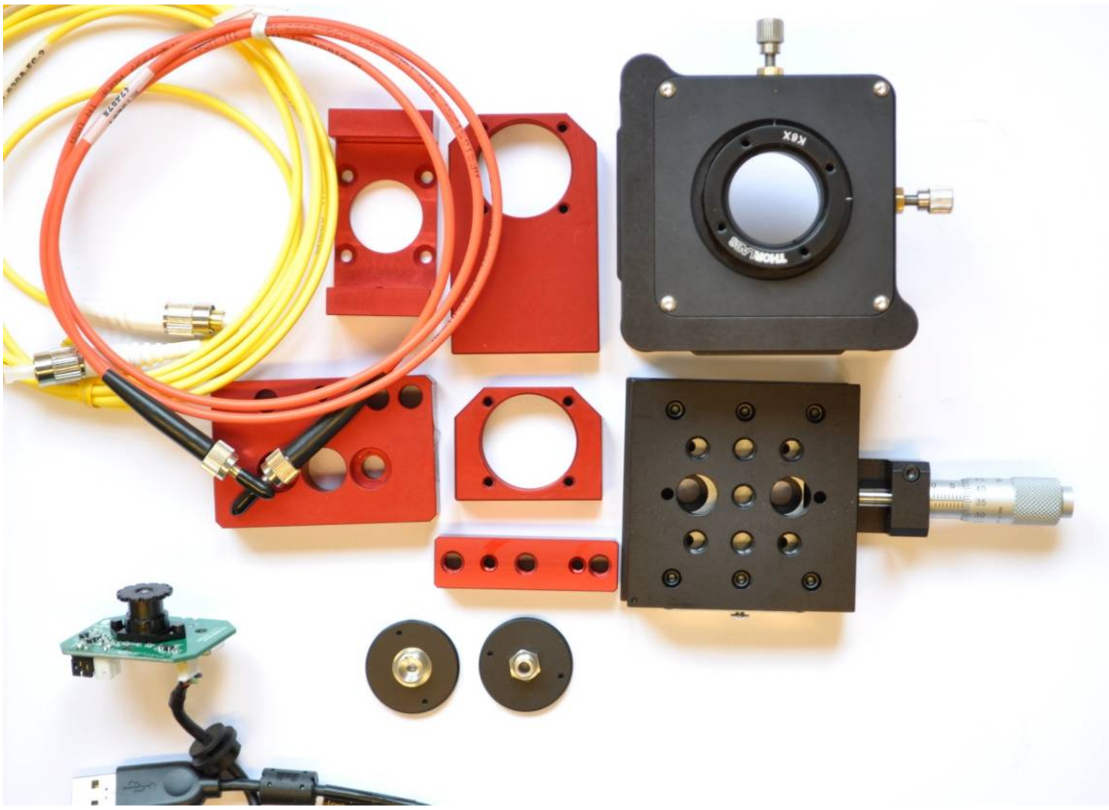
$$\eta_c = \frac{P_{in}}{P_s} = \frac{\Omega}{4\pi} = \frac{1}{4}\frac{\mathrm{NA}^2}{n_0^2} \tag{7}$$

As an example, a fibre with NA = 0.1 surrounded by air (n_0=1) has a maximum coupling efficiency η_c = 0.0025, or 0.25%.

4 Setup and equipment

4.1 Materials

- A CMOS camera (1600x1200 pixels, color, pixel size 2.835 μm) C600 from Logitech
- Three different light sources (Halogen, LED, laserdiode) USB driven
- Sheet polarizers
- The objective lens from the Logitech C600 camera
- A planconvex lens, diameter 9 mm, f=12 mm
- A multimode optical fibre, (orange patchcord)
- A monomode optical fibre (yellow patchcord)



For the experiment, the fibres are mounted in a mechanical stage using the adapter discs shown bellow, one for SMA (SM1SMA) and the other for FC (SM1FC) connectors.

SMA FCPC

Figure 13: Connectors and corresponding adapter discs, (left) SMA and (right) FC connectors.

4.2. Evaluation of the light guiding with skewed rays.

The aim is to test different regimes of fibre injection. We start with the multimode fibre of 100 micron diameter (M15L01, Thorlabs) and the SMA connector (orange patchcord). To investigate the skewed rays in the multimode fibre, we need a **collimated laser** source.

A collimated beam shows nearly no change of size when seen at different distances. To collimate the beam, the lens cap is moved along the optical axis. The lens is planconvex with f=12 mm and with a diameter of 9 mm (made from BK7, Thorlabs part number L1576). In addition, a polarizer is fixed inside the lens tube (Edmund ES45668). Moving the tube longitudinally (along the optical axis or body of the source) focuses the light. Turning the tube adjusts the beam intensity (because there is a polarizer in the tube and the source is polarized too).

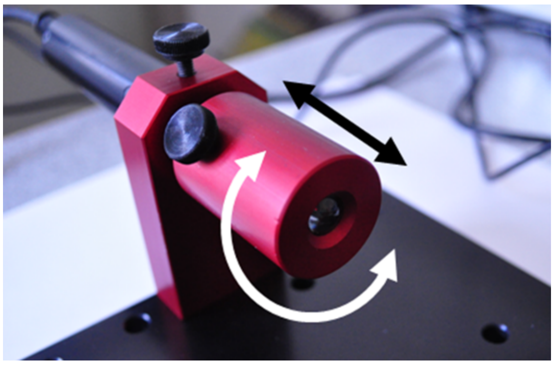


Figure 14. Focalization (black arrow) and intensity adjustment with the lens cap.

The collimation quality can be probed with a sheet of paper intercepting the beam at different distance fromthe source as shown in the image sequence below.

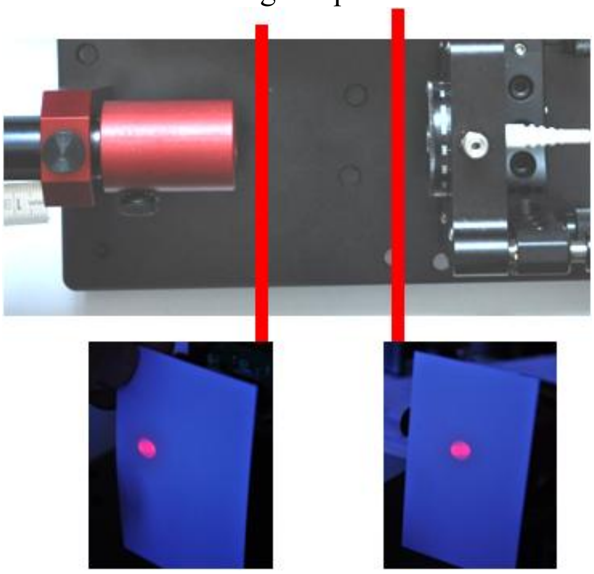


Figure 15: Light spot at different distances from the collimated source. There is nearly no change.

To visualise the light pattern generated by the skewed rays, the light is injected into the fibre with different incident angles. The following setup is used.

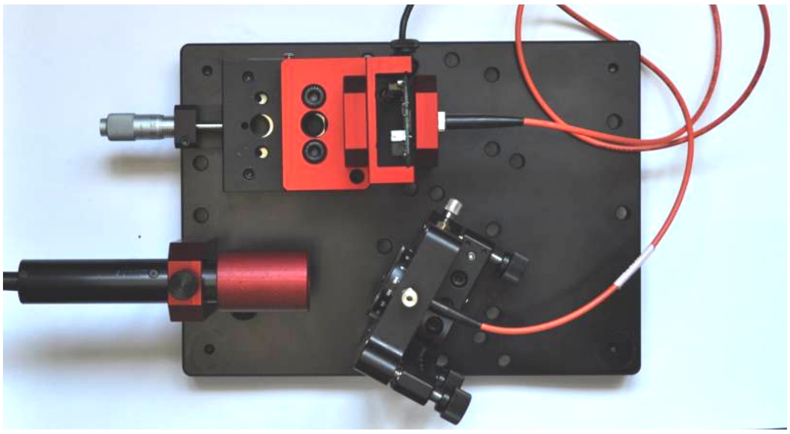


Figure 16. Top view of the breadboard for the skewed ray experiment. **NOTE the 6 axis table is mounted in way to let shine light on the fibre entrance and its axe is not in a direct line with the source housing!**

Figure 17. The breadboard from below to show the positions of screws. Please note the position of the laser on the left.

NOTE: Mount the fibres with GREAT care. Prevent small bending radius and torsion. Use the right connector. Do not touch the fibre ends.

The photos below illustrate the details of the setup.

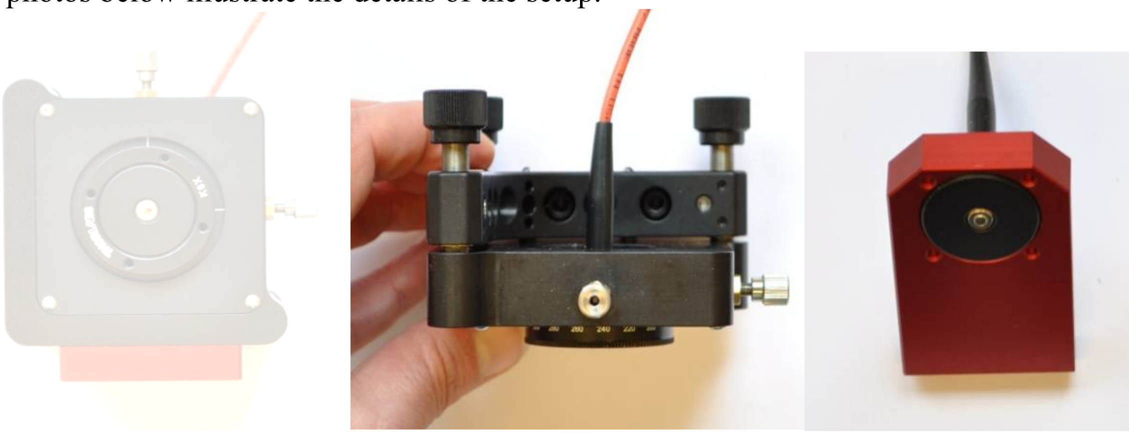


Figure 18. Details of the fibre attachment in the 6 axis stage and the holder.

The camera is used without objective and without the IR filter to let the fibre tip to come very close to the camera sensor.

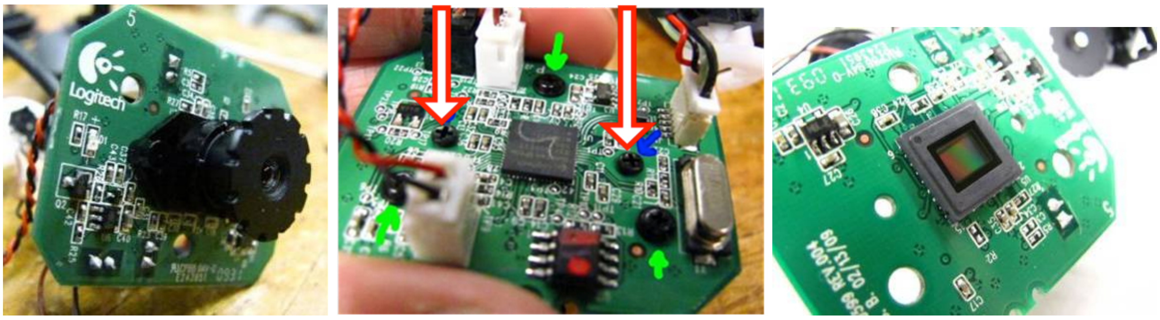


Figure 19. (Left) camera PCB with objective. (Middle) the red-white arrows indicate the screws that fixe the objective. (Left) the PCB with the naked sensor.

Adjust the setup in the following manner:

- Set the source power (laser) to maximum by rotating the lens/polarizer cap.
- Collimate the source
- Put the 6-axis stage in position and at a certain angle. **Attention the 6-axis stage is fixed in the middle of its support and on a particular hole NOT ON AXISs with the source optical axis.**
- Position the camera close to the fibre output using the linear stage such that the fibre exit is seen by the image sensor.
- Move the fibre entrance into the beam at a certain angle.
- Record images of the skewed rays at the fibre output. Try to find the largest “ray circle”. Measure the angle between the collimated source and the fibre entrance. This angle is the acceptance angle of the fiber. From it, compute the NA of the fibre.

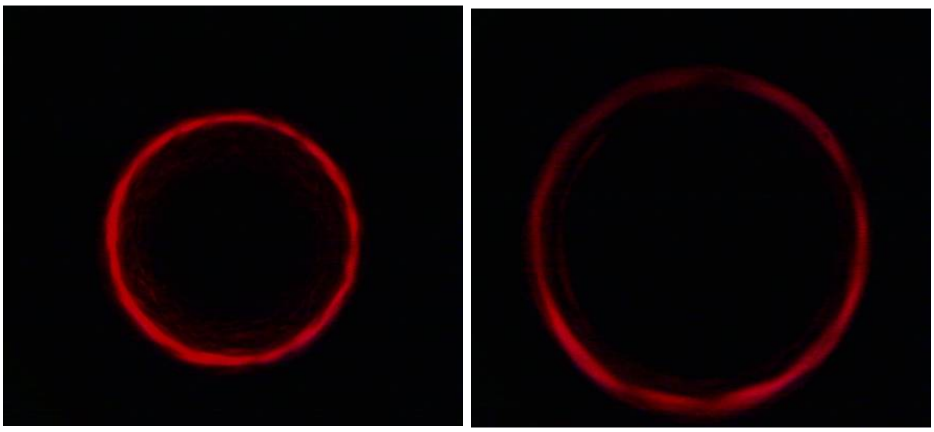


Figure 20. Example of skew ray images for different injection angles. The largest circle was obtained at the limiting injection angle of the fibre.

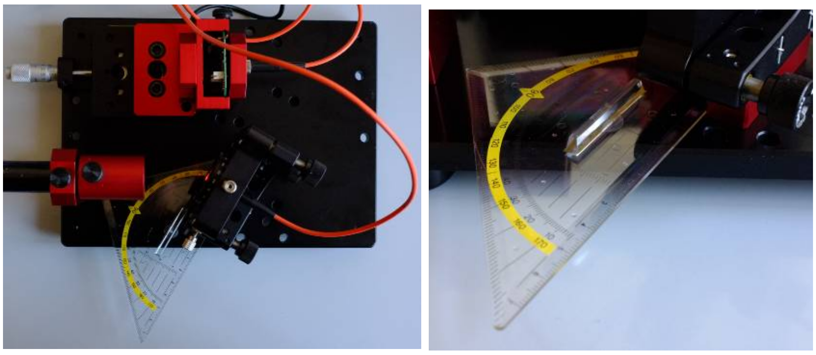


Figure 21 Details of the angle measurement procedure to determine the injection angle.

To be done for the report: Show images obtained at different skew ray configurations. **(2 images)** Measure the acceptance angle of the fibre and compute its numerical aperture. Provide an error estimation of the measurement. Compare the measured value with the datasheet of the fibre.

4.3 Measurement of the numerical aperture using exit cone of light

The numerical aperture of the fibre can also be measured, in a less illustrative manner, using the cone of light exiting the fibre. The setup should be modified to position the 6-axis stage perpendicular to the source tube. It should be fixed with **TWO** screws on the board to get it mechanically stable.

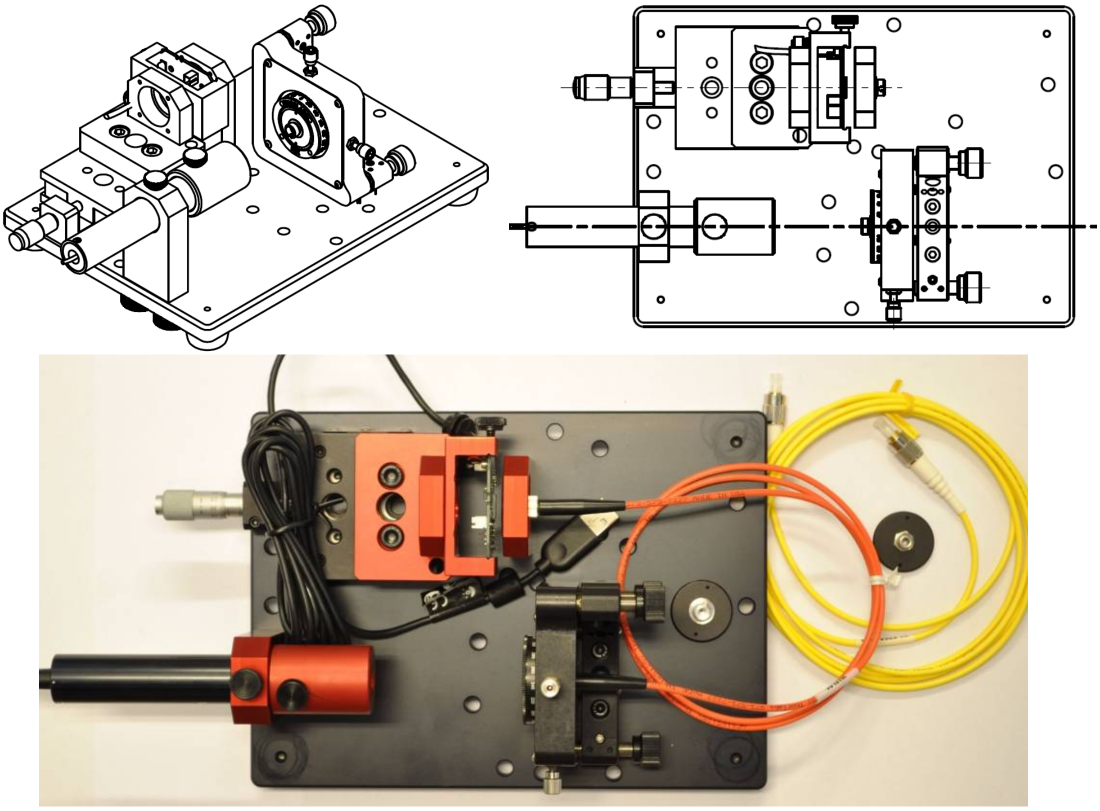


Figure 22. Setup to evaluate the numerical aperture of the fiber using the exit light cone. This setup will also be used to evaluate the coupling efficiency for the different sources

The numerical aperture can be measured in the same way as the numerical aperture of an objective (lecture Imaging #01). One measures the light distributions at different distances behind the fibre output by **changing the distance fibre output - camera with the linear stage**

- Build up the setup
- Use the LED source and the planoconvex lens.
- Mount the multimode fibre (orange cable) with the SMA connectors
- Adjust the camera position in height to have a well centred image
- Put the image sensor close to the fibre output using the linear stage

First we prepare the source focussing to get find the smallest focal spot and largest NA on the image side. This is achieved when the lens is set as far as possible from the source (imaging equation!). To have better control over the distances we measure the source position on the other side where no light is emitted.

- Introduce the source
- Fixing the lens cap
- Set the distance back distance at 45 mm as shown below.

Figure 23. Position of the LED source to achieve a high NA focalisation. The distance from the fibre to the lens will by approximately 20 mm. The lens diameter is 9 mm.

- Rotate the lens cap to adjust the light intensity. Chose a rather high intensity
- Move the lens cap to focus on the fibre entrance
- Take sheet a paper to control the result
- Observe the image at the fibre exit.
- Move the fibre input with the x-y adjustment screws of the 6-axis stage to maximise the coupled light by controlling the light level at the output.
- Adjust the exposure settings (gain and exposure) to avoid saturation
- **Adjust the coupling to get a uniform light distribution similar to Figure 24! (no rings or other fancy patterns)**
- **Measure the distance between the lens cap and the entrance of the fibre and write it down. Calculate the numerical aperture of the injection light and assure that it is comparable with the theoretical NA of the fiber.**

- Measure the light spread at the fibre output by moving the linear stage for minimum of 5 different positions, record the distances! Be careful to have the images well centred not as shown in Fig. 24.
- Measure the size of the illumination spot and calculate the numerical aperture (half-opening angle)

$\Delta z=0$ $\Delta z=2mm$ $\Delta z= 4mm$

Figure 24. Example images of the multimode fibre output at different relative positions after the fibre. The total movement distance in this example is 4 mm. Please note the images shown here are NOT well centred.

To be done for the report: Show sample images for light spot on the camera (**2 images**). Provide a table with the spot diameter as a function of distance (min. 5 points). Calculate the NA of the fibre. Provide an error estimation. Compare the value with the value obtain with skewed rays and with the datasheet of the fibre.

4.4. Injection for different sources

The light from the three sources can be concentrated over different areas. In addition, their spectral and coherent properties are different. These characteristics determine how much light from a source is coupled into a given fibre and can explain the appearance of the light at the fibre exit (on the camera). Although possible, the determination of the coupling efficiency is difficult with the present setup. First we look at the appearance of the exit light.

Choose a convenient position of the camera. Adjust the source to approximately 45 mm as shown below.

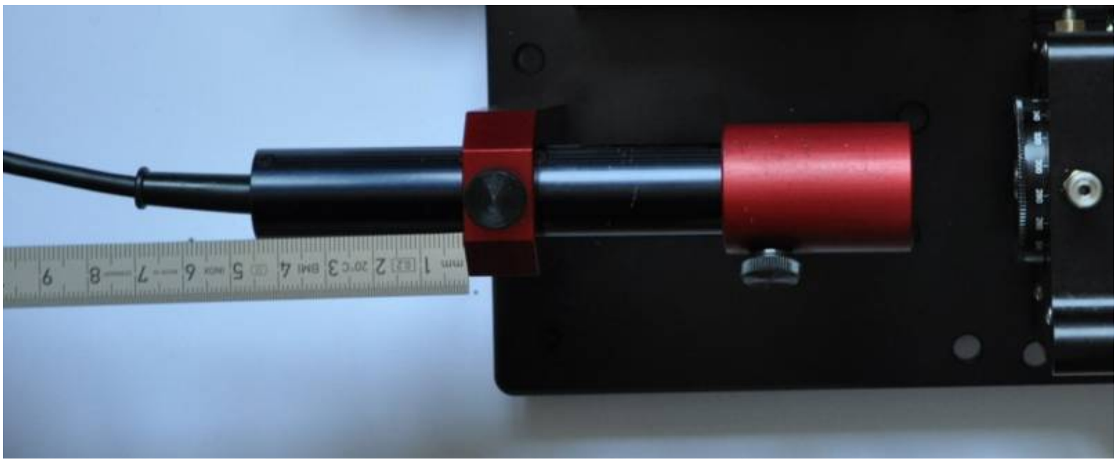


Figure 25 Position of the LED source to achieve a high NA focalisation.

Take images of the light exiting the fibre for the three sources: Halogen lamp, LED, and laser.

Figure 26: Example images of the light output of the multimode fibre for three different sources(left) Halogen lamp, (middle) LED and (right) laser. (Not at the same distance!) Please take care that the images are well centred.

To be done for the report: Show sample images for light spots on the camera for each source **(3 Images).** What is special each source? Please comment! (i.e. the granular structure of the laser, overall light level, size of the spot).

4.5 Measurement of relative injection efficiencies

How much light emitted by a light source can be coupled into a fiber? The answer to this question depends on the etendu. The etendu is the area A of a source (or of their image) times the solid angle Ω:

$$\text{Etendue} = A\Omega = A\pi NA^2 \tag{8}$$

where NA is the numerical aperture. The etendu is conserved through an imaging system, i.e. it cannot be decreased. However, we can change the ratio between surface and numerical aperture by a lens. Figure 27 shows two different positions of a lens in an imaging system. In Fig. 27(A) the lens is closer to the image, i.e. the magnification m is < 1. In Fig. 27(B) the magnification is higher $m > 1$. The system (B) collects more light from the source, because the input aperture is higher. On the other hand, the image becomes larger. The brightness remains the same.

In this experiment we want to compare the coupling efficiency for two configurations by measuring the total intensity that is injected and guided to the exit of the fibre.

When the injection is not done carefully, the efficiency, i.e., the ratio of the coupled light over the total emitted light can be very low. We demonstrate the change of injection efficiency with an example using different NA values of the illumination.

In our setup we can obtain different numerical aperture by placing the lens cap at different positions on the source tube. When the lens cap is placed such that the lens is the close to the source, the source is imaged at a large distance from the source/cap assembly providing a large image area and a small NA. The image of the source becomes larger than the source.

When the cap is placed such that the lens is as far as possible from the source, the source is imaged at a close distance from the source/cap assembly and the NA is larger. The image of the source is smaller than the compared to the first case. Refer to Figure 27 for a sketch of different situations.

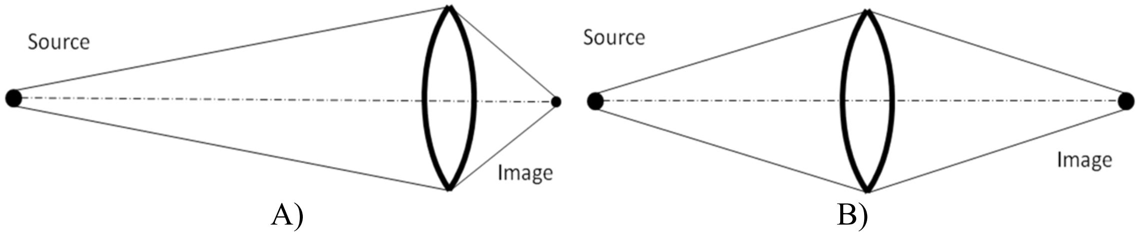


Figure 27. For different lens cap positions, one obtains different numerical apertures (NA) at the image side, and therefore, different values of illumination solid angle. This light must be injected into the fibre. A). High NA on image side and B) low NA on image side.

Please note that in an imaging configuration the conservation of brightness B is valid. The brightness B is defined as **B=P/(AΩ),** where P is the power of the source, A the emitting surface, and Ω is the solid angle of emission. A preserved brightness for the same source/object means that the couple AΩ is constant. Indeed, an image formation with a given magnification changes both, the illuminated area and the solid angle of illumination. An optical fiber also has a useful area, the diameter of the core, and a solid angle given by the angle of acceptance. An important consequence is that when the value of AΩ of the source is larger than the AΩ of the fibre, part of the light **cannot** be injected into the fibre. An optimal coupling is obtained when the illuminated area matches the fibre area, and at the same time, the illumination angle matches the acceptance angle of the fibre.

Light coupling measurements will be done with the multimode fibre and the LED source. The lens cap will be positioned at two different distances from the source.

- Mount the multimode fibre (orange cable) with the SMA connectors
- Use the LED source and the planoconvex lens.
- Set the source at 45 mm 'back side holder-source distance' as shown below in Figure 28.

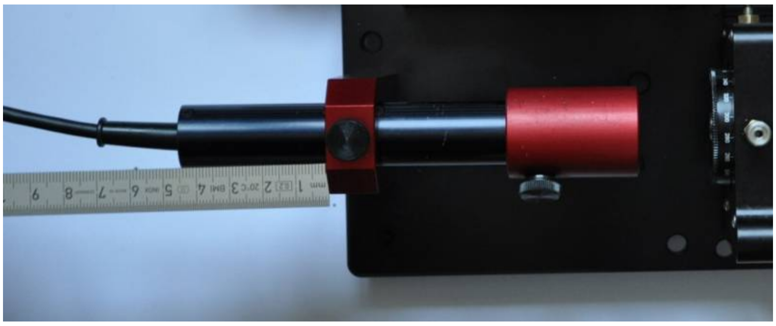


Figure 28.Position of the LED source to achieve a high NA.

- Adjust the camera position in height
- Put the image sensor close to the fibre output using the linear stage
- Rotate the lens cap to adjust the intensity, adjust for 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 (maximum light at the fibre output!)**

- Adjust exposure settings (gain and exposure) and fix it (no automatic, **no saturation**)
- Take images with most uniform illumination
- **Measure the distance between the lens cap and the entrance of the fibre and write it down**

This is position A) in the schematics of Figure 27 above. Now we take the second measurement with a lower NA. The lens has to be far away from the fibre entrance.

- Set the source at 70 mm back side holder-source distance' as shown below in Figure 29.
- Focus on the plane of the fibre entrance by moving the lens
- Rotate the lens cap to adjust the intensity, chose the **HIGHEST** intensity
- Move the fibre input with the x-y adjustment of the 6-axis stage to find the optimal coupling position

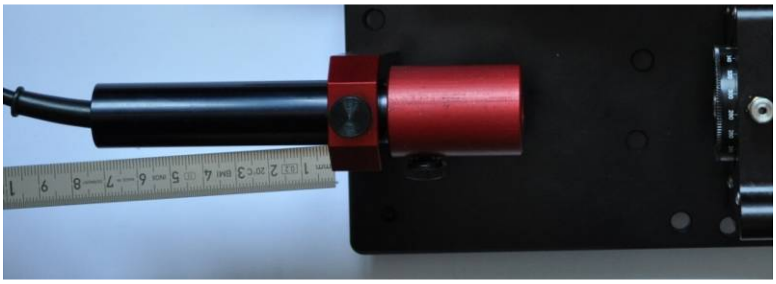


Figure 29 The position with 70 mm creates a much longer distance between the fibre entrance and the lens. The numerical aperture in this case can be approximated using the lens diameter and the distance between lens and fibre entrance.

- Adjust positions and focus to **maximize coupling**
- **DO NOT CHANGE the exposure settings**
- Take one or several images with most uniform illumination
- **Switch off the light and take an image without light (dark noise evaluation!) but with exactly the same exposure settings.**
- **Measure the distance between the lens cap and the entrance of the fibre and write it down**

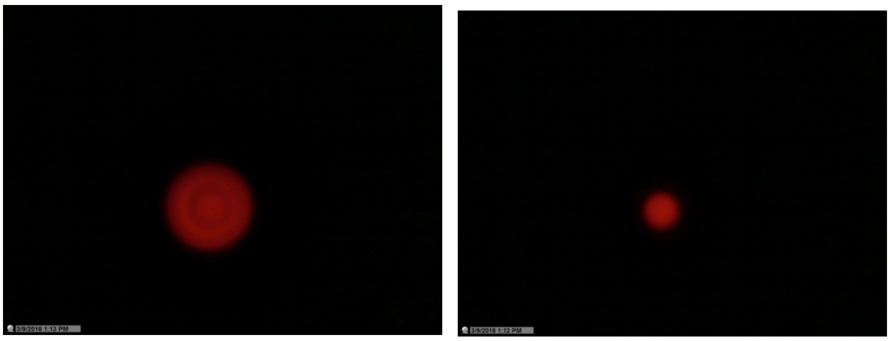


Figure 30 Images of the light exiting the fibre for LED illumination with different NA. Left the 45-mm position and right the 70-mm position.

In this experiment we want to compare the coupling efficiency for two configuration by measuring the total intensity that is injected and guided to the exit of the fibre.

The power P is proportional to the light intensity on the image sensor, that is, the integral over all point of the image. Different issues have to be considered:

- Background noise
- Color filters and spectral separation
- Filling factor
- Straylight

The background noise is influenced by the electronic amplification (gain) and the straylight (for instance from the control LED of the camera PCB). To minimize it, please use a low gain and switch of the control LED of the camera. Cover your setup with the black tissue.
Because our signal is concentrated over a small surface area (the spot size) it is important to subtract the dark noise contribution which can be very high because of the huge surface it covers.

The LED source emits at 660 nm. Therefore, the useful signal is recorded by the red channel only. The blue and green channels only add noise. **Please use only the red channel for intensity evaluation.**

The evaluation of efficiencies with images has to be done in several steps.

1. Subtract the dark noise image from both images
2. Evaluate the integral intensity
3. Calculate the ratio.

The integrated intensity can be evaluated with the MATLAB script (integral_intensity.m) given below.

```
%close all open figure windows
fclose ('all');
% Read image 1
I_1 = imread('picture 83.jpg');
% Read image 2
I_2 = imread('picture 84.jpg');
% Read image DARK NOISE
I_D = imread('picture 127.jpg');
% select a channel (here red)
Red_1 = I_1(:,:,1);
Red_2 = I_2(:,:,1);
Dark_Noise = I_D(:,:,1);
% format conversion
Red_1 = double(Red_1);
Red_2 = double(Red_2);
Dark_Noise = double(Dark_Noise);
%subtraction  of dark noise - background correction
Red_1 = Red_1 - Dark_Noise;
Red_2 = Red_2 - Dark_Noise;
%surface plot for control
figure
imagesc(Red_1,[0 255]); colormap(gray);
figure
imagesc(Red_2,[0 255]); colormap(gray);
```

```
% integral over intensity
INT_Red_1 = sum(sum(Red_1))
INT_Red_2 = sum(sum(Red_2))
INT_Dark_noise = sum(sum(Dark_Noise))
Ratio=INT_Red_1/INT_Red_2
```

NOTE: The evaluation is very sensitive to the dark noise in the image. Because the dark surface is large and therefore small values add up to large errors. Adjust the exposure and gain conditions to have low dark noise levels. (low gain!)

Evaluation can be done using the following thoughts. Assume that the brightness for the two imaging conditions is conserved. B_1 is the brightness at high NA and B_2 is the brightness at low NA.

$$B_1 = \frac{P_1}{A_1\Omega_2} = \frac{P_2}{A_2\Omega_2} = B_2 \tag{9}$$

Rewriting using $\Omega \approx \pi NA^2$

$$B_1 = \frac{P_1}{\pi A_1 NA_1^2} = \frac{P_2}{\pi A_2 NA_2^2} = B_2 \tag{10}$$

We assume that the power of the source has not changed between the acquisitions of the different frames. Then the value $\pi A NA^2$ is conserved during imaging.

- Fibre has large NA=0.22 and all light can be injected if the distance between lens and fiber entrance in larger than 20mm (NA=diameter of lens/(2 times distance to fiber).
- The source will be imaged on the fibre entrance at different magnifications. With f=12 mm and a distance between lens and fibre entrance of 20 mm (NA=0.22) the image of the LED (size 150 micron) will be 100 micron.
- In the situation NA and size source image and fibre matching we have optimal conditions.
- If we move the lens farther away from the fibre entrance the injection NA will be came smaller than the fibre NA. All angles will be injected. But at the same time the source size will change. The ratio of surfaces will change.

We have access to the NA (on the imaging side) by **measuring the distance between the lens and the fibre entrance z_i** and we know the diameter of the lens D = 9 mm.

$$NA_1 = \frac{D}{2z_1} \quad \text{and} \quad NA_2 = \frac{D}{2z_2} \tag{11}$$

The surface A_{fibre} (Diameter 0.105mm) and numerical aperture NA_{fibre} = 0.22 of our fibre are fixed.
As an example, let z_1= 30 mm and z_2=60 mm. **Of course you will find different values**. We obtain NA_1=0.15 and NA_2=0.075. The surface area of coupling is the fibre surface (image of source larger than fibre diameter) A_{fibre} (Diameter 0.105mm). The ratio between the two coupling efficiencies becomes

$$\frac{P_1}{\pi\, A_{fiber}\, NA_1^2} = \frac{P_2}{\pi\, A_{fiber}\, NA_2^2} \quad -> \quad \frac{P_1}{P_2} = \frac{NA_1^2}{NA_2^2} \tag{12}$$

and in **our example**, this ratio is

$$\frac{P_1}{P_2} = \frac{NA_1^2}{NA_2^2} = \frac{0.15^2}{0.075^2} = 4$$

To be done for the report. Show the **two images**. Measure the distance between the lens cap and the entrance of the fibre for both situations and calculate the NA. Compare the total intensity for the two injection conditions by integrating the intensities with Matlab. Give the integral intensities for all images. Give the ratio for the background corrected and non-corrected value. Calculate P_1/P_2 as given above. (no error calculations needed)

5. Summary of tasks of the experimental work

4.2. Evaluation of the light guiding with skewed rays. (40 min)

Show images obtained at different skew ray configurations. **(2 images)** Measure the acceptance angle of the fibre and compute its numerical aperture. Provide an error estimation of the measurement. Compare the measured value with the datasheet of the fibre.

4.3 Measurement of the numerical aperture (40 min)

Show sample images for light spot on the camera (**2 images**). Provide a table with the spot diameter as a function of distance (min. 5 points). Calculate the NA of the fibre. Provide an error estimation. Compare the value with the value obtain with skewed rays and with the datasheet of the fibre.

4.4. Injection for different sources (20 min)

Show sample images for light spots on the camera for each source **(3 Images).** What is special for each source? Please comment! (i.e. the granular structure of the laser, overall light level, size of the spot)

4.5 Measurement of relative injection efficiency (20 min)

Show the **two images**. Measure the distance between the lens cap and the entrance of the fibre for both situations and calculate the NA. Compare the total intensity for the two injection conditions by integrating the intensities with Matlab. Give the integral intensities for all images. Give the ratio for the background corrected and non-corrected value. Calculate P_1/P_2 as given above. (No error calculations needed)