Experiment 234: Multimode Optical Fibres

Aim

To measure the numerical aperture of a multimode optical fibre and to estimate the fibre attenuation using the cut-back method.

References

1. Newport Corporation, "Projects in fibre optics", 1986. An extract of this is beside the experiment. The most relevant pages are 9 – 10, 18 – 19 and 25 – 36.
2. J. Hecht, "Understanding Fiber Optics", Howard W. Sams & Co., 1990.
3. G. Keiser, "Optical Fiber Communications", 2^{nd} ed., McGraw-Hill International, 1991.

In addition to these references, there are many other books in the Library on fibre optics and optical communications.

Warnings

1. Optical fibres are difficult to see and easily broken — proceed with caution in the vicinity of the apparatus so that you don't accidentally break something (especially don't accidentally break the long fibre on the spool).
2. Optical fibres are glass and can be very sharp. If they get embedded in the skin it can lead to health problems. Work over the trays provided to ensure off-cuts are contained. Make sure all off cuts are disposed off properly. Short lengths go in the jars provided. Longer lengths go in the tube placed beside one set of apparatus.
3. Read the laser safety notice (beside the tag board in the main lab).

Theory

The optical fibres used in this experiment are made of glass. The glass is enshrouded in a plastic *jacket*. The jacket helps make the fibre mechanically strong, partly by distributing mechanical load and partly by protecting the surface of the glass from damage (the strength of a brittle material, like glass, is greatly reduced if any cracks are present, no matter how small).

The glass itself can be divided into two regions, an outer *cladding* of lower refractive index and an inner *core* of higher refractive index (the refractive index is influenced by the chemical composition of the glass). The multimode fibres used in this experiment are of the *graded-index* type. This means that the core itself is not homogeneous but has a refractive index which varies with position, as shown in Figure 1. Rays propagating in the core follow curved paths, also shown in Figure 1.

Since the core is of finite diameter, there is a maximum angle at which a ray can be launched into the fibre. In Figure 1 this is labelled as $\theta_{\max}$. It is also the maximum angle at which any ray will exit the fibre. The numerical aperture (NA) of the fibre is defined as:

$$NA = n_i \sin\theta_{\max}$$

where n_i is the refractive index of the material in which the fibre is immersed. Note that the angle $\theta_{\max}$ depends on the material in which the fibre is immersed (think of Snell's law bending at the front face of the fibre) while the numerical aperture does not. The concept of numerical aperture is also relevant to other

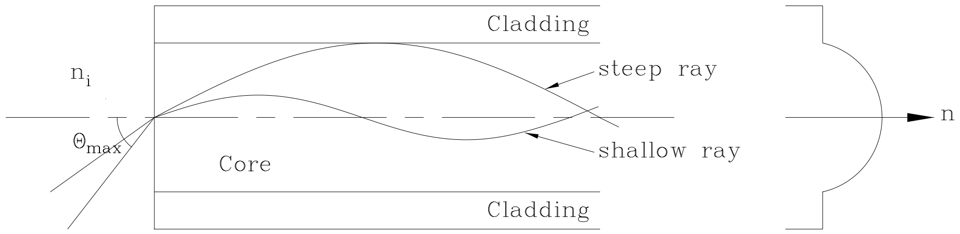

Figure 1: Rays propagating in multimode fibre.

optical systems. In a camera, for example, there is a maximum angle at which a ray can enter the front lens and still reach the film, and the numerical aperture is defined in the same way as for the fibre.

In the experiment, the laser beam is coupled into the fibre using a microscope objective. The objective focuses the beam to a waist which is a few microns in diameter. This is much smaller than the core of the fibre which is of order a hundred microns in diameter. Figure 2 shows how the rays in the beam focus to a waist and then diverge again. Also shown are two possible locations for the fibre (labelled A and B). If the

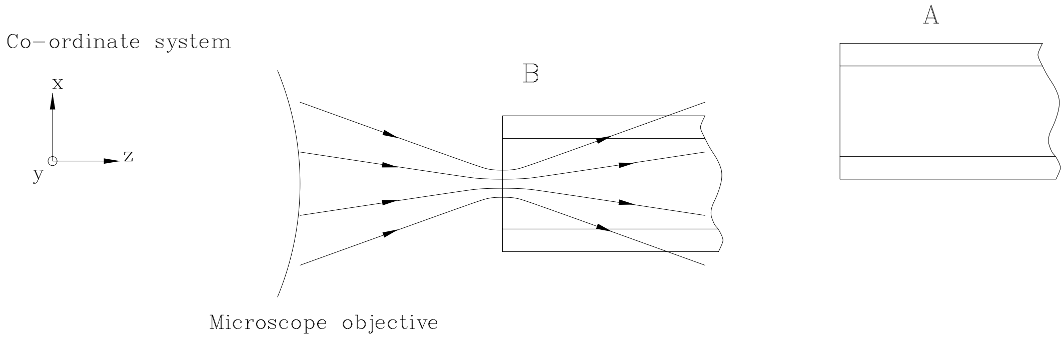

Figure 2: Coupling light into the fibre.

fibre is at A then:

(i) Most of the light misses the core of the fibre, so the coupling efficiency will be low.

(ii) The intensity of light is approximately uniform across the front face of the fibre core. As a consequence there will be both shallow and steep rays and light will exit the end of the fibre at all angles, up to and including, θ_{max}. The beam of light leaving the fibre will therefore be a cone of half apex angle θ_{max}.

If the fibre is at B then:

(i) All the light enters the core so the coupling efficiency will be high.

(ii) Only shallow rays will be present so the beam exiting the fibre will be narrower than a cone of half apex angle θ_{max}. Actually this is only true if the fibre is short. In a long length of fibre (kilometres), bends in the fibre, and also slight imperfections in the glass, tend to steepen the shallower rays. Eventually an equilibrium distribution of rays of various angles is achieved (called a stable distribution of modes). A *mode scrambler* can achieve the same result in a short length of fibre by bending the fibre into a zig-zag path.

An important characteristic of optical fibres is their optical loss or attenuation per unit length. The attenuation is strongly wavelength dependent with the minimum loss for silica fibres occurring around 1550 nm.

If a power P_0 is launched at the start of a fibre of length L, the power transmitted, P_T, is given by:

$$P_T = P_0 e^{-\alpha L} \tag{1}$$

where α is the attenuation constant or fibre loss. It is customary to express the fibre loss in units of dB/km:

$$\alpha\,(\mathrm{dB/km}) = \frac{10\log_{10}\left(P_0/P_T\right)}{L\,(\mathrm{km})}. \tag{2}$$

Question 1: Show that α (dB/km) is related to α (m^{-1}) by α (dB/km) = $4343\,\alpha$ (m^{-1}).

In an experiment, P_T is straightforward to measure, since it's just the power leaving the end of the fibre. P_0 is more difficult, since it's the power *inside* the fibre at the start. The easiest way to determine P_0 is to cut the fibre near the start and measure how much light comes out. This is the basis of the 'cut-back' method for determining fibre attenuation.

In multimode fibres steep and shallow rays experience different loss. It is therefore customary to measure the loss with a stable distribution of modes.

Preparation of fibre ends

(1) One end of the long fibre on the spool is clipped to the spool. This end has already been prepared for you. You are *not* to modify this end. But look at the end now — it shows how the fibre chucks are used.

(2) Some short lengths of fibre (approximately 1 metre long) are clipped to the wall beside the experiment. Take the one for *your* apparatus and *your* lab stream. You will prepare the ends of this short length of fibre.

(3) To prepare an end:

- Work over your tray.
- Thread the end through a fibre chuck (the chuck has to be put on before the end is prepared since a prepared end can be damaged if it is slid through a chuck).
- Remove approximately 3 cm of the plastic jacket from the end of the fibre. This is done using the red-handled strippers (shared between the two sets of apparatus). Place the fibre in the jaws of the strippers. Close the jaws carefully — aim for the jaws to bite the plastic jacket but *not* the glass cladding (you *don't* want to scratch the glass). Pull the fibre through the jaws. Hopefully the plastic will be stripped away without the fibre breaking. Dispose of stripped jacket (broken fibre?) into your off-cuts jar. If the jaws were closed the correct amount, the jacket will have been removed, leaving a visible shoulder on the fibre (see Figure 3). If some specks of plastic remain on the glass, it might be possible to remove them in the subsequent cleaning step. Note that using the strippers can take a little practice.

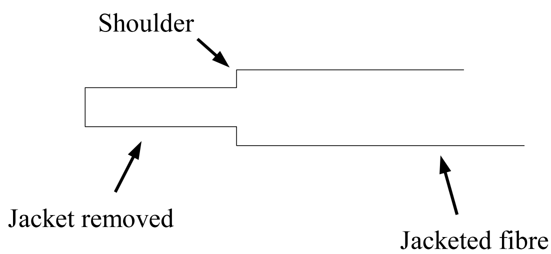

Figure 3: Successfully removing the jacket leaves a visible shoulder on the fibre.

- Position the chuck near the end of the fibre and clamp in position with insulated wire (refer to the long piece of fibre on the spool). This is a temporary measure to protect the fragile stripped part of the fibre. Take the fibre to the microscope (which has its own separate bench) and examine the end. The end will have been made by cutting the fibre with scissors. Draw a sketch of the end and include it in your report. Return to your tray and unclamp the chuck so that you can again access the fibre end.
- Clean the exposed cladding using isopropyl alcohol. The alcohol bottle has a pinhole in the top (do *not* unscrew the top). Impregnate a piece of tissue with alcohol by placing the tissue on top of the bottle and then upending the bottle. Draw the exposed cladding through the impregnated tissue. The fibre end should be squeaky clean with no specks of plastic remaining.
- Cleave the end of the fibre. Cleaving is accomplished by first making a crack in the surface of the glass using a carbide or diamond tipped blade. If this part of the glass is then stretched, by, for example, bending the fibre, the crack will propagate through the glass. If tension is applied correctly, the crack can be made to propagate at right angles to the fibre axis leaving an optically flat surface (see Figure 4).

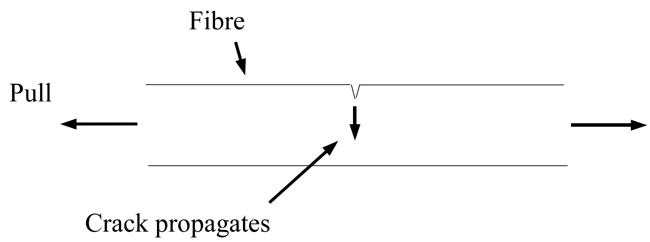

Figure 4: If a fibre is cracked and then pulled correctly, the crack will propagate at right angles to the fibre axis.

  The cleaver (a Fitel S-315) is shared between the sets of apparatus. When not in use, the cleaver must be kept in its box to keep it spotlessly clean. The cleaver has a white blade — see Figure 1 in the operation manual for the cleaver[1]. The blade should *never* touch anything *except* very clean glass.

  Do not push the blade against the leaf spring, against jacketed fibre, etc.

  By following the operation manual for the cleaver[1] *carefully*, cleave the end of the fibre.

  After cleaving, remember to transfer the off-cut fibre from the S-315 to your off-cuts jar and to put the S-315 back in its box. As with using the stippers, using the cleaver might take a little practice.

- Again position and clamp the chuck so that the fibre end just sticks out. Examine the cleaved end under the microscope. Draw a sketch to include in your report.

(4) Repeat procedure (3) for both ends of the short length of fibre.

Coupling light into fibres

(5) The mirror is held in a mount which can be tilted through small angles using two knobs, located behind the mirror. The mirror can also be turned through larger angles if the clamp on the lower stand is unscrewed and then retightened. Adjust the mirror so that the laser beam is incident on the microscope objective of the fibre coupler. The alignment can be optimized by observing the light reflected from the objective (use the screen with hole provided; see photo 8[1]). Adjust the mirror to make the pattern of light approximately symmetric about the hole. You should also observe some Newton rings formed by reflections from lenses in the objective.

[1]With the copy of these instructions that is with the apparatus.

(6) Put one chuck in the fibre coupler. *Do not allow the end of the fibre to hit the microscope objective.* Note that gravity plays a role holding the fibre in the chuck (so rotate the chuck to lower the end of the fibre). Position the end of the fibre a few millimetres from the microscope objective. Hold the other (output) end of the fibre at arm's length. You should see some light leaving the output end. By translating the input end in the x and y directions (see Figure 2) you should be able to make the light grow brighter. When you have the light as bright as you can make it, or if the light grows uncomfortably bright, place the output end in the fibre holder so that the light will land on the screen. The pattern of light should be circular. If it's not then either you have positioned the fibre at the beam waist (improbable, but easily checked by moving the fibre a small distance in the z direction) or the output cl eave is bad (you will need to recleave the output end). If you cannot discern whether or not the pattern of light is circular because it's too dim, try moving the fibre small distances in the z direction to improve the coupling efficiency (it may be necessary to reoptimize x and y each time z is changed).

(7) Repeat procedure (6) with the fibre ends swapped. This is the only way to check that both cleaves are good. Obtain a rough estimate of the numerical aperture by measuring the diameter of the circle of light on the screen and the distance between fibre end and screen.

(8) Now try positioning the input end of the fibre at the beam waist (position B in Figure 2). First position the power meter to collect the light leaving the fibre. Note that you do not need to worry about the wavelength calibration of the power meter in this experiment (you do not care whether you measure the optical power or only something proportional to it). Adjust x and y until the power is maximized. This positions the fibre at the axis of the beam. Now adjust z and then reoptimize x and y. Has the power increased or decreased? If the power has decreased you have moved the fibre away from the beam waist and should readjust z in the opposite direction. Continue adjusting z (then x and y) until the transmitted power is maximized. Do not be too fussy at this stage; just try and get within 5% of the maximum. Note that, when the fibre end is far from the beam waist, adjustments can be made in quite large steps, since the light is distributed over a large volume of space and has slowly varying intensity. However, when the end nears the beam waist, adjustments must be made in smaller steps, since the fibre core, which has a diameter of only about 100 μm, is being aligned to a beam with an even smaller diameter.

(9) Make an approximate determination of the power transmitted through fibre coupler and fibre. The transmission (in percent) is defined as:

$$T = \frac{P_{out}}{P_{in}} \times 100$$

where P_{in} is the power incident on the microscope objective and P_{out} is the power leaving the fibre. You should have achieved a transmission of at least 80%.

(10) Re-measure the diameter of the spot on the screen. Is it smaller than the circle in (7)? Try making small adjustments to z to minimize the spot size. Adjust x to scan the fibre through the beam waist. What do you observe on the screen? Repeat with y. Include your observations in your report and give an explanation.

(11) Obtain the FM-1 mode scrambler (there is one mode scrambler to be shared among the apparatus). It resembles a small vice. On each jaw there are some teeth. When the jaws are closed, the teeth mesh. Put the fibre between the jaws and gently tighten. Observe what happens to the small spot on the screen and the fibre in the mode scrambler as the jaws are tightened. Record your observations and include in your report. Remove the mode scrambler (you will not need it again).

(12) An approximation to a stable distribution of modes can also be obtained by misaligning the fibre input. Move the end of the fibre away from the microscope objective (increase z), adjusting x and y to keep the fibre centred on the axis of the beam, until the power leaving the fibre is reduced by about a factor of three. Measure the diameter of the spot on the screen; you should get the same result as in procedure (7). Adjust x and y to scan the fibre through the beam as in procedure (10). Record your observations.

Measurement of numerical aperture

The laser beam is directed at the fibre (see Figure 5) and the power leaving the fibre measured as a function of the angle θ. If this method is to be successful it is necessary that:

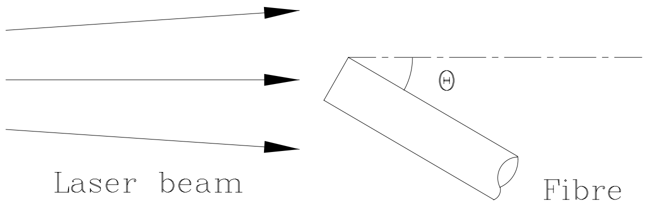

Figure 5: Measuring NA.

(i) the power of the laser does not change.

(ii) the front of the fibre remains centred on the beam (the beam is brightest at the centre and weakens towards either edge).

(13) Move one fibre end from the fibre coupler to the turntable. Centre the end of the fibre with the axis of the turntable (the axis has been marked with a pen). Rotate the mirror so that the laser beam is incident on the fibre end. Use the power meter to observe the power leaving the fibre. Block the laser beam to determine the contribution from background light — if significant, this will need to be subtracted from subsequent measurements of the power leaving the fibre (you might wish to put the box provided over the power meter to help exclude background light). Adjust the mirror to maximize the power leaving the fibre (this aligns the centres of beam and fibre end). For a range of angles, measure the power leaving the fibre. While doing this occasionally:

(i) measure the power of the laser to make sure it is not changing.

(ii) readjust the mirror to ensure centre of beam and fibre end are aligned (rotating the turntable will cause some misalignment, no matter how careful you have been to centre the end of the fibre with the axis of the turntable).

Plot a graph of the power verses angle and use it to determine the numerical aperture for the fibre.

You must do this in the laboratory or you will automatically fail the experiment!

Only by drawing the graph and trying to determine the numerical aperture will you be able to determine if you have chosen an appropriate distribution of data points. Use a logarithmic axis for the power and a linear axis for the angle. The Electronic Industries Association defines θ_{max} to be the angle at which the power leaving the fibre is reduced to 5% of its maximum value.

(14) You will no longer need the short length of fibre so dispose of it using the long tube provided.

Measurement of fibre attenuation

(15) Start by coupling light into the long fibre on the spool (you will need to cleave one end). Note that you are only allowed to cut one end of this fibre and you should aim to have this as the input end. Adjust the input coupling to maximize the transmission (see procedure (8)). Now move the fibre input away from the beam waist to achieve a stable distribution of modes (see procedure (12)). *From this point on, do not touch the optics* (you don't want to change the amount of power launched into the fibre). Measure the power leaving the fibre and the power in front of the microscope objective at three minute intervals for fifteen minutes (remember to correct for any background light). This is to determine how stable the apparatus is with time. Cut the fibre about 1 m from the input end. Cleave the short length and record the power exiting the cleave.

(16) Remove the short length and measure its length (tape measures are available from near the entrance to the quantum lab). *Record the length in the log book attached to the fibre spool.* Also record the fibre length remaining on the spool.

(17) The short length is now finished with. Work over your tray. Lower the ends of the fibre into the off-cuts jar and use the scissors to cut off the ends of the fibre where the jacket has been stripped (lowering the ends into the jar helps ensure the off cuts are collected). Clip the fibre to the wall for the next person to use the apparatus in your lab stream. Put the cleaved end of the long length of fibre back in the holder on the spool.

(18) Calculate the attenuation of the fibre. The loss at a wavelength of 850 nm is typically 2.3 dB/km. Assuming that the loss is due to Rayleigh scattering (proportional to λ^{-4}), what is the expected loss at a wavelength of 633 nm (the wavelength of the HeNe laser)? How does this compare with your measured value?

Question 2: For the purposes of this experiment, the reading on the power meter must be proportional to the optical power, but it does not need to be the optical power. Briefly explain why the absolute calibration is unimportant.

Write-up

Your report should include:

1. Answers to all questions.
2. Sketches of scissor cut and cleaved fibre ends.
3. Estimate of numerical aperture based on measuring spot size on screen.
4. Measured transmission of fibre coupler and fibre.
5. Observations of translating fibre through beam waist with an explanation.
6. Observations made with the mode scrambler.
7. Observations made with the fibre coupler deliberately misaligned.
8. A graph of power leaving fibre verses the input angle θ and a determination of the numerical aperture from the graph.
9. Measurement of fibre attenuation and comparison with the expected value.

List of Equipment

1. HeNe laser with cardboard screen
2. 1″ plane mirror (Al), mirror mount, post and post holder
3. Microscope objective and fibre positioner
4. Rotating platform
5. Spool of multimode fibre (ThorLabs GIF 625)
6. Fibre chucks ($\times$ 3)
7. Optical power meter (Newport or ThorLabs)
8. Scissors
9. Plastic tray
10. Off-cuts jar
11. Long tube for disposing of fibre
12. Strippers — shared between sets
13. Isopropyl alcohol and tissues
14. Fibre cleaver ($\times$1) — shared between sets
15. Newport mode scrambler ($\times$1) — shared between sets
16. Microscope (on a separate bench)
17. Cardboard screen with hole
18. Cardboard box to block out background light
19. Copy of Newport "Projects in Fiber Optics"
20. Laminated set of photographs

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