Optical Fibres
- Introduction

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OPTICAL FIBRES – THE BASICS
Types of Optical Fibre

We can subdivide the different types of optical fibre in many ways, for example:

• **Material**: Plastic, glass or glass and plastic.

• **Mode of Propagation**: Single-mode or multimode. Light can only propagate through certain modes – hence in a multimode fibre there are different modes (ways) the light can propagate.

• **Refractive index profile**: Step-index, graded index or double-clad (including triangular)

There are also other more “specialised” fibres, such as photonic crystal fibres, holey fibres and multicore fibres.

So we see that even though we started to discuss optical fibres in lectures 01 – 03 from a general system perspective (e.g. looking at attenuation and link power budget), the subject of optical fibres is large and covers many aspects.
“Single-mode” fibers
- One spatial mode but supports two modes (two polarization states)
- Only fiber used for distances > 1km

Multimode fibers
- Can support a few or many spatial modes
- Traditionally for short reach (~ 100 meters)

Multicore fibers
- Can exhibit coupling or not between cores
- Coupled-core fibers support “supermodes”

Hollow-core fibers
- Core made of air
- Only short lengths (a few hundred meters) with high loss have been fabricated
We begin our treatment of the subject of optical fibres by considering their main function – waveguiding (i.e. guiding light from an optical source).

https://www.youtube.com/watch?v=uRgdJYPh9G8

- In 1841, Daniel Colladon demonstrated that light could be guided inside a flowing jet of water

- A similar experiment was demonstrated by John Tyndall to the Royal Institution in London, and he explained it as:

  “the total reflexion of light at the common surface of two media of different refractive indices.

- The total internal reflection is made possible due to the fact that water has a higher refractive index than air.

- It is this mechanism that is used in optical waveguides.
A waveguide is a structure that is used to guide electromagnetic waves by confining them so as to allow propagation, e.g.:

Rectangular metallic waveguide, used at microwave frequencies.

The dimensions \((a, b)\) of the waveguide cross-section are important – they determine the frequencies at which the waveguide can be used.

The electromagnetic waves propagate through various modes that must “fit” the geometry:

Electric field \(E_x\) component of the \(TE_{31}\) mode inside an X-band hollow metal waveguide.
For the example of a parallel plate waveguide, we can see how the wave is guided by total internal reflection from either plate, which sets up a pair of waves that then add up to produce a wave travelling along the axis of propagation.

http://demonstrations.wolfram.com/ElectromagneticWavesInAParallelPlateWaveguide/
Total internal reflection is also the mechanism that is used to guide electromagnetic waves (i.e. light) in an optical waveguide.

Here, the materials used are dielectrics (or semiconductors).

For example, we can fabricate planar optical waveguides (semiconductor-based):

These however are only suitable for chip-scale applications such as diode lasers and integrated photonics.
• However, for long distance applications we use flexible optical waveguides with a cylindrical structure constructed from dielectric materials – these are known as optical fibres.

• The core of an optical fibre has a higher refractive index than the cladding that surrounds it, as in the water jet experiment of Colladon.

• Hence light propagates down the optical fibre by repeated total internal reflection at the core-cladding interface:
• The two main dielectric materials that are used to fabricate optical fibres are plastic and glass (specifically silica glass – SiO$_2$).

• Fibre cross-sections come in various sizes according to the application:

**Relative sizes of different fibre types**

- POF = plastic optical fibre
- HCS = hard clad fibre (silica fibre core, plastic cladding), also known as plastic clad fibre (PCF)

Note the relatively small core size of single mode fibre compared to the cladding.
• Although the structure of an optical fibre looks very simple, we should be aware that this is a precision piece of engineering, especially for single mode fibre which has a typical core diameter of between 8 μm and 10 μm:

Comparison between cross sectional size of a human hair and the core of a single mode fibre

• This precision is also reflected in the design of an optical fibre and the fabrication process.

• The relative size of components is also important in terms of how we analyse them; specifically we are interested in how the component size compares with the wavelength.
• We can (and do) analyse optical fibres using electromagnetic theory, i.e. solution of the wave equation (derived from Maxwell’s equations) for a cylindrical system.

• However, the simplest model of light is based on the assumption that light propagates as a ray:

Whenever an optical component has dimensions that are significantly larger than the wavelength of the light, we can use **geometrical optics** (also known as ray optics) to analyse that component.

• In **multimode** optical fibres, the core diameter is typically 50 μm or 62.5 μm, which is significantly bigger than the wavelength of light used (of the order of 1 μm).

• So we will begin by using ray optics to look at multimode fibres, although some of the results (e.g. numerical aperture) will also be used for single mode fibres.
RAY OPTICS ANALYSIS OF OPTICAL FIBRES
• We begin by defining the refractive index \( (n) \) of a material by:

\[
\begin{align*}
    n &= \frac{c}{v} \quad (1)
\end{align*}
\]

• Here \( v \) is the speed of light in the material, which is less than the speed of light in vacuo \( c \).

• We then examine what happens at the interface between two different materials with:

\[
\begin{align*}
    n_1 > n_2 \quad (2)
\end{align*}
\]

• From an approach based on electromagnetics, we can obtain these laws:

\[
\begin{align*}
    \theta_i &= \theta_r \quad \text{Law of reflection} \\
    n_1 \sin \theta_i &= n_2 \sin \theta_t \quad \text{Law of refraction (Snell’s law)} \quad (3)
\end{align*}
\]
Snell’s law for Refraction

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (4) \]

If we choose \( n_1 > n_2 \), we have:

- \( \theta_1 < \theta_C \)
- \( \theta_1 = \theta_C \)
- \( \theta_1 > \theta_C \)

Total internal reflection (TIR) is the mechanism with which light propagates in multimode optical fibres.
Example: Reflection coefficients for S and P polarisation (more about this in ECE333)

Here the incident ray goes from air (refractive index 1) to glass and total internal reflection does not occur.

Here the incident ray goes from glass towards air and total internal reflection will occur for angles above the critical angle.

Note that the reflection coefficient is 100% for TIR. This is important – the very large number of reflections in optical fibre would create a lot of loss if this was not the case.
By forming a “sandwich” of a central core with refractive index $n_1$ higher than the surrounding material refractive index $n_2$, we can produce waveguiding via multiple total internal reflections:

This “sandwich” can be in the form of the planar waveguide:
Or it can be “rolled up” to form fibre:

You will notice that the light rays travel in straight lines. This is because the refractive index of the core region is uniform throughout. (The refractive index of the cladding is also uniform.)

We term this a step index refractive index profile:
Standard single mode fibre is step-index, but for multimode fibres we can have both step-index and a parabolic profile called graded-index:

When we return to the subject of dispersion, we will see that special dispersion-compensated fibres have more complex refractive index profiles, such as:
We usually use laser diodes for high performance optical links. The light from a laser diode actually diverges:

Provided the light from the laser can be coupled into the entrance of the fibre within the correct range of angles, the light will propagate within the fibre.

We say that the light must be within the acceptance angle of the fibre:
Note: previous pictures and also the analysis to follow assumes meridional rays:

Skew Rays

Meridional Rays

Axial Rays

Propagation in an ideal step-index fibre

Air $n_0$

$n_1 > n_2 > n_0$

Does not propagate; $\phi < \text{critical angle at core-cladding interface}$

Propagates through repeated TIR at core-cladding interface; $\theta_0$ denotes the acceptance angle.
Numerical aperture (NA) in a step-index fibre

What is the maximum acceptance angle $\theta_0$?

Apply Snell’s law:

$$n_0 \sin \theta_0 = n_1 \sin \theta$$

$$\theta + \phi_C = \pi / 2$$
\[ n_0 \sin \theta_0 = n_1 \sin \theta \]
\[ = n_1 \sin (\pi/2 - \phi_C) \]
\[ = n_1 \cos \phi_C \]
\[ = n_1 \sqrt{1 - \sin^2 \phi_C} \]
\[ = n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \]
\[ = \sqrt{n_1^2 - n_2^2} \quad (5) \]

This equation defines the **numerical aperture** (NA) of a step-index fibre:

\[ \text{NA} = n_0 \sin \theta_0 = \sqrt{n_1^2 - n_2^2} \quad (6) \]
Normalised Frequency – The V-number

Using an electromagnetic analysis, we can determine the so-called dispersion relations for an optical fibre:

\[ V = 2.405 \]

Cut-off frequency – below this only one mode
For a step-index fibre, the normalised frequency or V-number is related to the numerical aperture by:

\[ V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} a \cdot NA \quad (7) \]

Core radius

The fibre is single mode if \( V < 2.405 \). Above this number, the number of modes rises quickly:

\[ M \approx \frac{V^2}{(\pi / 2)^2} \quad (8) \]

Number of modes
From equation (7), we have multimode operation if:

\[ \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} a \cdot NA \geq 2.405 \]

If we have either a large numerical aperture or a large core radius \((a)\) or both, then we will end up with multimode operation. In terms of ray optics, this leads to a picture as follows:
The problem with step-index multimode fibres is that the different modes (i.e. ray paths) all have the same speed (uniform refractive index) but they travel different distances for a fibre of length $L$ (because of different angles of TIR). So if a pulse is launched into a fibre and excites multiple modes, we end up with pulse broadening:

This is called **intermodal dispersion** (or **multimode dispersion**):
We can try to minimise intermodal dispersion by using an optical fibre with a graded index profile:

Replace this (step index multimode):

with this (graded index multimode):
Light on path 3 (blue) covers a greater overall distance than path 2 (red) or path 1 (green), but because of the varying refractive index, all three paths have the same average speed and exit the fibre at the same time.
Alternatively we can return to a step-index profile and to equation (9):

\[ \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} a \cdot NA \geq 2.405 \]

This shows that for a fixed NA, we can reduce the fibre diameter \( a \) until we have only single mode operation:
Hence we have now seen three types of optical fibre:

1. **Step-index single mode**
   - Cladding: 125 μm
   - Core: 8 - 12 μm
   - Typical dimensions:
     - Cladding: 125 μm
     - Core: 8 - 12 μm

2. **Step-index multimode**
   - Cladding: 125 - 400 μm
   - Core: 50 - 200 μm
   - Typical dimensions:
     - Cladding: 125 - 400 μm
     - Core: 50 - 200 μm

3. **Graded index multimode**
   - Cladding: 125 – 140 μm
   - Core: 50 - 100 μm
   - Typical dimensions:
     - Cladding: 125 – 140 μm
     - Core: 50 - 100 μm