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Optical Communications Systems

Dispersion in Optical Fibre (I)

School of Electronic and Communications Engineering

DIT · Dublin Institute of Technology · Institiúid Teicneolaíochta Átha Cliath

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Introduction

- Dispersion limits available bandwidth
- As bit rates are increasing, dispersion is becoming a critical aspect of most systems
- Dispersion can be reduced by fibre design
- Optical source selection is important

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Dispersion in Optical Fibres

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Dispersion in an Optical Fibre

Multimode fibre (LAN systems)

Modal dispersion

Chromatic dispersion

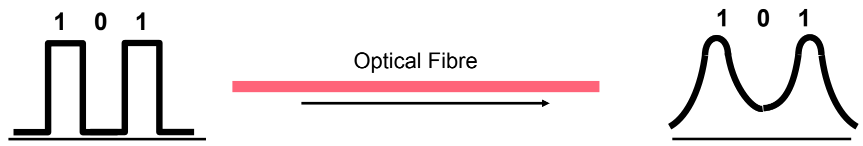
Polarization Mode dispersion (PMD)

Singlemode fibre (Telecom systems)

Why is dispersion a problem?

Dispersion → Pulse spreading → Intersymbol Interference → Degrades error rate

Example

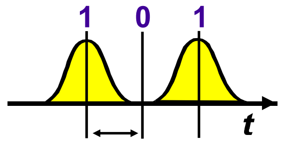


Data at fibre input

Data at fibre output
Pulse spreading makes it more difficult to distinguish "0"

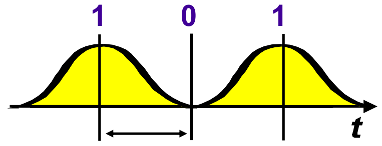
Dispersion and Bit Rate

Fibre output with no Dispersion



Bit interval "T"

Fibre output with Dispersion



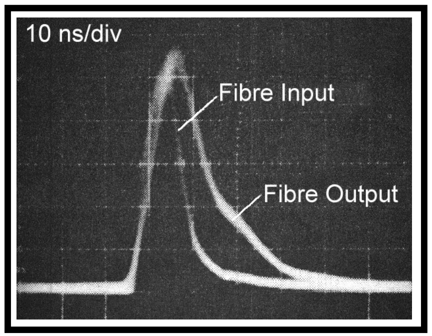
Longer bit interval

- **The higher dispersion the longer the bit interval which must be used**
- **A longer the bit interval means fewer bits can be transmitted per unit of time**
- **A longer bit interval means a lower bit rate**

Conclusion: The higher the dispersion the lower the bit rate

Dispersion Example

Photo of Input and Output pulses for a 200 micron core Polymer Clad Silica fibre showing pulse broadening (dispersion)

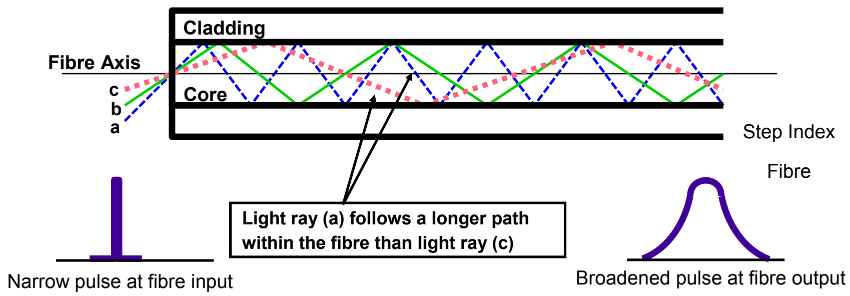


Modal Dispersion

- **In a multimode fibre different modes travel at different velocities**
- **If a pulse is constituted from different modes then intermodal dispersion occurs**
- **Modal dispersion is greatest in multimode step index fibres**
- **The drive to reduce modal dispersion led to the development of graded index multimode fibre and singlemode fibre.**
- **A ray model can give and adequate description of modal dispersion**

Modal Dispersion

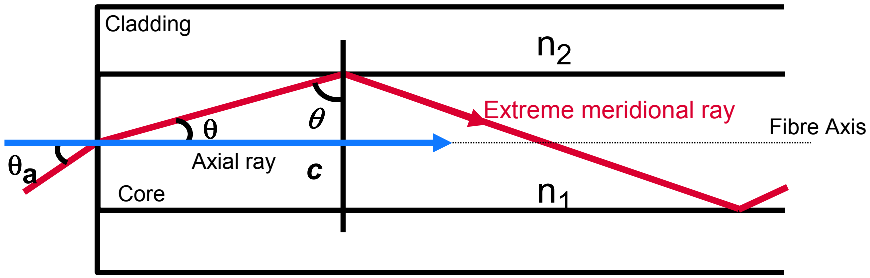
- Modal dispersion is greatest in multimode step index fibres
- The more modes the greater the modal dispersion
- Typical bandwidth of a step index fibre may be as low as 10 MHz over 1 km



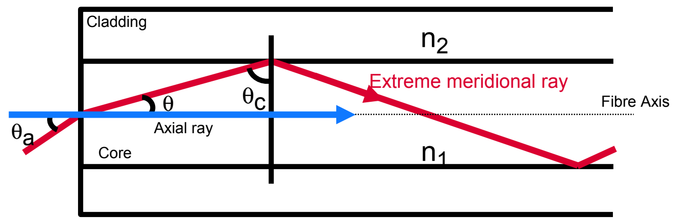
Analysis for Modal Dispersion

Estimating Modal Dispersion (Step Index Fibre)

- Assume:
  - Step index fibre
  - An impulse-like fibre input pulse
  - Energy is equally distributed between rays with paths lying between the axial and the extreme meridional
- What is the *difference in delay* for the two extremes over a linear path length L?



Step Index Modal Dispersion: Analysis (I)



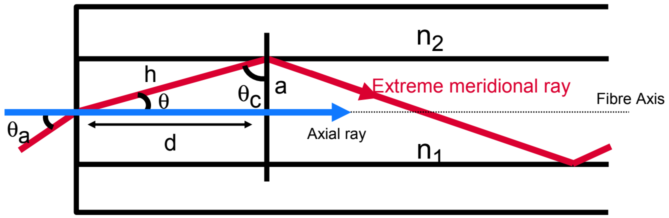
Transmission distance = L

T_{max} = Transmission time for extreme meridional ray

T_{min} = Transmission time for axial ray

Delay difference $\delta t = T_{max} - T_{min}$

Step Index Modal Dispersion: Analysis (II)

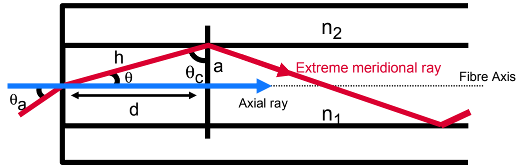


$$T_{min} = \frac{\text{Distance}}{\text{Velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

To find T_{max} realise that the ray travels a distance h but only travels a distance d toward the fibre end (d<h). So if the fibre length is L then the actual distance travelled is:

$$\frac{h.L}{d}$$

Step Index Modal Dispersion: Analysis (III)



$$T_{max} = \frac{Ln_1}{c \cos \theta}$$ Using simple trigonometry

Using Snell's law: $\sin \theta_c = \frac{n_2}{n_1} = \cos \theta$

$$T_{max} = \frac{Ln_1^2}{cn_2}$$

$$\text{Delay difference } \delta t = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

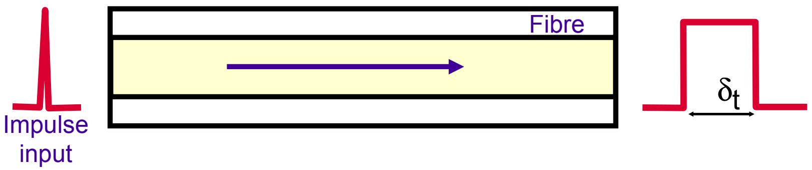
Step Index Modal Dispersion: Analysis (IV)

$$\delta t = \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right) = \frac{L\Delta n_1^2}{cn_2}$$ Assumes $\Delta << 1$

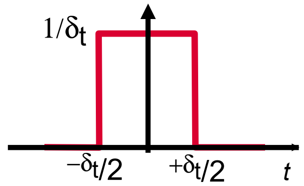
Show for yourselves that:

$$\delta t = \frac{L(NA)^2}{2\, c\, n_1}$$

Impulse Response for Step Index Fibre



- Assume an impulse input to the fibre
- Output is a pulse of uniform amplitude over a time period $T_{max} - T_{min} = \delta_t$
- Output pulse of width δ_t is thus the impulse response of the fibre.
- Assuming an output pulse amplitude of $1/\delta_t$,the impulse response h(t) is given by:



$h(t) = 1/\delta_t \quad -\delta_t/2 < t < +\delta_t/2$

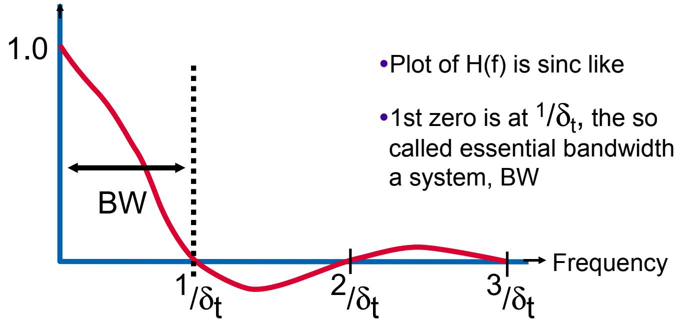
$h(t) = 0$ elsewhere

Transfer Function for a Step Index Fibre

- Take the Fourier transform of the impulse response
- The transfer function of the fibre H(*f*) is given by:

$$H(f) = \text{sinc}\, f\, \delta_t$$

Note: $\text{sinc}\, x = \dfrac{\sin \pi x}{\pi x}$



- Plot of H(f) is sinc like
- 1st zero is at $^1/\delta_t$, the so called essential bandwidth for a system, BW

Bandwidth for a Step Index Fibre (I)

- Essential bandwidth, BW, for the fibre is $^1/\delta_t$
- Based on the previous analysis BW can be written as:

$$BW = \frac{2\, c\, n_1}{L (NA)^2}$$

- BW get smaller as fibre length L increases
- High NA fibres have lower bandwidths, eg plastic fibre has high NA: Poor bandwidth
- Lowering NA to improve bandwidth makes source coupling more difficult as the acceptance angle decreases

Bandwidth Problem: Plastic Optical Fibre

- Conventional plastic optical fibre is step index, low bandwidth
- NA is about 0.4, core refractive index is about 1.5
- Show that the BW over 1 km is about 6 MHz
- Measured values are about 6 to 10 MHz so analysis is about right

$$\boxed{BW = \frac{2\, c\, n_1}{L (NA)^2}}$$

Reducing Modal Dispersion

Reducing Modal Dispersion

Reduce the difference between the propagation velocities of different modes

↓

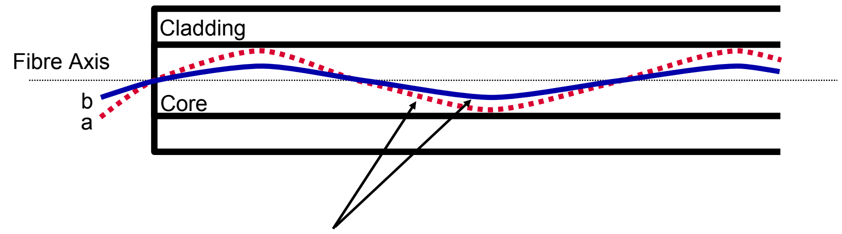
Graded index fibre design

Reduce the number of modes to one

↓

Singlemode fibre design

Reducing Dispersion using a Graded Index Fibre



Light ray (a) and (b) are refracted progressively within the fibre. Notice that light ray (a) follows a longer path within the fibre than light ray (b)

- Ray (a) follows a longer path, but the much of the path lies within the lower refractive index part of the fibre.
- Ray (b) follows a shorter path, but near the fibre axis where the refractive index is higher
- Since the velocity increases as the refractive index decreases the time delay between (a) and (b) is equalised

The Profile Parameter and Intermodal Dispersion

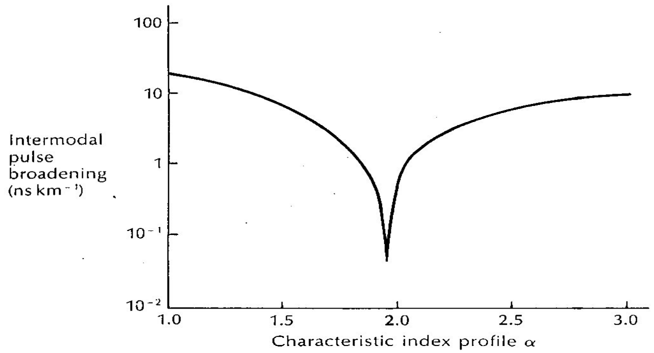
- Recall that the profile parameter α for a graded index fibre dictates the shape of the refractive index profile
- Why does the profile parameter α used for graded index fibre has a common value of about 2?
- It can be shown that the optimum value of α that maximises the bandwidth of GI fibre is given by:

$$\alpha = 2.(1-\Delta)$$

- A common Δ value for GI multimode fibre is 0.02 (2%) (Lucent 62.5/125 μm)
- For this Δ value the optimum profile parameter α has a value of 1.96.

Variation in Modal Dispersion with the Profile Parameter

- Plot below shows variation in intermodal dispersion with the profile parameter.
- Plot assumes a Δ value of 1% for the fibre.
- Large value of α > 3 means a profile approaching step index.
- Dispersion drops by more than 100:1 with α circa 2 by comparison with α > 3
- Thus bandwidth of graded index is > 100 times higher than step index



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Quantifying Dispersion in a GI Fibre (I)

- Very involved analysis
- As in the step index case one determines maximum time difference between the two most extreme modes
- Most common expression is:

$$\delta t_{GI} = \frac{L\,\Delta^2 n_1}{c.8}$$

- By comparison the equivalent value for a step index fibre has been shown to be:

$$\delta t_{SI} = \frac{L\,\Delta\, n_1^2}{c n_2}$$

- Because of the Δ^2 dependence for graded index the dispersion is much lower since Δ is << 1.

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Quantifying Dispersion in a GI Fibre (II)

- Using the formulas below and assuming an n_1 value of 1.5, plot the maximum time delay or dispersion for a step index and a graded index fibre for values of Δ from 0.01 to 0.05 using the units "ns per km" and using a common axis for Δ .

$$\delta t_{GI} = \frac{L\,\Delta^2 n_1}{c.8}$$

$$\delta t_{SI} = \frac{L\,\Delta\, n_1^2}{c n_2}$$

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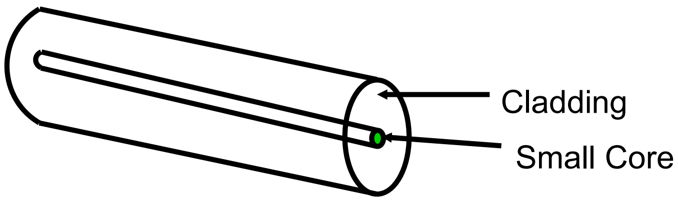
Using Singlemode Optical Fibre to Eliminate Modal Dispersion



- **No modal dispersion since only one mode propagates**
- **Most effective way to overcome modal dispersion**
- **Potential bandwidth is in the order of 20 THz**