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Optical Communications Systems

Dispersion in Optical Fibre (I)

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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)

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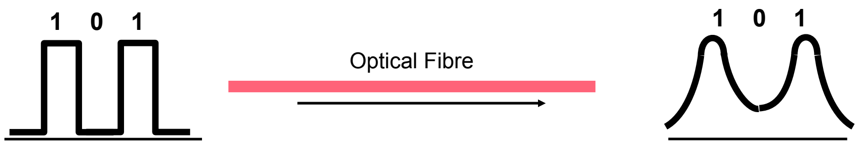
Why is dispersion a problem?

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"

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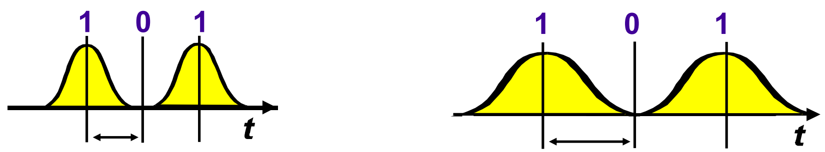
Dispersion and Bit Rate



- **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

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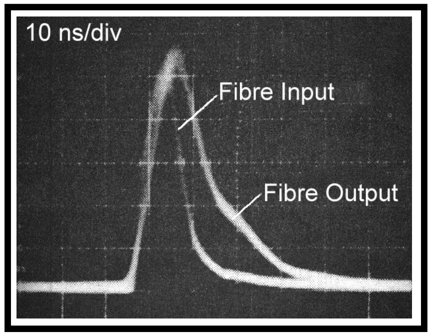
Dispersion Example

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



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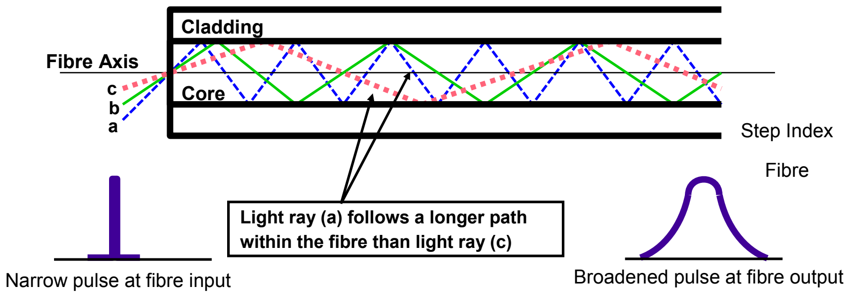
Modal Dispersion

- **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

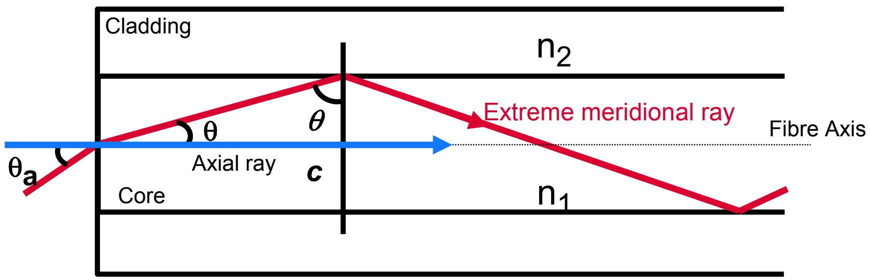
- Modal dispersion is greatest in multimode step index fibres
- The more modes the greater the modal dispersion
- Typical bandwidth of a step index fibre may be as low as 10 MHz over 1 km



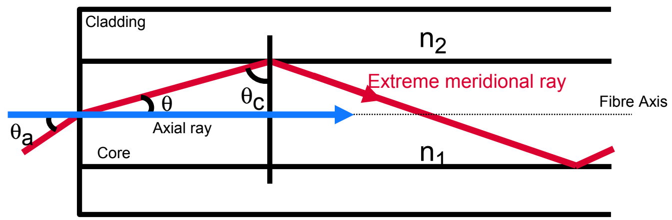
Analysis for Modal Dispersion

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)



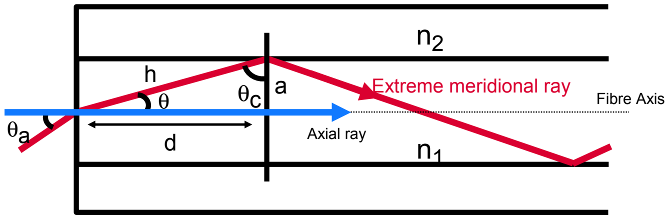
Transmission distance = L

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)

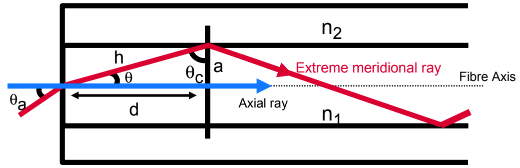


$$T_{min} = \frac{\text{Distance}}{\text{Velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

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: $\sin\theta_c = \frac{n_2}{n_1} = \cos\theta$

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

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

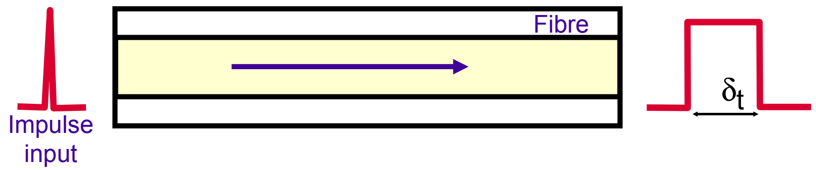
Step Index Modal Dispersion: Analysis (IV)

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

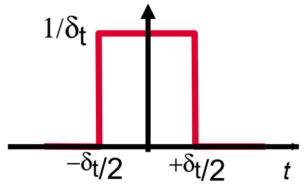
Show for yourselves that:

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

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:



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

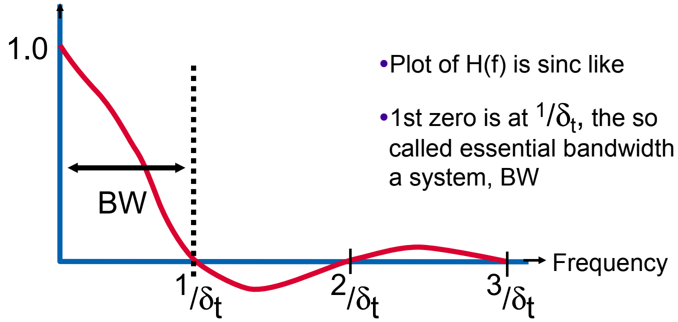
$h(t) = 0$ elsewhere

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: $\text{sinc}\ x = \frac{\sin \pi x}{\pi x}$



- 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

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

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

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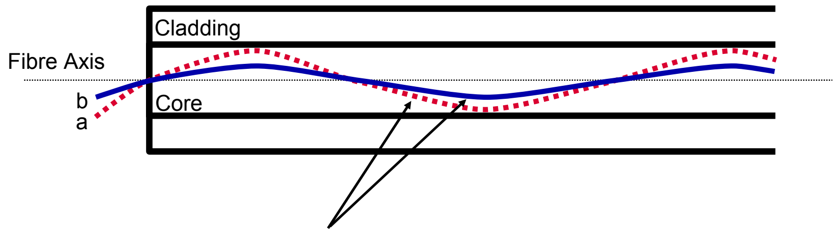
Reducing Dispersion using a Graded Index Fibre



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

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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.

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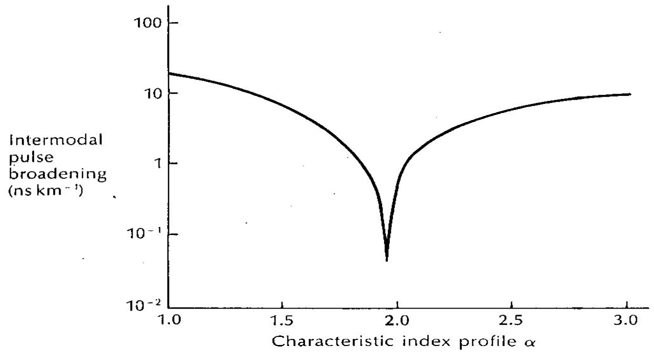
Variation in Modal Dispersion with the Profile Parameter

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

$$\delta t_{SI} = \frac{L \Delta n_1^2}{cn_2}$$

- 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 .

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

$$\delta t_{SI} = \frac{L \Delta n_1^2}{cn_2}$$

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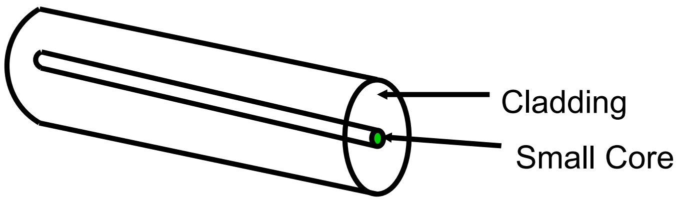
Using Singlemode Optical Fibre to Eliminate Modal Dispersion



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