OPTICAL FIBRES

Numerical Aperture (NA) & Acceptance angle

Modal dispersion in multimode fibre

GRIN fibre

Single mode fibres

Dispersion

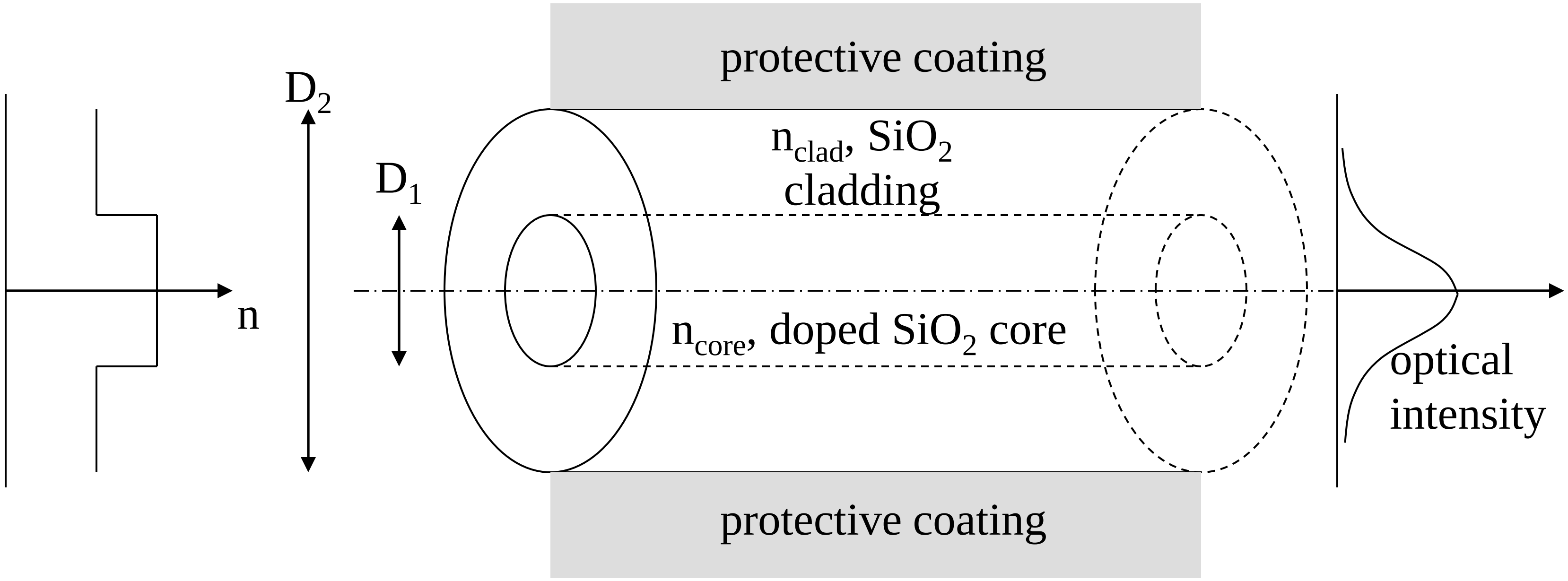
Types of Fibres

- Single mode/Multi-mode
- Step Index/Graded Index
- Dispersion Shifted/Non-dispersion shifted
- Silica/fluoride/Other materials

- **Major Performance Concerns for Fibres**
  - Wavelength range
  - Maximum Propagation Distance
  - Maximum bitrate
  - Crosstalk

Fibre Optic Cable

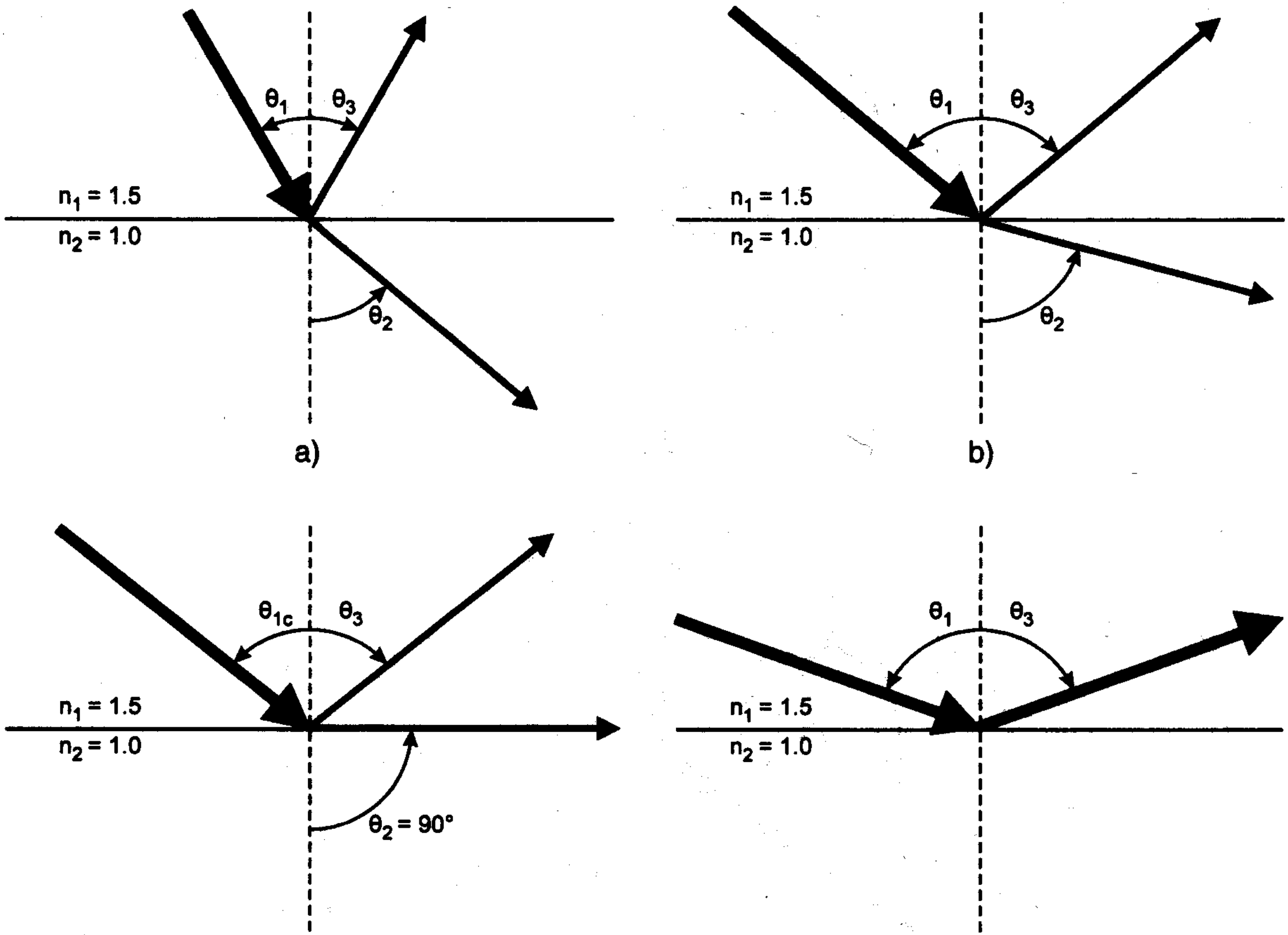
Total internal reflection



SiO2- high purity: low loss, n_{ref} ~ 1.45

<u>Dopants</u>: Boron, Fluorine: decrease n_{ref} ,

Phos, Ge, Ti: increase n_{ref}


θ_1
θ_3
$n_1 = 1.5$
$n_2 = 1.0$
θ_2
a)
θ_1
θ_3
$n_1 = 1.5$
$n_2 = 1.0$
θ_2
b)
θ_{1c}
θ_3
$n_1 = 1.5$
$n_2 = 1.0$
$\theta_2 = 90°$
θ_1
θ_3
$n_1 = 1.5$
$n_2 = 1.0$

$Snells\ Law:$

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\mathrm{Re}flection\ Condition$

$\theta_1 = \theta_3$

$When\ n_1 > n_2\ and\ as\ \theta_1\ increases\ eventually\ \theta_2$

$goes\ to\ 90\ \mathrm{deg}rees\ and$

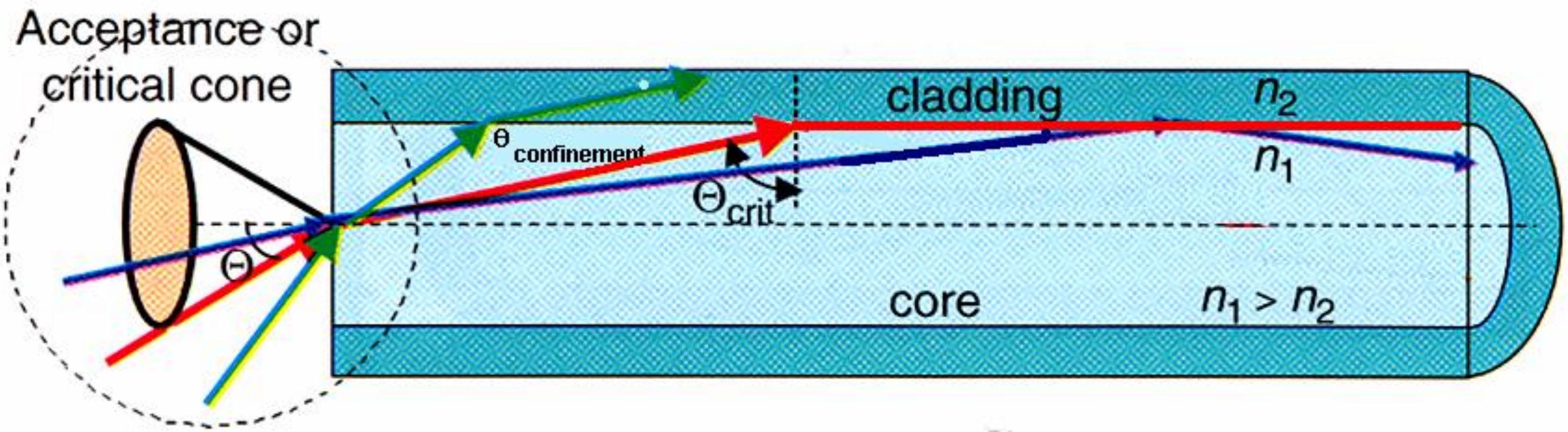
$$n_1 \sin\theta_c = n_2\ or\ \sin\theta_c = \frac{n_2}{n_1}$$

$\theta_c\ is\ called\ the\ Critical\ angle$

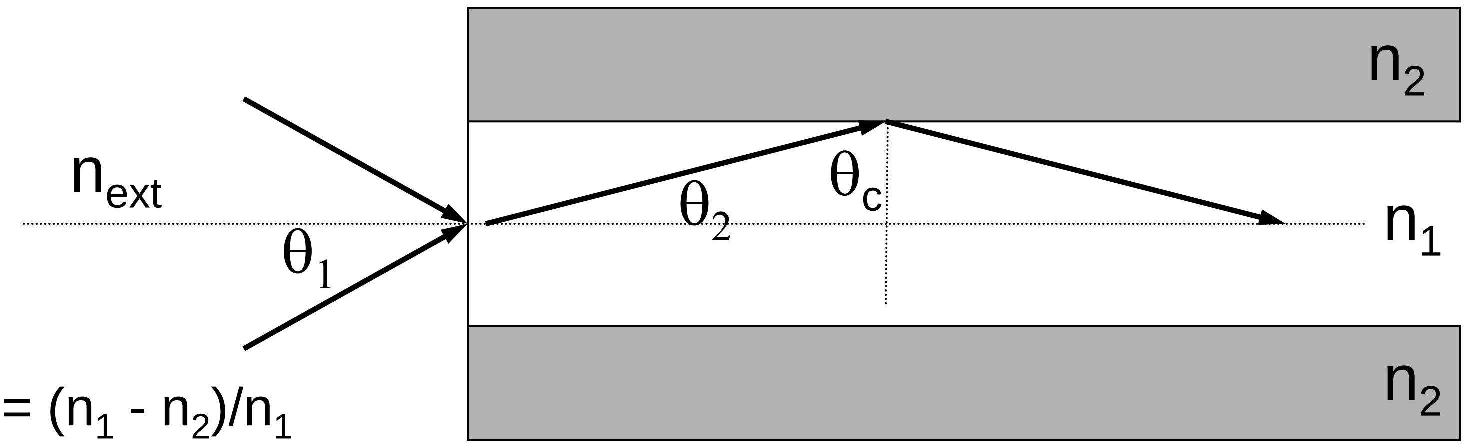
$For\ \theta_1 > \theta_c\ there\ is\ no\ propagating\ refracted\ ray$

For all angles θ_1 larger than this get total internal reflection

Coupling Light into an Optical Fiber



Acceptance Angle and Numerical Aperture



$\Delta = (n_1 - n_2)/n_1$

Acceptance angle – largest θ_1 such that all light is guided

$n_{ext}\mathrm{Sin}\theta_1 = n_1\mathrm{Sin}\theta_2 = n_1\mathrm{Cos}\theta_c$

Use; Snell's Law $\mathrm{Sin}\theta_c = n_2/n_1$ and Trig Identity $\mathrm{Sin}^2\phi + \mathrm{Cos}^2\phi = 1$

$$n_{ext}\mathrm{Sin}\theta_1 = \sqrt{(n_1^2 - n_2^2)} = \mathrm{NA}$$

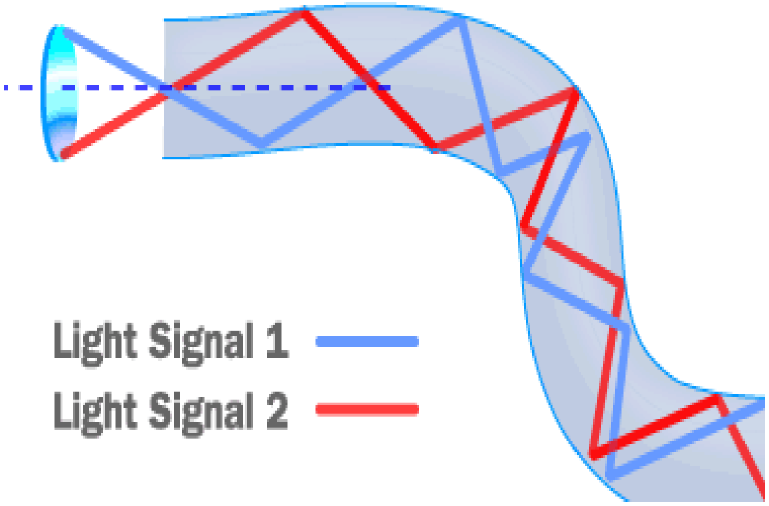
N.A. and Acceptance Angle

- Numerical aperture NA is a measure of the **light gathering ability** of an optical instrument.

- It is usually used when referring to microscopes but can also be defined for optical fibres.
- How much light can be accepted by a single optical fibre?
- The answer depends upon the **difference** between the refractive index of the core and cladding.
- If fibre is immersed in air, then $n_{ext} = 1$, and
  – NA = sin θ_1 (N.A. is measure of acceptance angle)
- If fibre is immersed in water or oil, then $n_{ext} \neq 1$
  – N.A. unchanged, but acceptance angle (θ_1) is smaller

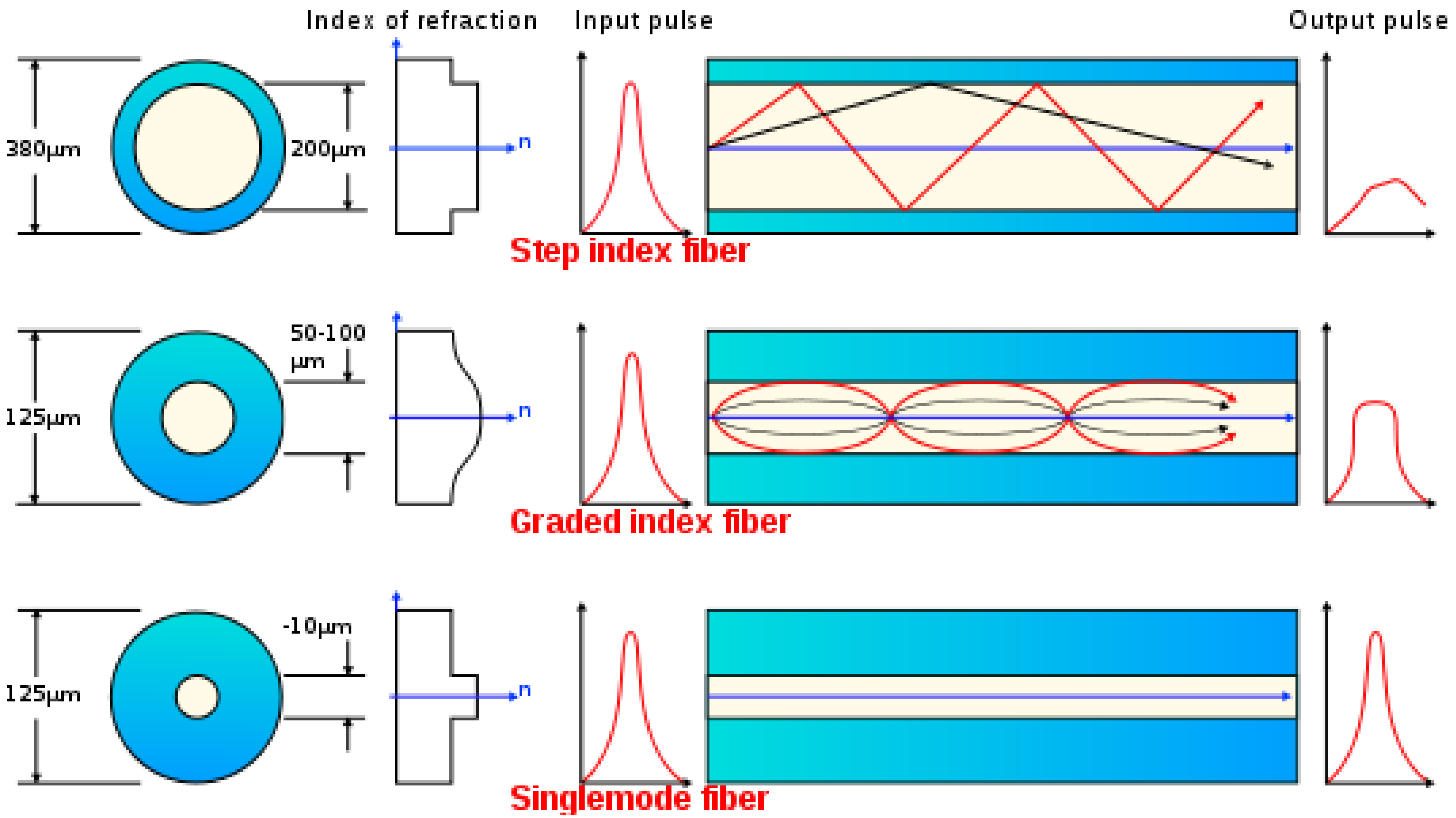
Operation of the fibre optic system

- Light is injected into the glass core at the correct angle and transmitted; it will reflect back repeatedly with internal reflections, even when the rod is curved. Light cannot escape from a fibre optics cable. A bundle of rods of fibres is capable of taking an image projected at one end of the bundle and reproducing it at the other end.



Reflected path of light in the glass rod

OPTICAL FIBRE TYPES



Main types of optical fibre

Step Index Fibre

- This cable has a specific index of refraction for the core and the cladding. It causes deformations due to the various paths lengths of the light ray. This is called modal distortion. It is the cheapest type of cabling. Within the cladding and the core, the refractive index is constant.

Graded Index Fibre

- In graded index fibre, rays of light follow sinusoidal paths. Although the paths are different lengths, they all reach the end of the fibre at the same time. Multimode dispersion is eliminated and pulse spreading is reduced. Graded Index fibre can hold the same amount of energy as multimode fibre. The disadvantage is that this takes place at only one wavelength.

Single mode fibre

- Single mode propagates, low dispersion and loss.

Limitations in Fibres

- **Attenuation**

  - Absorption, Scattering

- **Dispersion**

  - Modal, Chromatic, Polarisation mode dispersion (PMD)

- **Nonlinear effects**

  - SPM and XPM (cross phase modulation), FWM (wave mixing), SBS (Brillouin scattering), SRS (Raman scattering)

Transmission Loss

- The transmission loss or attenuation of an optical fibre is perhaps the most important characteristic of the fibre; this determines if a system is practical. It controls (1) spacing between repeaters and (2) the type of optical transmitter and receiver to be used.

- As light waves travel down an optical fibre, they lose part of their energy because of various imperfections in the fibre. These losses are measured in decibels per kilometers (dB/km).

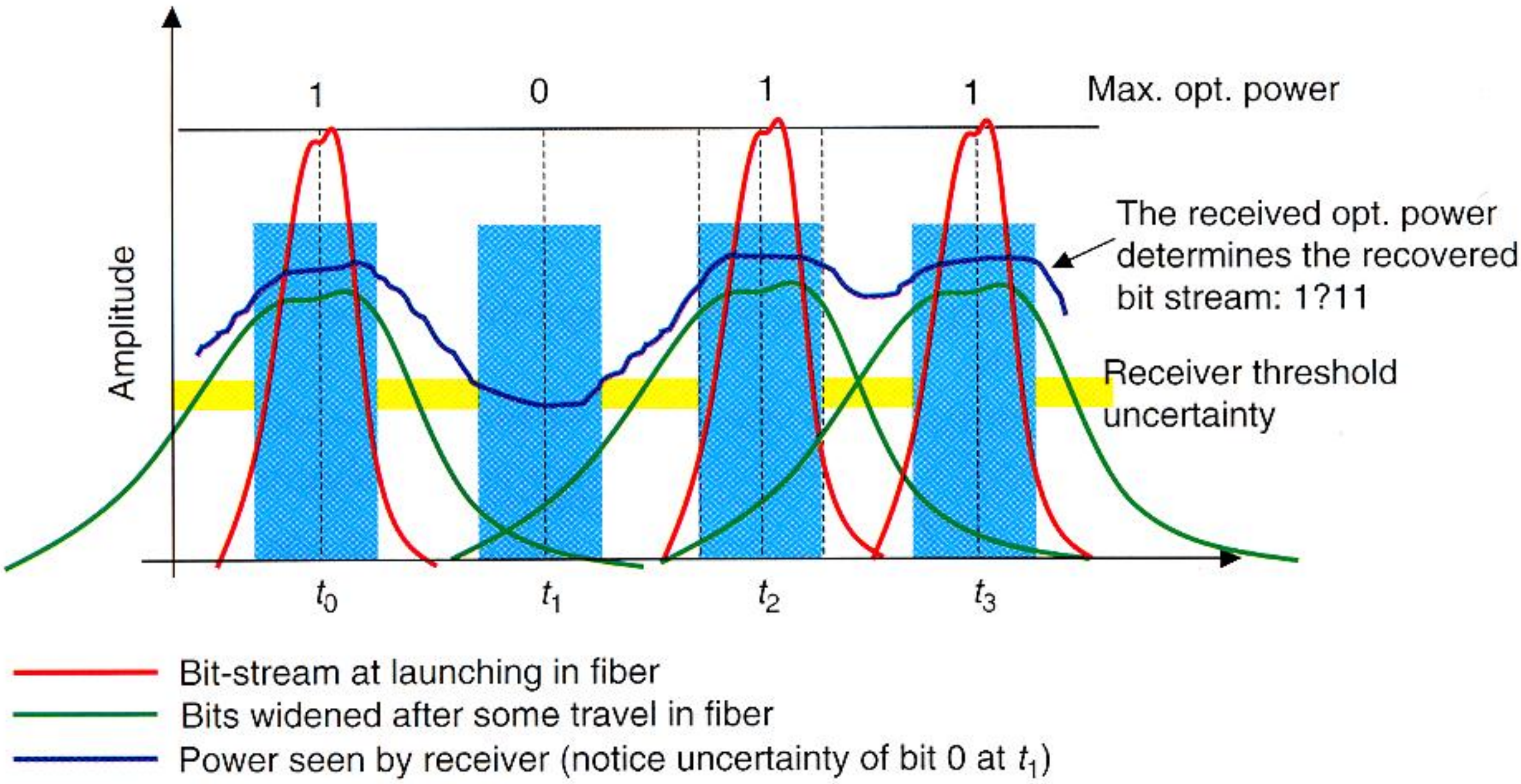
Pulse Spreading

- Optical fibres that carry data consist of pulses of light energy following each other. The fibre has a limit as to how many pulses per second can be sent to it and be expected to emerge intact at the other end. This is known as pulse spreading which limits the Bandwidth of the fibre.

- The pulse sets off down the fibre with a square wave shape. As it travels along the fibre, it progressively gets wider and the peak intensity decreases.

- Known as Dispersion

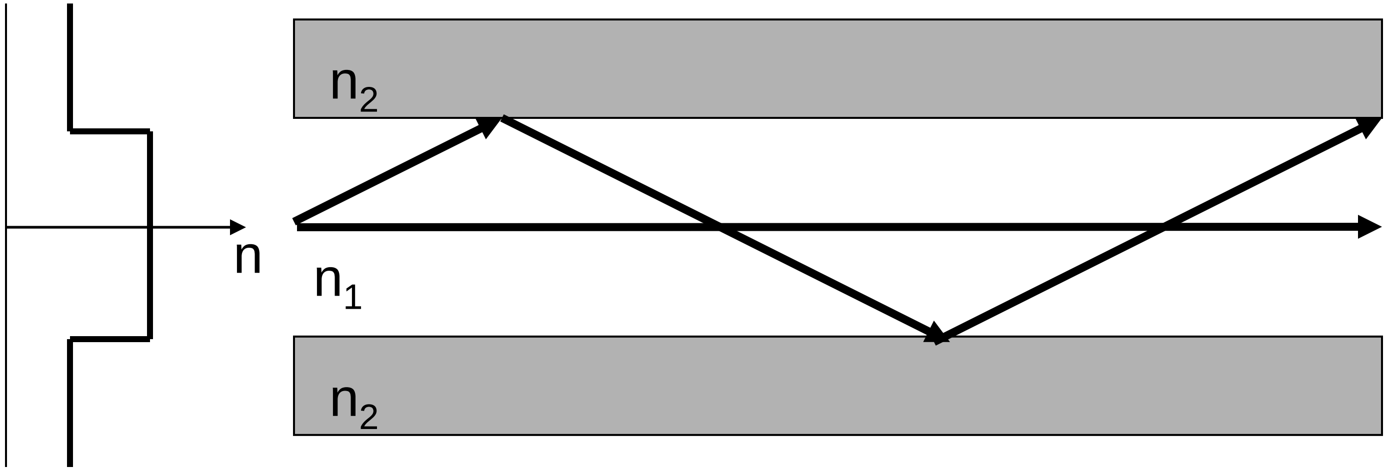
- When dispersion is too large, pulses interfere with each other.



Optical Propagation in Stepped-Index Multimode Fibre

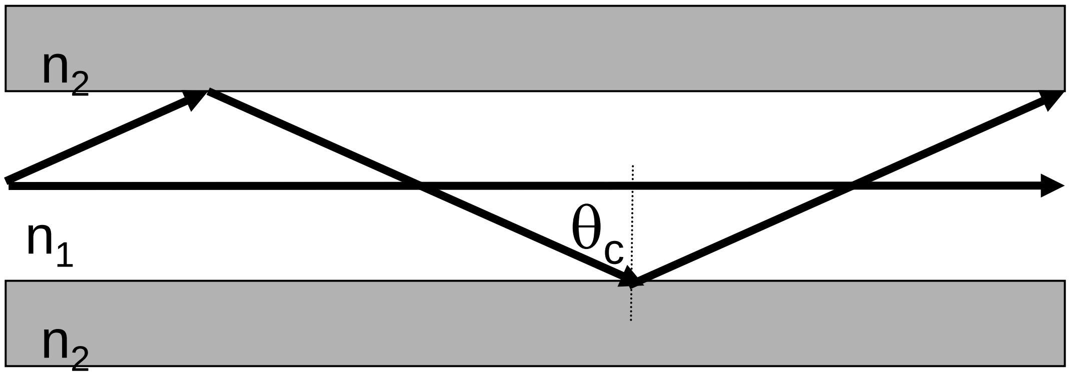
- Fibre has a core diameter of ~100 microns +

- All light rays in the core travel at the same velocity (since n_{core} is constant throughout this region)



- Get *Modal* dispersion due to different path lengths

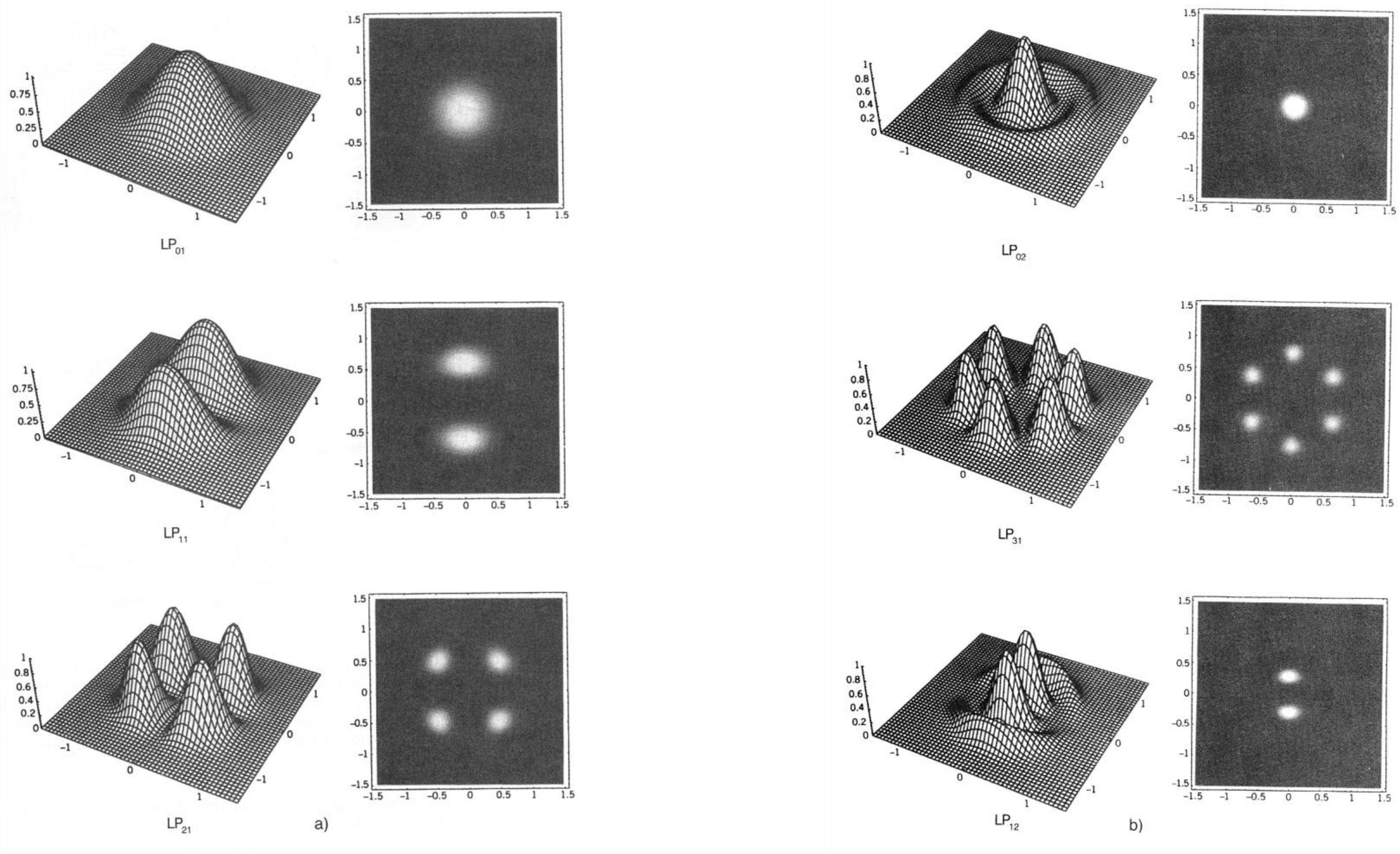
Multimode Fibre - Modal Dispersion



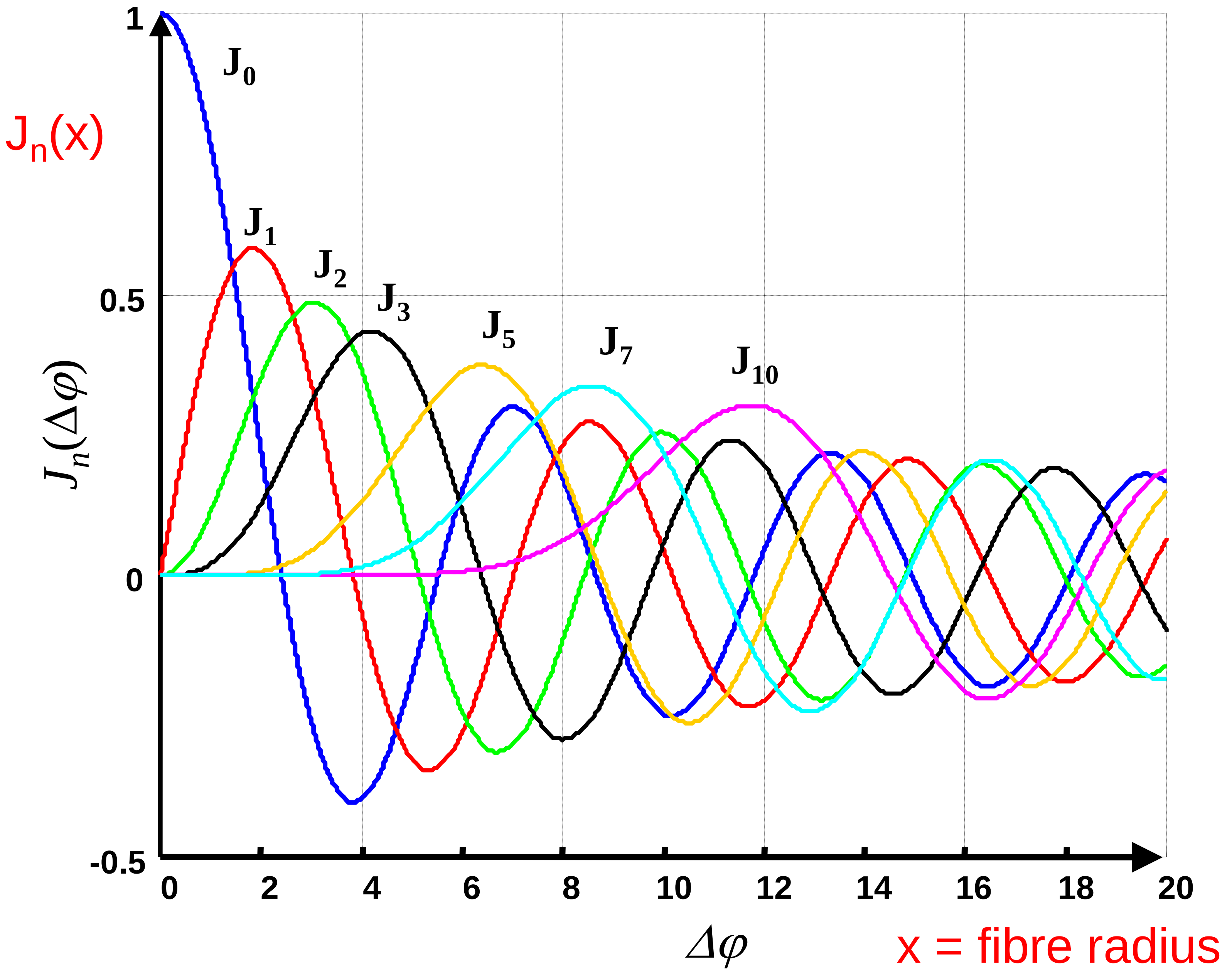
Time to travel distance L down fibre for

- Axial ray: $t_A = L/v_1 = Ln_1/c$
- Critical ray: $t_C = Ln_1/(c \times \sin\theta_C) = (Ln_1/c)(n_1/n_2)$.
- Differential time delay: $\delta t = t_C - t_A = (Ln_1/c)\{(n_1/n_2) - 1\}$
  $= (Ln_1/c)(n_1 - n_2)/n_2 \approx (Ln_1/c)(n_1 - n_2)/n_1 = Ln_1\Delta/c$.
- The pulse spreads in time by $\delta t = Ln_1\Delta/c$ in a distance L.

High Order Fiber Modes 2



Fiber Optics Communication Technology-Mynbaev & Scheiner



$J_n(x)$
J_0
J_1
J_2
J_3
J_5
J_7
J_{10}
$J_n(\Delta\varphi)$
1
0.5
0
-0.5
0
2
4
6
8
10
12
14
16
18
20
$\Delta\varphi$
x = fibre radius

V - normalised frequency

In an optical fibre, the **normalized frequency**, V (also called the **V number**), is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} \quad = \frac{2\pi a}{\lambda}\mathrm{NA},$$

where a is the core radius, λ is the wavelength, n_1 is the maximum refractive index of the core, n_2 is the refractive index of the homogeneous cladding, and NA the numerical aperture.

In multimode operation of an optical fiber, the approximate number of bound modes is given by

$$\frac{V^2}{2}\left(\frac{g}{g+2}\right) \quad ,$$

where g is the profile parameter, and V is the normalized frequency, which must be greater than 5 for the approximation to be valid.

For a step index fibre, the mode volume is given by $V^2/2$. For single-mode operation is required that $V < 2.405$, which is the first root of the Bessel function J_0.

Modal Dispersion and Bit Rate

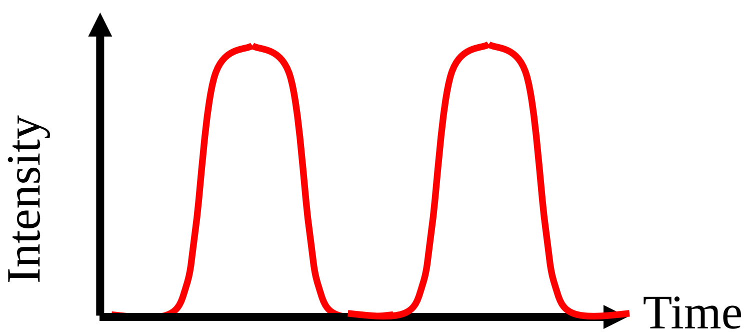
The pulse spreads in time by $\delta t = L n_1 \Delta / c$ in a distance L.

Modal Dispersion = $\delta t / L = n_1 \Delta / c$

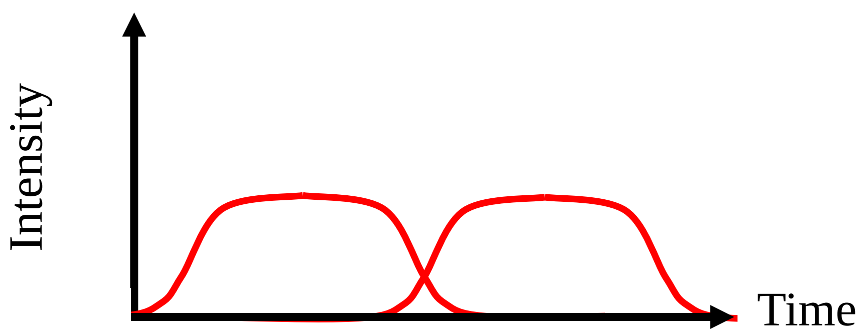
E.g. for $n_1 = 1.5$, $\Delta = 1\%$, Modal Dispersion = 50 ns/km

So for L = 10km: $\delta t = 0.5 \mu s$

$\Rightarrow B_{max} \approx 1/\delta t$ = 2MB/s



In

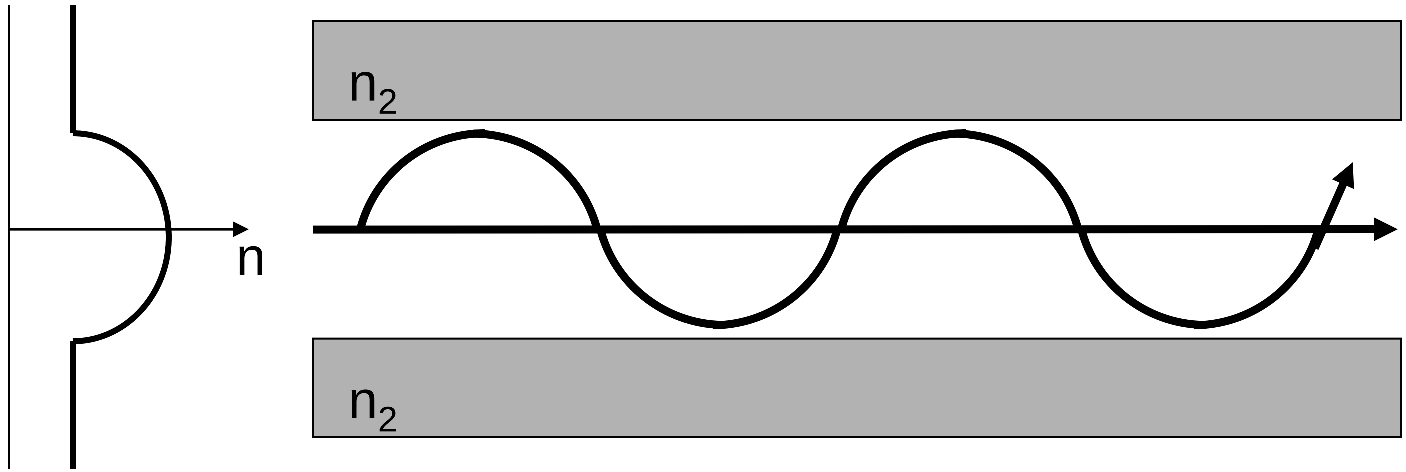


Out

Graded-Index Multimode Fibre

- Fibre has a core diameter of 50 micron
- Refractive Index profile:
  - n_{core} has a high value at the centre of the core and then gradually decreases towards the core cladding interface.
  - The index of refraction in the fibre core has a parabolic profile.

$n(r) = n_{max} \{1 - k(2r/D)^2\}$



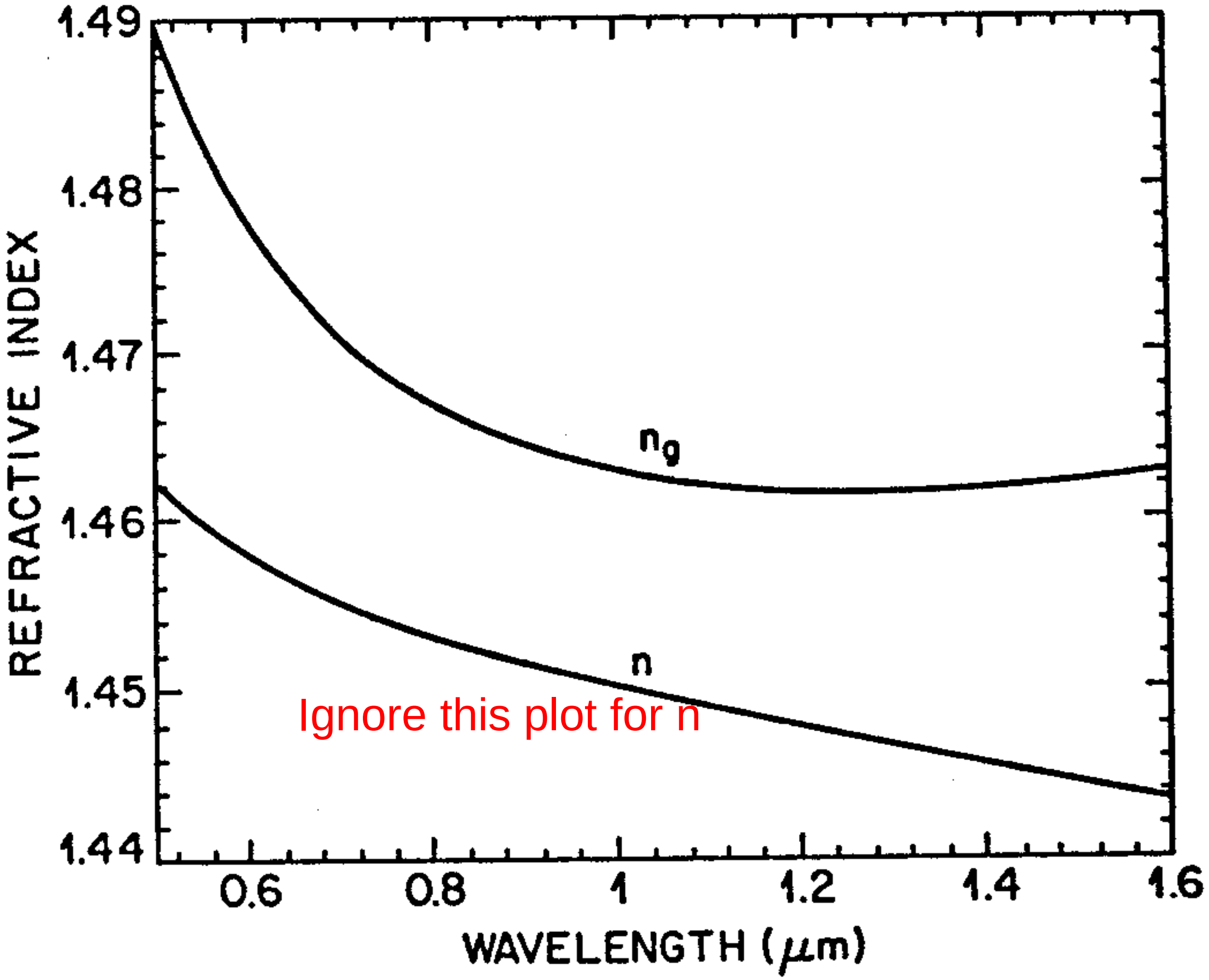
Graded-Index Multimode Fibre –Modal Dispersion

- ALL modes transit the fibre in approximately the same time
- Light travelling close to the centre of the core has the slowest velocity (since n is highest here) (Short distance and slow velocity)
- Light travelling further from the centre of the core has a higher velocity. (Longer distance but higher velocity)
- Modal dispersion only about 1 ns per km

Single Mode Fibre

- Fibre has a core diameter of ~ few μm
- Refractive Index profile:
  - n_{core} has a constant value throughout the core
  - Core is so small that only the LOWEST ORDER (AXIAL) MODE can propagate through the fibre.
- Zero modal dispersion
- RAY model breaks down when core ~ wavelength of light
- Need wave model to correctly explain SM fibre behaviour (Maxwell's equations)

Group Index - Silica



Ignore this plot for n

Chromatic Dispersion - SM Fibres

Material and waveguide dispersion

For silica – group index is a function of wavelength

Turning point at 1.25 μm

To first order – signals with reasonable emission linewidths will propagate with no dispersion

Away from this point - different wavelength components of emission will travel with different velocities

Speed of wavepacket = c/n_g

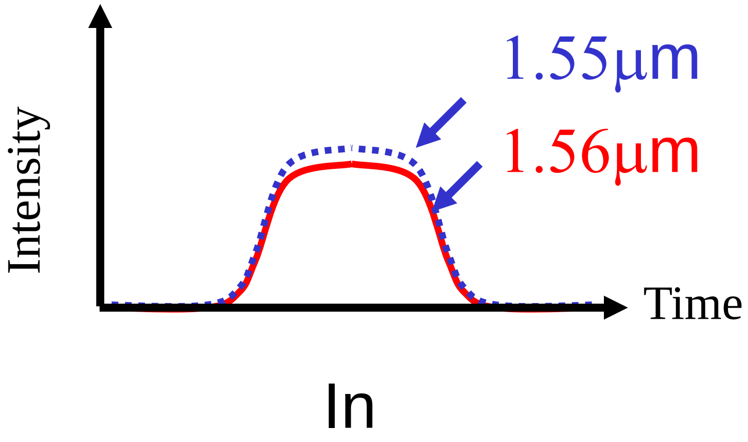
Longer than 1.25 μm -red faster than blue
Shorter than 1.25 μm- blue faster than red

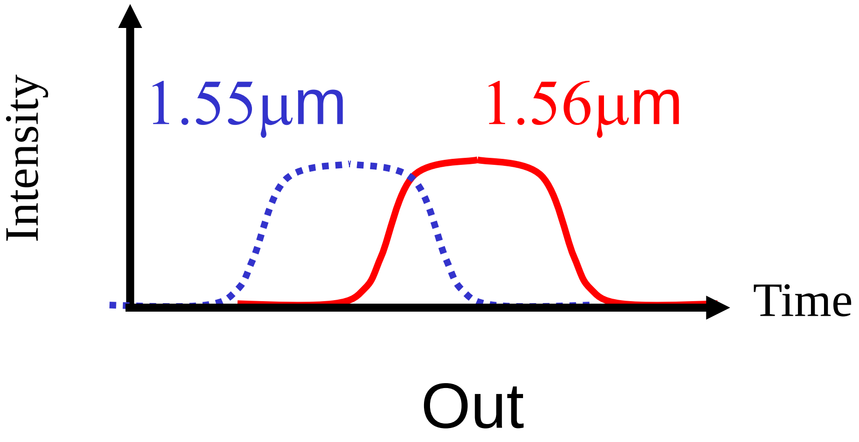
Pulse Broadening

Take case of two simultaneously injected pulses of peak wavelengths – 1.55um and 1.56um ($\Delta\lambda$ = 10nm).

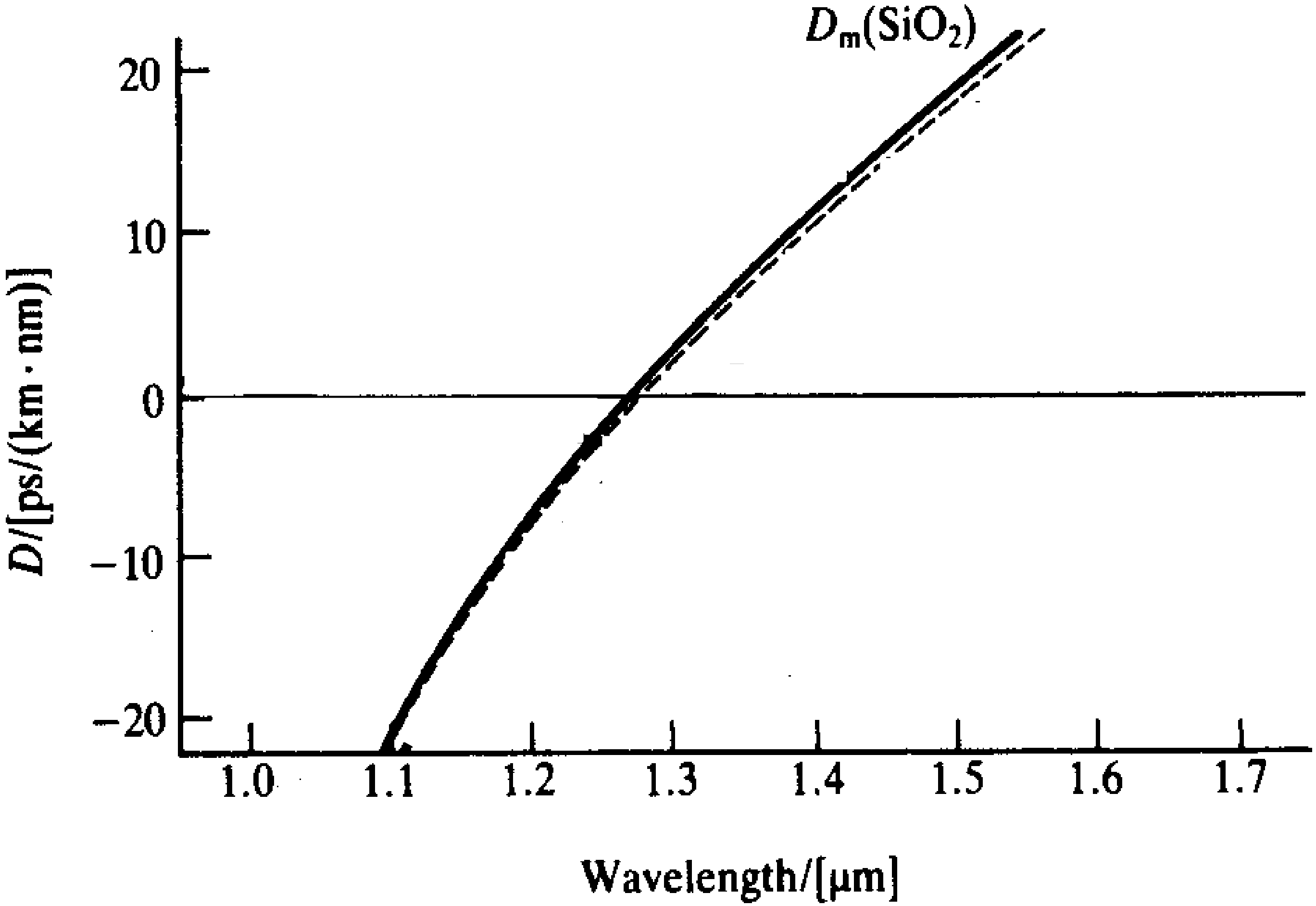
The 1.56um pulse arrives first after travelling through length L km of SiO_2 - As n_g at 1.55 um higher than at 1.56um (+ve Dispersion)

How much later does 1.55 um pulse arrive? (depends on n)

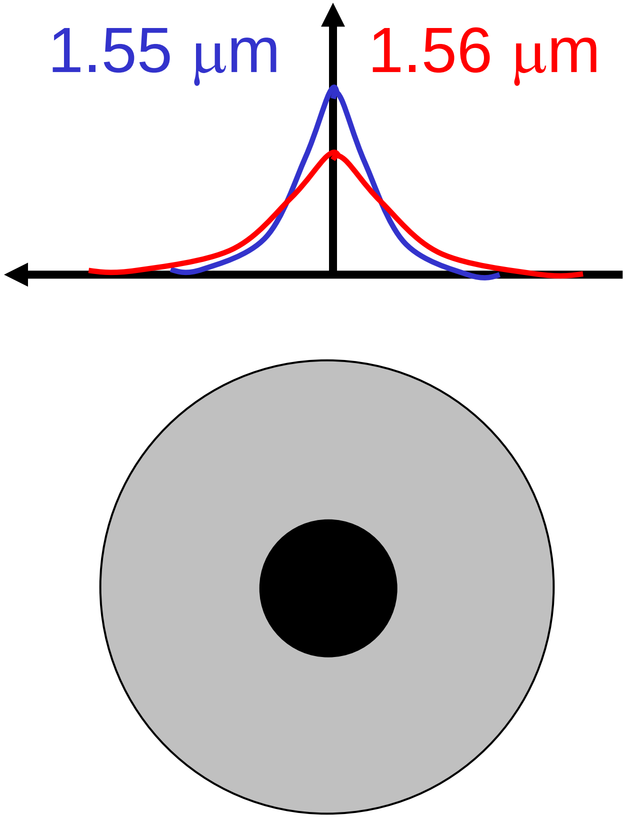




Material Dispersion – Silica Glass



Waveguide Dispersion in SM Fibres



Now have to include fact that two colours have different intensity distribution within the fibre

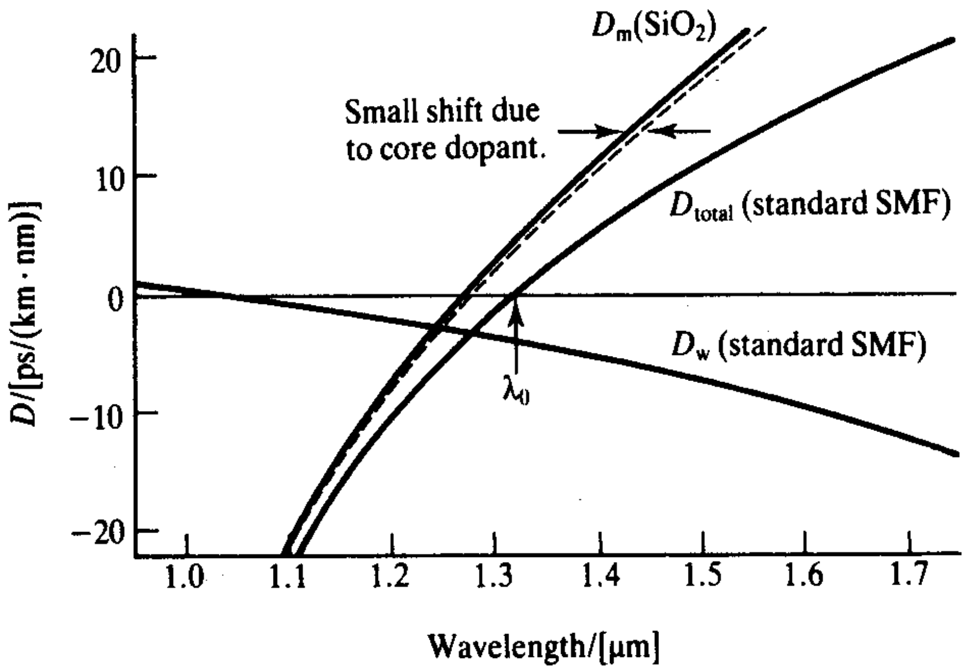
Longer wavelength light spreads out laterally - more than shorter wavelength light

Each pulse will be broadened due to the difference in core and cladding refractive index – waveguide dispersion

Two pulses broadened differently due to different effective refractive index and hence speed of travel

Chromatic Dispersion - SM Fibres

For silica – refractive index is a function of wavelength – so have Material Dispersion



D_m – material dispersion
D_w – waveguide dispersion

Hence have zero dispersion at ~1.3 μm

Dispersion Coefficient

$$\Delta t = L\Delta\lambda \, D(\lambda)$$

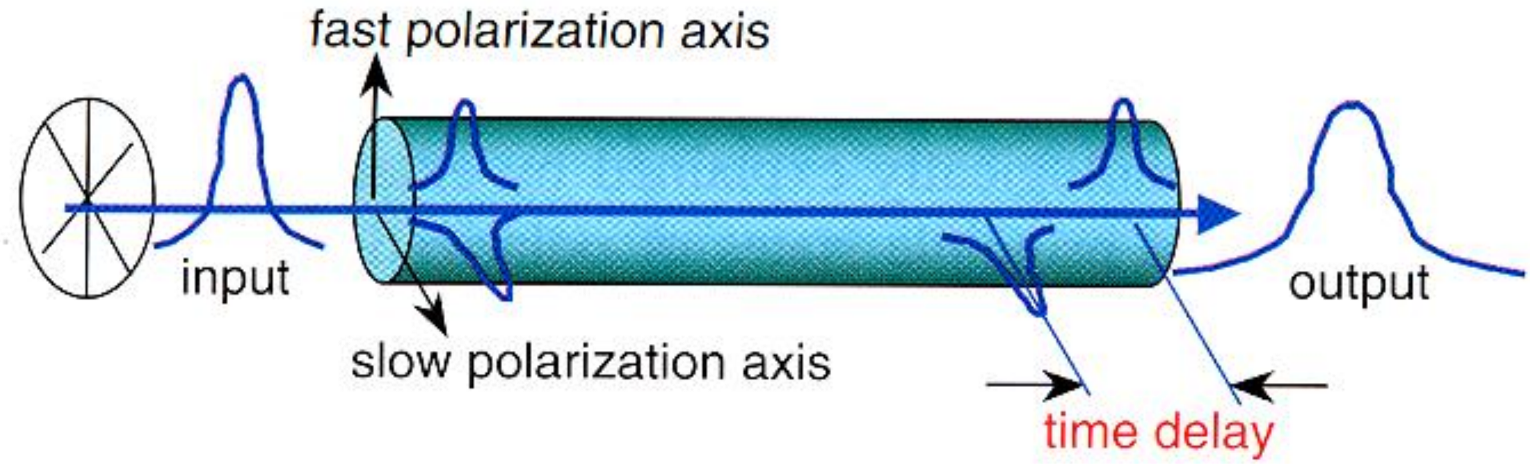
Choose $\lambda = 1.31\mu m$ for $D(\lambda) = 0$.

- Note $dD/d\lambda \neq 0$, leading to second order dispersion:
- At $\lambda = 1.55\mu m$ (minimum loss) $D(\lambda) = 20ps/(km.nm)$.
- Eg, when $\Delta\lambda = 5nm$ (linewidth Fabry-Pérot laser), $L = 10km$, $\Delta t \approx L\Delta\lambda D = 1ns$, and $B \approx 1/\Delta t = 1GB/s$.
- Design single mode fibre so that 'waveguide dispersion' (variation of speed of single mode with λ) compensates for this.

Polarization Mode Dispersion (PMD)

Asymmetry and stress in the fiber core results in birefringence (double refraction splitting ray into 2 components)

- An arbitrarily polarized pulse of light entering the fiber can be resolved into two components. These polarization modes will travel at different speeds through the fiber. It leads to pulse broadening
- PMD is measured in ps/(Km$^{1/2}$)



PMD is important over 40 Gbps

Dispersion Summary

Intermodal dispersion (ie between modes) → **MODAL DISPERSION**

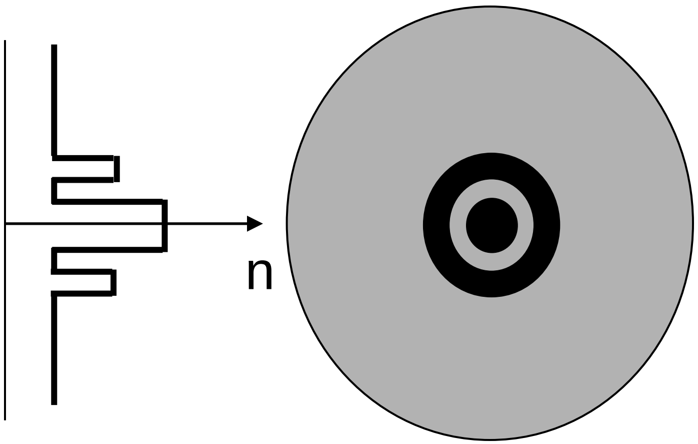
Multi-mode fibres only; minimised for graded-index fibres

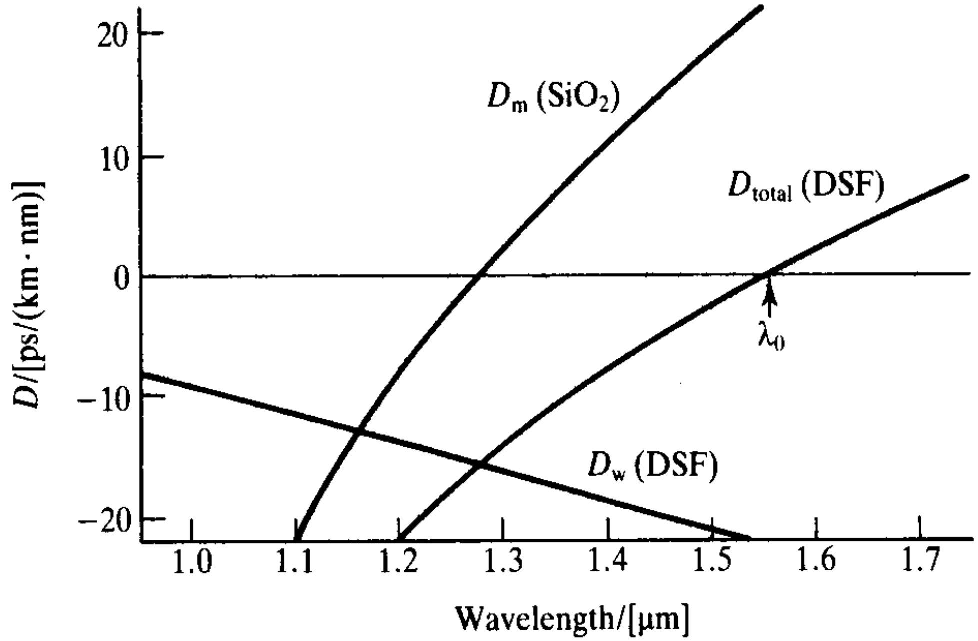
Chromatic or Intramodal dispersion (ie within a single mode) → **MATERIAL DISPERSION**, **WAVEGUIDE DISPERSION**

Single or multi-mode fibres but only significant for single mode fibres.

Chromatic dispersions are wavelength dependent

Dispersion Shifted SM Fibre





The fibre geometry shown increases the waveguide dispersion (ie makes it more negative).This means that the material dispersion is now cancelled at longer wavelengths (ie zero dispersion where attenuation is also a minimum: 1550nm).

Degradation of a 40 Gb/s Signal

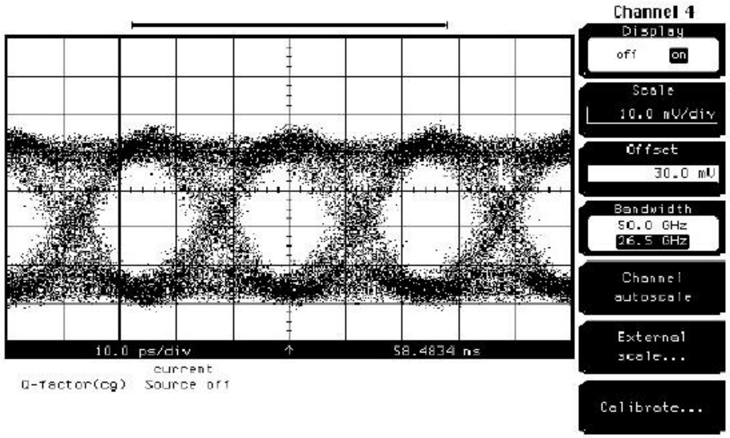


Figure 2. 40 Gb/s signal at Transmitter

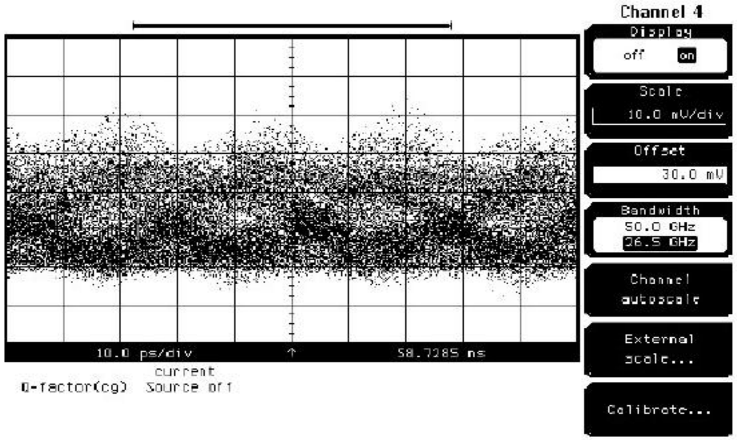


Figure 3. 40 Gb/s signal after traversing 80 km of NZDSF fiber without compensation

T2 Summary

- **Multimode Fibre**
- Consider ray picture for light propagation
- Snell's law – a ray of light incident at a particular angle to a step change in refractive index will be totally internally reflected
- Allows acceptance angle and numerical aperture to be determined

- **Inter-Modal Dispersion**
- Considering critical ray and meridional ray – transit time down a length of fibre is different for the two different modes
- This intermodal dispersion severely limits distance-bit rate product
- Can be partially overcome by using graded index fibre – extra path compensated by lower n, higher v_{group}

T2 Summary

- **Single Mode Fibre – Chromatic Dispersion**
- Cannot use ray picture – solving Maxwell's equations gives a single mode which sits within the core *and* the cladding region
- As only one mode intermodal dispersion is eliminated - Dispersion is now due to $n_{group}(\lambda)$
- Chromatic Dispersion of single mode fibre made up of two components – material ($n_{group}(\lambda)$) and waveguide dispersion (average n_{group} the mode sees is a function of λ as mode size is fn of λ)
- Can engineer waveguide dispersion by fibre design to give zero dispersion at a chosen wavelength