OPTICAL FIBRE PRINCIPLES
Linear Transmission

Light Guidance in Fibres

Optical Fibre Types

Scattering and Absorption Loss

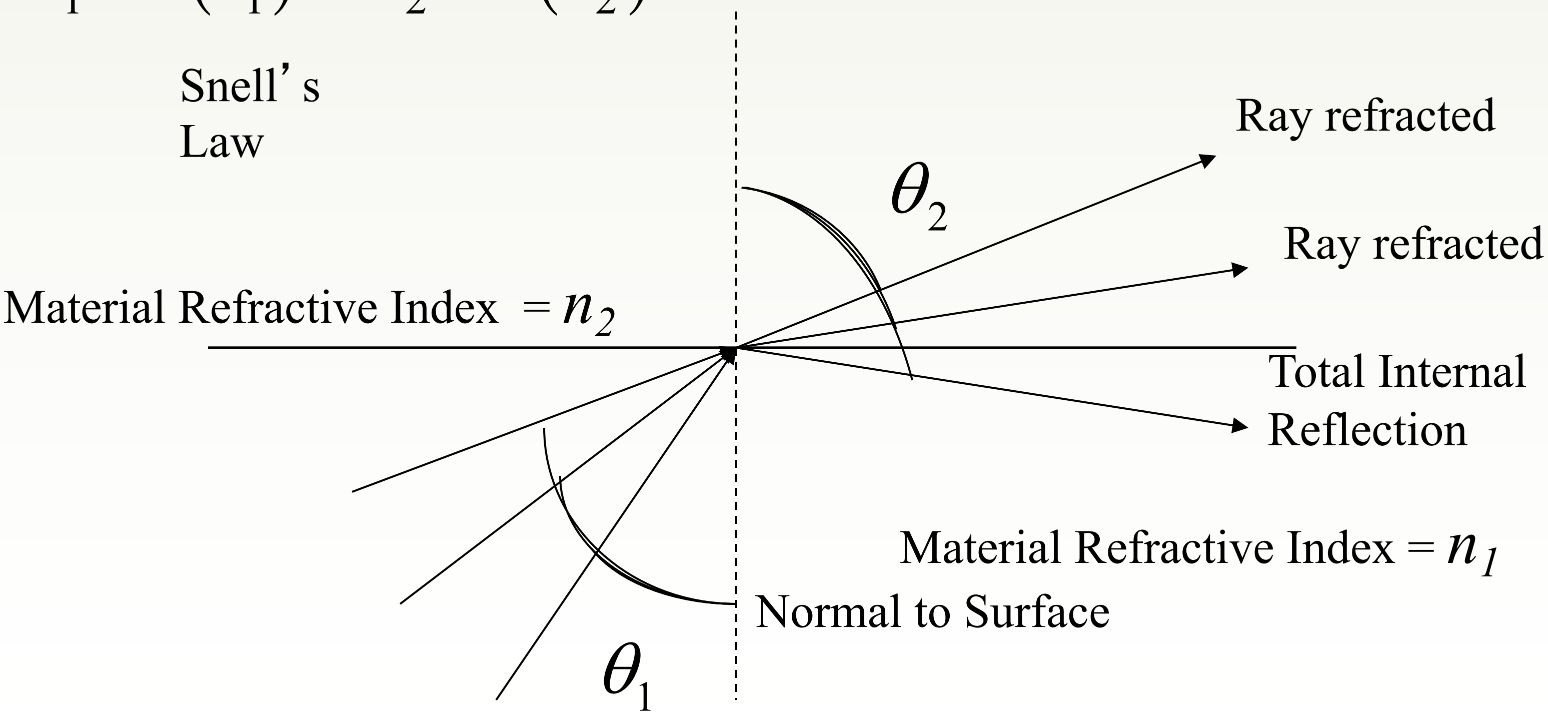
Material Dispersion

Total Fibre Dispersion

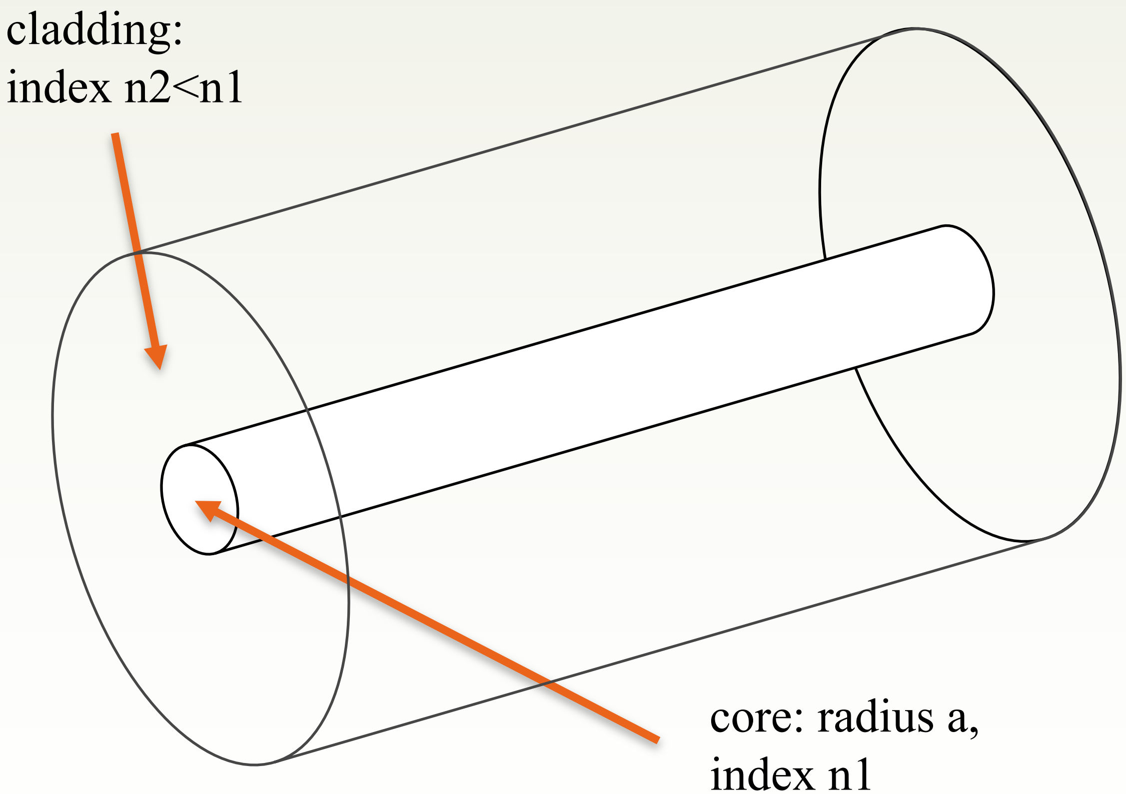
Guidance in an Optical Fibre

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \qquad (n_1 > n_2)$$

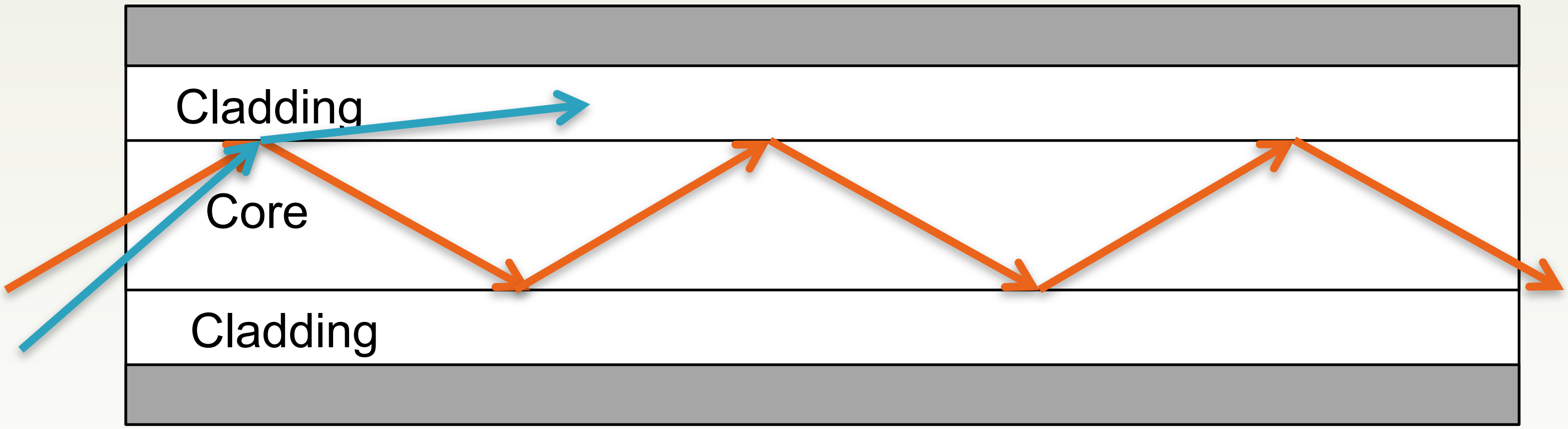
Snell's Law



Fibre Structure



Total Internal Reflection



- The light gathering capacity of the fibre is quantified by the *Numerical Aperture (NA)*

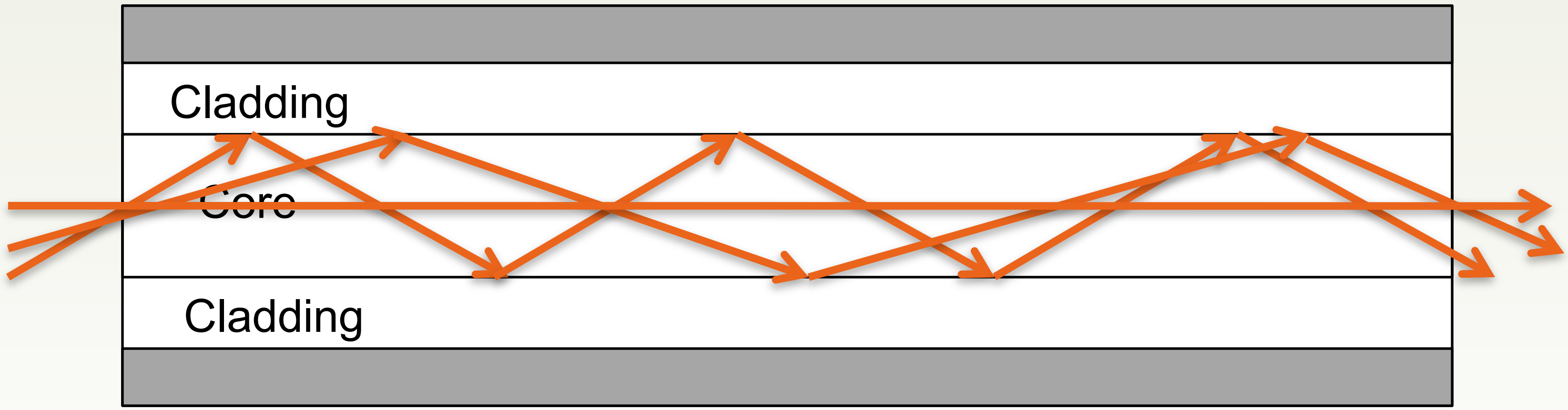
$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$$

Modal Dispersion

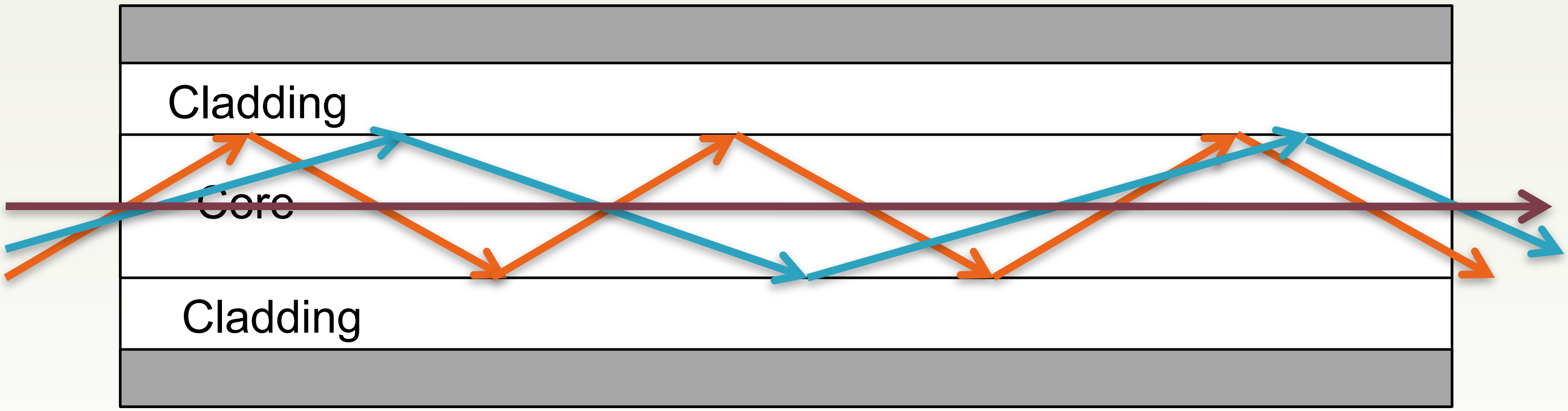
- Dispersion – A fibre property that causes difference parts of the light to travel at different velocities
- Different path lengths result in *fibre modes*
- A narrow pulse of energy will be spread out of a larger time period due to the different propagation velocities of the modes
- Causes a severe penalty to digital transmission

We will meet other forms of dispersion later on….

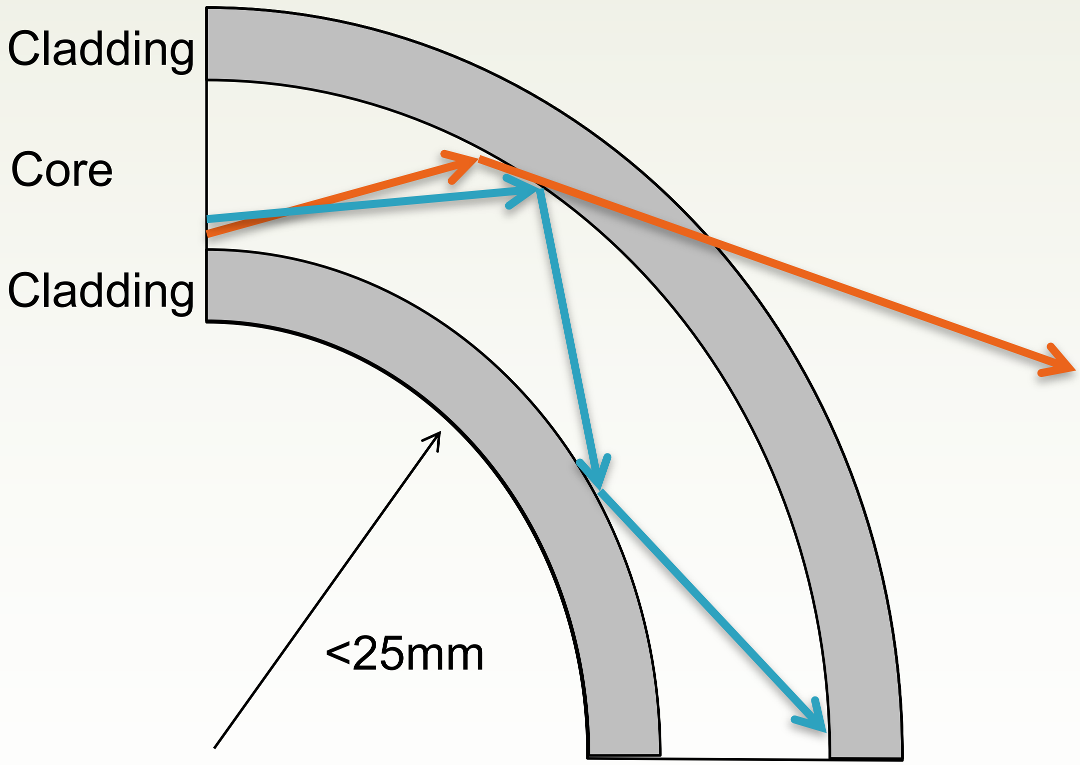
Modal Dispersion



Modal Dispersion



Fibre Bends



The Propagation Coefficient

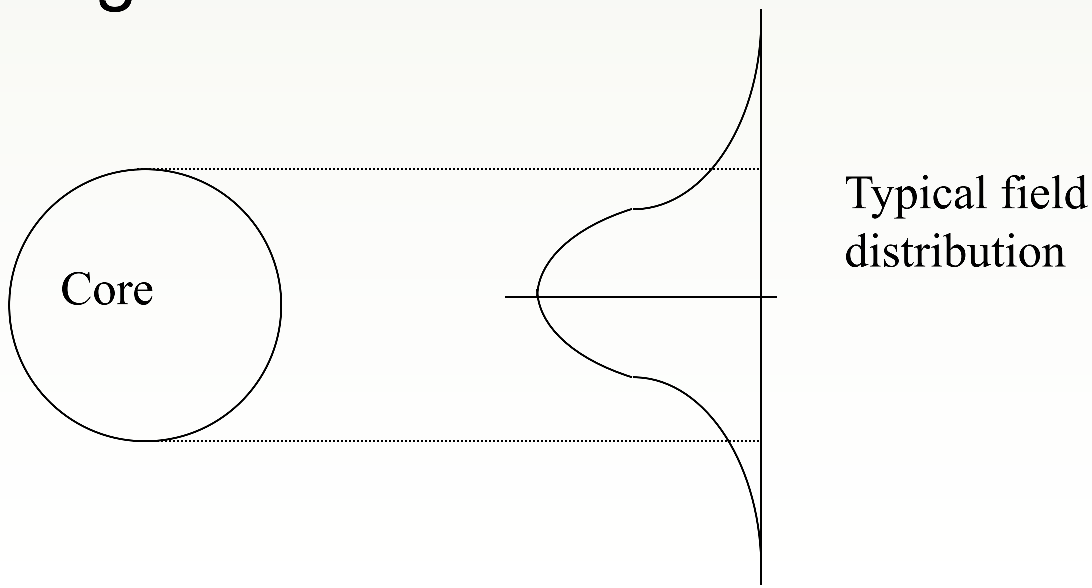
- If the core of the fibre is made very small ~5μm, only one mode can propagate $\Rightarrow$ single mode fibre with mode dispersion $\cong$ 0.
- The condition for single mode is:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \leq 2.405$$

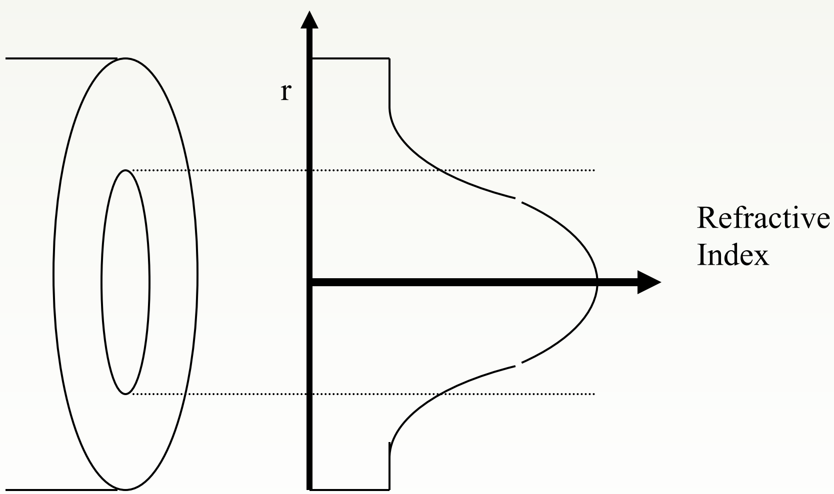
- From the solution of Maxwells equations.
- Typical fibre V $\approx$ 2.2
- Spot size increases as index difference is reduced, which leads to microbending loss

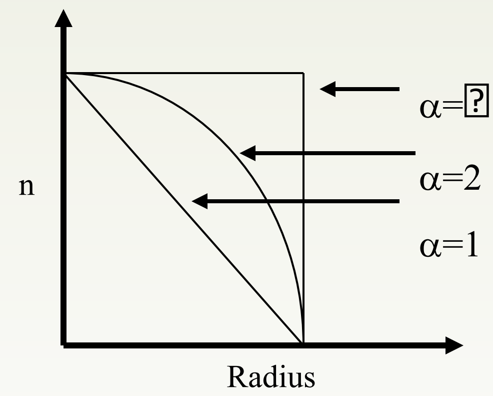
Single Mode Fibre

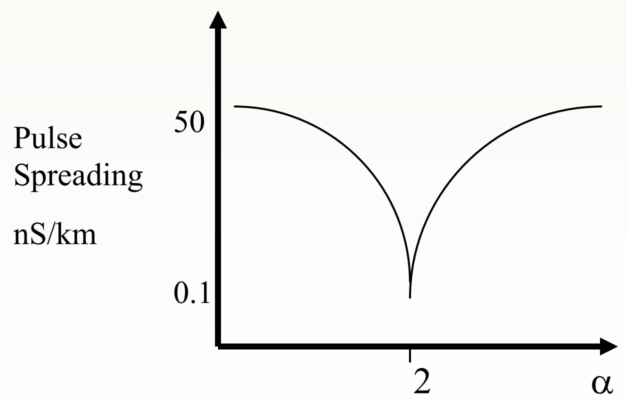
- If we look at the field distribution in a single mode fibre we see that the field penetrates into the cladding, typically to a distance of the order of one wavelength



Graded index fibres





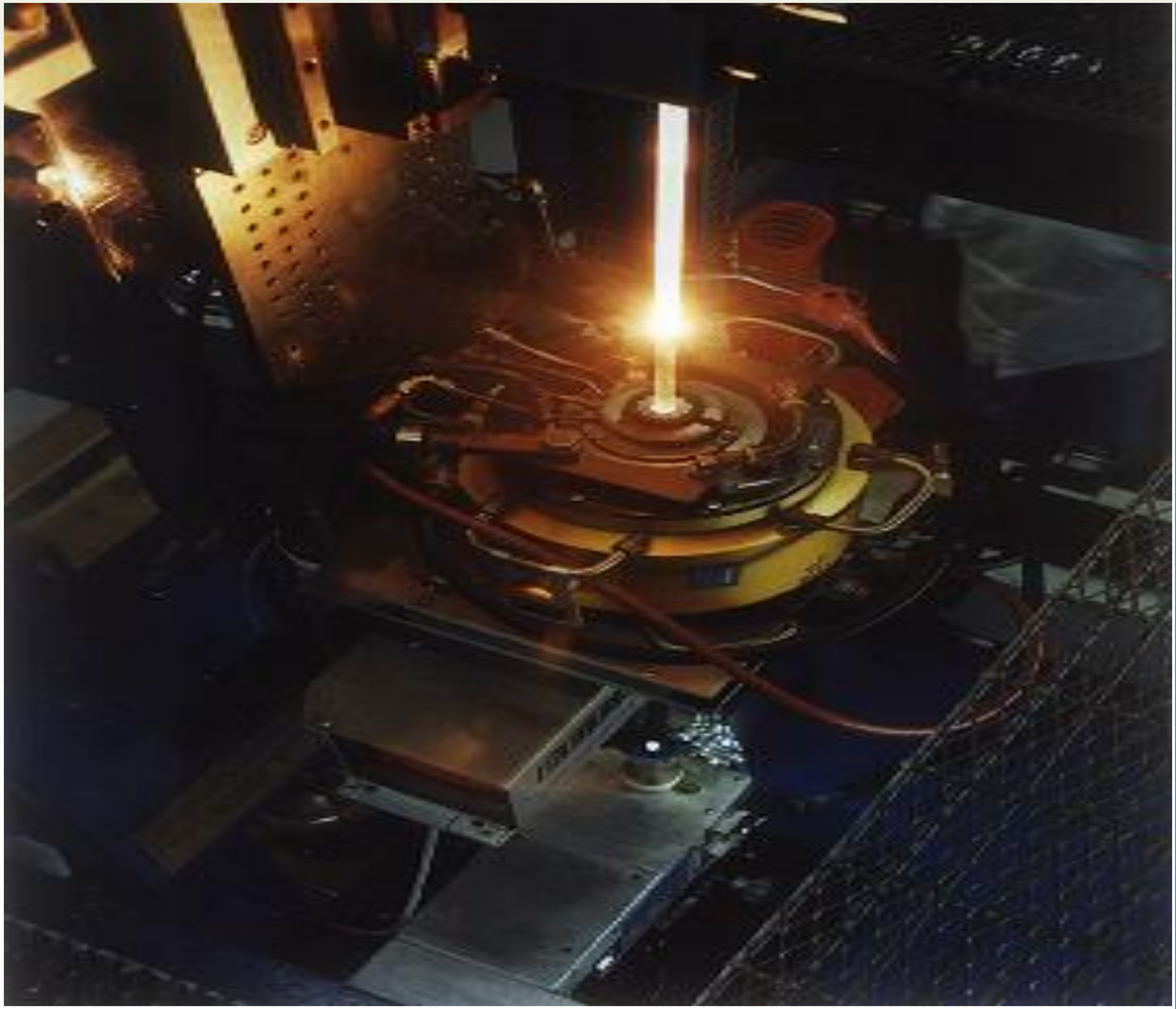


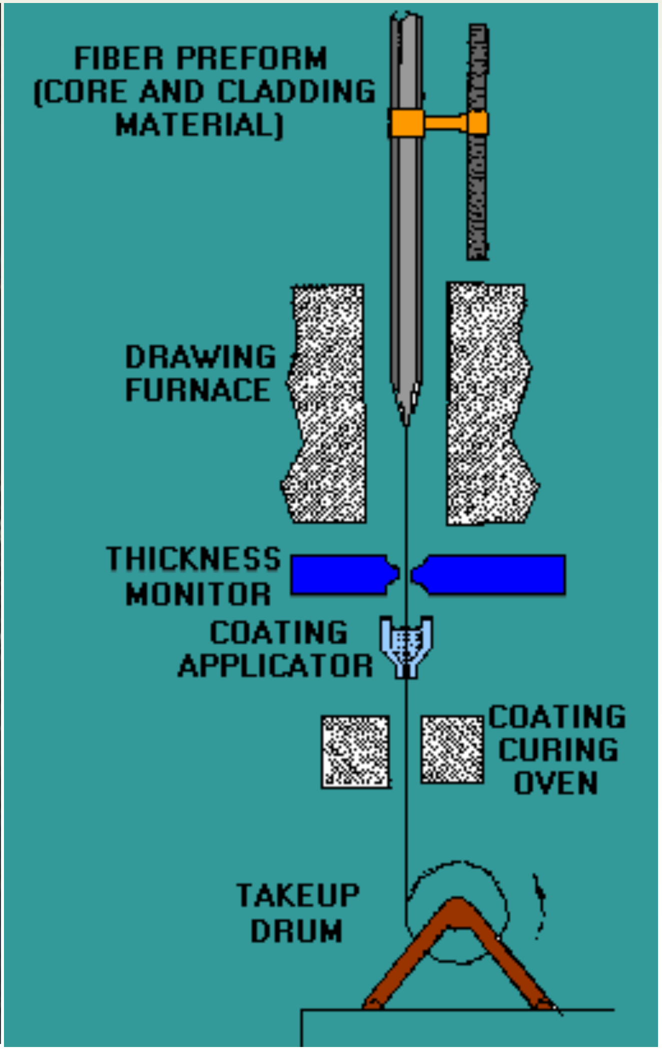
- core refractive index follows a parabolic profile.

Comparison of optical fibres.

	Multimode step index	Multimode graded index	Single mode	Plastic
Core Diameter	50μm	30μm	5μm	200μm
Cladding Diameter	125μm	100μm	125μm	450μm
n_1	1.48	1.48	1.460	1.50
n_2	1.45	1.46	1.456	1.40
Advantages	Efficient Coupling.	Low intermodal dispersion with efficient coupling.	Zero intermodal dispersion, reduced attenuation	Cheap and easy to couple due to large core.
Disadvantages	Intermodal dispersion.	Can not match single mode performance.	Small core, difficult coupling and slicing.	Very poor loss performance.
Applications	Short haul, low bandwidth.	Medium haul, low bandwidth.	Long haul, high bandwidth.	Very short, low rate data links.

Optical Preform

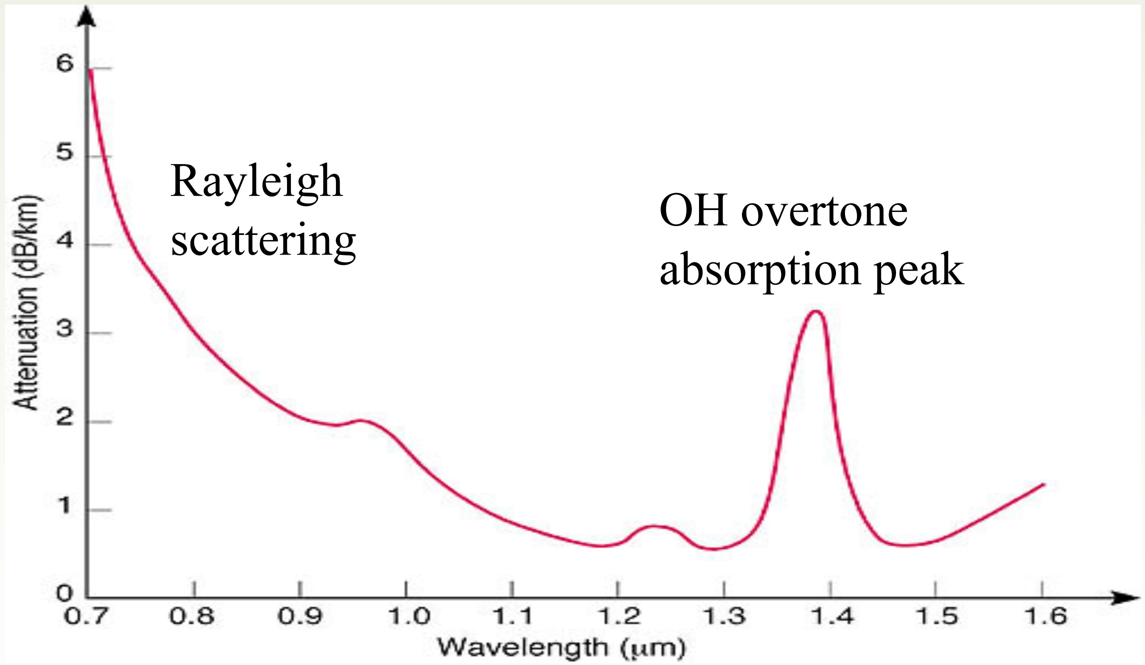




Fibre Attenuation

- Intrinsic loss due to ‘tails’ of UV (~200nm) and Infra-red (~10,000nm, Si-O bond resonance) absorption bands
- Rayleigh scattering - local structural fluctuations ‘frozen in’ as the glass forms result in λ^{-4} dependent scattering in forward and reverse directions
- Impurities - such as OH, with fundamental molecular vibration at 2800nm such that overtones at 1400nm and 900nm are significant
- Bends and microbends - loss varies as exp(-R), significant for R< few cm and increasing rapidly with λ

Fibre Loss Spectrum



- Loss ~ 0.35 dB/km at 1300nm, 0.2 dB/km at 1550nm
- Loss < 0.18 possible using pure silica core with 'index depressed' cladding

Dispersion - 1

- Total chromatic dispersion is a combination of material and waveguide effects
- Material dispersion
  - Refractive index of silica varies with λ, reducing with increasing λ in the relevant region
  - Group delay spread depends on the second derivative of refractive index with λ
- Waveguide dispersion
  - The mode propagation constant varies with λ, giving waveguide dispersion

Dispersion - 2

Consider a plane wave, $\exp(j(\omega t - \beta z))$

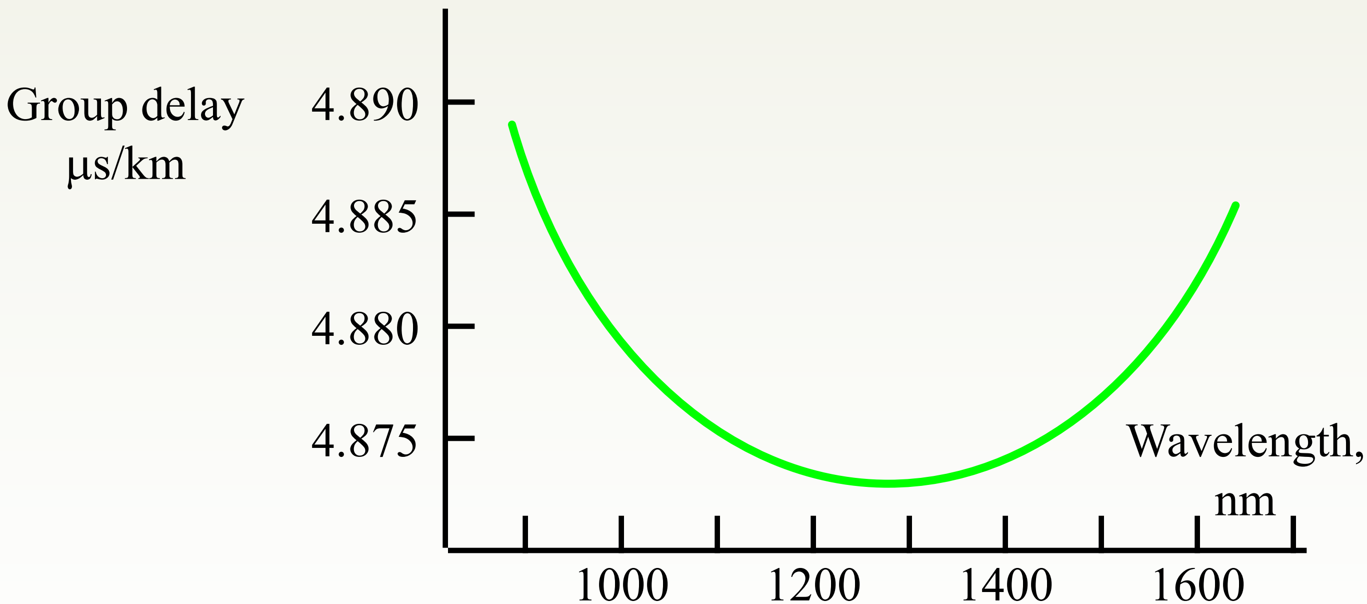
Phase velocity $v_p = \omega/\beta$; Group velocity $v_g = d\omega/d\beta$

Hence $v_p = \dfrac{\omega}{\beta} = \dfrac{c}{n}; \beta = \dfrac{2\pi n}{\lambda}$

differentiating gives:

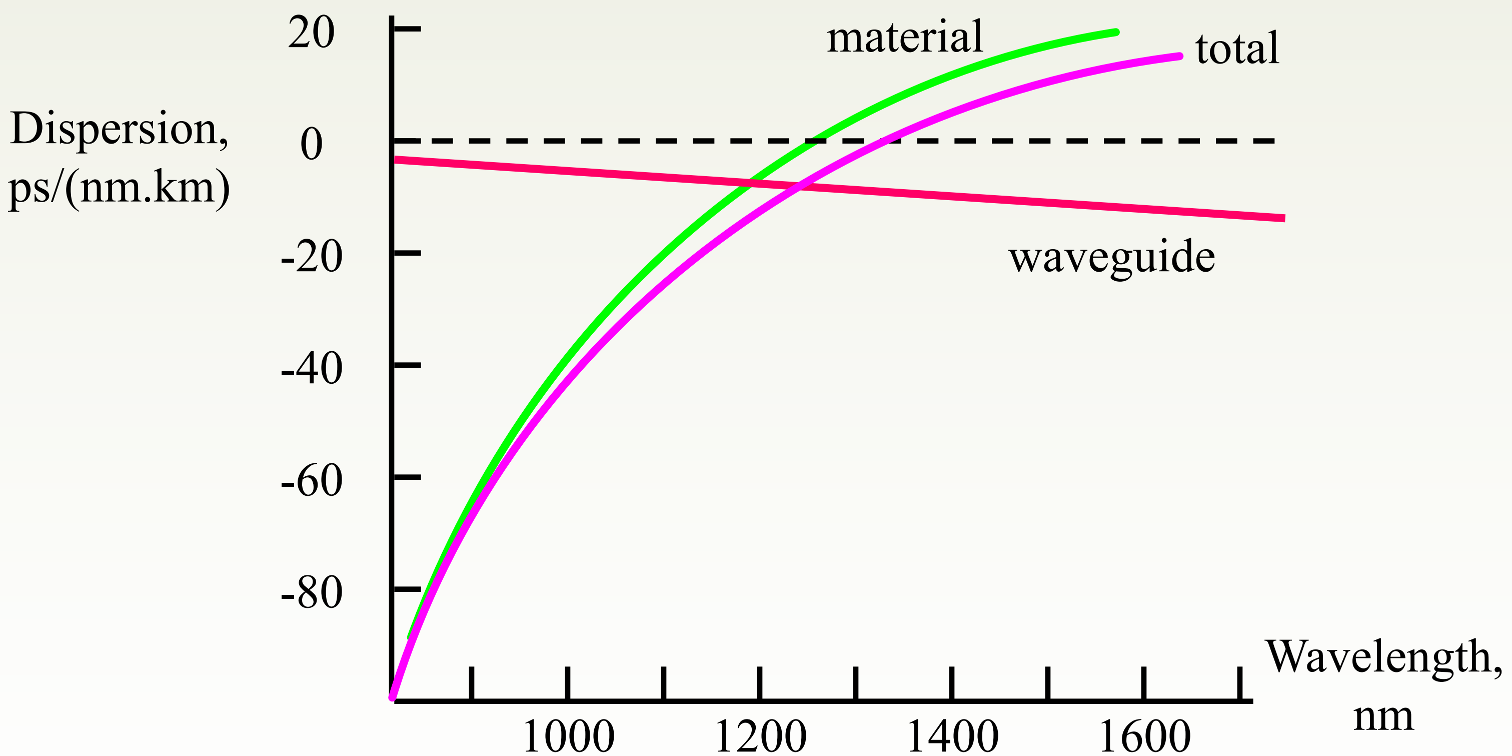
$$\mathrm{v_g} = \frac{d\omega}{d\beta} = \frac{c}{n - \lambda\, dn/d\lambda} = \frac{1}{\tau_g}\ ; \quad D = \frac{d\tau_g}{d\lambda} = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$

Dispersion - 3



- The group delay versus wavelength for silica has a minimum at λ ~ 1300nm

Dispersion - 4



- Dispersion components for single-mode fibre
- Zero material dispersion for silica ~ 1270 nm
- Typically zero dispersion λ ~1310 nm for standard fibre

Dispersion - 5

- D=0 at λ=1310nm for SMF and operation at this wavelength minimises pulse spreading

dispersion

- D<0 is referred to as the normal dispersion regime; operation at D>0 corresponds to anomalous dispersion
- With normal dispersion higher frequency components travel slower than lower frequency components in a pulse and vice-versa for anomalous dispersion
- Operation at the dispersion zero, with β_2=0, does not result in zero pulse dispersion since higher-order effects play a part
- Little control over material dispersion, much greater control over waveguide dispersion

Pulse Spreading

- **Finite source linewidth and non-zero fibre dispersion cause pulses to spread out as they propagate along a fibre**
- **Even with an ideal source of zero linewidth, once modulated to produce a pulse or data signal, there are information sidebands - essentially a form of line broadening inversely proportional to pulse duration**
- **As an illustration, for an ideal Gaussian pulse and operation away from D=0, the pulse broadens with distance, z, as below**

$$\frac{\tau_1}{\tau_0} = \left[1 + \left(\frac{\beta_2 z}{\tau_0^2}\right)^2\right]^{1/2} ; \; L_d = \frac{\tau^2}{\beta} \text{ is the dispersion length,}$$

corresponding to distance for pulse to broaden by $\sqrt{2}$

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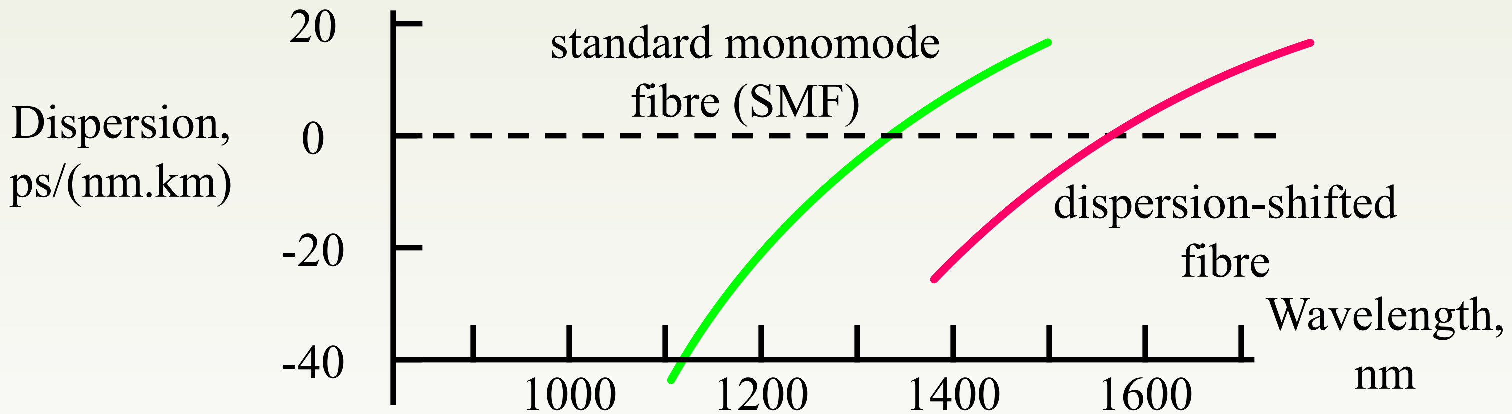
Chirp-Dispersion Interaction

- A directly modulated laser exhibits transient wavelength fluctuations
- The instantaneous group delay experienced thus changes during a pulse
- This can give rise to expansion or compression of the pulse, depending on the sign of the dispersion relative to the chirp
- Chirp-enhanced transmission, over distances greater than would be expected given the source linewidth and fibre dispersion, is sometimes possible

Dispersion Shifted Fibre

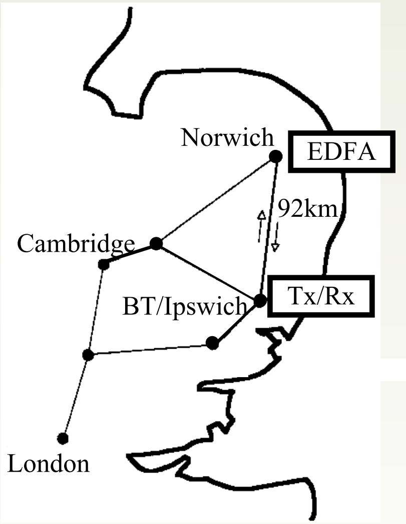


- Dispersion in SMF ~ 0 for 1300nm but ~17 ps/(nm.km) for 1550 nm
- By reducing core size and manipulating the index profile the waveguide dispersion can be enhanced such that for wavelengths ~1550nm, where it is of opposite sign to material dispersion - the total chromatic dispersion is brought to zero

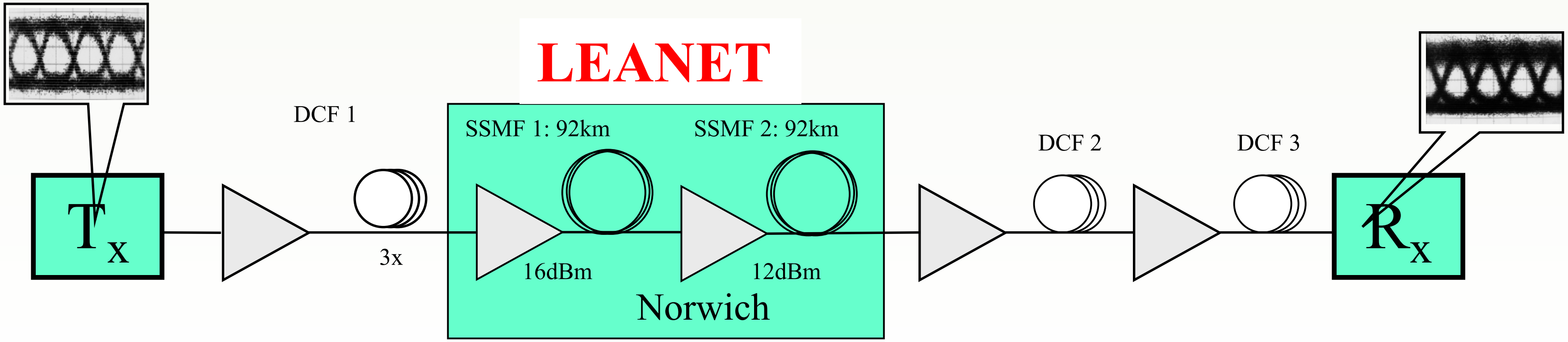
Dispersion Compensating Fibre

- Much as with dispersion shifted fibre (DSF) but taken further, such that the overall chromatic dispersion for DCF is strongly negative at 1550nm
- Cascading appropriate lengths of DCF with SMF can produce overall net zero dispersion
- It is difficult in practice to achieve dispersion values more than 10 times that of SMF, so substantial lengths of DCF are required to achieve effective compensation

Dispersion Compensated Link -Example



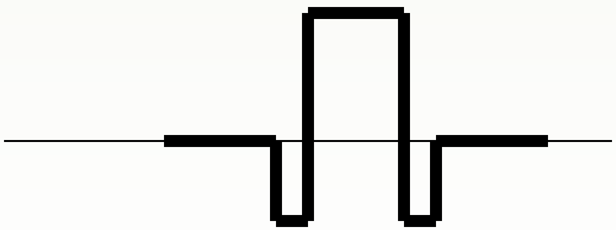
- Investigation of XPM distortion using link between BT-Labs and Norwich, UK
- Installed fibre: 184km of SSMF
- Laboratory experiments for comparison (UCL)



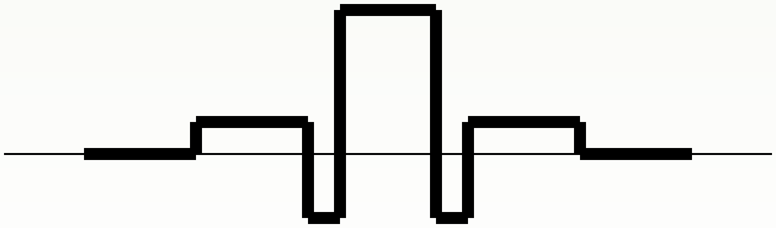
From H J Thiele, R Killey, P Bayvel, UCL Optical Networks Group

Dispersion Flattened Fibre

- Achieves a low dispersion window over a large region of the spectrum.
- Requires the fabrication of multi-layer index profiles, to give in effect two wavelengths with zero dispersion.



Double clad fibre



Triple clad fibre

Advances in Optical Fibre

"AllWave fiber solves the problem of unacceptable attenuation in the fibre window, 1350–1450 nm. By expanding the range of usable wavelengths to the entire region of 1280 to 1625 nm, AllWave fiber allows multiple services on each fibre."

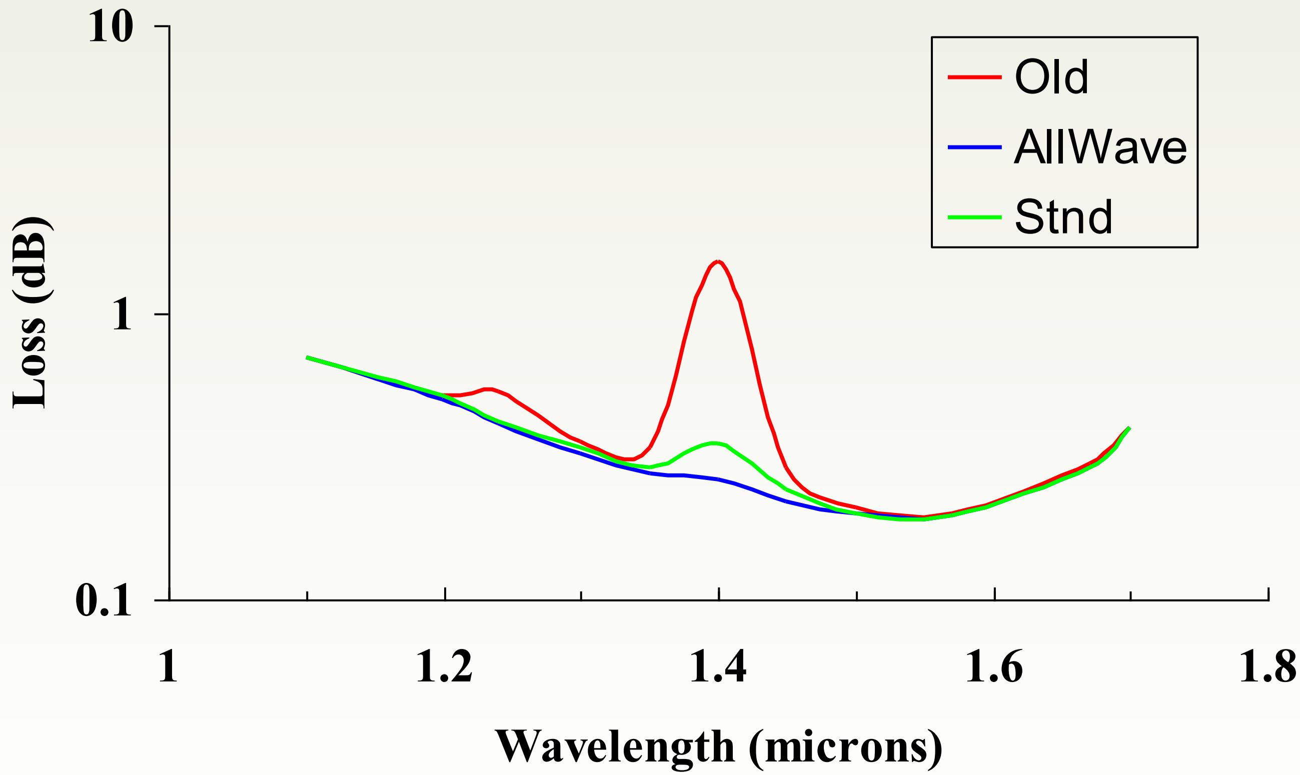
Features:

- **Low attenuation in the 1400 nm window**
- **50% increase in usable wavelength (300 nm versus 200 nm).**

AllWave™ Single-Mode Fiber

Lucent Technologies
Bell Labs Innovations

All-Wave Fibre



Improvements in fiber fabrication results in a much larger transmission Window

< 0.40 dB/km	400 nm
<0.30 dB/km	300 nm
<0.25 dB/km	200 nm

Advances in Optical Fibre

"TrueWave fiber is specially designed for use in dense WDM applications. It has nonzero dispersion in the EDFA passband to eliminate four-wave mixing which typically occurs in dispersion shifted fibers. This permits many closely spaced channels to be transmitted simultaneously without cross interference. The dispersion value is still small enough to allow single channel data rates up to 10 Gb/s without dispersion compensation. "

TrueWave® Single-Mode Fiber

Lucent Technologies
Bell Labs Innovations

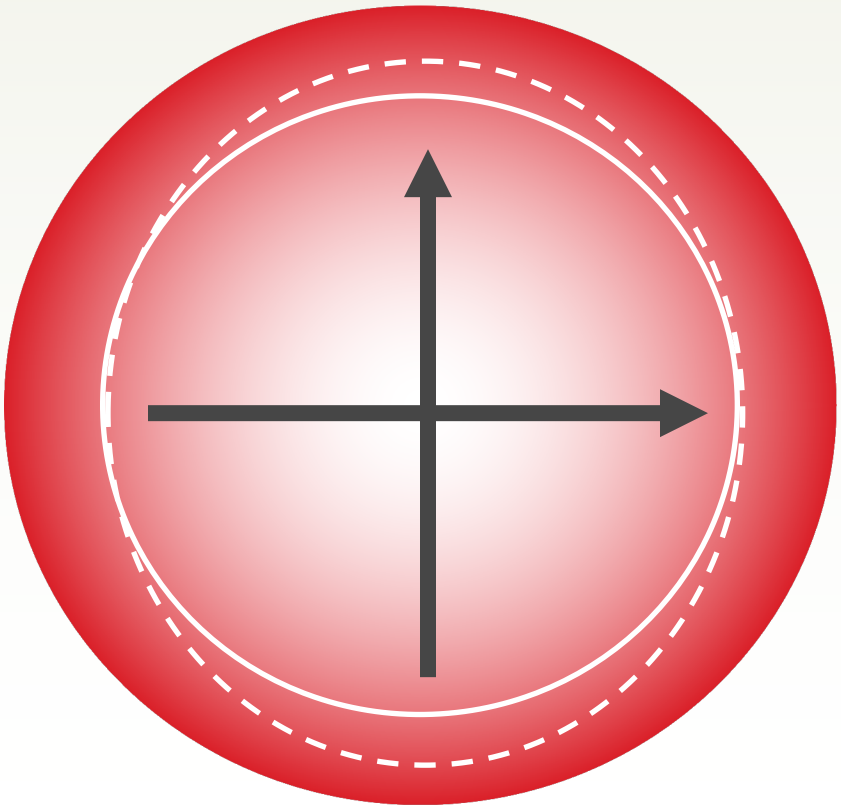
Advances in Optical Fibre

"Single Mode Non-zero dispersion shift fibre with a large effective area. Designed for high capacity long haul systems"

Corning LEAF® Single-Mode Fiber

Orthogonal Polarisations

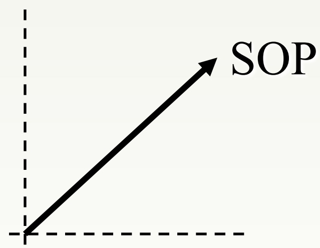
- **A so-called single mode fibre supports TWO orthogonal, linearly polarised modes**
- **Degenerate in a fibre with perfect circular symmetry they are in practice distinct**



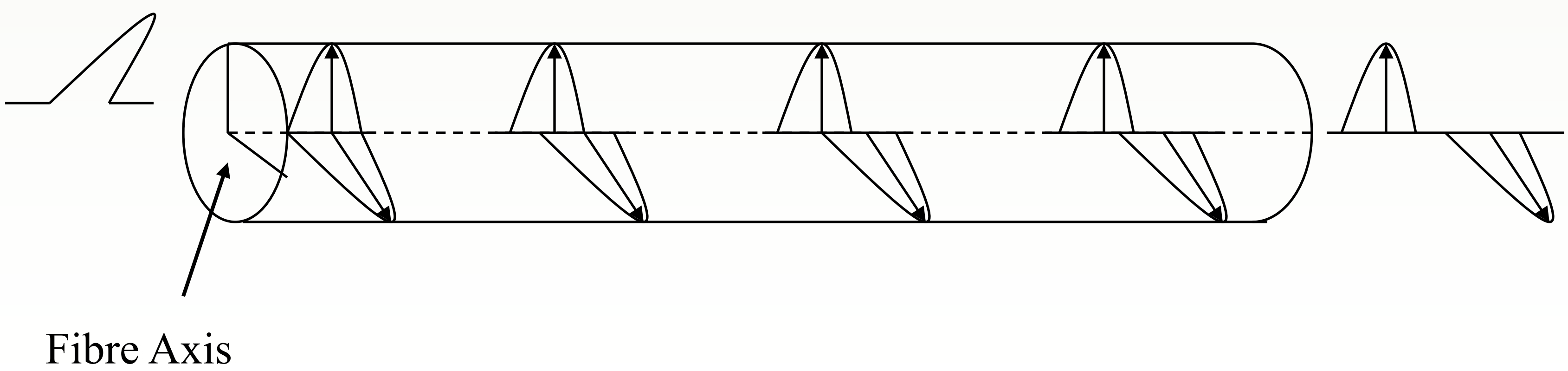
Polarisation Mode Dispersion

- **A so-called monomode fibre supports two orthogonally polarised modes, degenerate with perfect cylindrical symmetry**
- **In practice a fibre is slightly birefringent due to non-perfect symmetry**
- **Polarisation state of signal evolves as it propagates**
- **There is a group delay difference between the two polarisation states, giving rise to polarisation mode dispersion (PMD)**

Polarisation Mode Dispersion



- Time-domain effect of polarisation mode dispersion (PMD) in a short fibre



Summary

- **Attenuation**
  - Scattering
  - Absorbtion
- **Dispersion**
  - Modal Dispersion
  - Material
  - Waveguide
  - Total chromatic dispersion
  - Normal & anomalous regimes
  - Pulse spreading/compression
- **Polarisation Mode Dispersion**