



IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Capteurs et Propagation

TAF OPE – PCPO et TAF STAR – CPC

Guided optical canal

Kevin Heggarty
Département Optique

- ▶ **Introduction/overview : why optical fibres ?**
- ▶ **Quick history of optical transmission**
- ▶ **Light propagation in optical fibres:**
 - Ray model
 - EM model
- ▶ **Properties of optical fibres**
 - Different types of optical fibre
 - Absorption in optical fibres
 - Dispersion in optical fibres
- ▶ **Fibre Sensors**
- ▶ **Conclusion**

Recommended books

- ▶ **Single-mode fiber optics, L. Jeunhomme, Marcel Dekker (1983)**
- ▶ **Télécoms sur fibres optiques, P.Lecoy, Hermes 1997.**
- ▶ **Fibre-optic communication systems, G.Agrawal, Wiley-Interscience (2002)**

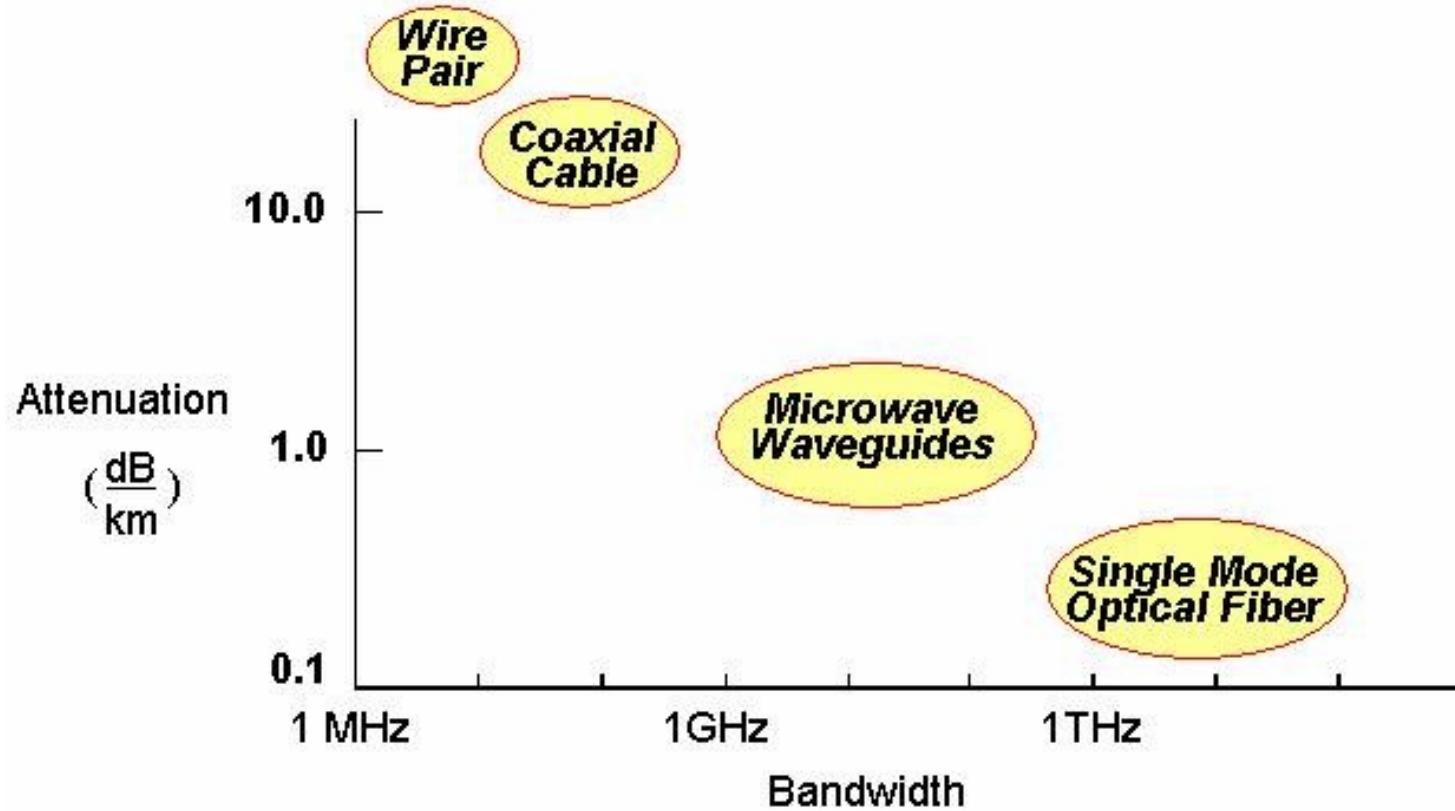
Acknowledgements

Thanks to Bruno Vinouze and Laurent Dupont of the Optics department who provided material for many of the slides in this lecture.

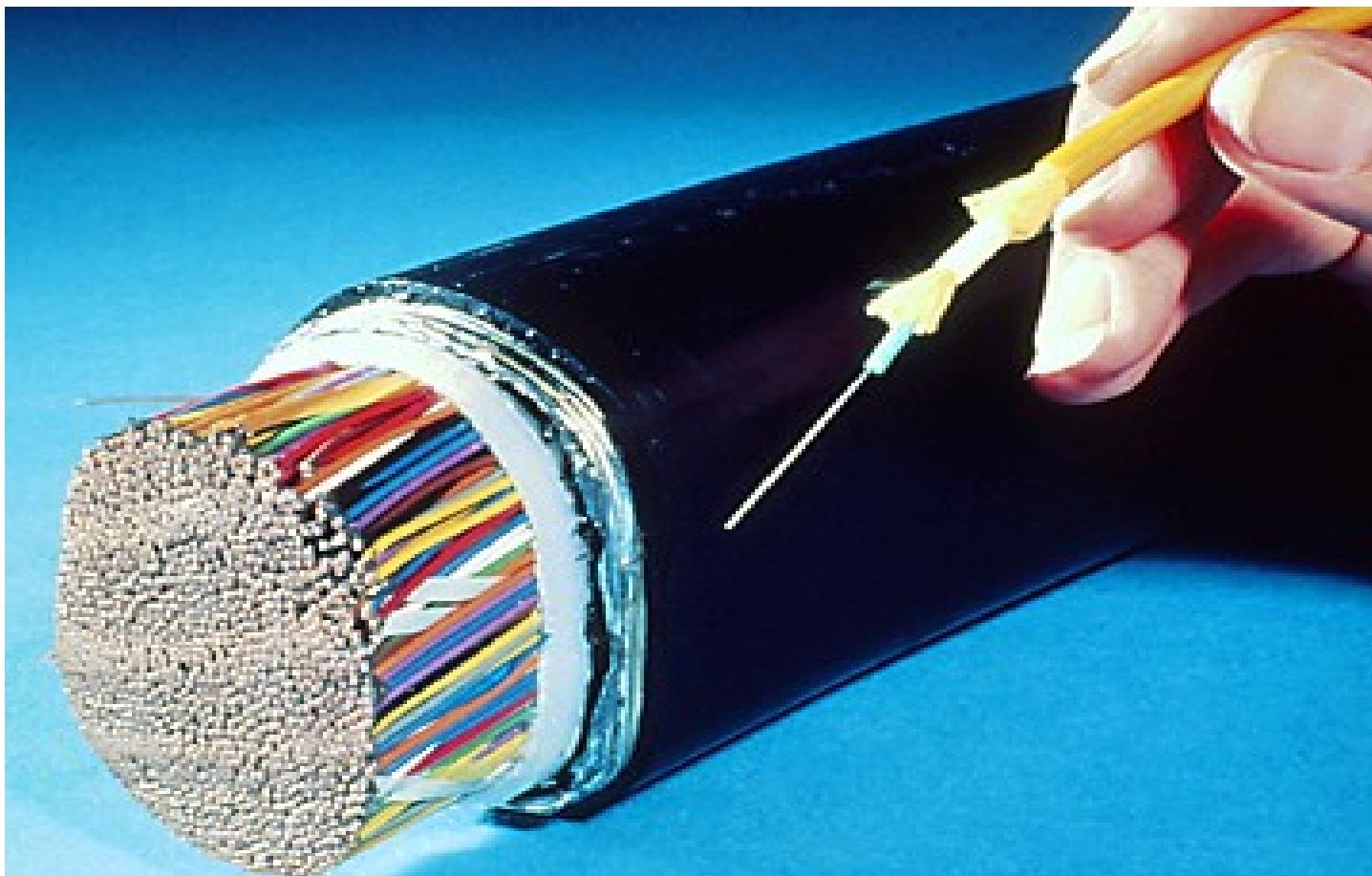
Advantages of optics for telecommunications

- **NOTHING TO DO WITH THE SPEED OF LIGHT !!!**
- **Very high carrier frequency (10^{15} Hz) : high bandwidth/datarates**
 - “Rule of thumb” : datarate $\sim 10\%$ carrier frequency
 - Carrier frequencies :
 - twisted copper pair, $f \sim 0 - 100\text{Mhz}$
 - coaxial waveguide, f up to $\sim 10\text{Ghz}$
 - radiowaves (TNT, WiFi, GSM ...), $f \sim 100\text{MHz}-10\text{GHz}$
 - optics, $f \sim 10^{15} \text{ Hz}$
- **Low attenuation of optical fibres**
- **Low cost of cables (silica = sand)**
- **Immunity to electromagnetic interference.**
- **Small size/weight of the cables**

Why use optical fibres in Telecommunications ?



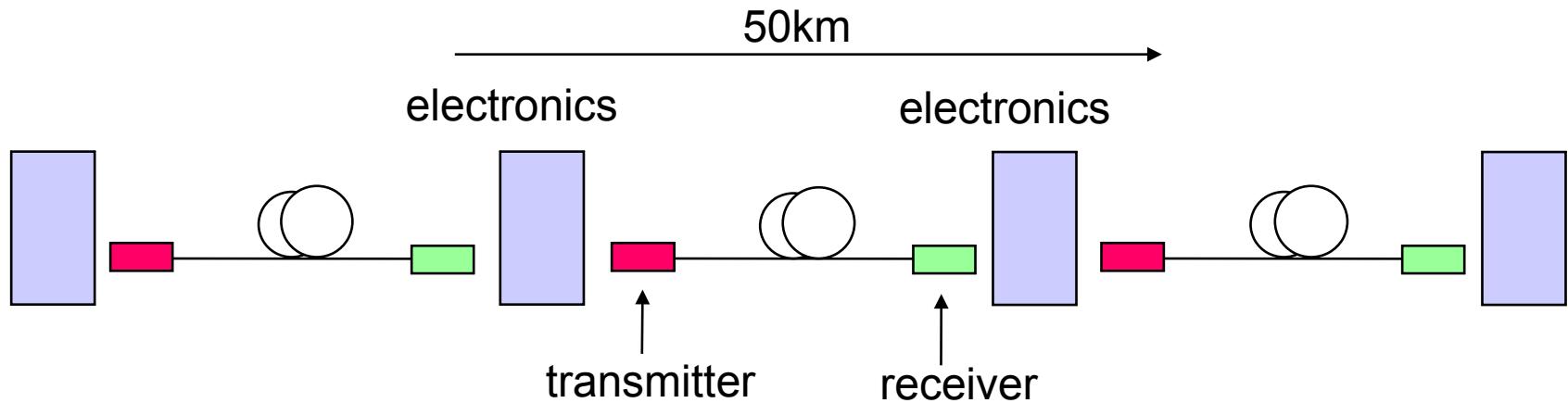
Optical fibre versus copper



Historical dates

- 1864 First telegraphic cable between Europe and USA.
- 1950-85 Coaxial cable links 36 → 4000 channels of 4kHz, span 5km.
- 1960 First optical fibre : losses : 1000 dB/km !!
- 1965 Satellite INTELSAT 240 channels (BW: 4 kHz)
- 1975 Optical fibre losses : 20 dB/km
- 1970s First generation of lightwave systems: wavelength = 0.85 μm
- 1984 Semi-conductor laser wavelength 1,3 μm (fibre losses : 0.2 dB/km)
- 1986 Semi-conductor laser wavelength 1.55 μm
- 1987 Second generation of lightwave systems: 1.55 μm
Erbium Optical amplifier, WDM
- 1988 First submarine optical cable (TAT 8 : 280Mb/s)
- 1996 First submarine optical cable with optical amplifiers
Span length : 50 km !! (TAT12-13: 5 Gb/s)
- 2009 Charles K. Kao wins Nobel prize for work on optical fibres

History ~ 1985



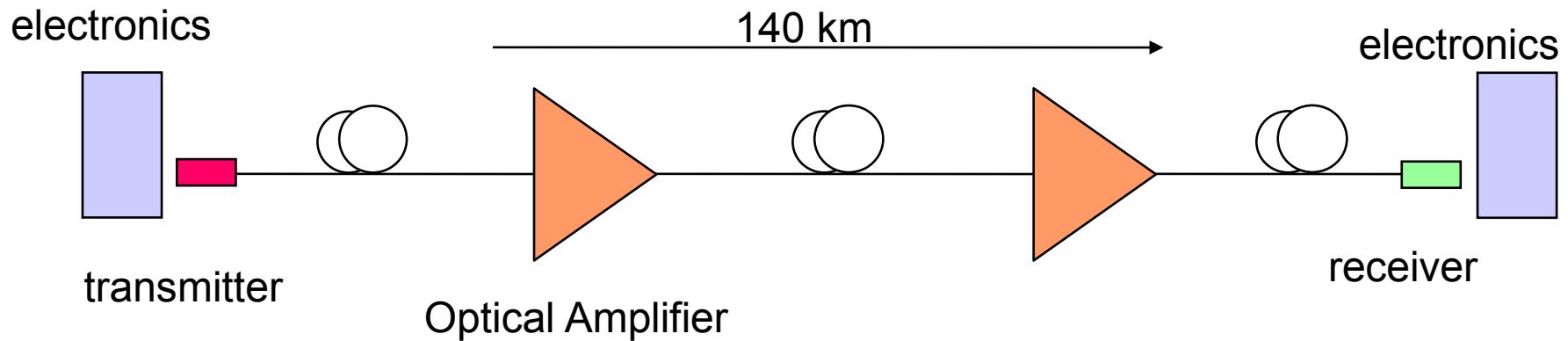
0.85µm then 1.3µm at 150 Mbit/s datarates

50 km between repeaters

Note : on coaxial (copper) cable links the span between repeaters is 12km

History ~ 1990

Invention of the **optical fibre amplifier** around 1985.

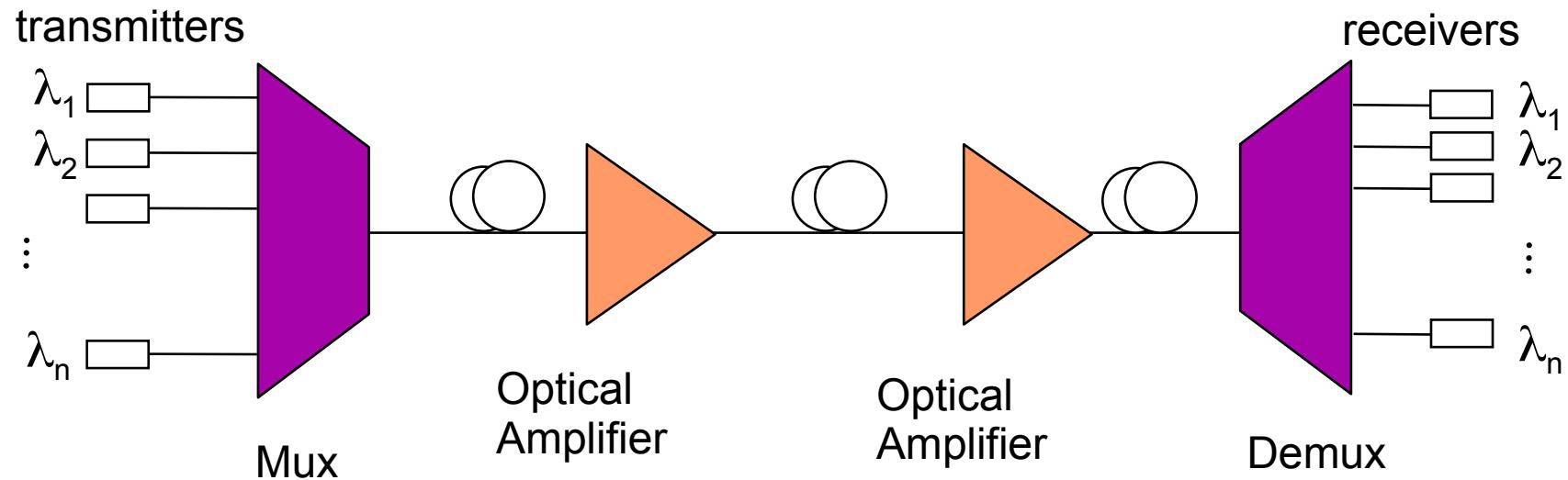


1.55 μm at 650 Mbit/s datarate

History ~ 2000

Invention of wavelength multiplexers and fibre Bragg gratings in the 1990s.

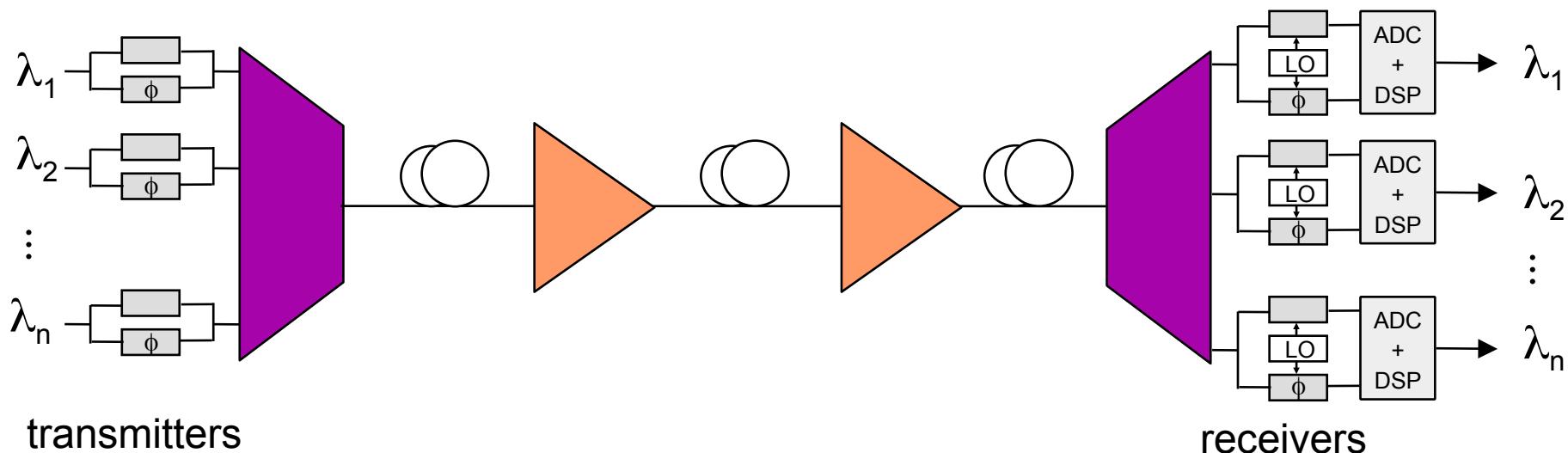
In 1998, arrival of **wavelength division multiplexing** (WDM) at $1.55\mu\text{m}$ in commercial systems.



32 wavelengths at a datarate of 2.5Gbit/s each

First coherent detection systems

Optical interference between detected signal and a local oscillator (LO) with very high speed electronic digital signal processors (DSP and ADC)
→ High performance modulation schemes (QAM), polarisation modulation, PMD correction, electronic chromatic dispersion correction ...

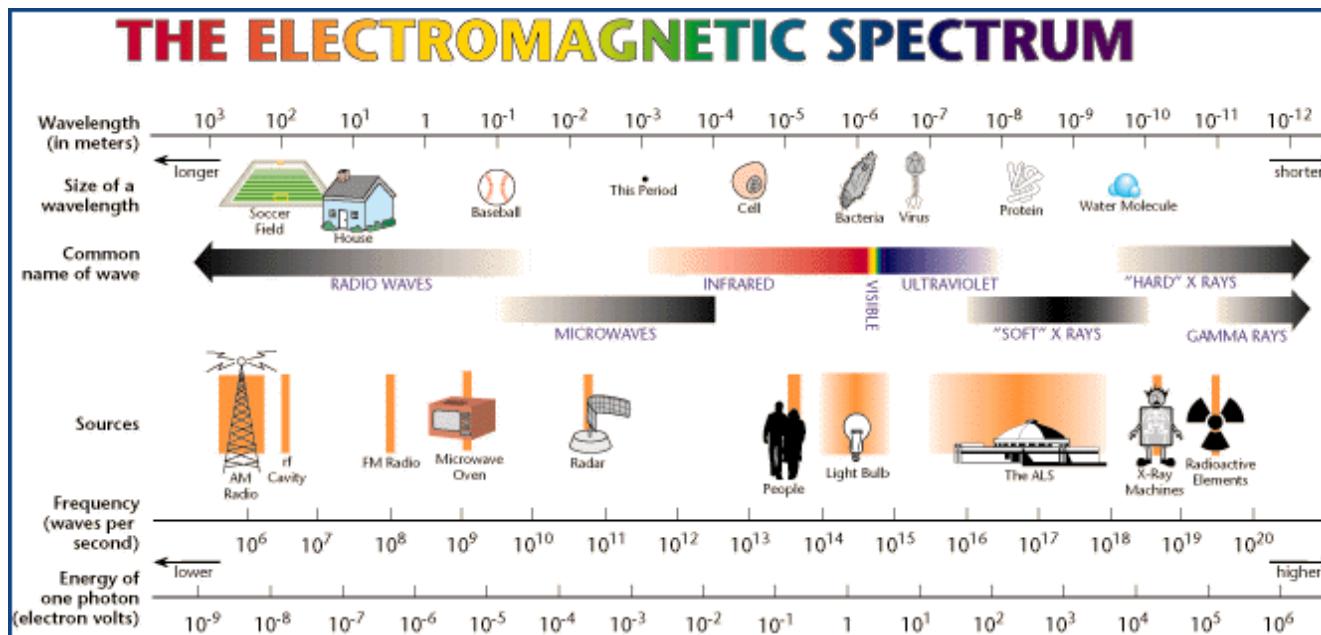


100Gbit/s per wavelength (10Gbaud/s line rate)

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Optics refresher – refractive index

- Light is an electro-magnetic wave
- In a vacuum it travels at a velocity of $c = 2.998 \times 10^8$ m/s
- In a transparent (eg. water, glass) material it travels at a slower velocity, v
- The ratio of “velocity vacuum/velocity materiel” = **refractive index**, $n = c/v$
- Refractive index of glass ~ 1.5 , different glasses have different refractive indices.



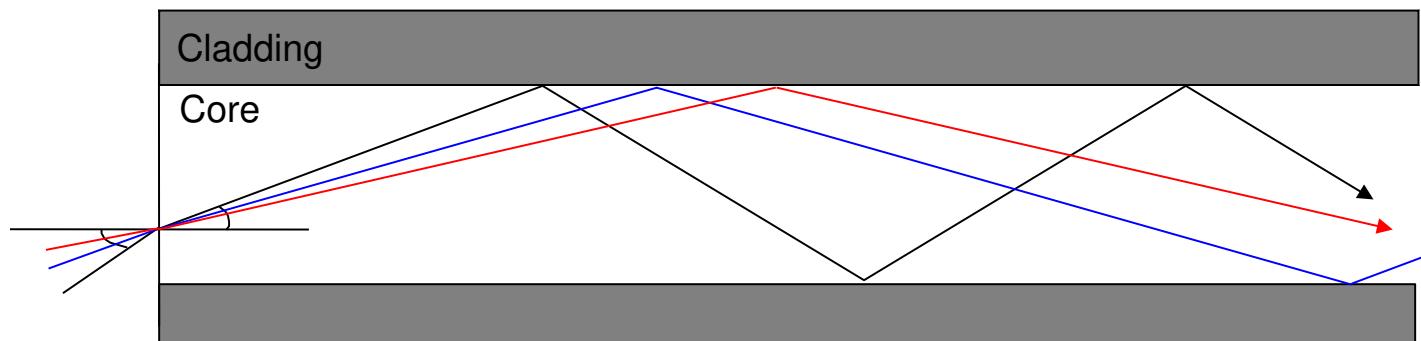
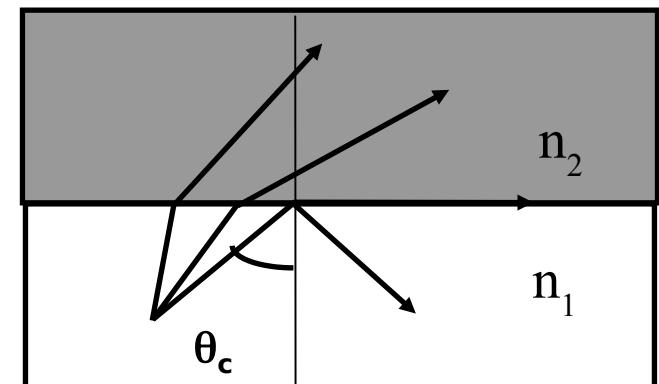
Light propagation – basic ray model

- A glass (silica) fibre guides light using “total internal reflection”
- The Snel/Descartes law of refraction tells us that a light ray arriving at a dielectric interface, from a high refractive index material towards low index material at an angle less than the critical angle (θ_c) will be totally reflected (zero loss).

Snell/Descartes $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$

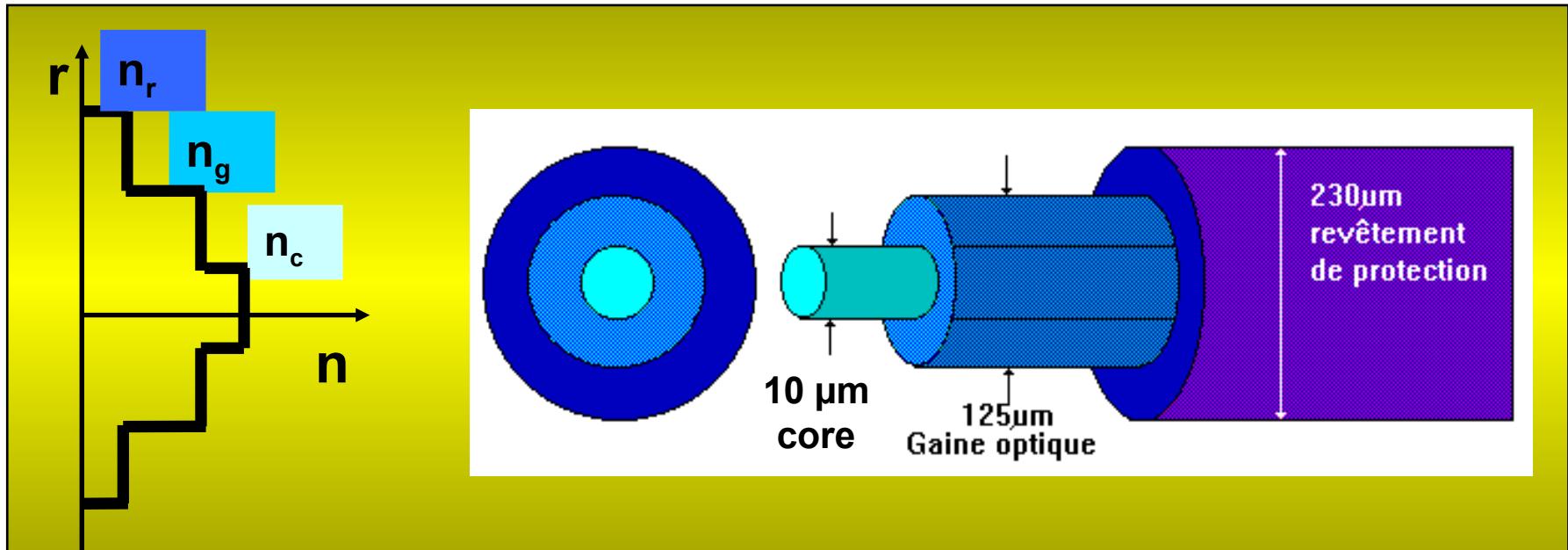
Total internal reflection
(refracted ray parallel to interface :

$$\theta > \theta_c = \arcsin(n_2 / n_1).$$



Single-mode fibre characteristics – G652

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Core diameter = 10 μm

Cladding diameter = 125 μm

NA = 0.13 ($\theta = 7.5^\circ$)

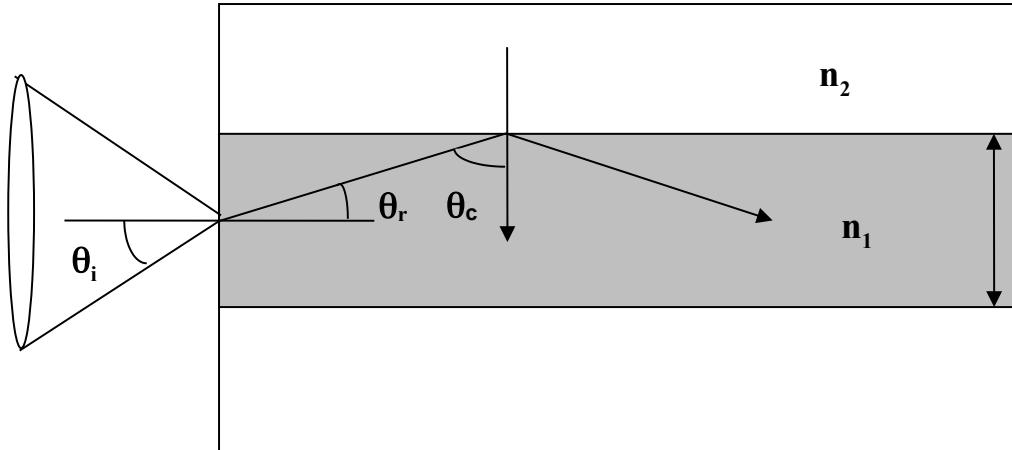
Silica refractive index, $n = 1.457$

$$(n_c - n_g) / n_g = \Delta n = 3 \cdot 10^{-3}$$

Mode diameter @ 1,55 μm : 11.2 μm

Fibre numerical aperture

- Numerical aperture is the angle of the acceptance cone of an optical fibre
- Light entering a fibre inside this cone will be guided along the fibre



Snel's law : input, air-glass interface:

$$\sin \theta_i = n_1 \sin \theta_r$$

2a Snel's law : core-cladding interface:

$$\theta > \theta_c = \arcsin (n_2 / n_1)$$

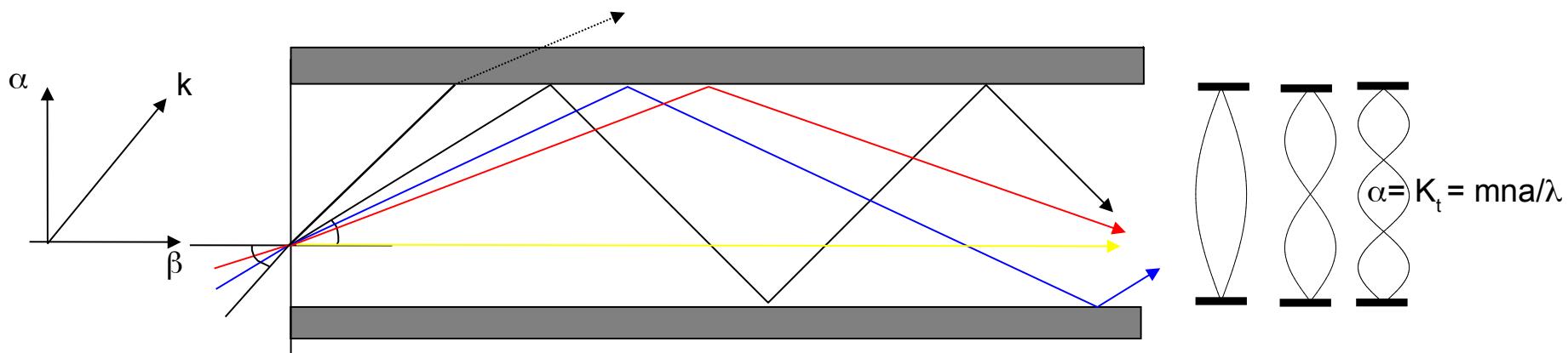
$$\cos \theta \leq \cos \theta_c = \sqrt{1 - \sin^2 \theta_c} = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$$

$$\sin \theta_i = n_1 \sin \theta_r = n_1 \cos \theta_c = n_i \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = \sqrt{n_1^2 - n_2^2}$$

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

$$NA = 0.1 \Rightarrow \theta_{0,\max} \approx 6^\circ$$

Light propagation – advanced ray model

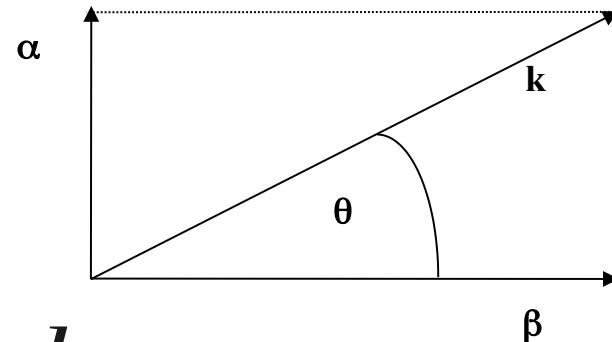


- Extension of basic model separates skew rays into longitudinal (β) (propagating) and transverse (α) components.
- Transverse components must form standing waves
 - $\alpha = mna/\lambda$ with m the mode integer, a the fibre core radius and λ the wavelength
- Transverse components are quantised – not all ray angles possible : discrete “propagation modes” of different “propagation speeds” (β)
- Phase shift on reflection (Goos-Hanschen) must also be taken into account.

Properties of wave-vector

$$\beta = k \cos \theta \quad k = n_1 \frac{2\pi}{\lambda} = n_1 k_0$$

$$\alpha = k \sin \theta$$



$$n_2 k_0 \leq \beta \leq n_1 k_0$$

Total reflection

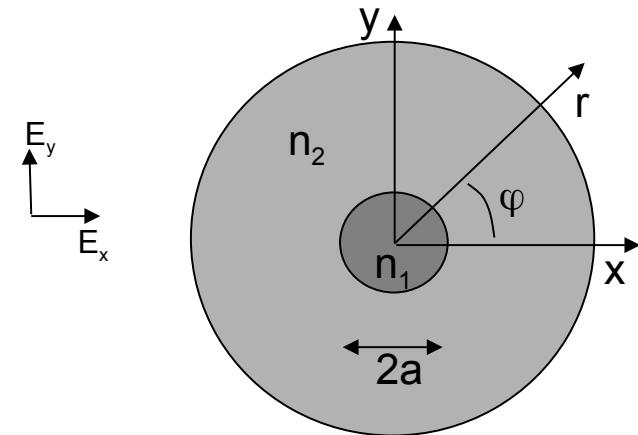
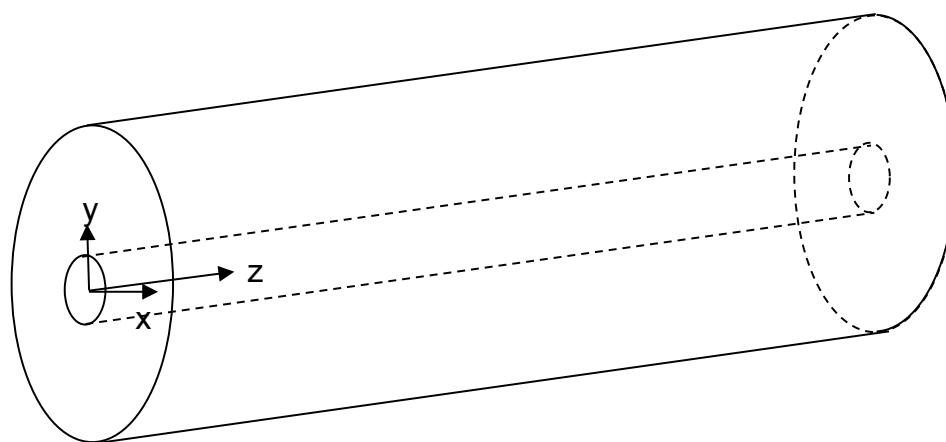
Geometrical

$$\text{Effective index : } n_{eff} = \beta / k_0 \Rightarrow n_1 \geq n_{eff} \geq n_2$$

- If $n_{eff} \sim n_1$, light spends most of time in core, corresponds to “direct ray”
- If $n_{eff} \sim n_2$, light spends more time close to cladding, corresponds to “critical angle reflected ray”

Light propagation – full EM approach.

- The light ray model gives an intuitive understanding of light propagation in a fibre but cannot explain all aspects (coupling, cladding thickness ...)
- To fully understand light propagation in an optical fibre we must use the full electromagnetic approach = solve Maxwell's equations in the fibre.



- Use Maxwell's equations (Helmholtz form) in cylindrical coordinates
- Two concentric dielectric media, assume infinite cladding
- Find propagative solutions of finite energy
- Apply boundary conditions (continuity of E and H fields at interfaces) to obtain the dispersion relationships.

Light propagation – full EM approach.

Wave equation in cylindrical coordinates

$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + (k^2 n_i^2 - \beta^2) \right] \begin{bmatrix} E_z \\ H_z \end{bmatrix} = 0$$

This equation has (mode) field solutions of the form:

$$E = \vec{E}_0(r) e^{im\phi} \exp[i(\omega t - \beta z)] \quad \vec{E}_0 = (E_r, E_\phi, E_z)$$

Transverse part

Mode number

Propagative, longitudinal part



$$\Rightarrow \left[\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \left(k^2 n_i^2 - \beta^2 - \frac{m^2}{r^2} \right) \right] \begin{bmatrix} E_z(r) \\ H_z(r) \end{bmatrix} = 0$$

Two sets of transverse field solutions, $E_z(r)$, appear :

$$\kappa^2 = k^2 n_i^2 - \beta^2 > 0$$

$$E_z(r) = A J_m(\kappa r) + B Y_m(\kappa r)$$

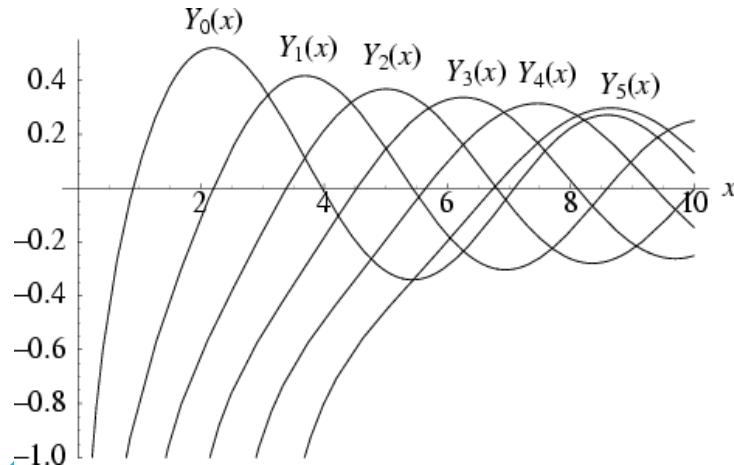
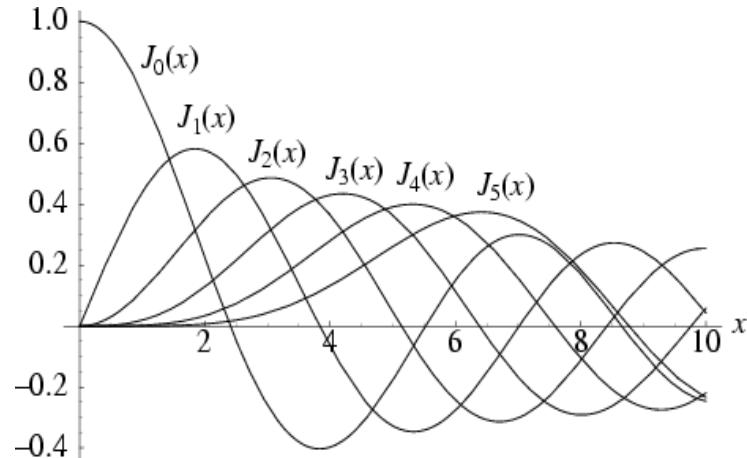
$$-\gamma^2 = k^2 n_i^2 - \beta^2 < 0$$

$$E_z(r) = A' I_m(\gamma r) + B' K_m(\gamma r)$$

Field solutions – transverse field

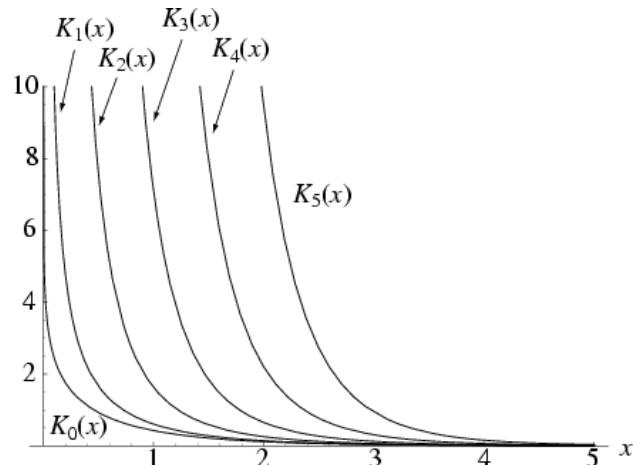
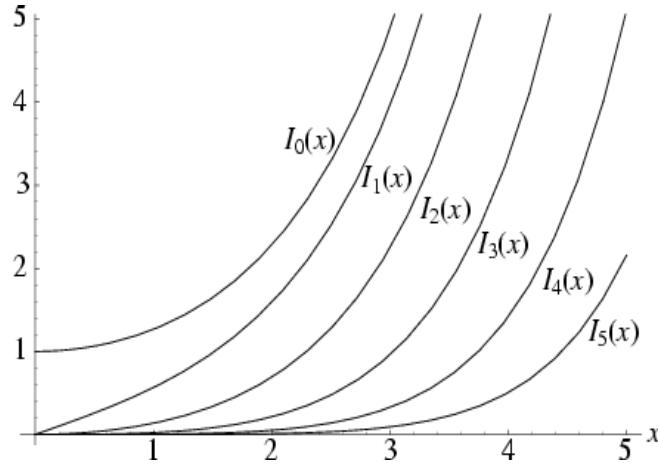
J_m : Bessel Function of the first kind

Y_m : Bessel Fonction of the second kind



I_m : Modified Bessel function of the first kind

K_m : Modified Bessel function of the second kind

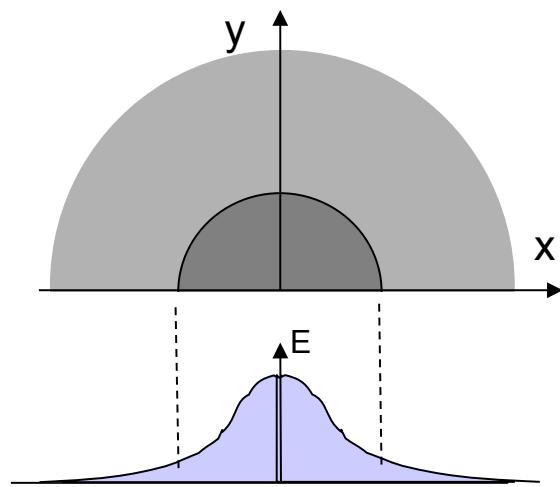


- Of these solutions, only those with finite energy are physically possible
- In the fibre cladding:
 - Electrical field must be evanescent $k^2 n_2^2 - \beta^2 < 0$
 - Field amplitude must be finite when $r \rightarrow \infty$: $E_z = E_0 K_m(\gamma r) e^{i(\omega t + m\phi - kz)}$
- In the fibre core:
 - Propagative solutions $k^2 n_1^2 - \beta^2 > 0$
 - Finite field when $r \rightarrow 0$: $E_z = E_0 J_m(\kappa r) e^{i(\omega t + m\phi - kz)}$
- Dispersion relations

$$\gamma^2 = a^2 (\beta^2 - k^2 n_2^2) \quad \kappa^2 = a^2 (k^2 n_1^2 - \beta^2)$$

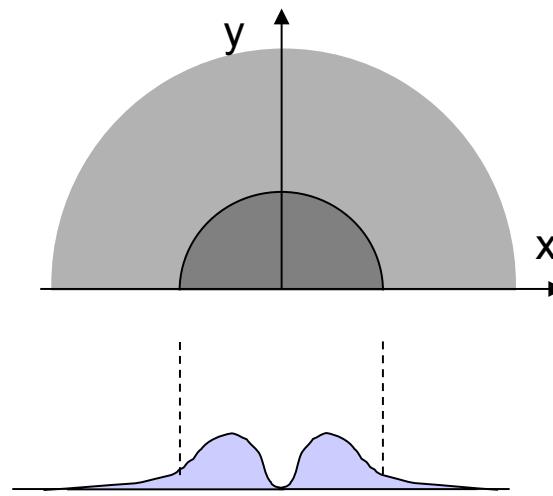
Mode fields - examples

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First order mode, $m=0$

- Field concentrated in core
- Field present in cladding
- Field tends to zero outside cladding
- Continuous field at boundary



Higher order mode, $m>0$

- Field in core and cladding
- Relatively more field in cladding
- Field tends to zero outside cladding
- Continuous field at boundary

These different modes see different effective indices (n_{eff})

→ different mode velocities

Eigenvalue equation

Continuity of E_z and H_z component through interface core-cladding

⇒ Eigenvalue equation:

$$\frac{\beta^2 m^2}{a^2} \left(\frac{1}{\gamma^2} + \frac{1}{\kappa^2} \right)^2 = \left(\frac{J'_m(\kappa a)}{\kappa J_m(\kappa a)} + \frac{K'_m(\gamma a)}{\gamma J_m(\gamma a)} \right) \left(\frac{k_0^2 n_{core}^2 J'_m(\kappa a)}{\kappa J_m(\kappa a)} + \frac{k_0^2 n_{clad}^2 K'_m(\gamma a)}{\gamma J_m(\gamma a)} \right)$$

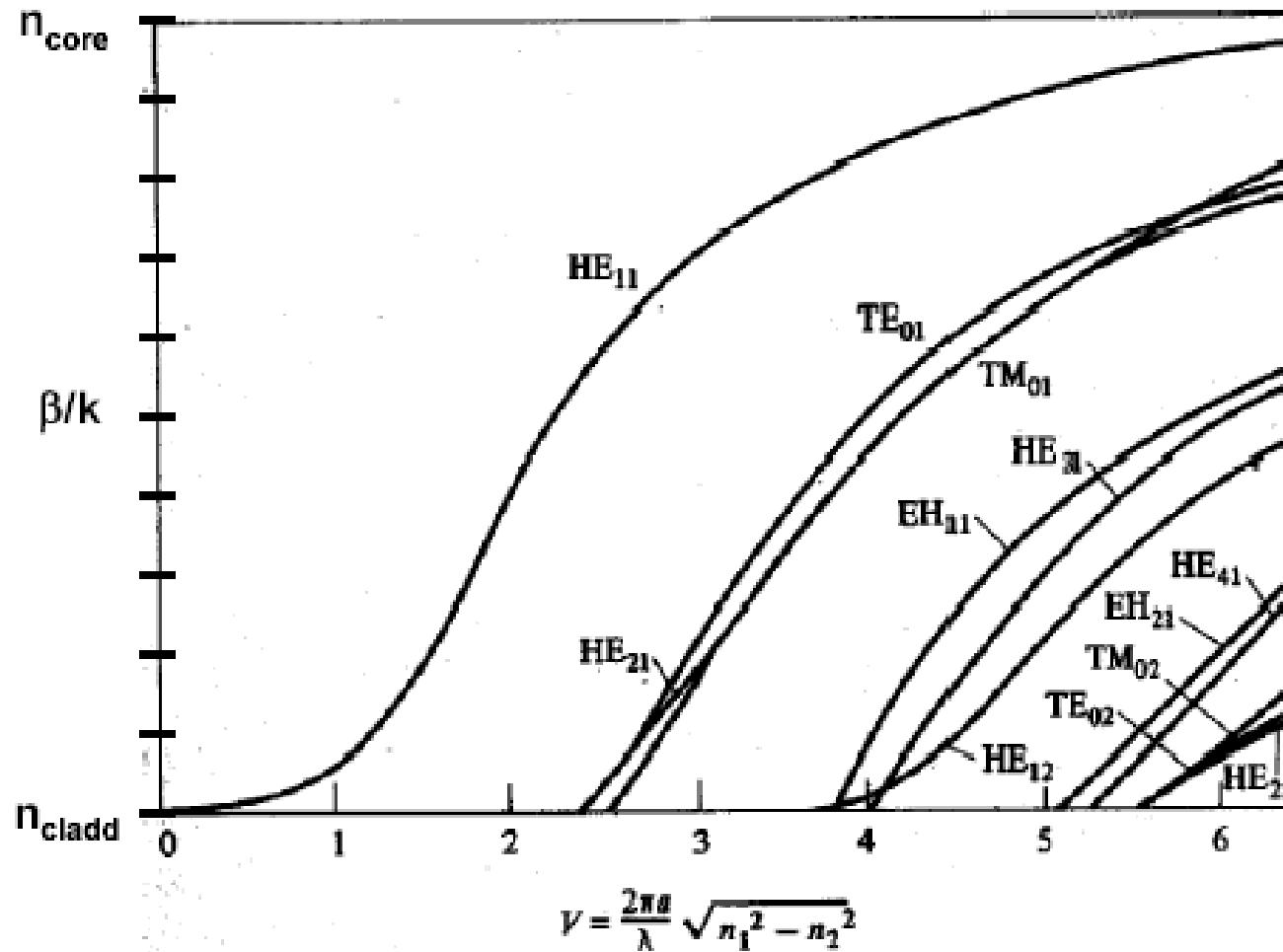
This equation gives the values of β

- Often, the dispersion coefficients are combined into V (V number) :

$$V^2 = \kappa^2 + \gamma^2 \quad \Rightarrow \quad V = k a \sqrt{n_1^2 - n_2^2}$$

Dispersion curves

Plot of dispersion relationships against V number for different modes

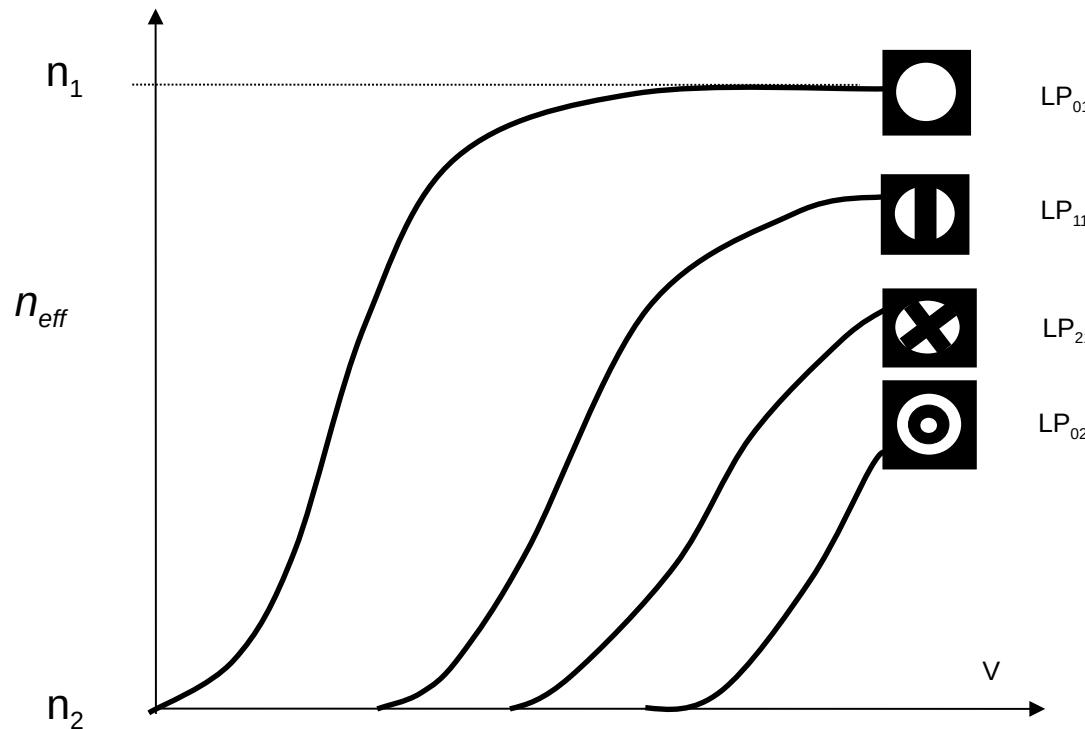


Linearly Polarized Modes

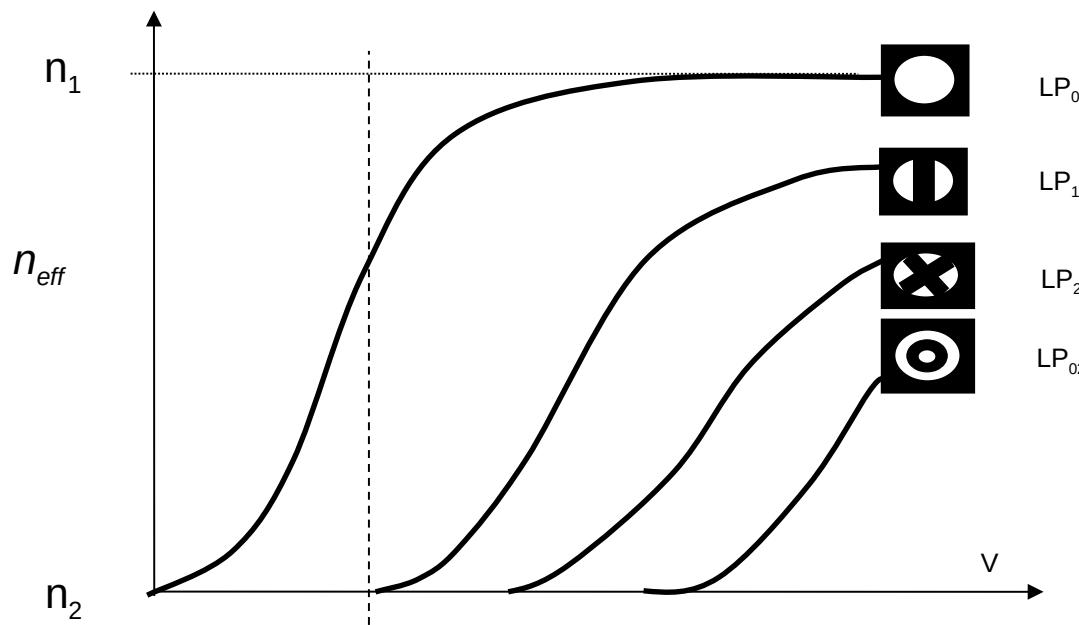
If $\Delta n \ll 1$: homogeneous polarization modes

Modes of similar dispersion relationships grouped together:

Linearly Polarized Modes (LP modes)



LP Mode Dispersion



Single mode condition:

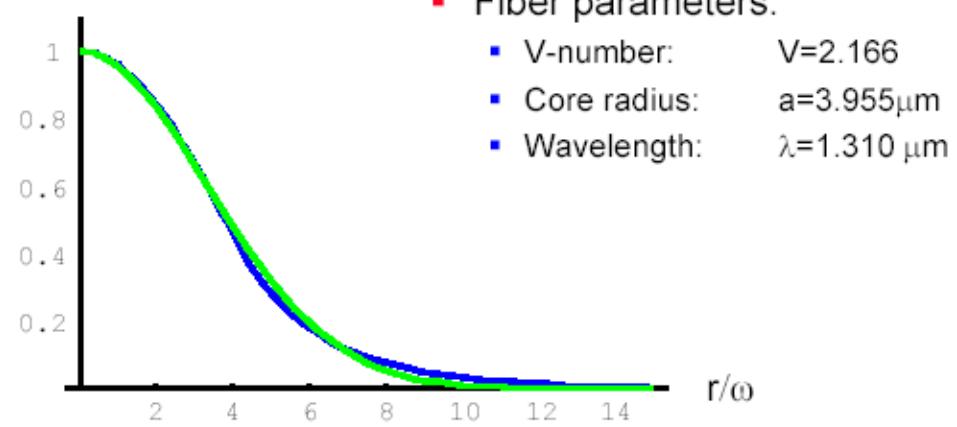
$$0 < V < 2.405 \quad \text{where} \quad V = \frac{2\pi a}{\lambda} \sqrt{(n_1^2 - n_2^2)}$$

- For a given wavelength, if the fibre core is small enough (radius “a”) then $V < 2.405$ and only the first (fundamental) mode can propagate
- The fibre is therefore **single-mode** : only one mode velocity (no modal dispersion)
- Example: single-mode for wavelength $1.55\mu\text{m}$ and $10\mu\text{m}$ diameter core

Gaussian approximation

- **LP₀₁ mode can be approximated as a Gaussian function**
- **This approximation is sufficiently accurate for the majority of fibres**

$$E(r) = \exp\left(-\frac{r^2}{w_0^2}\right)$$



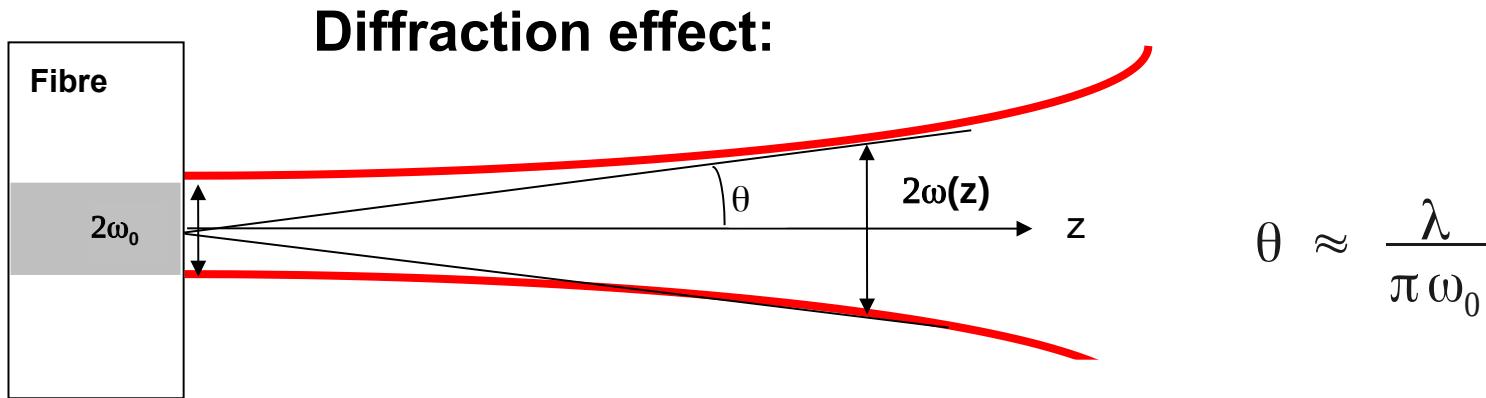
Comparison of LP₀₁ mode (blue) and the Gaussian approximation (green) to the HE₁₁ mode

- **For a step-index fibre with radius a , the Gaussian beam radius is:**

$$\frac{w_0}{a} = 0,65 + 1,619V^{-3/2} + 2,879V^{-6}$$

Gaussian Beam

- As the beam exits the fibre it diverges (spreads)
- Gaussian beam remains Gaussian in shape but width, $w(z)$, increases



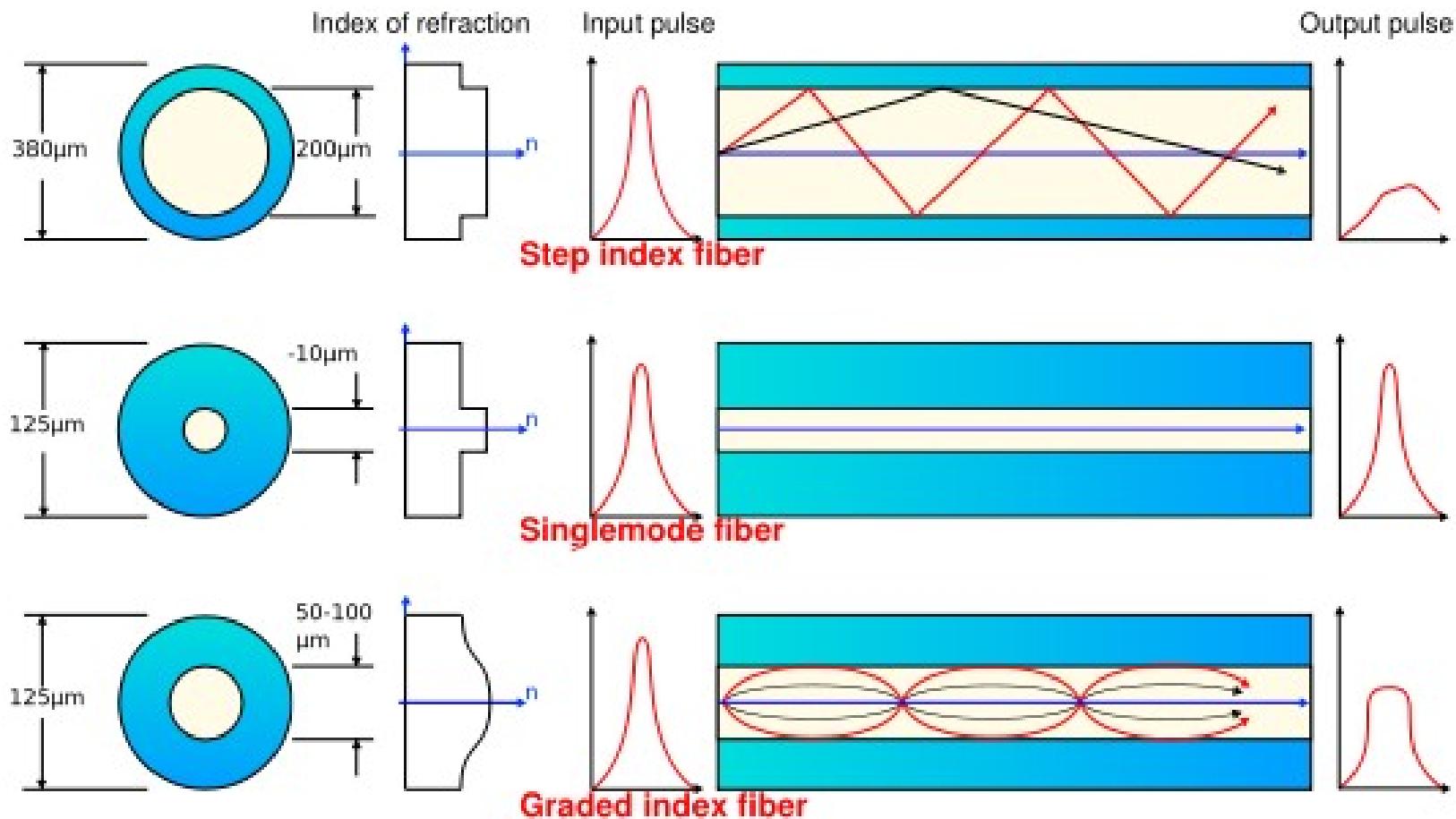
$$w(z) = w_0 \sqrt{1 + (z/z_0)^2} \quad z_0 = \frac{\pi w_0^2}{\lambda}$$

Advantage of Gaussian approximation:

- easy optimization of end coupling (with laser or photodiode)

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Different types of Optical Fibre

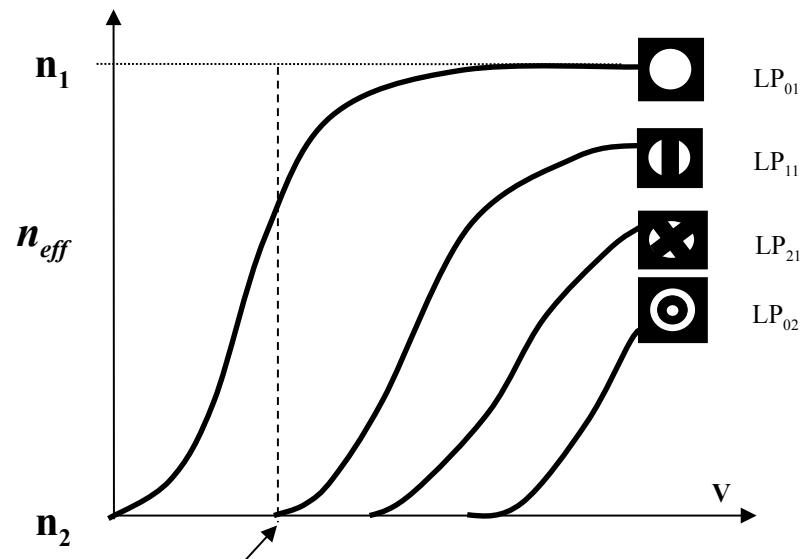


Step index fibres

- Two major types : **single-mode** and **multimode** determined by V parameter (dependent mainly on fibre core diameter)
- Single-mode core ~10microns. Multi-mode core 50 or 62.5 microns.
- Single-mode fibre is used for all long distance links : no modal dispersion, but expensive connectors.
- Multi-mode fibre is mainly used for short distance (LAN, datacom) links (<5km) where lower cost connectors are the major benefit.

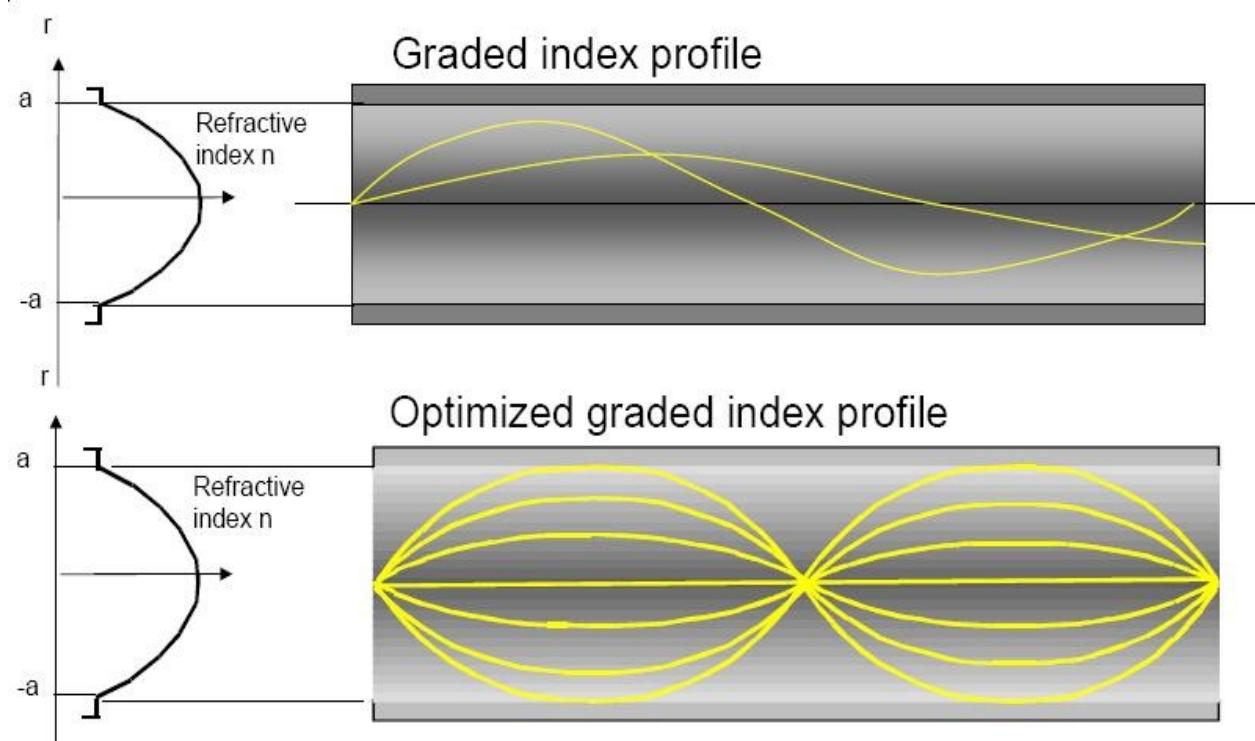
Single mode condition:

$$0 < V < 2,405$$



Gradient index fibres

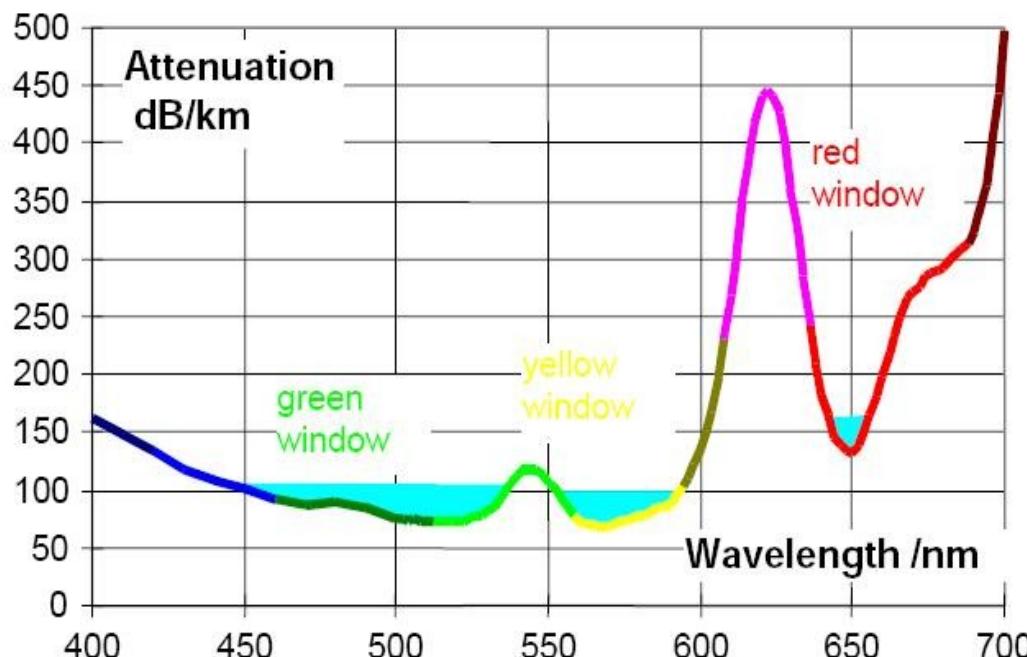
- Radially varying refractive index (parabolic profile)
- Deflection by varying refractive index
- Light rays follow paths of same “optical” length : low dispersion.
- Used extensively in LAN, datacom networks (core 50 μm , easy connection)



Plastic Optical Fibres (POF)

- Very large step index fibres (2mm core diameter)
- Very high attenuation but extremely cheap connectors, splices ...
- Best transmission in visible spectrum.
- Applications in very short links (<50m) : home and in-vehicle.

Attenuation of POF



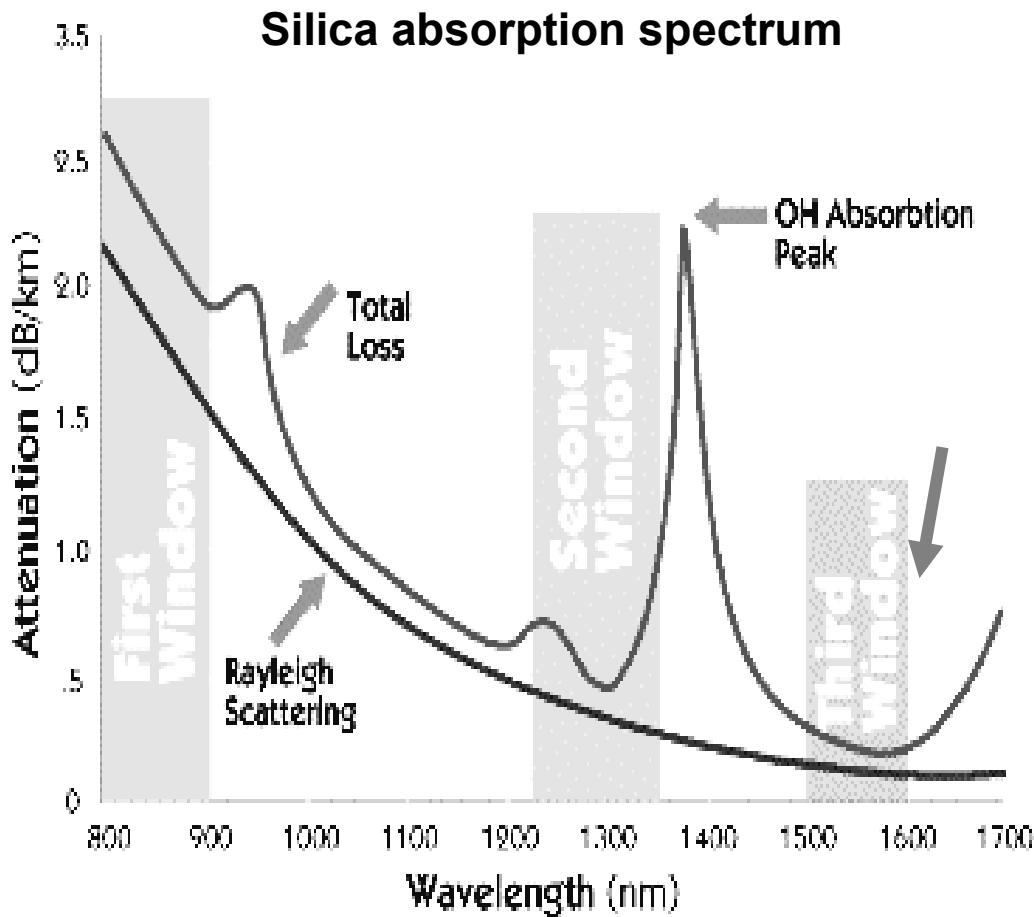
Attenuation in optical fibres

- Attenuation is the reduction in optical power between the fibre input, P_0 and the fibre output, $P(L)$, for fibre length L
- Power decreases exponentially with length

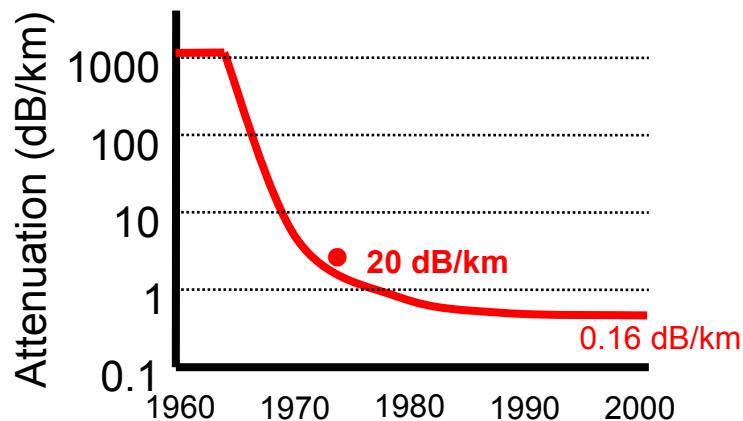
$$P(L) = P_0 e^{-\alpha' L} \quad \text{or} \quad P(L) = P_0 10^{-\alpha L}$$

- α is the linear attenuation coefficient (usually in dB/km)
- Major causes of loss in optical fibre are :
 - **Absorption** by impurities (particularly OH bonds) – improvements in glass purity have reduced this effect recently
 - **Rayleigh scattering** – naturally occurring density fluctuations diffuse light out of the fibre (dependant on $1/\lambda^4$)
 - **Infrared absorption** : molecular resonances beyond $\sim 1.6\mu\text{m}$
 - **Curvature losses** – if the fibre is bent too tightly (bend radius <5cm) then light can escape the core.

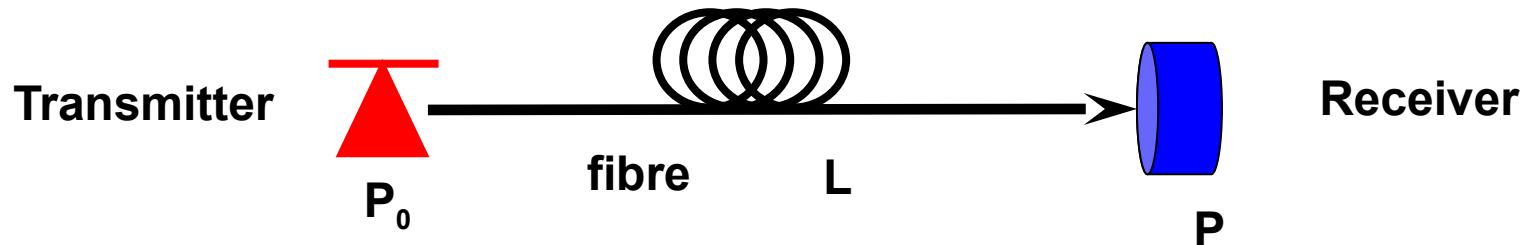
Attenuation in optical fibres



Reduction in fibre attenuation with improving silica purity



Intrinsic losses



- Due to these mechanisms, as light propagates along the fibre, the power level drops. Optical loss, A , defined:
 - in mW, : $A = P_0 - P$
 - in dB, difference in the dBm powers :
 - in dB : $A_{dB} = -10 \log_{10}(P/P_0)$
- Example : $P_0 = 10$ mW and $P = 1$ mW
 - $A = -10 \times \log (0.1)_{mW} = 10$ dB
 - $A = (10 - 0)_{dBm} = 10$ dB

Reminder - dBm

$$P(dBm) = 10 \log P(mW)$$

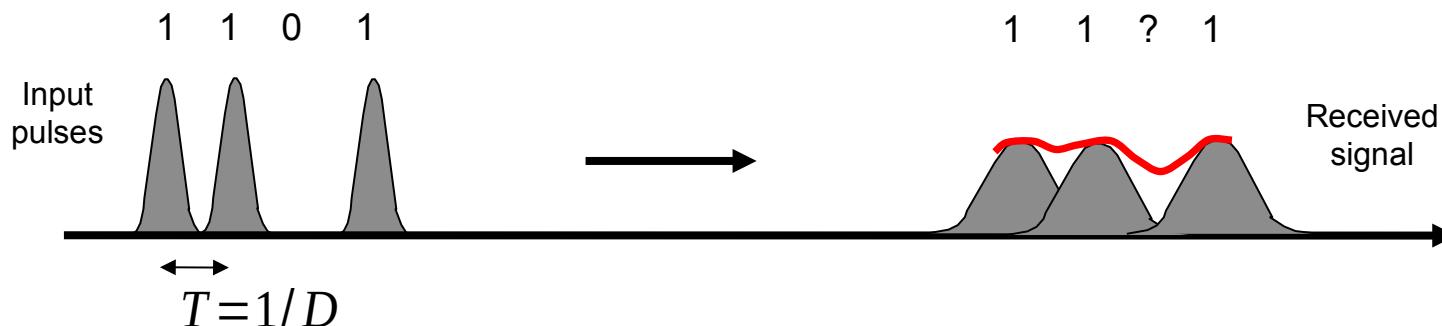
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■ What is dispersion in an optical fibre ?

- Dispersion occurs when different parts of a light pulse or wave propagate in the fibre with different speeds

■ Why is it a problem ?

- It causes the light pulses (“bits” of information) to spread during propagation so we must increase the separation between the pulses to avoid interference – limiting the data rate (or transmission distance)
- In practice, most modern optical transmission systems are limited by dispersion rather than attenuation



Dispersion

Three major types of dispersion in optical fibres

■ **Modal dispersion**

- Strong dispersion effect present in multimode fibres
- Different modes have widely differing propagation speeds

■ **Chromatic dispersion**

- **Waveguide dispersion** : residual dispersion in single-mode fibres as light energy present in core and cladding with different indices
- **Material dispersion** : the refractive index of glass varies slightly with wavelength so different wavelengths have different speeds.

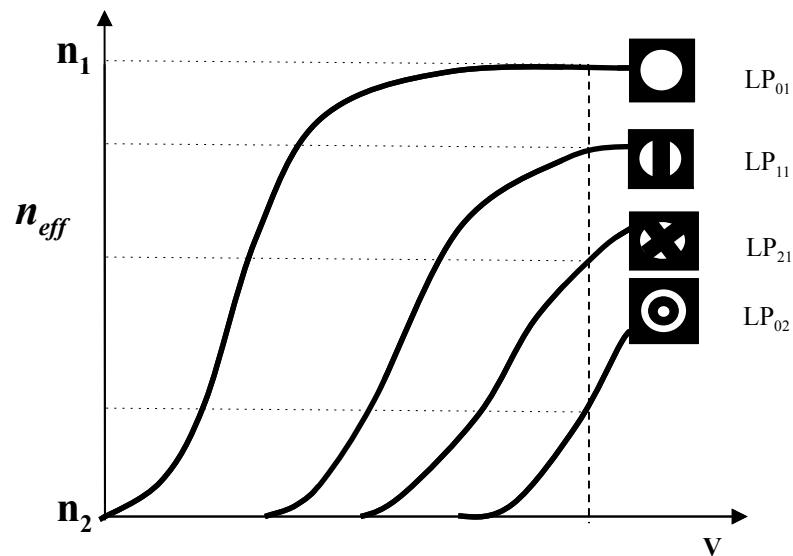
■ **Polarisation dispersion**

- Different light polarisations (electrical field directions) can propagate with slightly different speeds

Modal Dispersion

- Occurs in **multimode fibres** (step or gradient index)
- Light pulse energy spreads across the different propagation modes which can have widely differing propagation speeds
- **Strong effect** : in fibres generally much stronger than chromatic dispersion.
- The **major limitation** on bandwidth/distance product in multimode fibres:
 - 10 - 100MHz.km for step-index multimode fibres
 - 100 – 1000MHz.km for gradient index fibres

Here, for this value of V (dependant on a and λ), four modes are excited, each with different n_{eff} so different speeds.

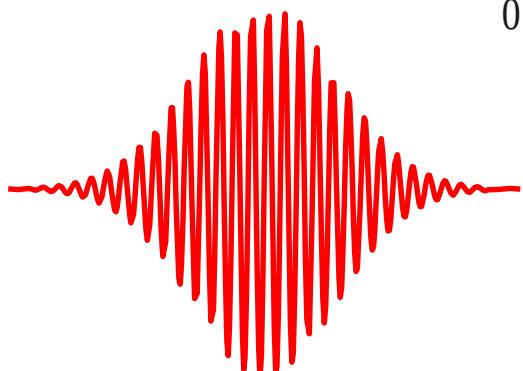


Chromatic dispersion

- To understand chromatic dispersion must recall concepts such as **group velocity** (seen on course in 1st year so only reminder here).
- If signal was monochromatic there would be no chromatic dispersion, but:
 - perfectly monochromatic light does not exist !
 - a light pulse necessarily contains several frequencies/wavelengths

Wave-vector: $k = k(\omega_0) + \left(\frac{\partial k}{\partial \omega} \right)_{\omega_0} (\omega - \omega_0) + \frac{1}{2} \left(\frac{\partial^2 k}{\partial \omega^2} \right)_{\omega_0} (\omega - \omega_0)^2 + \dots$

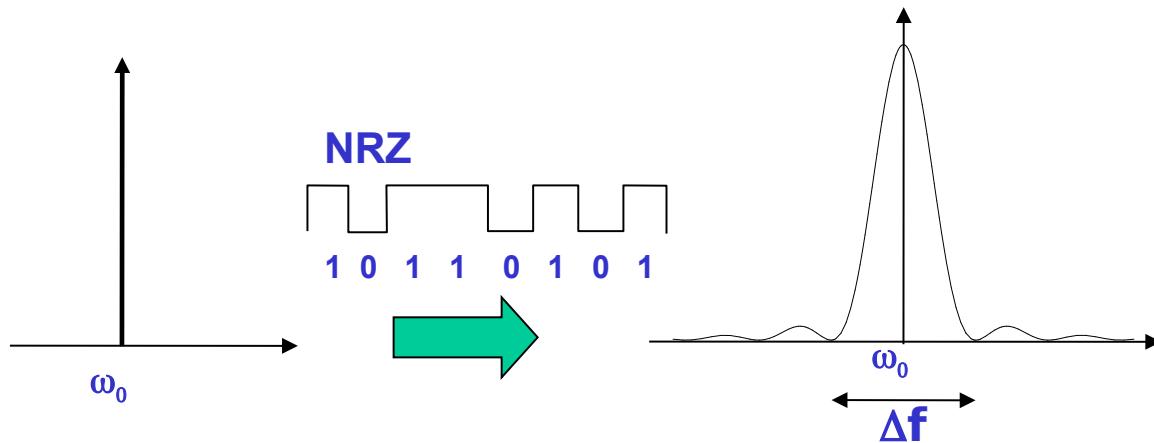
Optical pulse: $A(t) = \int_0^{\infty} A(\omega) \exp(i\omega t - ik(\omega)z) d\omega$



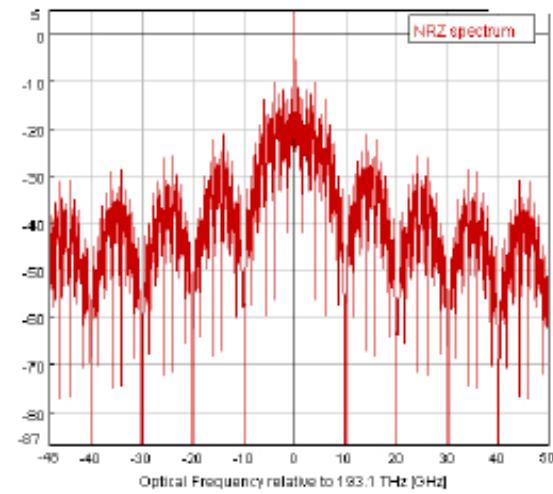
Fourier Transform !!

Modulation formats and optical spectrum

Even if we had a perfect (monochromatic) source, as soon as we modulate it – transmit information – its spectrum necessarily spreads !!



Format NRZ : $\Delta f \approx 2D_n$



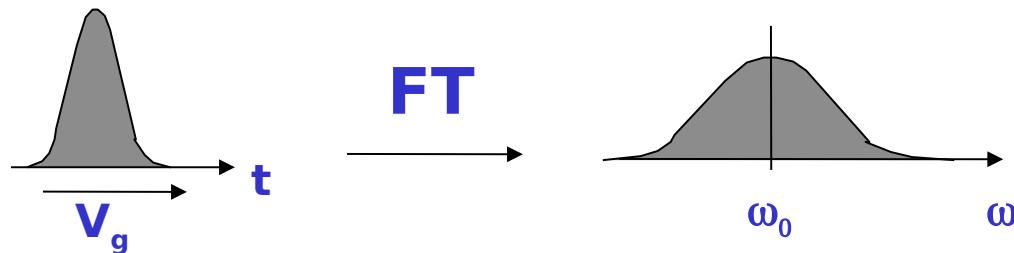
Group velocity and group index

- **Information** (energy) is transmitted by the **pulse**, not the wave
- Pulse moves with **group velocity**, not the phase velocity

Phase velocity: $v = \frac{\omega_0}{k_0} = \frac{c}{n}$

Group velocity: $v_g = \frac{dw}{dk} = \frac{c}{N_g}$

Group velocity:



$$v_g = \left(\frac{\partial \omega}{\partial k} \right)_{\omega_0}$$

Group index:

$$N_g = \frac{c}{\partial \omega / \partial k} = c \left(\frac{\partial k}{\partial \omega} \right) \Rightarrow N_g = \left(n + \omega \frac{\partial n}{\partial \omega} \right) = \left(n - \lambda \frac{\partial n}{\partial \lambda} \right)$$

Chromatic Dispersion

The effective group delay of a single mode is given by:

The duration of pulse propagation is then: $\tau = \tau_g L$

$$\tau_g = \left(\frac{\partial k}{\partial \omega} \right)_{\omega_0}$$

Chromatic dispersion of the group velocity:

$$\tau(\lambda) = \tau(\lambda_0) + \left(\frac{\partial \tau}{\partial \lambda} \right)_{\lambda_0} \Delta \lambda$$

$$\frac{\Delta \tau_g}{\Delta \lambda} = \frac{\partial}{\partial \lambda} \left(\frac{\partial k}{\partial \omega} \right) = -\frac{2\pi c}{\lambda^2} \left(\frac{\partial^2 k}{\partial \omega^2} \right)$$

With

$$D_\lambda = -\frac{2\pi c}{\lambda^2} \left(\frac{\partial^2 k}{\partial \omega^2} \right)$$

The pulse broadening is then:

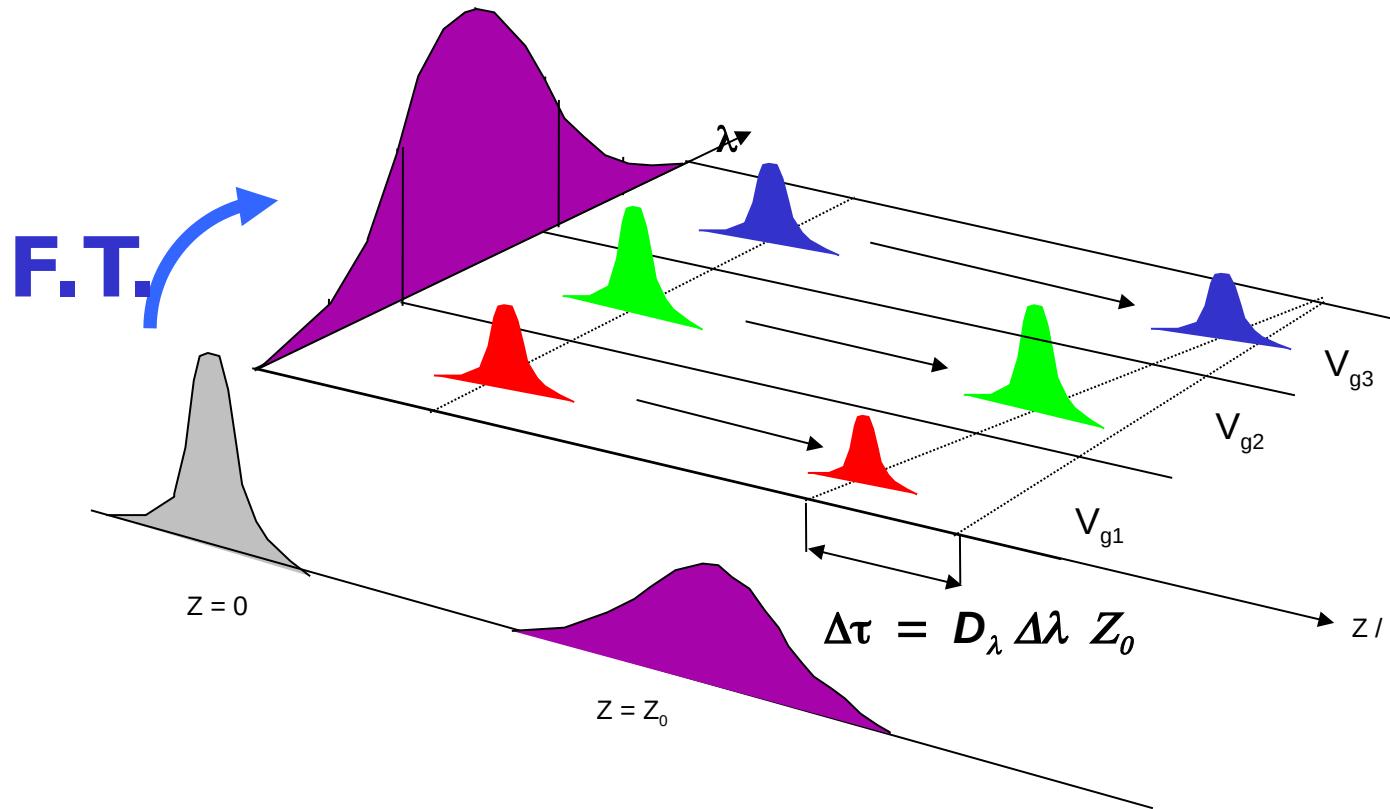
$$\Delta \tau = D_\lambda \Delta \lambda L$$

D_λ “Chromatic Dispersion” is a key characteristic of a transmission fibre.

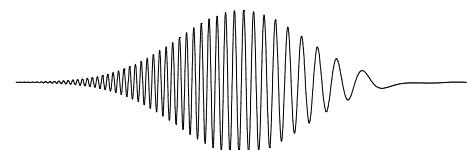
Units often in ps/(nm.km). $\Delta \lambda$ is the source effective spectral width, L the transmission distance

Impact of chromatic dispersion

Pulse broadening :

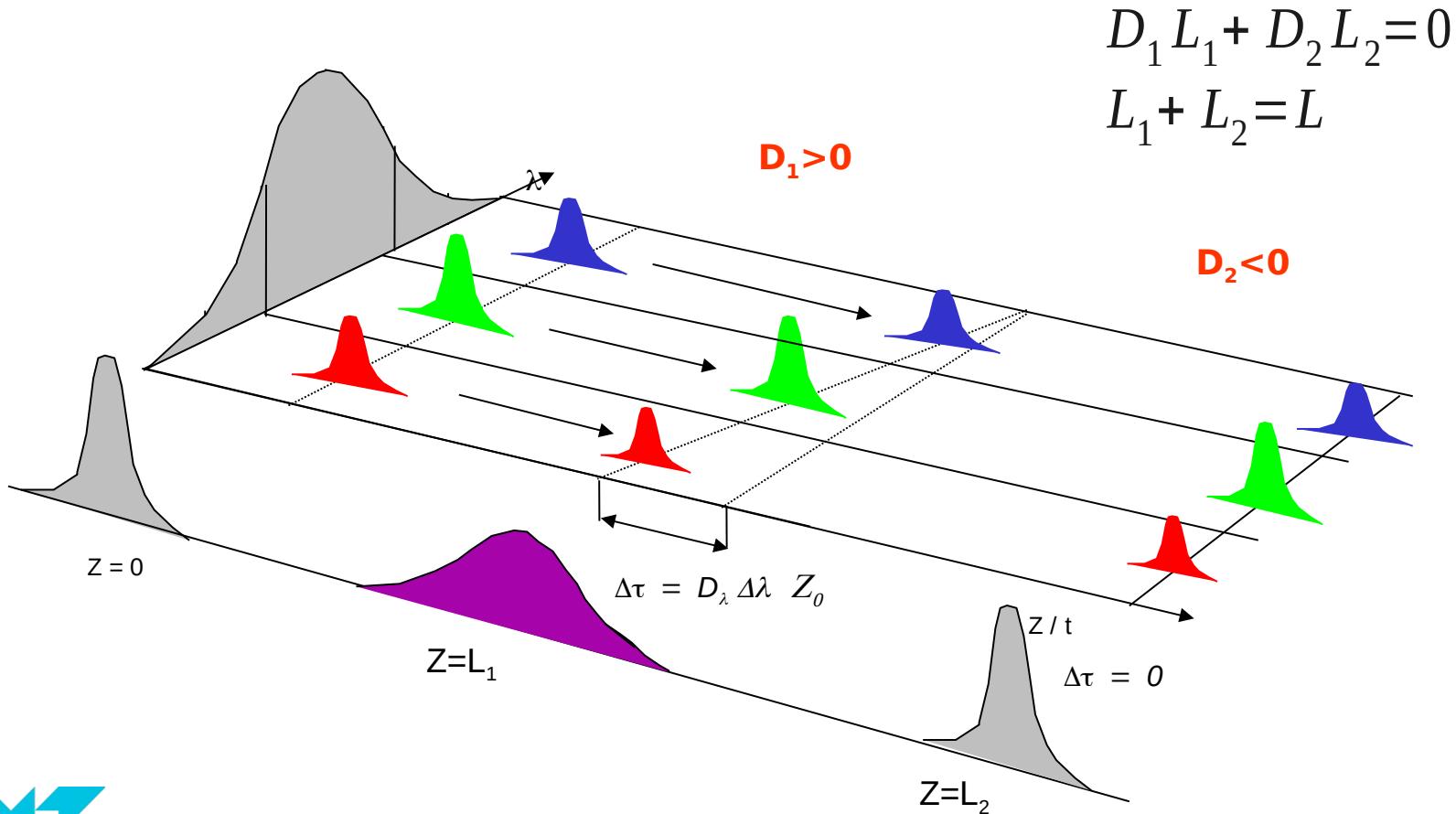


Frequency chirp depends on sign of D_λ



Chromatic dispersion compensation

- Using a fibre with low chromatic dispersion
- Using two different fibres with opposite chromatic dispersion :



Impact of chromatic dispersion on transmission



$$T = \frac{1}{D_n}$$

Information that was sent by the transmitter is not recoverable

D_n : data rate (bit/s)

The limitation on the bit rate:

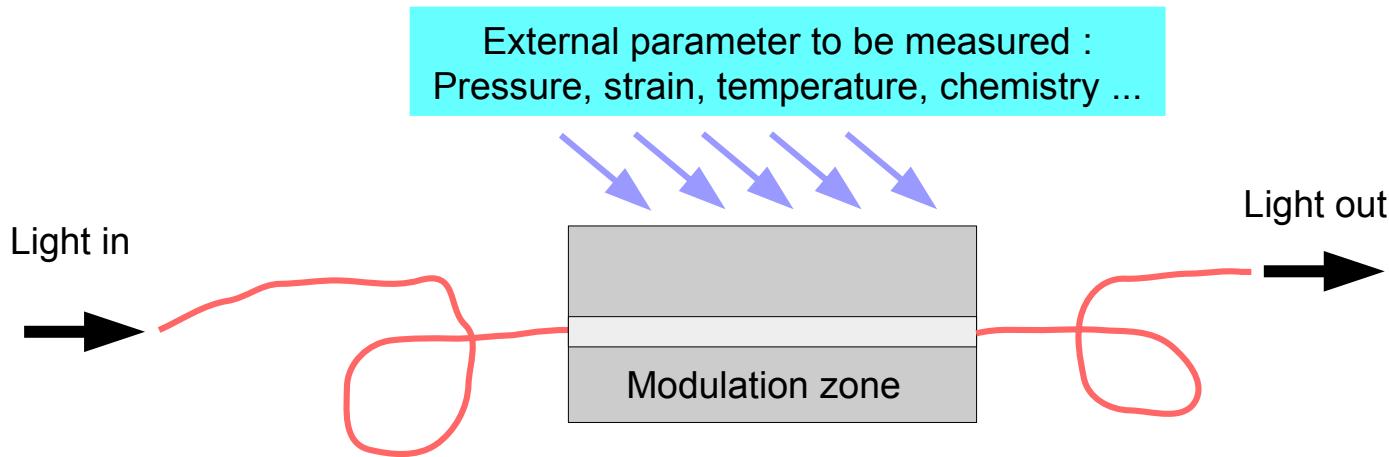
$$T > \Delta\tau \Rightarrow D_n z_0 D_\lambda \Delta\lambda < 1$$

- ▶ Introduction/overview : why optical fibres ?
- ▶ Quick history of optical transmission
- ▶ Light propagation in optical fibres:
 - Ray model
 - EM model
- ▶ Properties of optical fibres
 - Different types of optical fibre
 - Absorption in optical fibres
 - Dispersion in optical fibres
- ▶ Fibre Sensors
- ▶ Conclusion

What are Fibre Sensors

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- ▶ The massive development of optical telecommunications over the last 40 years has greatly reduced the price of fibres, transmitters and detectors
- ▶ Fibre sensors take advantage of the availability of these cheap devices
- ▶ Global market for fibre sensors > \$3Bn in 2024, projected growth >9%/yr



- ▶ The external environment modifies the fibre's transmission characteristics
- ▶ The change in light attenuation, delay, spectrum, polarisation ... is measured at the fibre extremity : remote sensing

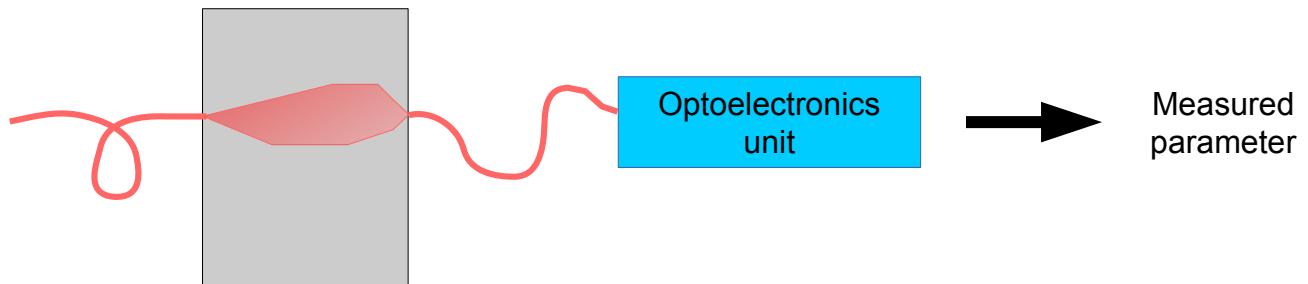
Advantages of Fibre Sensors

- ▶ **Remote sensing possible (no power needed at sensor)**
 - Up to tens of kilometres
- ▶ **Intrinsically safe in hazardous environments**
 - Inflammable environments (e.g. oil and gas)
- ▶ **Immune to electromagnetic disturbances**
 - Compatible with high voltage / high electrical power environments
- ▶ **Chemically passive, bio-compatible**
 - No chemical discharges from silica
- ▶ **Small physical dimensions and low weight**
 - In vehicle applications : aeronautical, automotive
 - Medical applications : endoscopy

Different types of Fibre Sensors

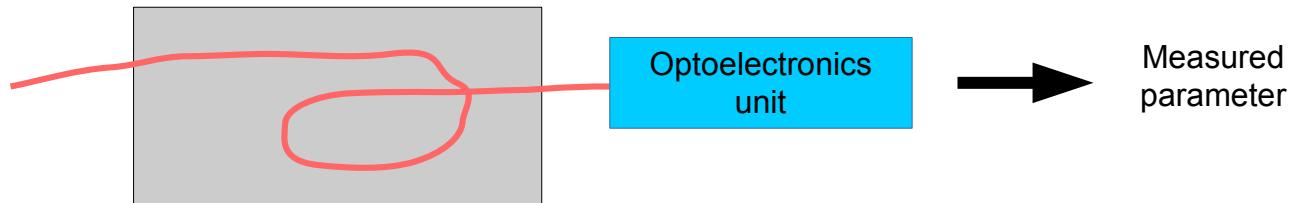
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Extrinsic



Light leaves the fibre, passes through some external modulating medium and is then coupled back into a fibre

Intrinsic

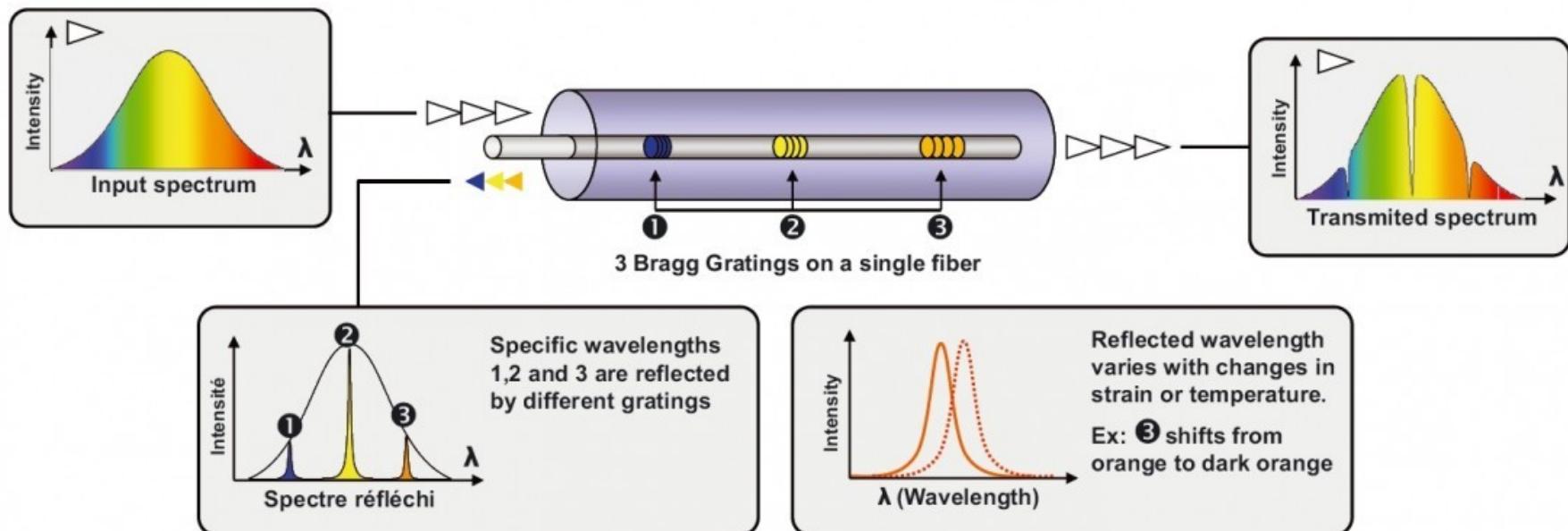


Optical signal modulation occurs while the light is guided within the fibre

Fibre Sensor example : Bragg Fibre Grating

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- ▶ A Fibre Bragg Grating (FBG) is a periodic variation of refractive index inside a fibre
- ▶ FBG as a mirror – but only for a specific wavelength (depends on grating period)
- ▶ As the temperature or strain elongates fibre, the reflected wavelength changes
- ▶ Highly accurate distributed measurement (e.g. of strain points in a bridge or pipeline)
- ▶ WDM technology allows multiple measurement points with a single fibre.



Other Fibre Sensor examples

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Gas / humidity sensor



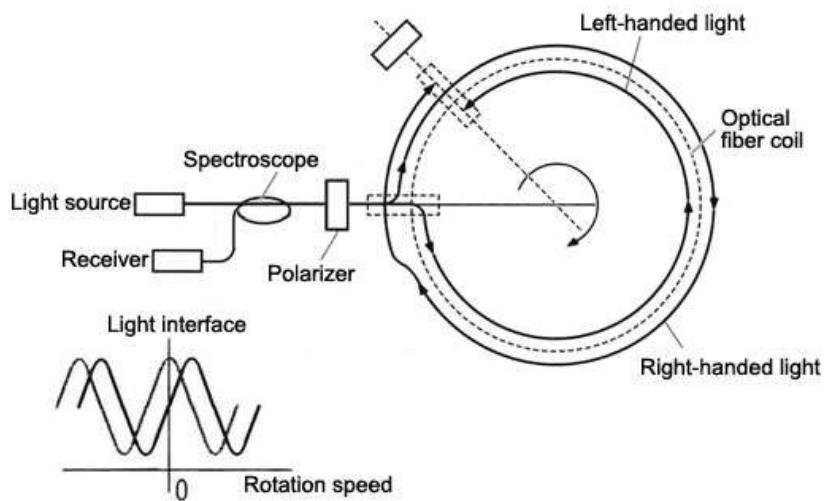
Water detection sensor



Oil drilling pressure sensor



Optical Fibre Gyroscope



- ▶ **Advantages of optical fibre (attenuation and bandwidth)**
- ▶ **Ray model and its limitations**
- ▶ **Results of EM model – existence of modes**
- ▶ **Differences: single mode, multimode fibre**
- ▶ **Critical dimensions fibres**
- ▶ **Limitations on performance and when important:**
 - Attenuation
 - Dispersion : modal, chromatic ...
- ▶ **Fibre sensors and applications**

Bibliography - Illustrations

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