Optics
ELEC E-5730 Spring 2021

Fibre Optics and Optical Telecom

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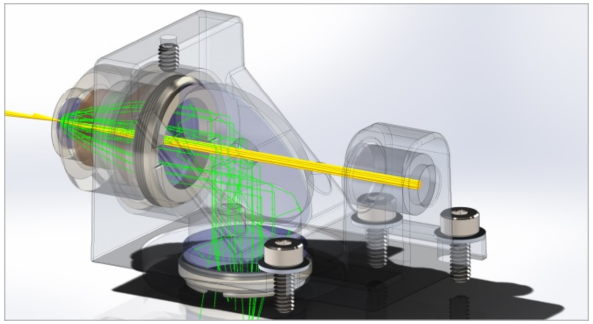
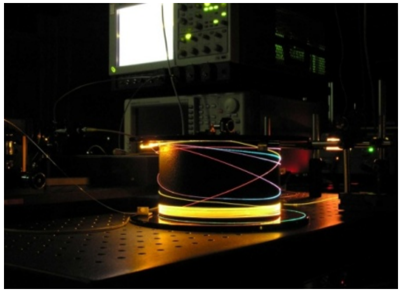
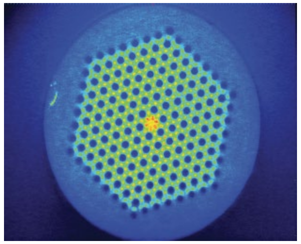
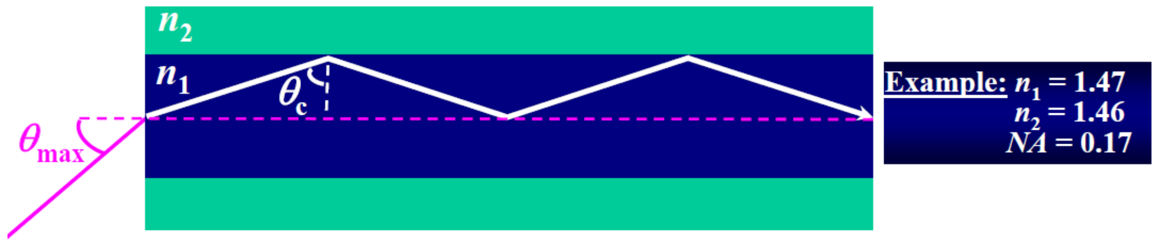
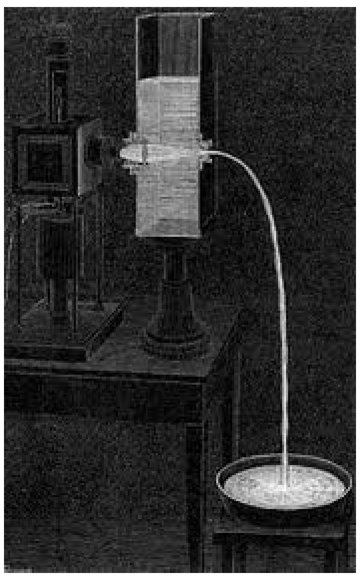



Optical Fibre

- based on total internal reflection in the core-cladding interface
- critical angle θ_C defines the acceptance angle of the fibre

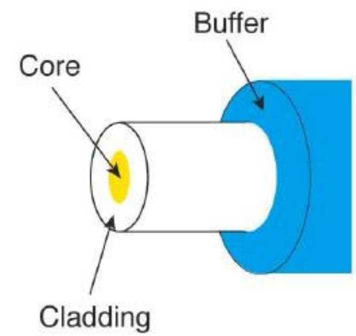




1842 light pipe

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

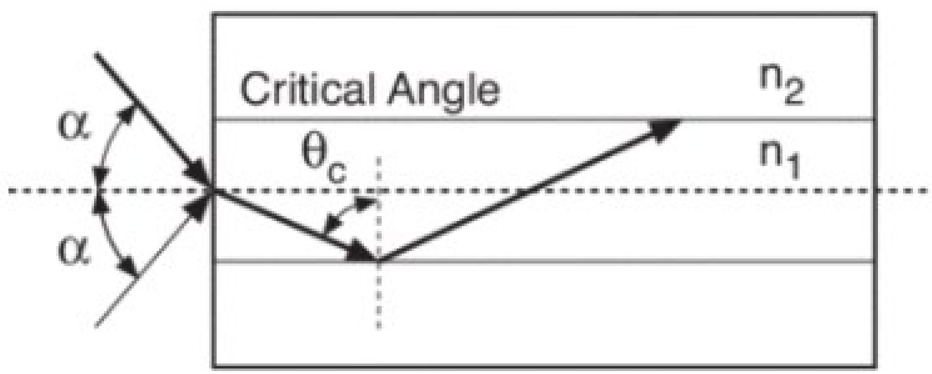
$$n_1 \sin\theta_C = n_2$$



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

Optical Fibre's NA or the 'Acceptance Cone'

Numerical Aperture

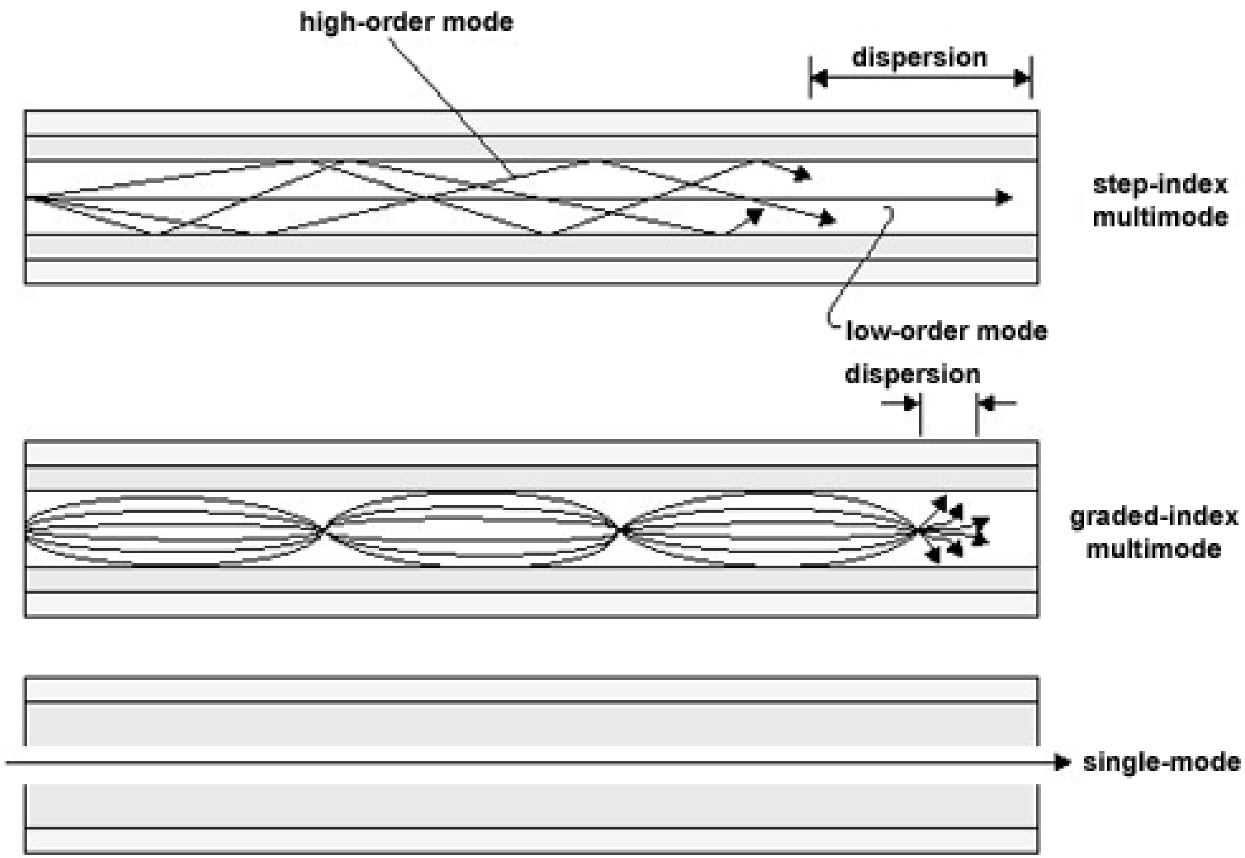


$$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

Full Acceptance Angle = 2α

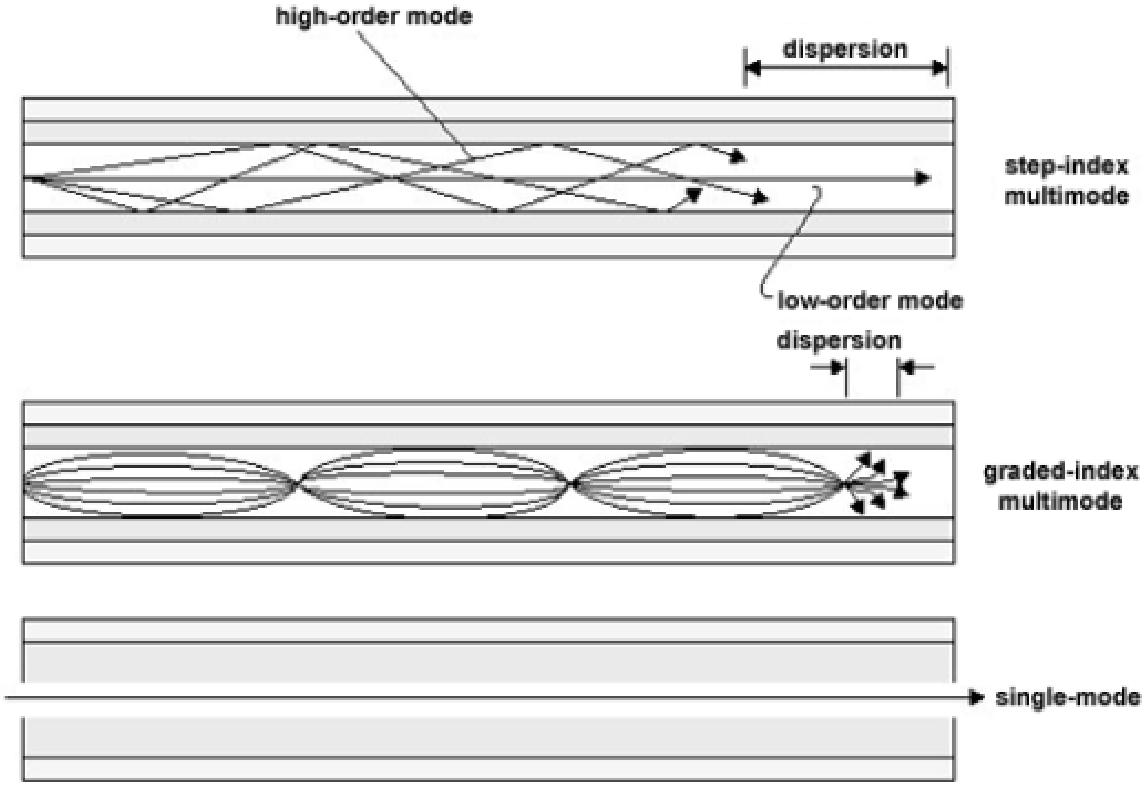
Single-mode Fibre (SMF)

- telecom practically uses only SMFs
- fibre's small core (diameter 8-10 μm) and ste-like refractive index change Δ have been designed so that energy propagates only in a single mode
- SMF has no mode dispersion



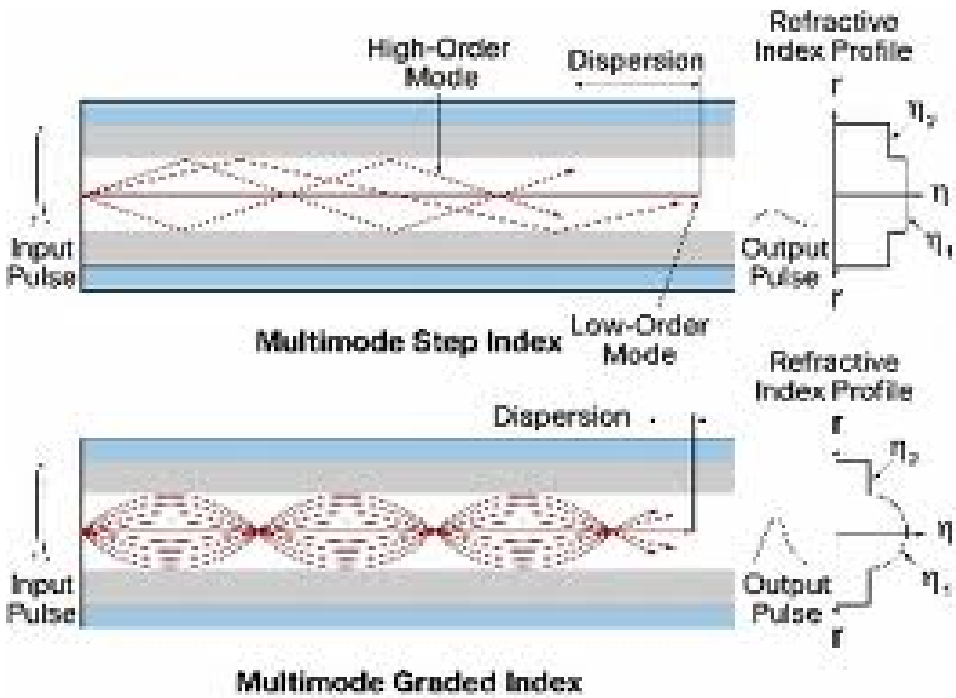
Fiber types

- Fiber types strongly effect on how the power of the pulse travelling through a fiber is *dispersed* in time



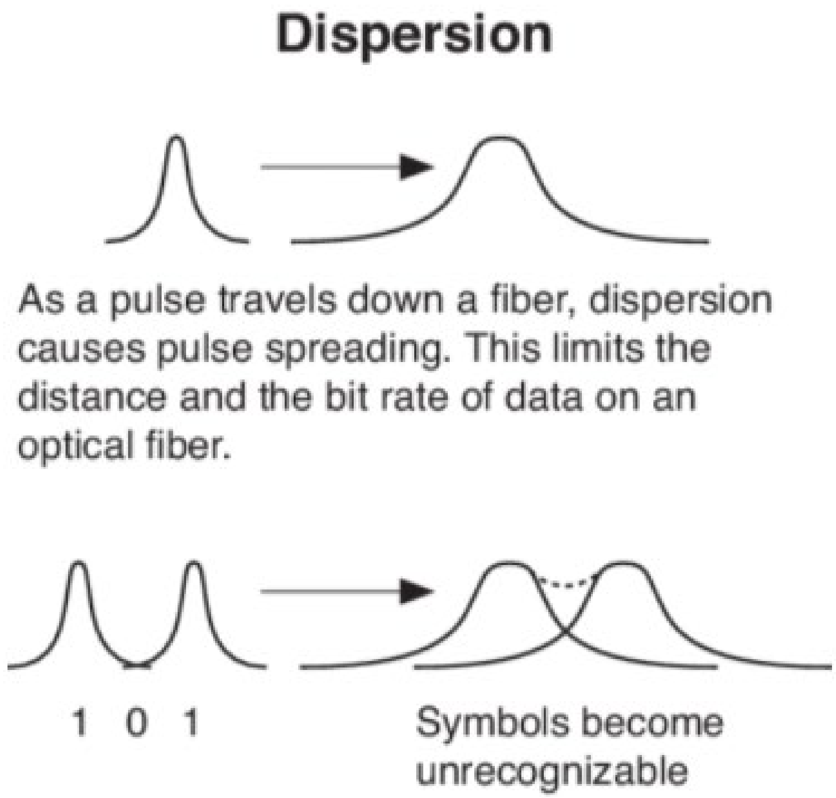
Graded-index Fibre

- no clear change in the refractive index between the core and cladding.
- refractive index changes smoothly as a function of fibre's radius r
- refractive index is smaller near the cladding and thus light propagates faster
- graded-index profile can partially compensate for mode dispersion



Dispersion in Optical Fibres

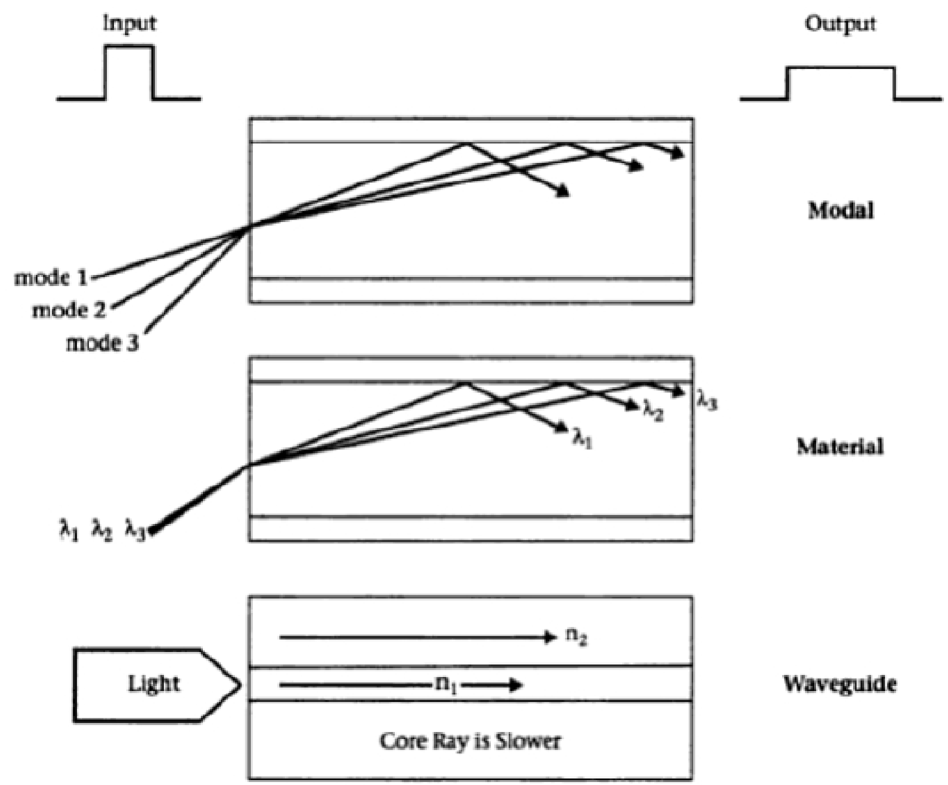
Dispersion means that different wavelengths of an optical pulse propagate at different speeds causing spreading of the pulse in time upon transmission through the fibre.



Dispersion in Optical Fibres

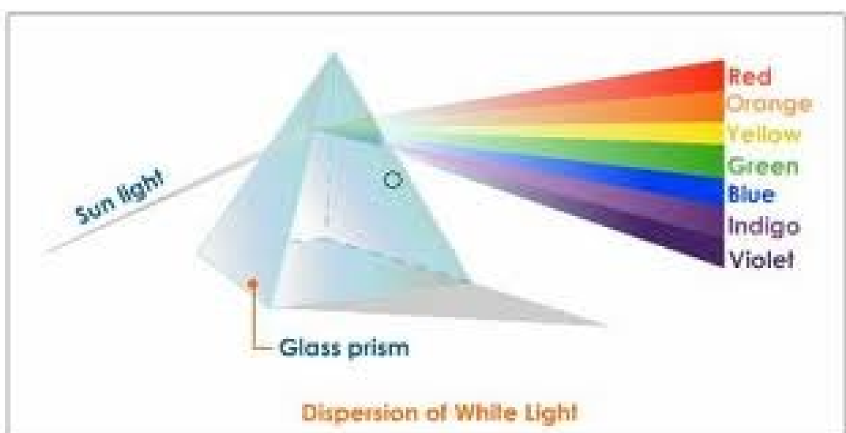
Generally speaking, an optical fibre can have three types of dispersion:

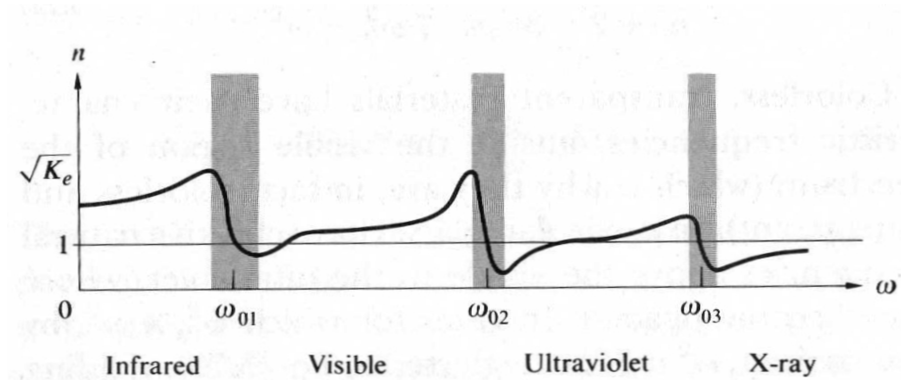
- **material or chromatic dispersion** (refractive index depends on wavelength)
- **modal disperion** (modes of a multi-mode fibre propagate at different speeds)
- **waveguide dispersion** (caused by waveguide geometry)

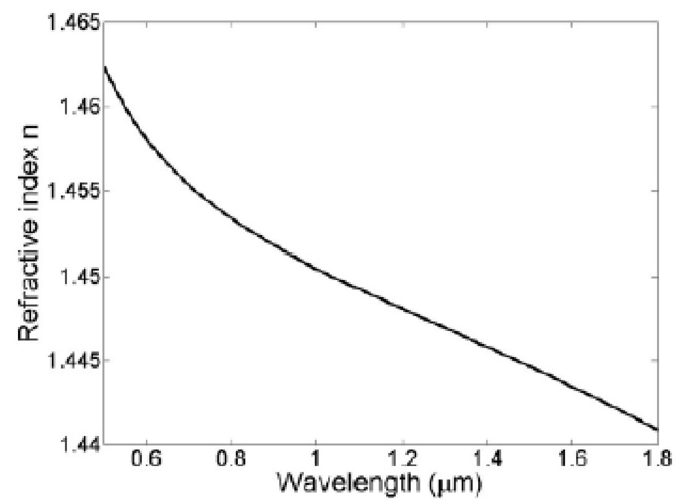


1. Material Dispersion

- refractive index is a function of wavelength in the fibre material (SiO_2)
- stems from the absorption of atoms and molecules at different resonance frequencies
- for ordinary optical fibres the resonance absorption bands are far away in the UV and IR spectral regions so dispersion can be modelled using smoothly behaving polynomes



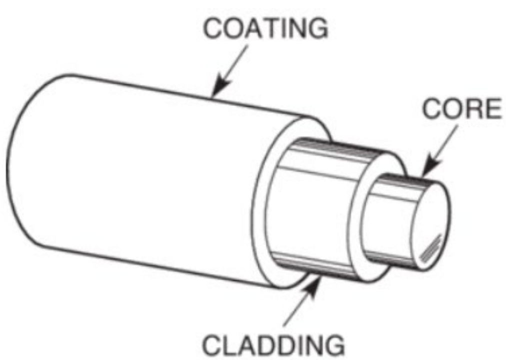


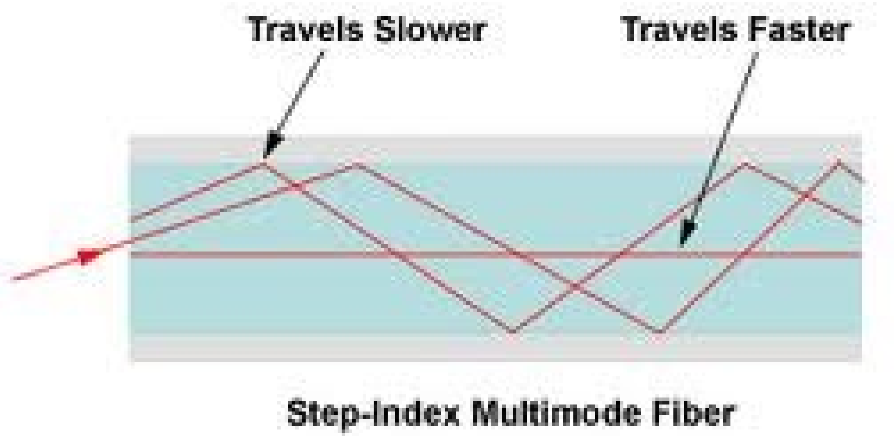


2. Mode Dispersion

- inter-modal or mode dispersion is a problem in multi-mode fibres and is typically the strongest type of dispersion
- time difference between the fastest and slowest rays can be calculated as:

$$\Delta T = \frac{\Delta(path\ length)}{speed} = \frac{\frac{L}{\sin\theta_C} - L}{\frac{c_0}{n_1}} = \frac{Ln_1^2}{c_0 n_2}\Delta \qquad \Delta = \frac{n_1 - n_2}{n_1}$$

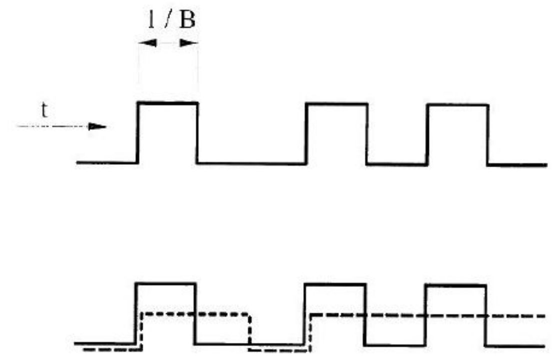




Mode Dispersion and 'BL product'

- if the data transfer speed is B (**B**andwidth) bits per second the temporal width of a single bit is 1/B
- in a multi-mode fibre mode dispersion sets the upper limit for transmission capacity:

$$\Delta T < \frac{1}{B}$$



$$\Delta T = \frac{L n_1^2}{c_0 n_2} \Delta \qquad BL < \frac{n_2 c_0}{n_1^2 \Delta}$$

- for example, assuming n_1=1,5 and n_2 = 1 yields BL < 0,4 Mbit / (s km)
- in real telecom fibres Δ is much smaller, e.g., n_1=1,5 and n_2 = 1,498 yielding BL < 150 Mbit / (s km)

SMF Wave-equation - Phase and Group Velocity

$$\left[\nabla_{\perp}{}^{2} + \frac{\omega^2}{c^2} n^2(x,y)\right] E_m(x,y) = \beta_m{}^{2} E_m(x,y)$$

where $\beta_m = nk_0 = n\frac{2\pi}{\lambda_0}$ is so called propagation constant

$$E_m(x,y,z,t) = E_m(x,y)e^{-i(\omega t - \beta_m z)}$$

$$n_{eff} = \frac{\beta_m}{k_0} = \frac{\beta_m}{\frac{\omega}{c_0}}$$

$$n_{cladding} < n_{eff} < n_{core}$$

The propagation constant depends both on *n* (x,y) and on the wavelength (angular frequency).

SMF Wave-equation - Phase and Group Velocity

$$\phi = n_{eff} k_0 L = n_{eff} \frac{\omega}{c_0} L$$

Group delay of a propagating pulse:

$$\tau = \frac{d\phi}{d\omega} = \mathrm{L}\left[\frac{n_{eff}}{c_0} + \frac{\omega}{c_0}\frac{dn_{eff}}{d\omega}\right]$$

$$\tau = \mathrm{L}\left[\frac{n_{eff}}{c_0} - \frac{\lambda}{c_0}\frac{dn_{eff}}{d\lambda}\right]$$

Group Velocity Dispersion $\quad GVD \quad D \equiv \frac{d}{d\lambda}\left(\frac{\tau}{L}\right) \quad \frac{ps}{nm \cdot km}$

$$\mathrm{D} = -\frac{1}{c\lambda}\left(\lambda^2 \frac{d^2 n_{eff}}{d\lambda^2}\right)$$

$$\Delta\tau = DL\Delta\lambda$$

SMF Wave-equation - Phase and Group Velocity

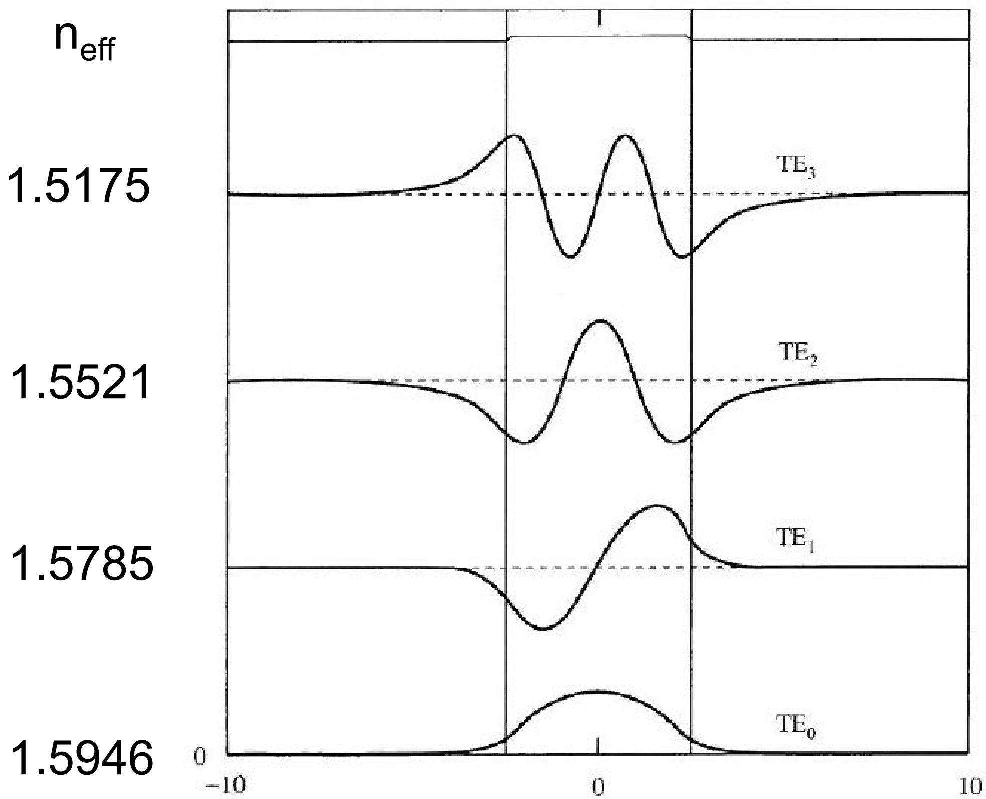
Phase velocity $v_p \equiv \frac{c}{n}$

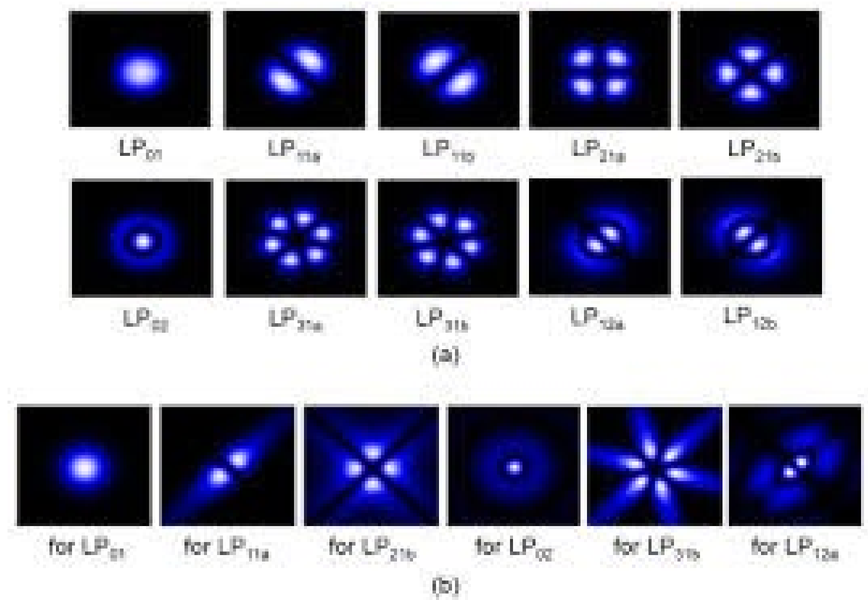
Group velocity $v_g \equiv \frac{d\omega}{dk}$

$$k = n(\omega)\frac{\omega}{c}$$

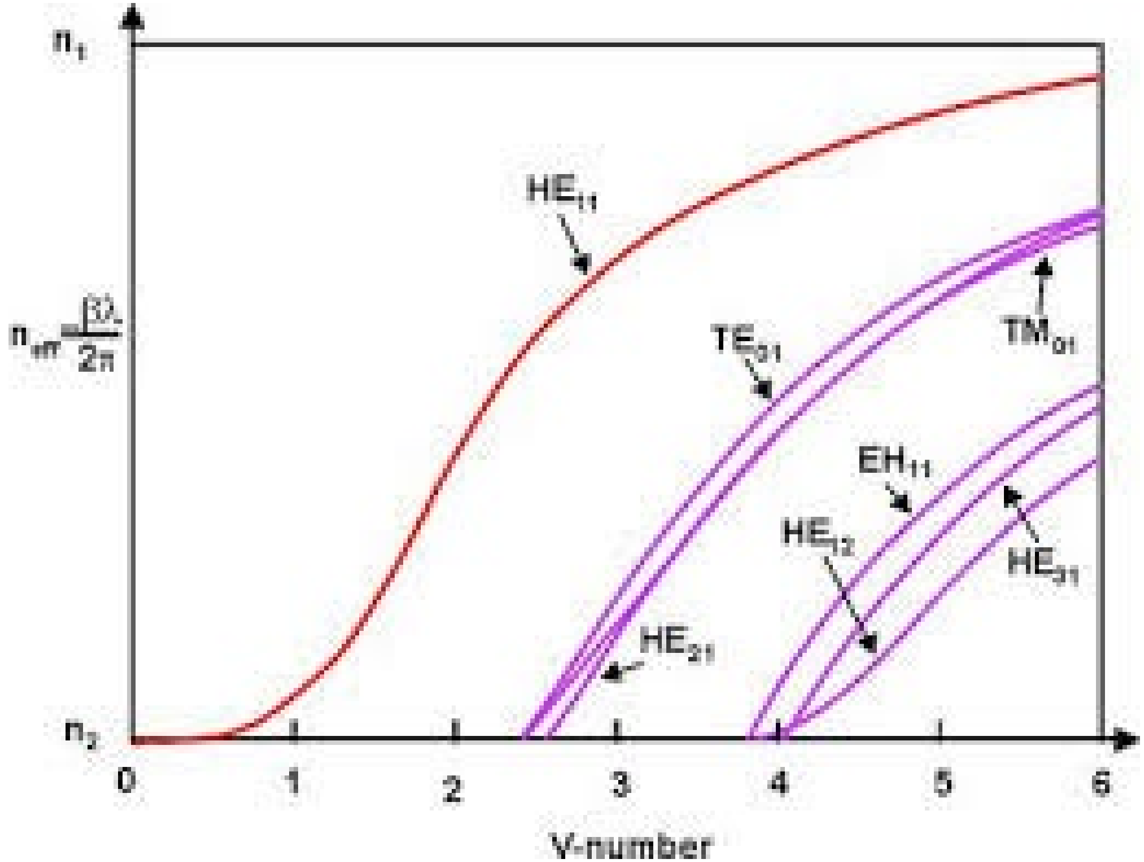
$$\Rightarrow \quad v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} = v_p\left(1 + \frac{\lambda}{n}\frac{dn}{d\lambda}\right) < v_p$$

Wave-equation Solutions and Dispersion in SMF





Wave-equation Solutions and Dispersion in SMF



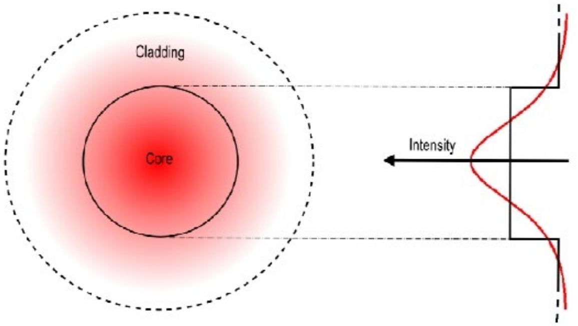
A step index fibre becomes single-mode for a given wavelength when V<2.405. a is the fibre core radius.

$$V = k_0 a n_1 \sqrt{2\Delta} \qquad \Delta = \frac{n_1 - n_2}{n_1}$$

3. Waveguide Dispersion

- power distribution between the core and cladding varies with wavelength
- power distribution in a SMF can be approximated as:

$$\frac{P_{core}}{P_{total}} = e^{-\frac{2a^2}{w^2}}$$



where $$\frac{w}{a} \approx 0.65 + 1.619V^{-\frac{3}{2}} + 2.879V^{-6}$$

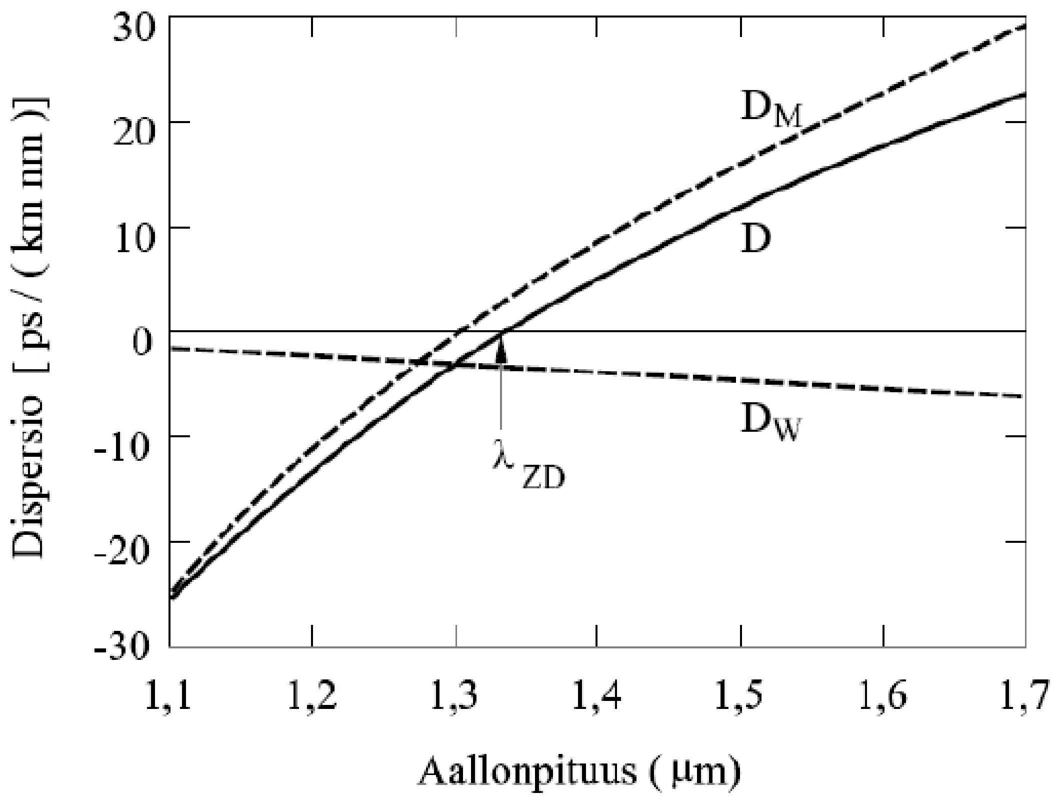
and $$V = k_0 a n_1 \sqrt{2\Delta} \qquad \Delta = \frac{n_1 - n_2}{n_1}$$

wavelength-dependent

- As the wavelength increases the power distribution changes so that less and less of the power propagates in the core and which effectively makes the signal to travel faster because the cladding has smaller refractive index.

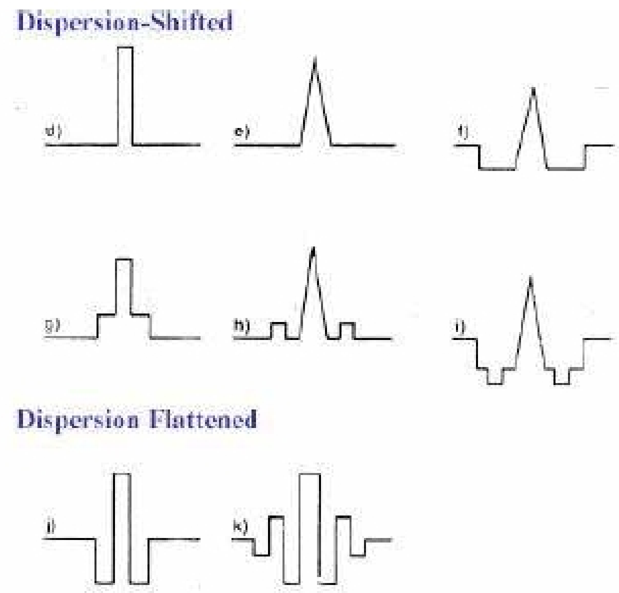
Total Dispersion in SMF

- Total dispersion parameter (D) is sum of material dispersion (D_M) and waveguide dispersion (D_W)
- standard telecom SMF has zero dispersion at 1.32 μm wavelength



SMF Dispersion Management

• if one wants to change the zero dispersion wavelength the geometry of the fibre has to be changed as the material dispersion is nearly constant for all silica fibres
• it is more demanding and more expensive to manufacture fibres with alternative refractive index profiles



Typical index profiles of a) 1300 nm-optimized, b) dispersion-shifted, and c) dispersion-flattened single-mode fibers

Example: Pulse Spreading

Consider transmission of 10 Gb/s signals at 1500 nm wavelength in a 100 km long SMF with a group velocity dispersion of D = 17 ps/(nm km). The pulse spreading after a transmission of distance L can be written

$$\Delta\tau = DL\Delta\lambda$$

where $\Delta\lambda$ is the spectral bandwidth of the signals. For 10 Gb/s the pulse width τ_0 = 100 ps. The spectral bandwidth is approximately $\Delta\nu = 1/\tau_0$ = 10 GHz. In terms of nanometers the bandwidth is

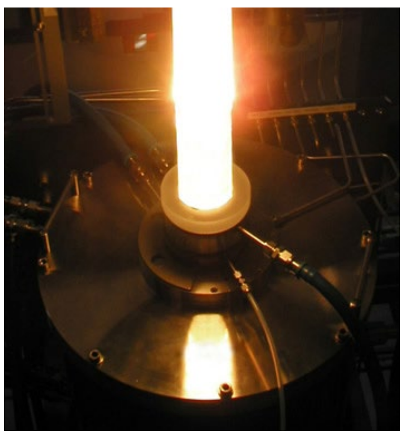
$$\Delta\lambda = \frac{\lambda^2}{c}\Delta\nu = 0.075nm$$

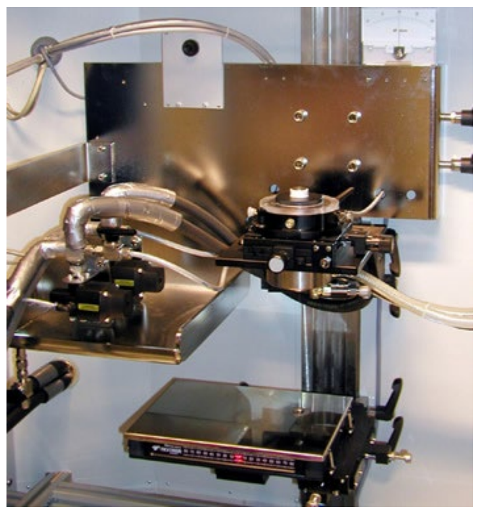
The pulse spreading is thus

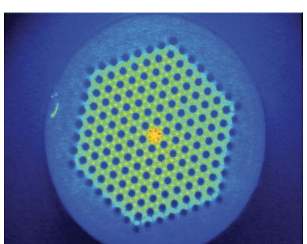
$$\Delta\tau = DL\Delta\lambda = 128\,ps$$

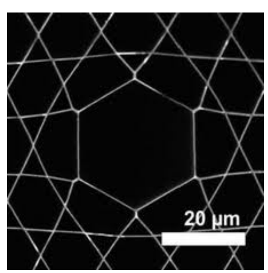
Optical Fibre Manufacturing

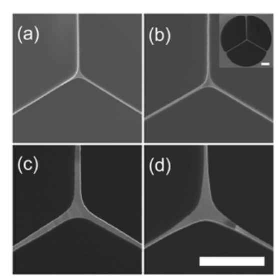
- fibres manufactured from extremely pure silicon dioxide (SiO_2)
- a preform: 2-10 cm thick and ca 1 m long glass rod
- preform has the geometry and refractive index profile of the final fibre
- preform heated to 2000 °C so that glass melts and drops in a fibre drawing tower
- upon melting the cross-sectional area decreases by 1:500 and length increases by 500^2 = 250 000











Attenuation in an Optical Fibre

- signal attenuation is described by Beer-Lambert law:

$$P(L) = P_0 e^{-\alpha L}$$

- attenuation coefficient is in many cases given in units of dB/km or dBm:

$$\frac{P(L)}{P_0} = 10^{-\alpha[dB/km]L[km]/10}$$

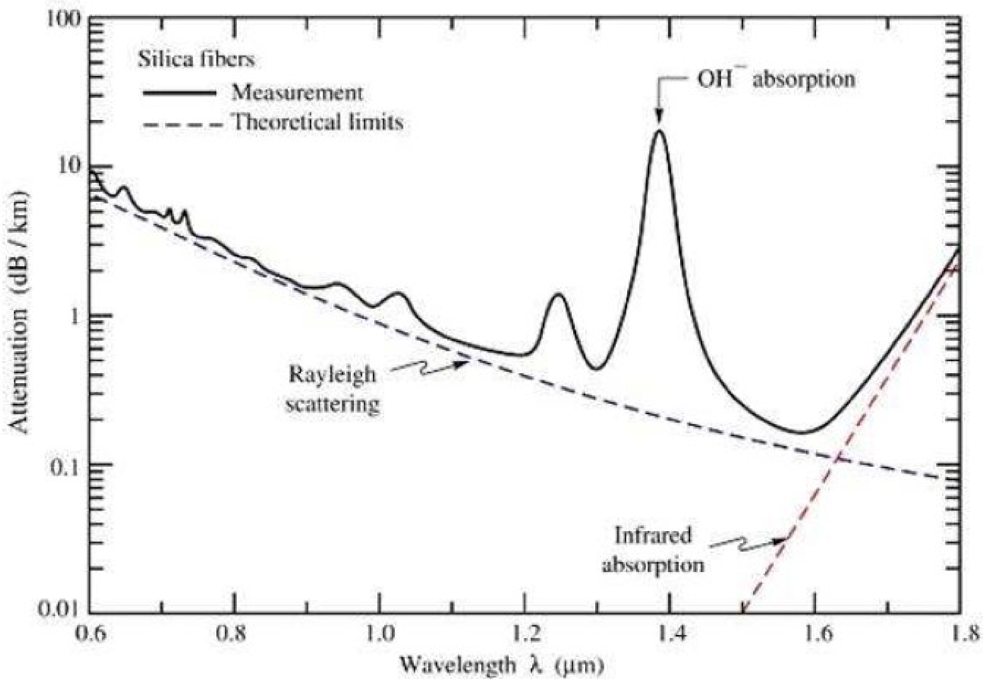
$$P_{dBm} = 10 log_{10}(\frac{P}{1\ mW})$$

- in the mid-60s $\alpha \approx 1000$ dB/km so 1 km fibre attenuated 10^{-100} !
- in the beginning of 70's $\alpha \approx 20$ dB/km (C. Kao, Nobel Prize in Physics 2009)
- today's telecom SMFs @ 1300-1600 nm have $\alpha \approx 0.03$ dB/km, that is, after 330 km of such fibre 10% of the power is still remaining

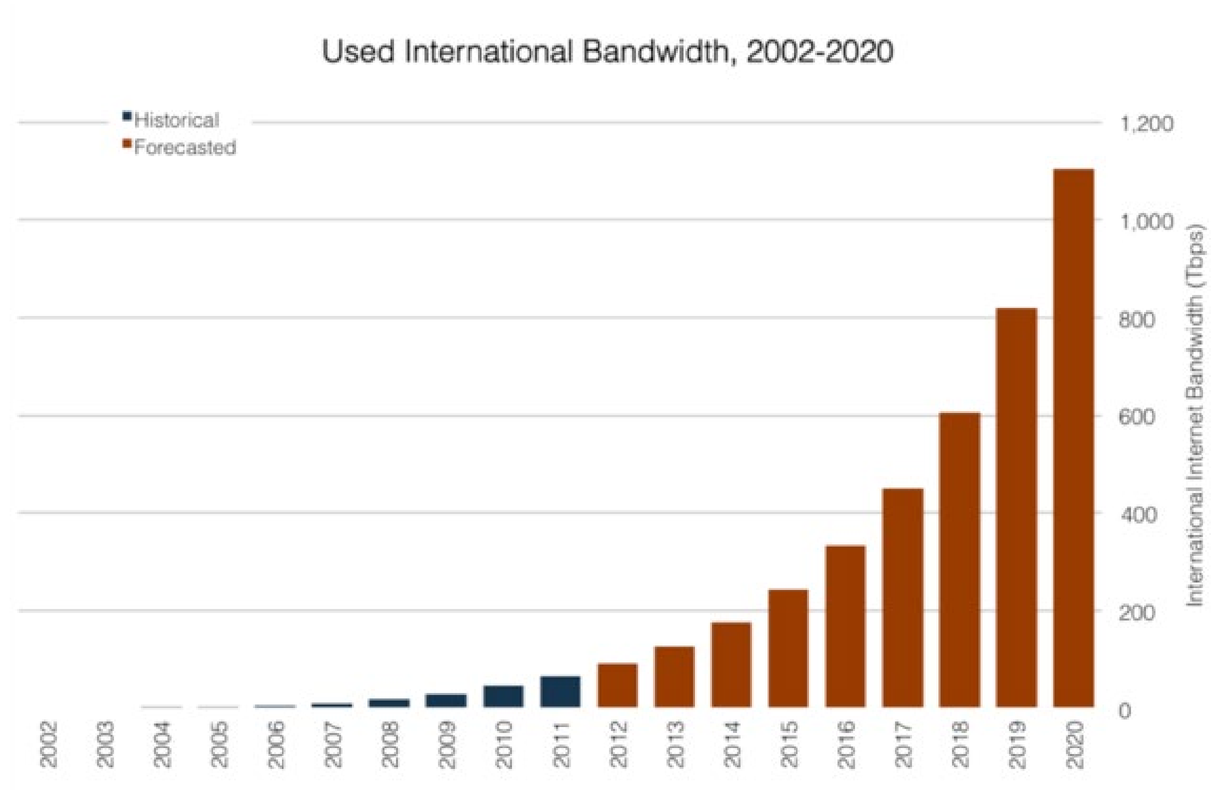
Attenuation in an Optical Fibre

Light gets attenuated upon transmission due to the following phenomena:

- **material absorption**: SiO_2 molecules absorb in UV and IR
- **impurity absorption**: OH^- ions absorb near 1.4 μm, for example
- **Rayleigh scattering**: at short wavelengths inhomogeneities of the glass (size is order of wavelength of light) $\alpha_R = C/\lambda^4$ ($C = 0.27\ \mathrm{km^{-1}\mu m^4}$)
- **bending losses**: light escapes from the core if total internal reflection condition is not fullfilled

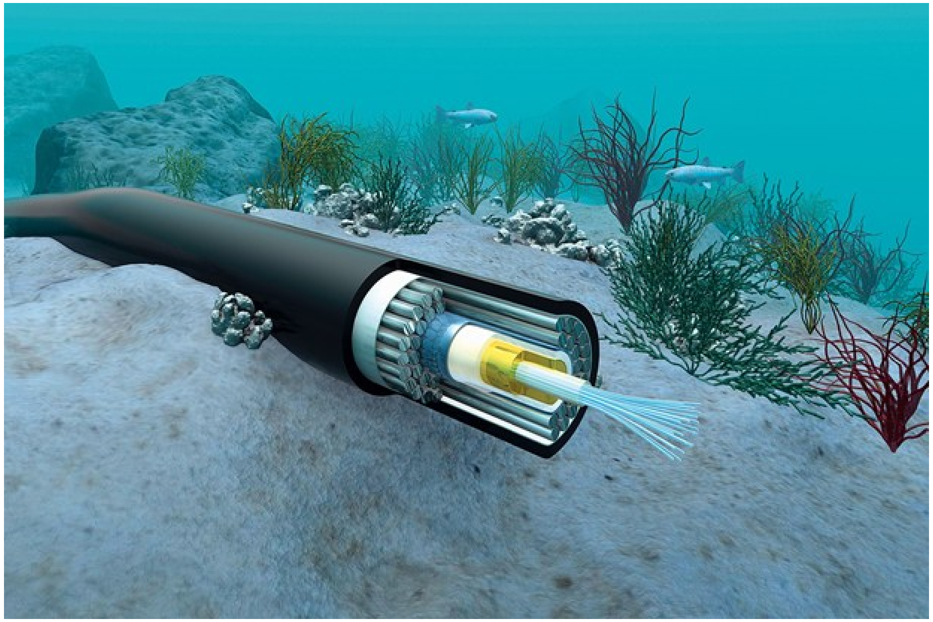


Optical Telecommunication



- growth in the capacity demand and advances in fibre optics led to the replacement of copper-based telecom with optical telecom
- there is no near-future end to the capacity growth (music, pictures, movies, Youtube)

Optical Telecommunication

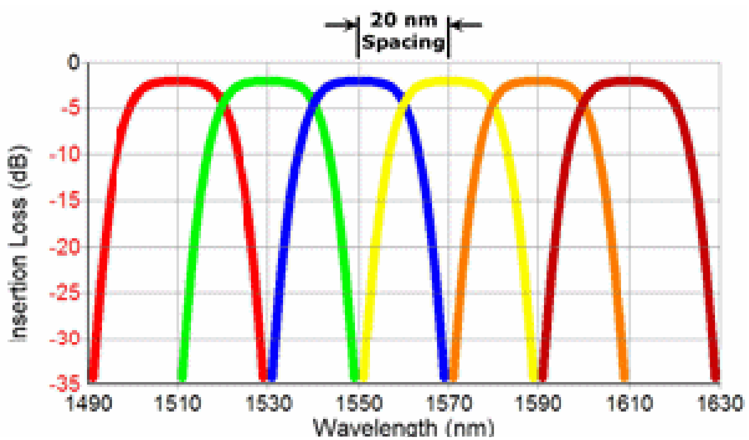


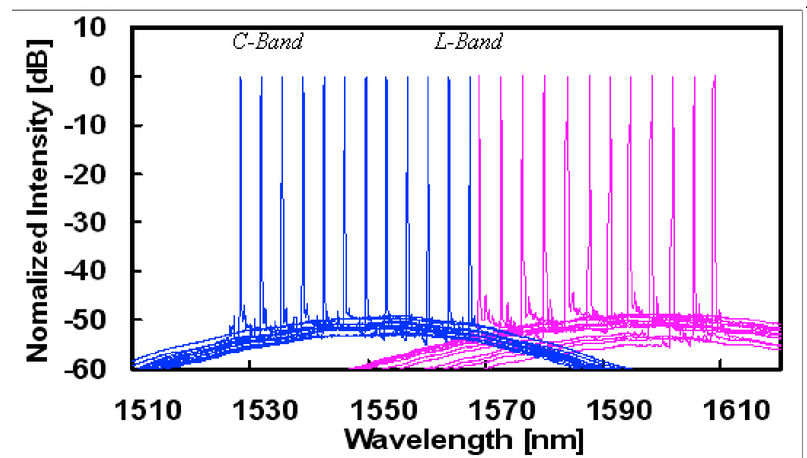
First trans-Atlantic fibre optic cable in 1988.

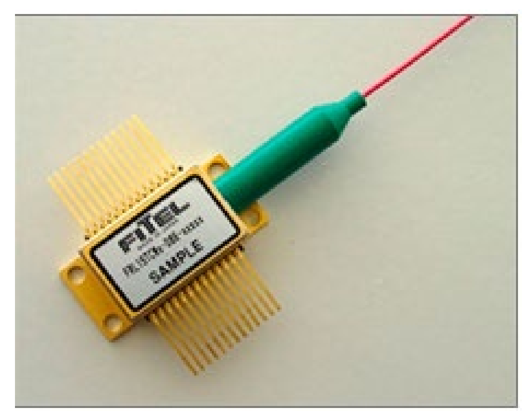
Two major technological breaktroughs, WDM and EDFA, in the 1990s led to doubling of optical data transfer capacity every 6 months since 1992 until a bit rate of 10 Tb/s was reached in 2001.

Wavelength Division Multiplexing (WDM)

Parallel telecom channels can be placed in the same optical fibre by using lasers having small mutual wavelength separation.
Today's dense WDM (DWDM) uses 50 GHz or even 25 GHz spacing for 160 channel operation → 'easy' to obtain 1 Tb/s operation





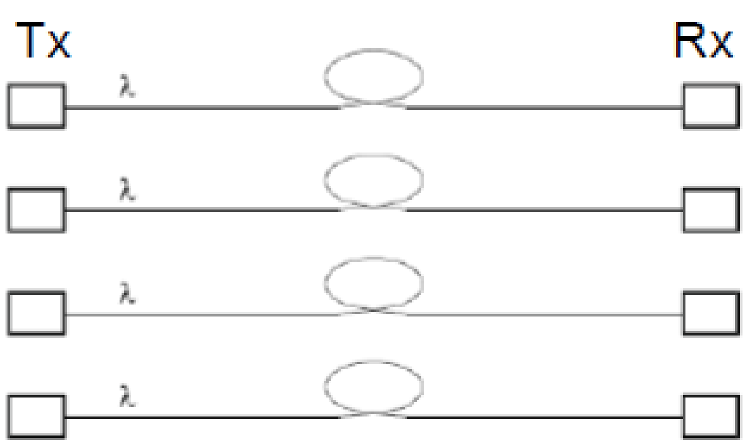


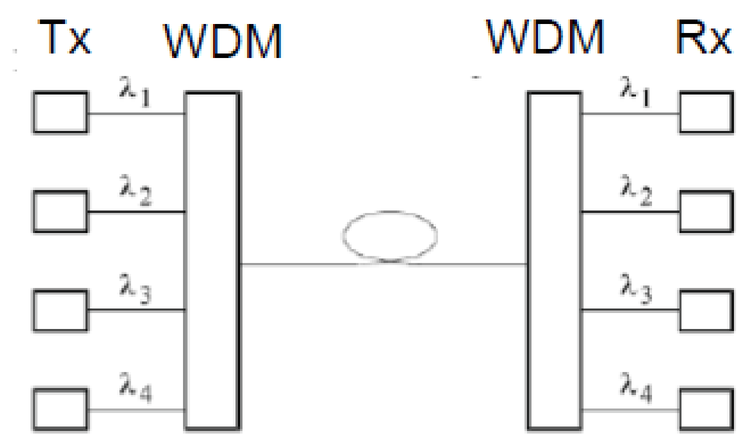
Wavelength Division Multiplexing (WDM)

According to ITU standard 100 lasers at 50 GHz steps can be placed btw 190 and 195 THz carrier frequencies (1.54-1.58 μm).

Theoretical limit for the number of lasers: the bandwidth requirement for a single laser is at least equal to the bit rate B; for typical laser B = 2.5Gb/s

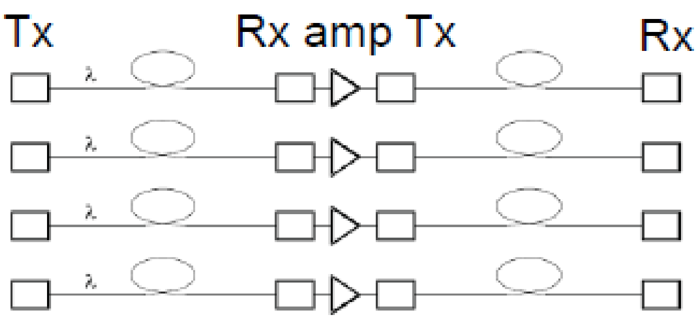
What optical components can be used to split and combine wavelengths?



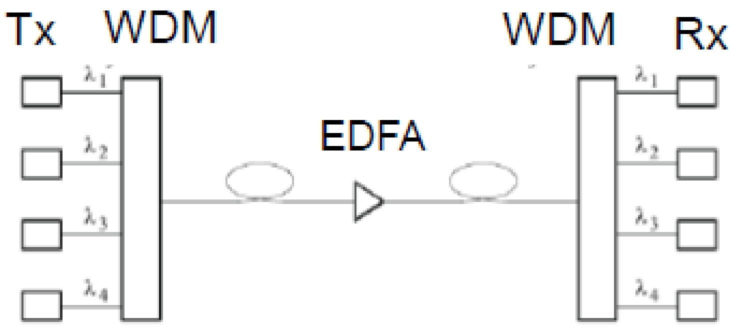


Optical fibre amplifier

Advantages over electrical amplification: works simultaneously for all wavelengths and optical amplifier does not limit the bandwidth of each channel.



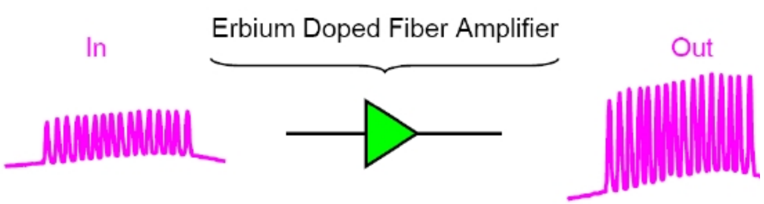
electrical amplification

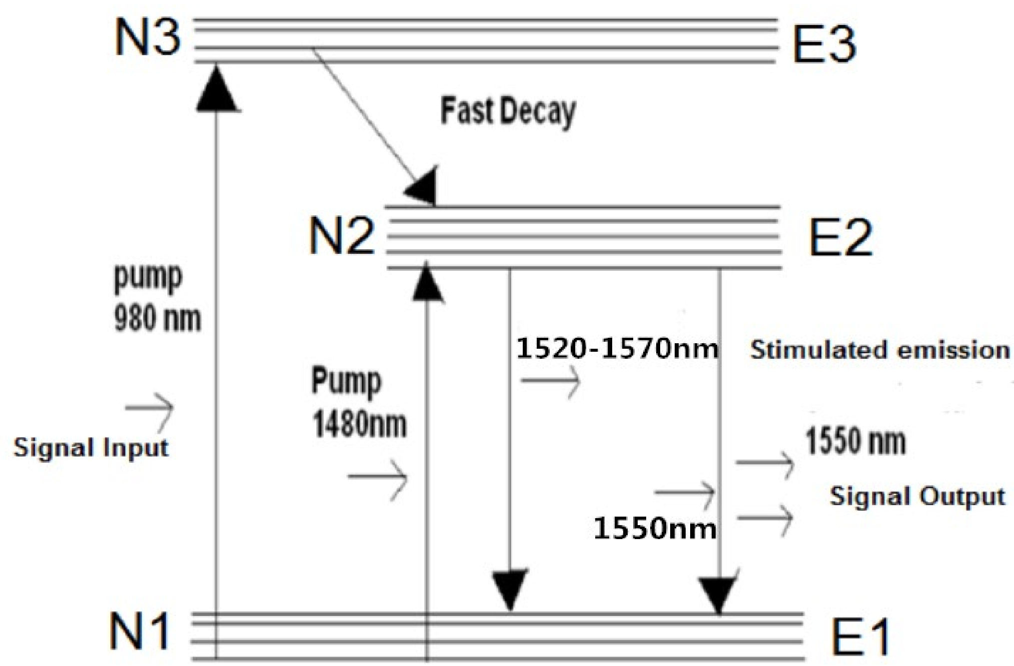


optical amplification

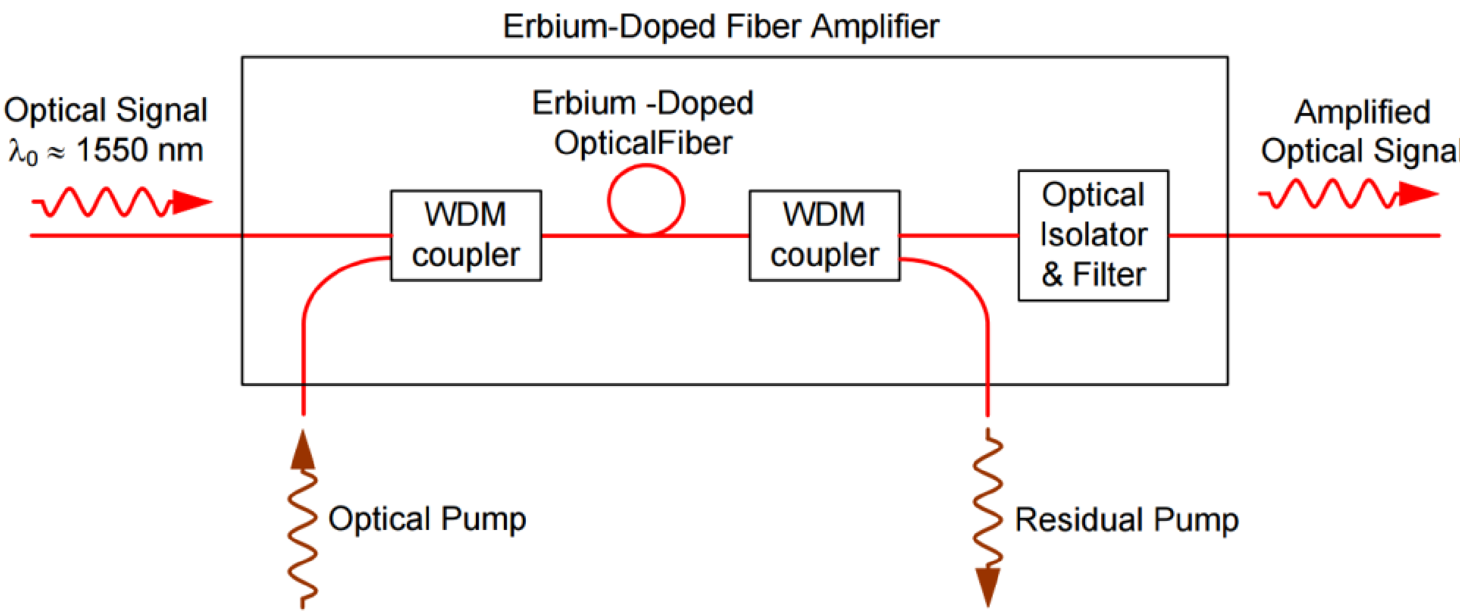
EDFA (Erbium-doped Fibre Amplifier)

- realised in 1987
- Er^{3+}ions dobed in the fibre's glass material exhibit transitions which match with the optical telecom wavelengths around 1.55 μm wavelength
- operating bandwidth 40-90 nm so it amplifies one data transfer band at a time
- erbium ions are optically pumped to the excited state by using either 0.98 μm or 1.48 μm diode lasers creating population inversion





EDFA


Erbium-Doped Fiber Amplifier
Optical Signal
λ0 ≈ 1550 nm
Erbium -Doped
OpticalFiber
WDM
coupler
WDM
coupler
Optical
Isolator
& Filter
Amplified
Optical Signal
Optical Pump
Residual Pump