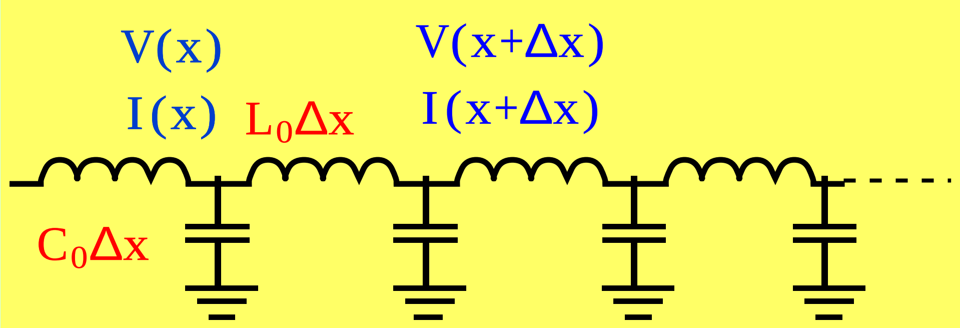
Transmission of data

- Real systems are often distributed
  - data **source** is remote from signal processing
    - *instruments in hazardous or very remote environments,eg satellites, HEP, nuclear reactors,..,*
    - *but*
    - *also applies to much shorter distances - like nearby labs or instruments in the same room*
  - so need to transfer data from source to receiver
    - *and usually send messages (eg.control signals) back*

- need to understand
  - practical ways of doing this
  - issues: power, speed, noise,... other physical constraint
- methods - a mixture
  - electrical, but increasing use of optical fibres,
    - radio for satellites and space, mobile telephones,...

Electrical transmission lines

- Line with characteristic inductance and capacitance per unit length



An important assumption

R negligible

- Voltage and current satisfy 2nd order differential equation

$d^2V/dx^2 = -\omega^2 L_0 C_0 V = -k^2 V$ ie $k = \omega(L_0C_0)^{1/2}$

- Solution

$V = Ae^{jkx} + Be^{-jkx}$

Inject signal $\sim e^{j\omega t}$ $V = Ae^{j(kx+\omega t)} + Be^{-j(kx-\omega t)}$ *two opposite direction waves*

- Speed $v = \omega/k = 1/(L_0C_0)^{1/2}$

- Impedance $Z_0 = (L_0/C_0)^{1/2}$

NB real, ie resistive, but defined by L and C

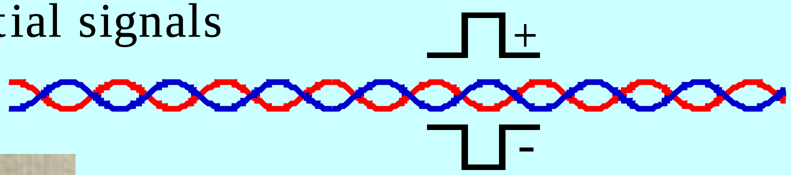
Cables

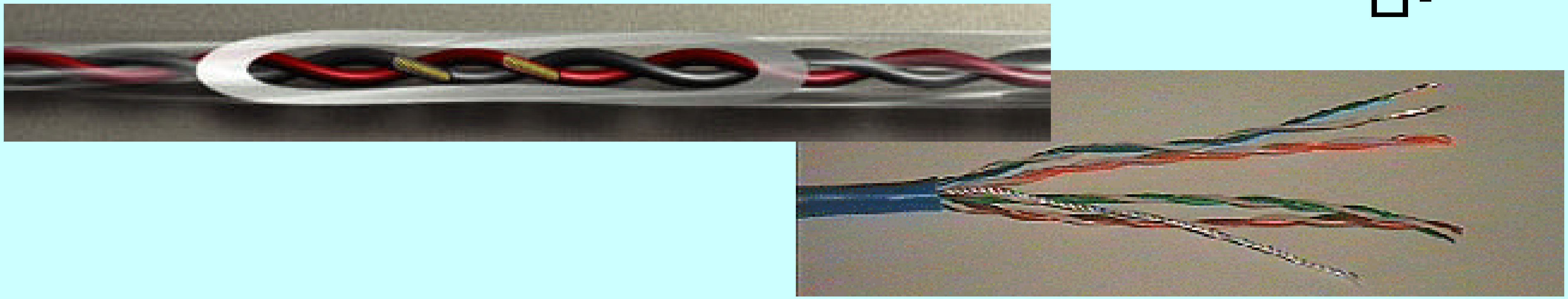
- Any wire has inductance, capacitance and resistance

  so when is it a transmission line?

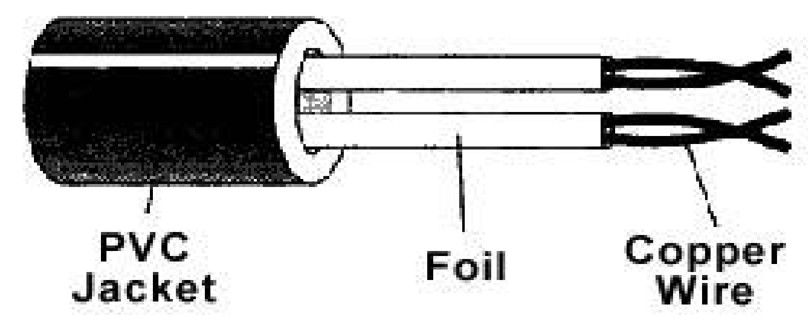
- Twisted pair

  simple pair of wires, mainly intended for differential signals

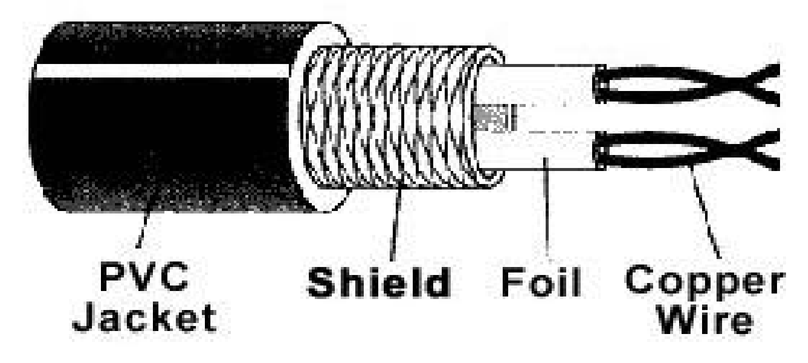




Can also be unshielded...



or shielded



Coaxial cable

central copper core radius r_1, with plastic dielectric, braided metal shield in cylindrical geometry radius r_2

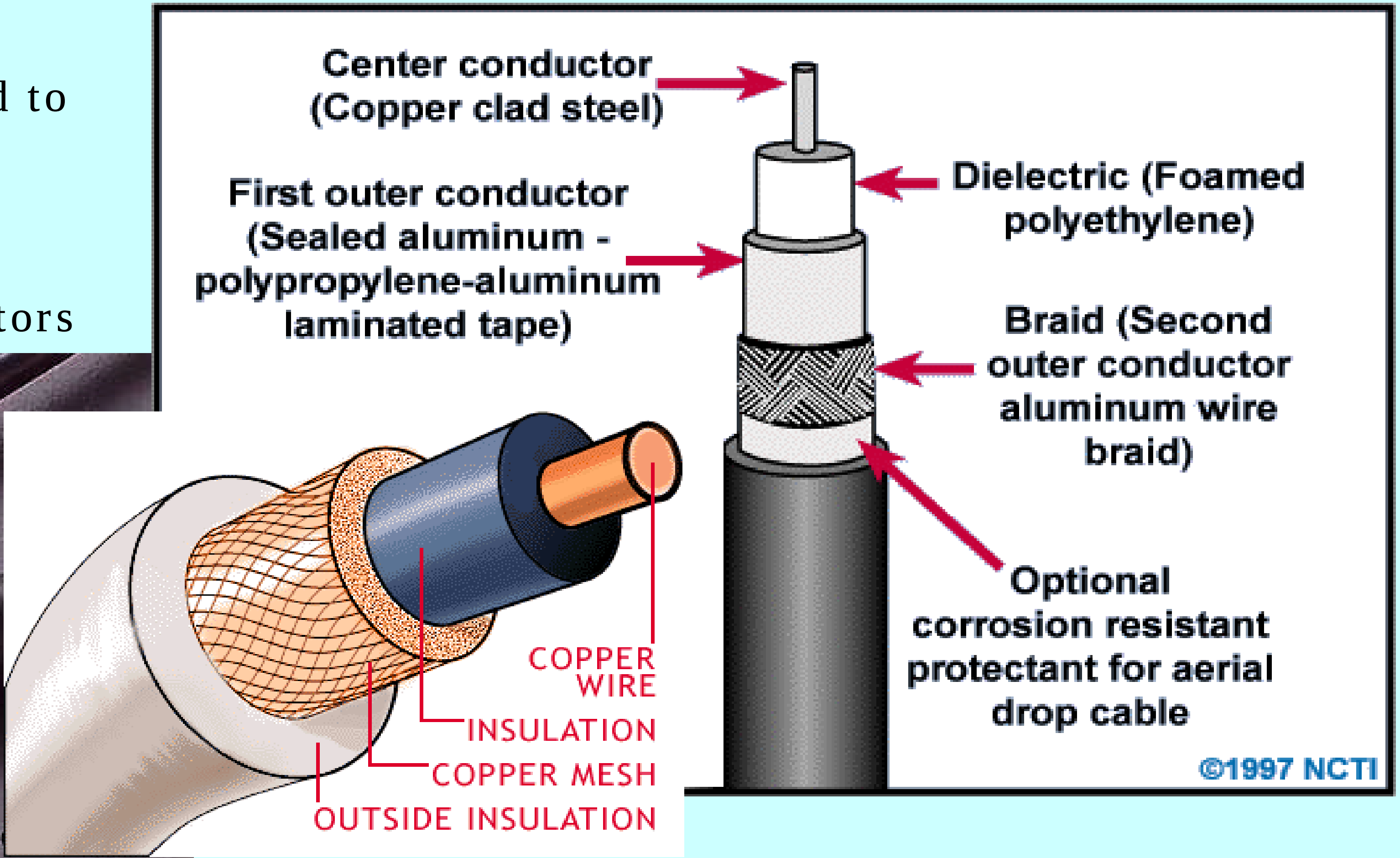
$C_0 = 2\pi\varepsilon/\ln(r_2/r_1)$ $L_0 = (\mu_0/2\pi).\ln(r_2/r_1)$ *see lecture 1 notes*

- Design

Cu braid connected to ground provides electrical shield

use special connectors

1001
BNC plug to BNC plug, moul
RG-58U coaxial cable.



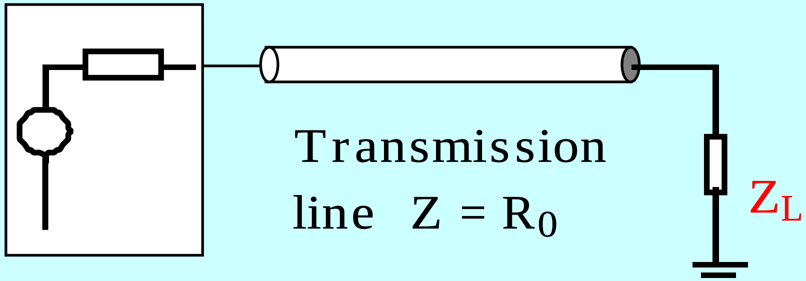
Coaxial cable properties

from G. Knoll see also **http://www.colemancable.com/fstechnical.htm**

	RG-58	RG-178	RG-8	RG-11	RG-62	
typical dielectric	Polyethylene	Teflon	Polyethylene	Gas injected polyethylene	Foamed Fluorinated Ethylene Propylene	
outer diameter	5.0	1.8	10.3	10.3	6.1	**mm**
v/c	0.659	0.694	0.659	0.659	0.840	
Z_0	50	50	52	75	93	Ω
C_0	100.1	95.1	96.8	67.3	44.3	**pF/m**
calculated data						
L_0	0.25	0.24	0.26	0.38	0.38	**µH/m**
dielectric constant	2.30	2.08	2.30	2.30	1.42	
inner diameter	1.4	0.5	2.8	1.5	1.0	**mm**
C_0	101.2	96.1	97.3	67.5	42.7	**pF/m**
R_{core} [ρ_{Cu}=17.2nΩ.m]	2.8	18.7	0.7	2.3	5.9	**mΩ /m**
RC (1m)	0.28	1.78	0.07	0.15	0.26	**ps**
RC (100m)	2.8	17.8	0.7	1.5	2.6	**ns**

- TV antenna cables typically have 75Ω, although look similar to these
- Twin lead portable TV cables Z ~ 300Ω

Termination and Matching



- boundary conditions at termination

$$I_{inc} + I_{ref} = I_L \quad \& \quad V_{inc} + V_{ref} = V_L$$

apply them (NB $V_{ref} = -I_{ref} Z_0$)

$$V_{ref}/V_{inc} = (Z_L - Z_0)/(Z_L + Z_0)$$

$$V_L/V_{inc} = 2Z_L/(Z_L + Z_0)$$

- open circuit termination $Z_L = \infty$

$V_{ref}/V_{inc} = +1$ $V_L/V_{inc} = 2$ reflected signal = incident signal

- short circuit termination $Z_L = 0$

$V_{ref}/V_{inc} = -1$ $V_L/V_{inc} = 0$ inverted fully reflected signal

- matched termination $Z_L = Z_0$

$V_{ref}/V_{inc} = 0$ $V_L/V_{inc} = 1$ 100% transmission to load

- improper termination usually causes unwanted effects

but can sometimes make make use of reflection

eg short circuit termination + step pulse = square pulse with width = $2\Delta t$

- why don't we always match terminate?

To match or not? (i)

- Impedance matching is a general question, not only for transmission lines
- Match if
  - to transfer maximum power to load (source must be capable)
    - eg audio speakers
  - minimise reflections from load
    - very important in audio, fast (high frequency) systems, to avoid ringing or multiple pulses (eg in counting systems)
  - fast pulses
    - pulse properties can contain important information
    - usually don't want to change
    - sometimes we wish to do this with "too fast" signals - "spoiling"
- Usually match by choosing impedances, adding voltage buffers
  - transformer matching is another method if this is impractical
- The same physics is encountered in other areas
  - eg optical coatings, gel in ultrasound scans, optical grease,...

To match or not (ii)

- Don't match if
  - High impedance source with small current signals - typical of many sensors
    - photodiode, or other sensors must drive high impedance load
    - short cables are required to avoid difficulties
  - Weak voltage source, where drawing power from source would affect result
    - eg bridge circuits
  - require to change properties of fast pulse
    - eg pulse widening for ease of detection
  - electronics with limited drive capabilities
    - eg logic circuits, many are designed to drive other logic, not long lines
    - CMOS circuits, even with follower, are an example

- If you get this wrong, often end up with new time constants in the system

  or prevent system from working at all, eg diode with low R load

Coaxial cable limits

- Transmission speed and bandwidth limiting

  all cables have finite resistance

  remarkably small - see table for calculated values

  for long cables, RC time constant per unit length becomes noticeable

  therefore expect delay, attenuation and finite rise time in fast pulses

- When is a cable a transmission line?

  not reasonable to assume transmission line behaviour unless length of line is at least ~ 1/8 wavelength

- Other forms of transmission line

  in high speed circuits, tracks must be laid out carefully using knowledge of the characteristics of the boards to control delays, rise times and signal velocities

  eg parallel tracks,...

  often need measurement to define parameters precisely

  ultra high freqencies need waveguides or alternative

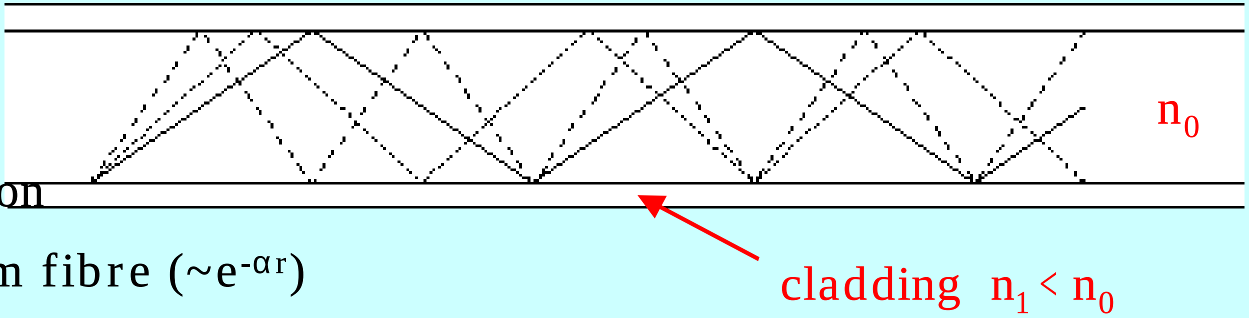
Optical fibres

- Principle: transparent dielectric with $n_0 > n_1$ = lightguide

  usually glass: high silica content, doped with fluorine or oxides

  Light propagates by multiple reflections - expect attenuation

  $T \sim R^n$



- Cladding - as well as n_1 provides

  mechanical strength & protection

  limits evanescent radiation from fibre ($\sim e^{-\alpha r}$)

  limits spread of velocities down fibre (different routes) - $\Delta t/L \approx \Delta n/c$

- Advantages of fibre

  size, weight and flexibility - typical diameter ~ 250µm

  electrical isolation - interference immunity, can mix with electrical cable

  low transmission loss - as low as 0.2dB/km

  security - hard to tap into

- Cons - (more fragile), connections, need for opto-electronic conversion

  electronic circuits matching speed of fibres ~ multi-Gb/s

Modes

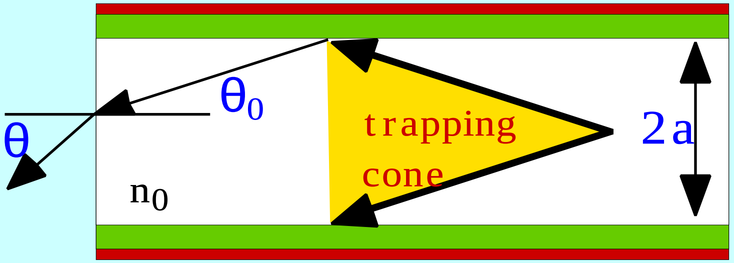
- ray picture inadequate - need to consider wave equations in waveguide

  solutions to Maxwell's equations - cylindrical symmetry

  $\psi = \psi(r,\varphi)\exp[-j(\omega t-\beta z)] \qquad \beta = 2\pi/\lambda$

  eigenvalue solutions for different β at given ω: modes

  ie not all rays permitted



- Single and multi-mode fibre

  $NA = \sin\theta = n_0 \sin\theta_0 = (n_0{}^2 - n_1{}^2)^{1/2}$

  no. modes ~ core area and $(NA)^2$

  but find solutions where only single mode propagates

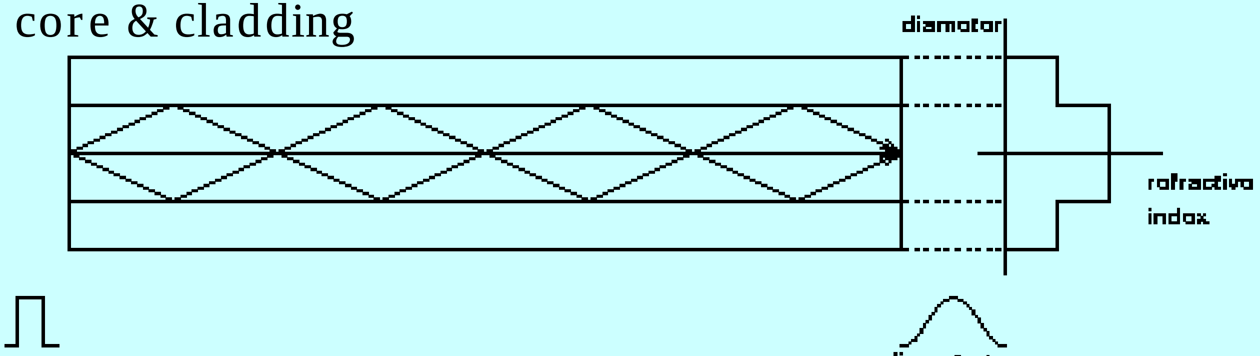
  provided $\lambda > 2\pi a.NA/2.405$

- single mode fibre

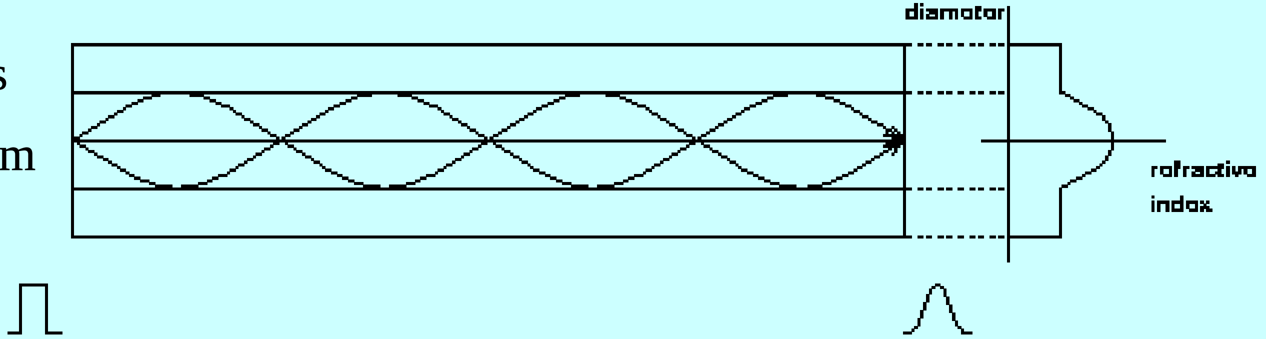
  dominates long distance telecomms

Fibre types

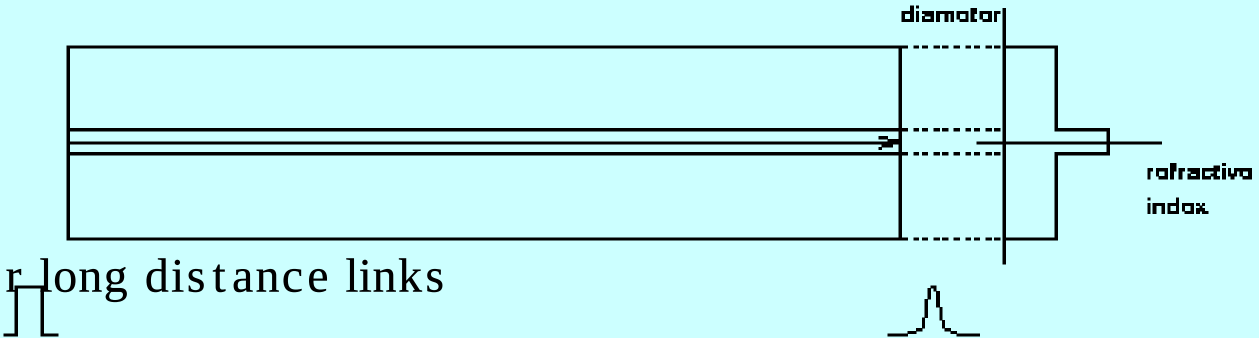
- Step index
  - uniform ref. index throughout core & cladding
  - core diameter ~100-500µm
  - multi-mode



- Graded index
  - ref index changes with radius
  - core diameter 50µm or 62.5µm
  - multi-mode



- Single mode
  - very narrow core ~8µm
  - Δn ~ 0.35%
  - minimum dispersion so ideal for long distance links
  - cheaper to produce than graded index



Attenuation in fibres

- Quality is now so high that attenuation is close to physical limits

  Rayleigh scattering λ ≤ 1.2μm

  glass absorption (GeO_2, B_2O_3, SiO_2 band edges at longer wavelengths)

  absorption peak λ ~ 1.4μm (OH- impurity ions)

  waveguide imperfections & bending - low level

- Telecommunications

  λ ≈ 1.3μm & 1.55μm

  optical amplifiers ~ 80km

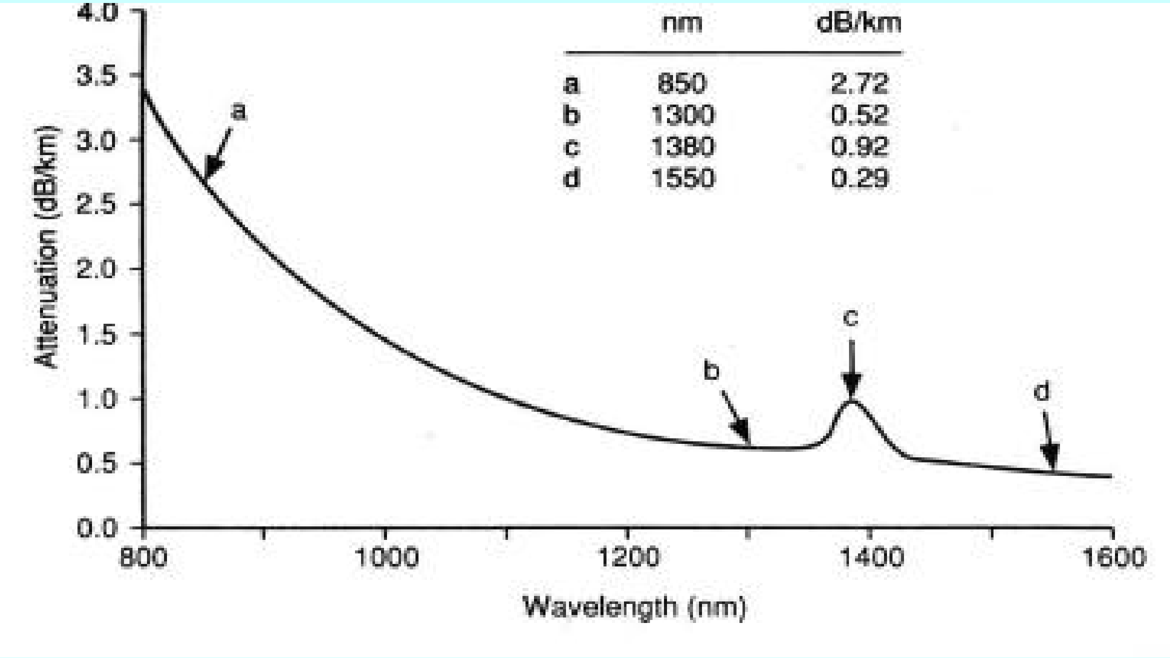
- Short distance, eg LAN

  λ ≈ 0.85 - 0.9μm

  earlier attenuation minimum

  &

  availability of optical transmitters



	nm	dB/km
a	850	2.72
b	1300	0.52
c	1380	0.92
d	1550	0.29

Limits

- Dispersion- mainly chromatic

  material: λ dependence of n

  waveguide: λ dependence of c_{fibre}

$$D(\lambda) \approx S_0[\lambda - \lambda_0^4/\lambda^3] \ \text{ps/(nm.km)}$$

$$S_0 \approx 0.025 \ \text{ps/(nm}^2\text{.km)} \quad \lambda_0 \approx 1310\text{nm}$$

- Analogue vs digital - both kinds of data are transmitted

	Pros	Cons
Analogue	Avoid digitisation circuits/power	Signal distortion/attenuation require good linearity
Digital	Transmit 0/1	need complex circuits & power many bits needed => high speed

  telecommunications and computer: digital dominates

  cable TV, phone: analogue

- Bandwidth constantly striving to increase, eg fibre quality
- Connectors typically expensive and care needed to avoid dirt, damage

  but fibre is cheap so maximise length before connections