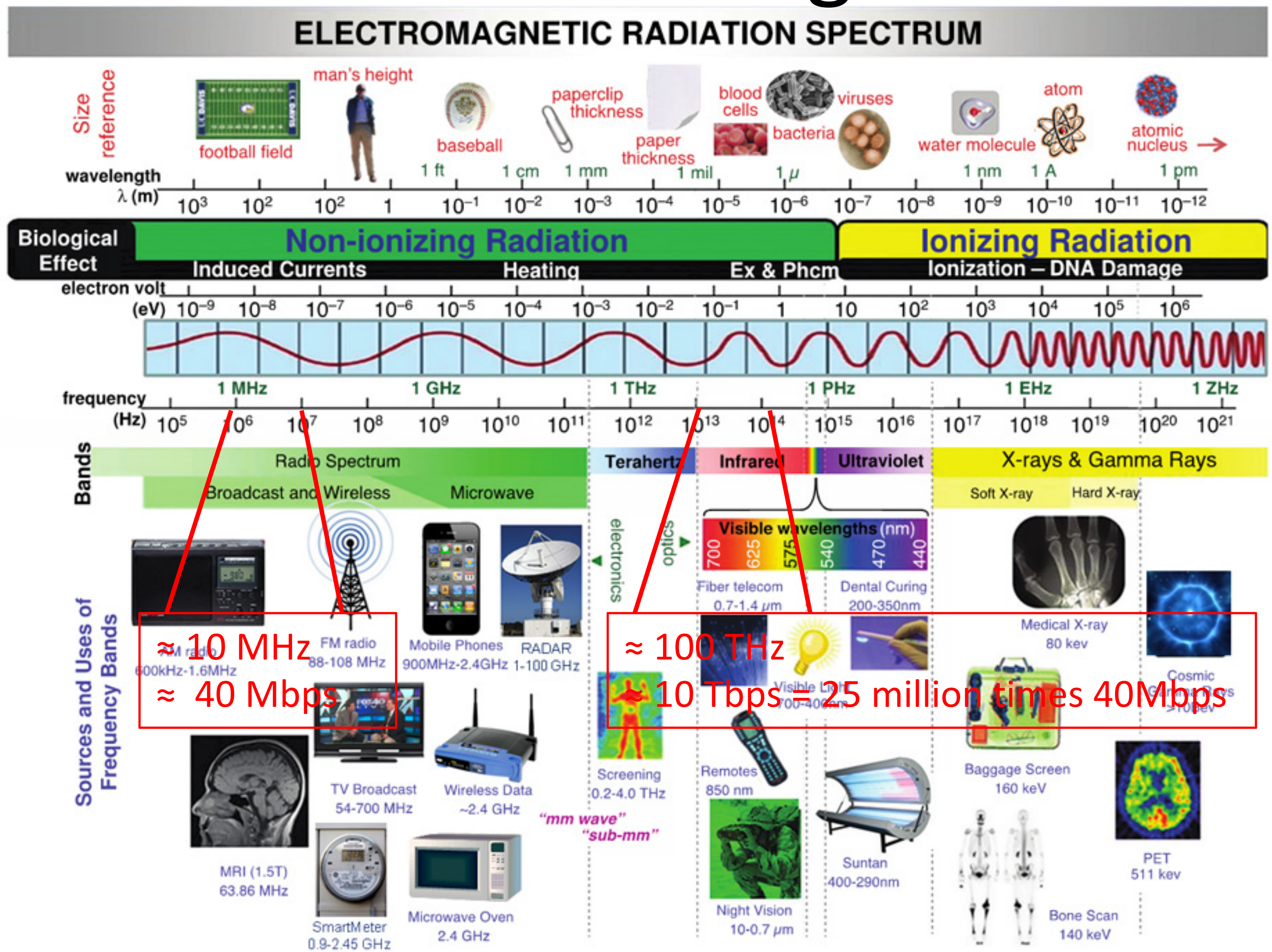
Transmission of signals and impairments (attenuation and distortion)

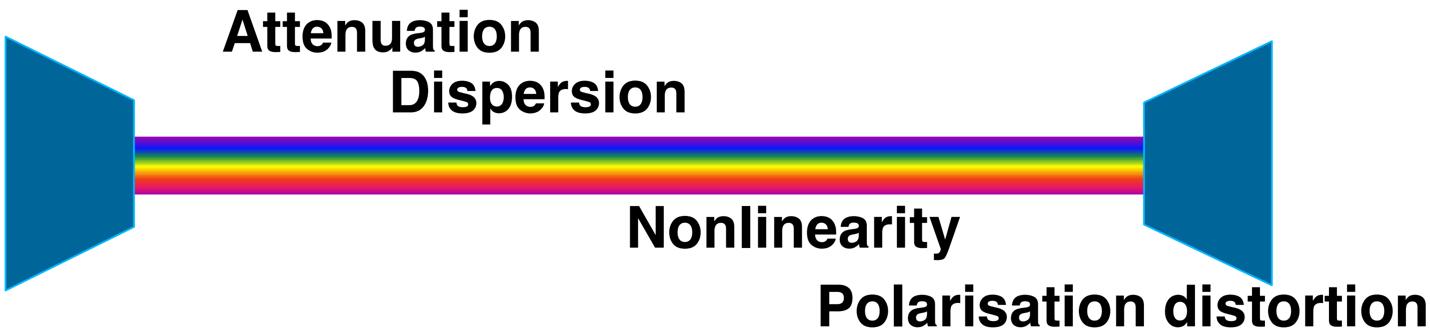
Optical fibre

- Uses the total internal reflection phenomenon
- Typical path loss is 0.2 dB/Km
  - Signal can go 150 Km without amplification

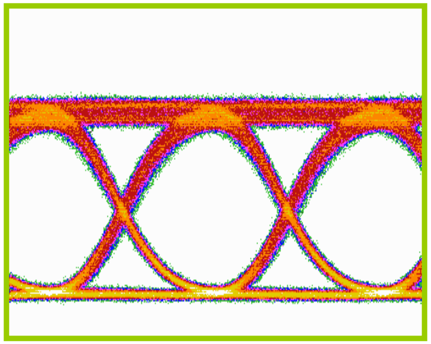
What is light?



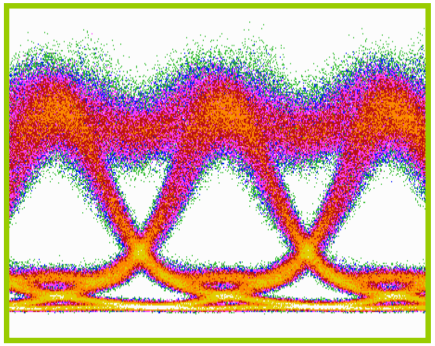
FIBRE FUNDAMENTALS



The aim is to transmit signals with the minimum distortion



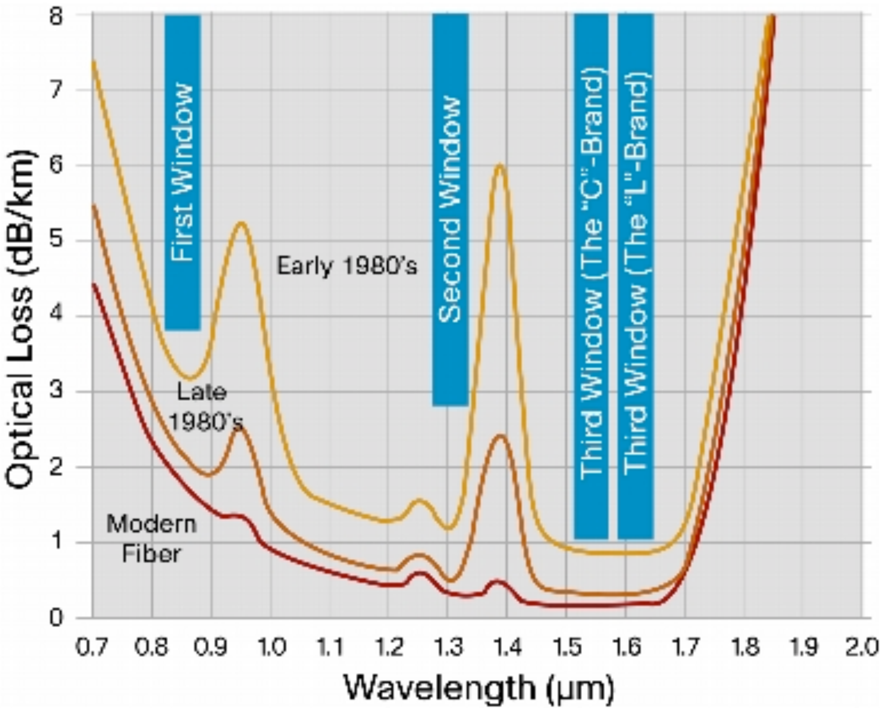
Transmitted Data Waveform



Waveform After 1000 Km

Path loss in fibre

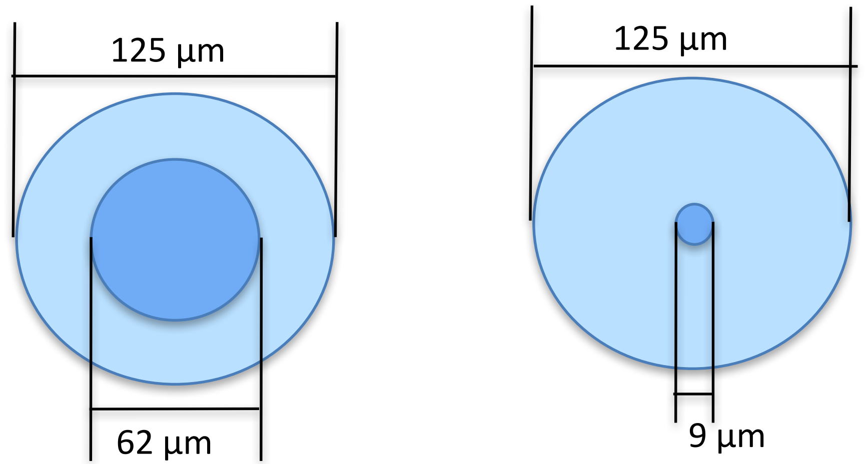
- The amount of power lost during propagation depends on the frequency (or wavelength) used for transmission.
- The smallest loss is at a wavelength of 1.55 μm, and is 0.2 dB/Km



Single-mode vs. multi-mode

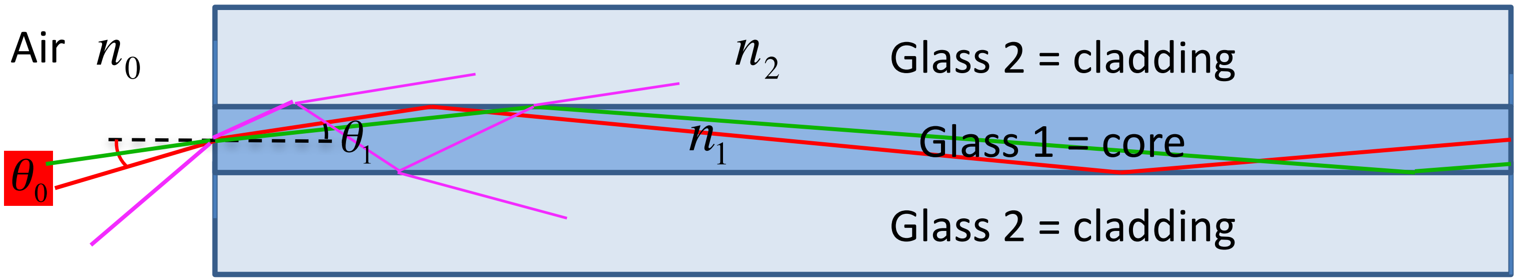
- An optical fibre is made of very pure glass
  - It has a core and a cladding, both made of glass, but with different refraction indexes
- A multi-mode fibre has a larger core, which allows multiple modes of propagation to coexist
- A single-mode fibre has a smaller core, which only allows one propagation mode.

Multi-mode fiber   Single-mode fiber



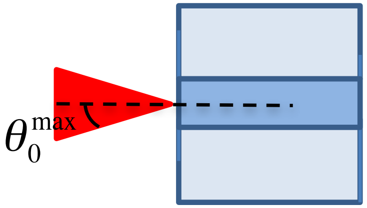
Single-mode fiber is the most used in telecommunications

Propagation in optical fibre



This fibre is called step-index, because the index n changes suddenly between cladding and core.

- Rays (green, red) incident at an angle $\leq \theta_0^{max}$ will propagate in the fibre through total internal reflection
- Rays (magenta) incident at anangle $> \theta_0^{max}$ will loose power while propagating through the refracted ray



All rays with $\theta_0 \leq \theta_0^{max}$ form a "Cone of acceptance"

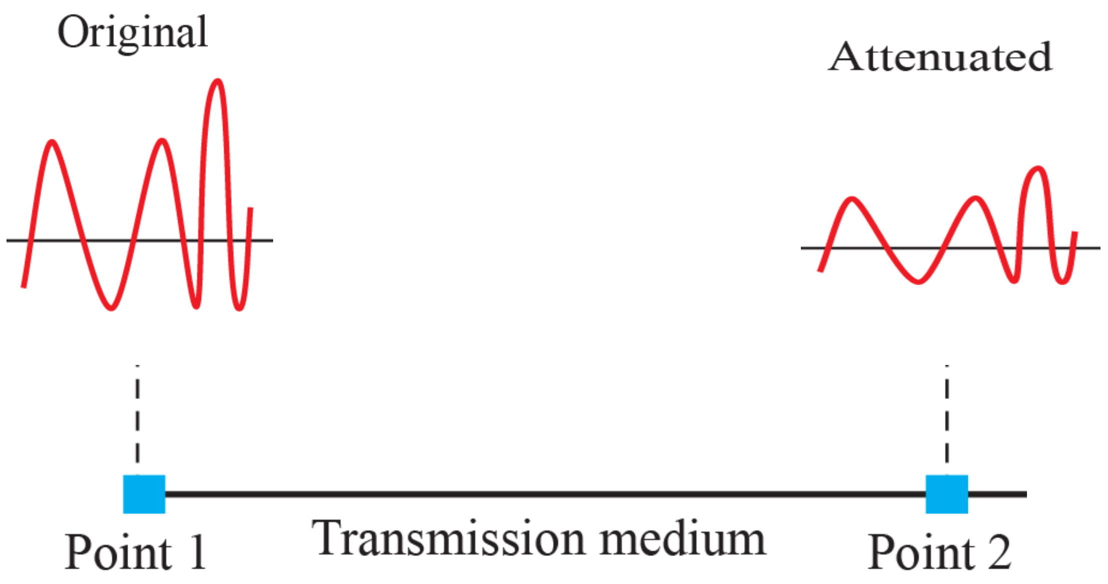
$$\theta_0^{max} = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

Signal impairments

- In the real world, signal are transmitted through media which are imperfect, and will change some of the signal properties, thus deteriorating the information it carries.
- Signal impairments can be grouped into three categories:
  - **Attenuation**: the signal looses power as it propagates
  - **Distortion**: the signal changes shape as it propagates
  - **Noise**: interference with other man-made or random signals.

Attenuation

- Attenuation reduces the signal power progressively as it propagates in a lossy medium.



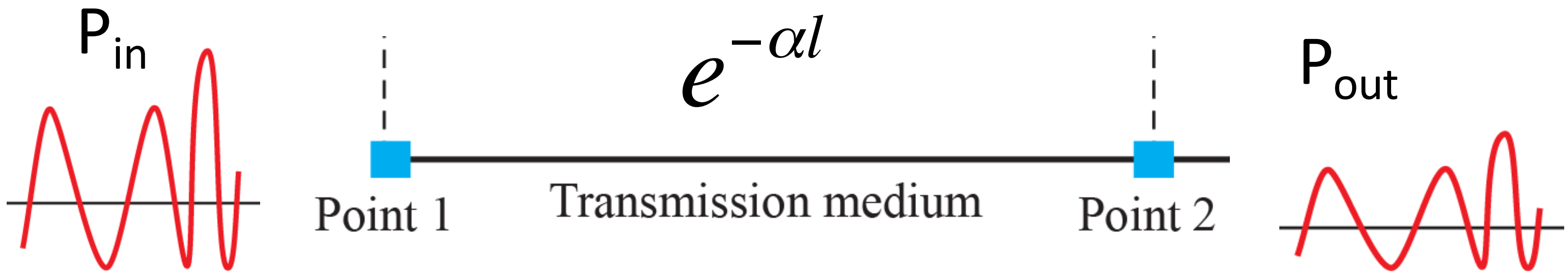
Attenuation calculations

- The loss of power in a lossy transmission medium follows an exponential law.
- If we name P_{in} the input power we launch in the medium and P_{out} the output power, this relation holds:

$$P_{out} = P_{in} e^{-\alpha l} \text{ [W]}$$

α is the loss coefficient, l the transmission distance

- Power is measured in Watts [W]



Power loss

- In telecommunication systems it is common to measure the power loss, which can be expressed as the ratio between output power and input power

$$L = \frac{P_{in}}{P_{out}} = e^{\alpha l}$$

The Decibel unit (dB)

- Decibels (dB): since power loss follows an exponential law, typical ranges can be several order of magnitude: i.e. from 0.0000001 to 1000 Watts [W]
- It is common to use a **logarithmic** scale to represent the **<u>ratio</u>** between two quantities.
- Since power loss (L) is the ratio between two quantities, this can be well expressed in dB

$$L_{dB} = 10 \log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

- notice that being a ratio of two similar dimensions **L is dimensionless**

dB conversions

- $L = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$ tells how to calculate exactly the dB value, so you can do that precisely with a calculator

- However there are also simple useful rules that can be applied:
  - doubling the loss equals adding 3dB
  - halving the loss equals subtracting 3dB

  - Multiplying the loss by 10 means adding 10dB
  - Dividing the loss by 10 means subtracting 10dB

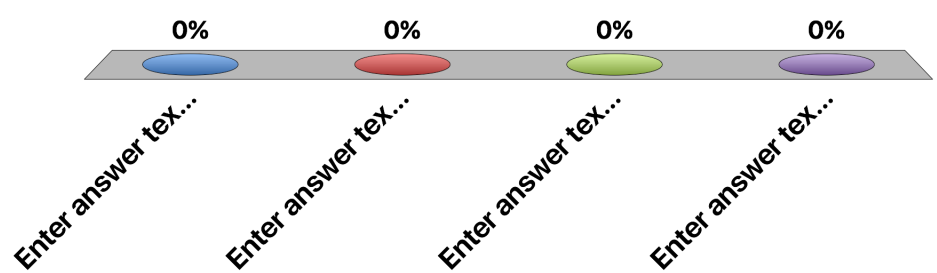
Loss ratio	Loss in dB
1	0
2	3
4	6
10	10
100	20
0.4	-4
0.1	-10
0.01	-20

Examples of dB conversion

- Convert a loss of 80 into dB
  - ➔ 80 = 1 x 2 x 2 x 2 x 10
  - ➔In dB= 0 + 3 + 3 + 3 + 10=19dB
- Convert a loss of 0.04 into dB
  - ➔ 0.04 = 0.01 x 2 x 2 = 1 / 100 x 2 x 2
  - ➔ In dB = 0 - 20 +3+3 =-14
  - (A negative loss is an amplification!)
- Convert a loss of 22 dB into decimal
  - ➔23 = 0 +3 +20
  - ➔ In dB = 1 *2 *100 = 200

Why use dB (i.e., logarithmic scale)?

A. It expands a small range into a large interval of numbers
B. It can be measured in Watts
C. It increases by multiple of 3 dB
D. It compresses a large range of values into smaller numbers



dBW and dBm

- We said that dB is dimensionless, so it cannot be used to measure input or output power but only their ratio (i.e., the power loss)
- However, if I put at the denominator a fixed reference power of 1W, then I can express power unit in **dBW**.

$$P_{dB} = 10\log_{10}\left(\frac{P_{in}}{1W}\right)$$

- P_{dB} is measured in:
  - dBW (dB_Watt), if the reference power is 1 W
  - dBm (dB_MilliWatt) if the reference power is 1mW

dBW

- $P = 10\log_{10}\left(\frac{P_{in}}{1W}\right)$ gives the precise amount of dBW

- However the same simple rules we saw can be applied here as well:
  - doubling the power equals adding 3dB
  - halving the power equals subtracting 3dB

  - Multiplying the power by 10 means adding 10dB
  - Dividing the power by 10 means subtracting 10dB

Loss ratio	Loss in dB
1	0
2	3
4	6
10	10
100	20
0.4	-4
0.1	-10
0.01	-20

dBm

$$P = 10\log_{10}\left(\frac{P_{in}}{1mW}\right) = 10\log_{10}\left(\frac{P_{in}}{0.001W}\right)$$ expresses power in dBm

- Same simple rules apply…
- Notice the relation between dBW and dBm:
- 1 mW = 0.001 W= 1 W / 1000

➔ 0 dBm = = 0 dBW -30= -30dBW

So dBm and dBW are separated by 30 dB

Loss ratio	Loss in dB
1	0
2	3
4	6
10	10
100	20
0.4	-4
0.1	-10
0.01	-20

Attenuation calculations in dB

- One advantage of dB calculations is that when using logarithms, multiplication and divisions become addition and subtraction
- If I have an input power of 8 mW and a loss value of 200:
  - Out power in mW: $P_{out} = \frac{8}{200} = 0.04mW$
  - Out power In dBW: $P_{out} = 9dBm - 23dB = -14dBm$

Example

- A signal with a launch power of 4 mW propagates through 100m of line with loss of 0.1 dB/m, it then gets amplified by 200 times, and is transmitted again through another transmission line with an overall loss of 22 dB.
- What is the power at the receiver in mW?

- The best way is to work in dB, so change all values into dB and then operate sums and subtractions:
  - Launch power 4 mW ➔ 6dBm
  - First loss: 100m x 0.1dB/m ➔ -10dB
  - Amplification of 200 times ➔ +23dB
  - Second loss ➔ -22 dB

  ➔ Received power = 6-10+23-22=-3 dBm ➔0.5 mW

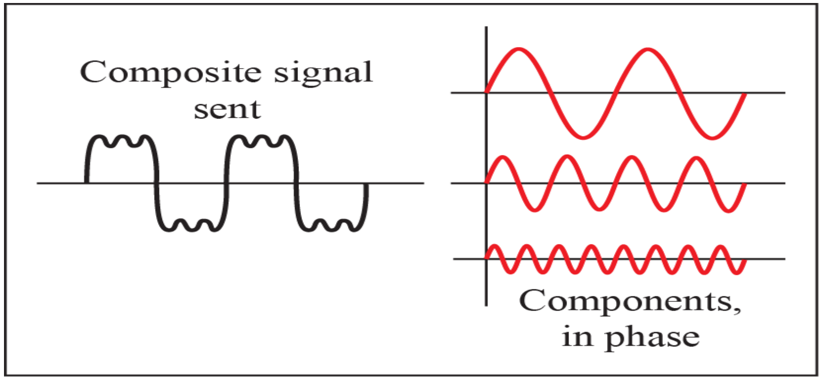
Notice that when I calculate output power, losses are subtractions and amplification are sums!

Signal impairments

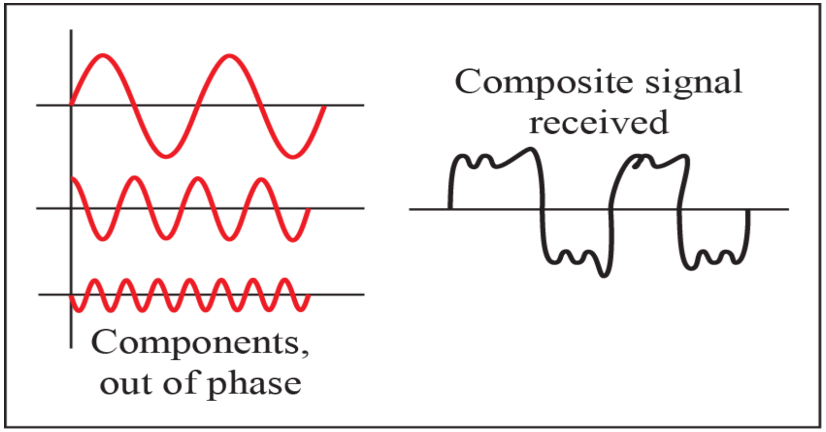
- **Attenuation**: the signal looses power as it propagates
- **Distortion**: the signal changes shape as it propagates
- **Noise**: interference with other man-made or random signals.

Distortion

- Distortion changes the shape of the signal as it propagates. The reason is that the different frequencies propagate differently in the transmission medium (i.e., at different speed).
- Since a signal is the sum of multiple frequency components, at the receiver the frequency components will sum up with different delays, building a different signal from the original



At the sender



At the receiver

Dispersion in optical fibre

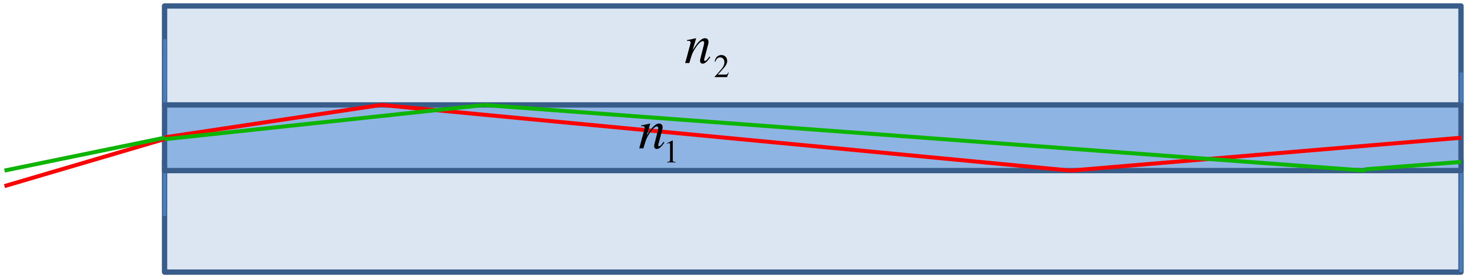
- Dispersions is a major cause of distortion in optical fibre. There are three types of dispersion:
  - Modal dispersion: occurs in multi-mode fibre, where different modes can propagate in parallel at different speed. This is very severe, but it only occurs in multi-mode fibres.

  ➔ Today typically single-mode fibres are used, which do not suffer from this issue.

  - Chromatic dispersion: because a light pulse (even if made of a single mode) is composed by different frequencies (remember the Fourier Series/Integral) which propagate at different speed. This causes the light pulse to spread out.

  - Polarization mode dispersion: because pulses typically propagate across two perpendicular polarizations, a vertical one and a horizontal one. Due to fibre asymmetries one polarization can propagat at a different speed than the other, causing the whole pulse (seen as the sum of the two polarizations) to spread out.

Modal dispersion



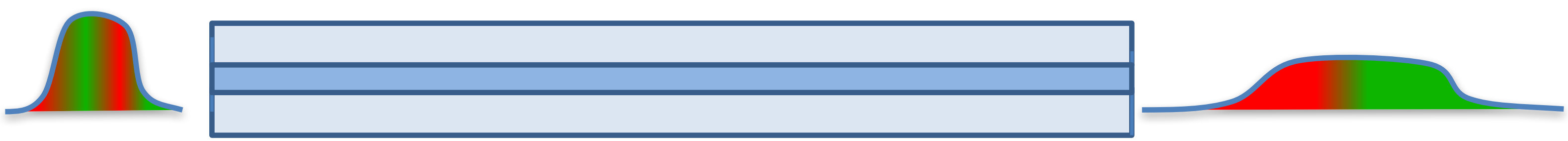
-The green and red rays are called modes of propagation in the fiber.

-Since red is reflected at a narrower angle than green, it will travel a longer distance for a same amount of fibre.

-Since green and red travel at the same speed, red will arrive at destination later than green.

Impairments caused by modal dispersion

- If I transmit a pulse it will be composed of a number of different rays, for example red and green

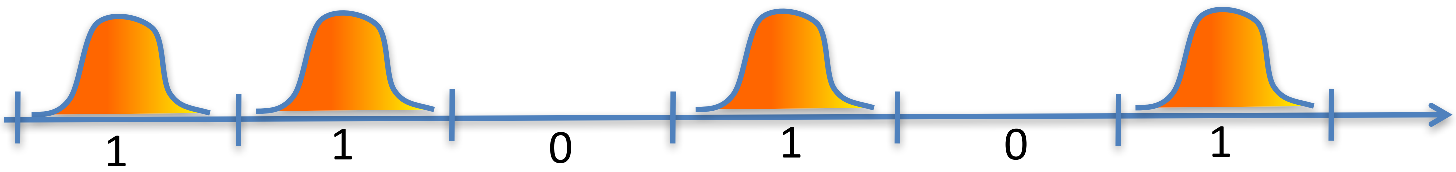


because red is slower than green the pulse spreads, and its peak power decreases

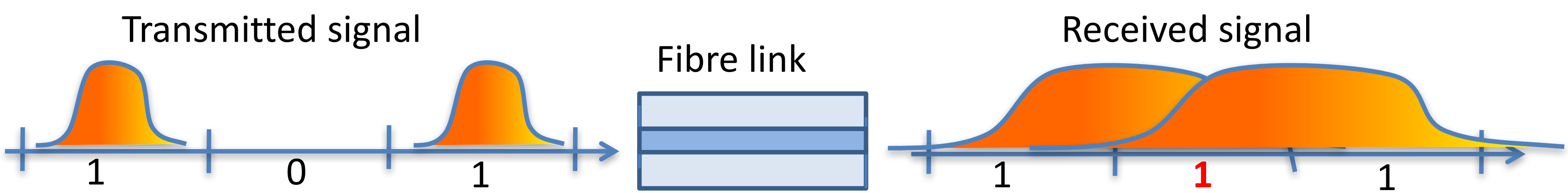
- In a communication channel where I transmit a series of pulses, they end up overlapping ➔ <u>*intersymbol interference*</u> **(ISI)**

Chromatic dispersion

- Each pulse has a finite spectral width as it's made of a number of adjacent frequencies (remember the Fourier series/integral)



- Chromatic dispersion makes different frequencies travel at different speed: as a result the pulse spreads, causing transmission errors



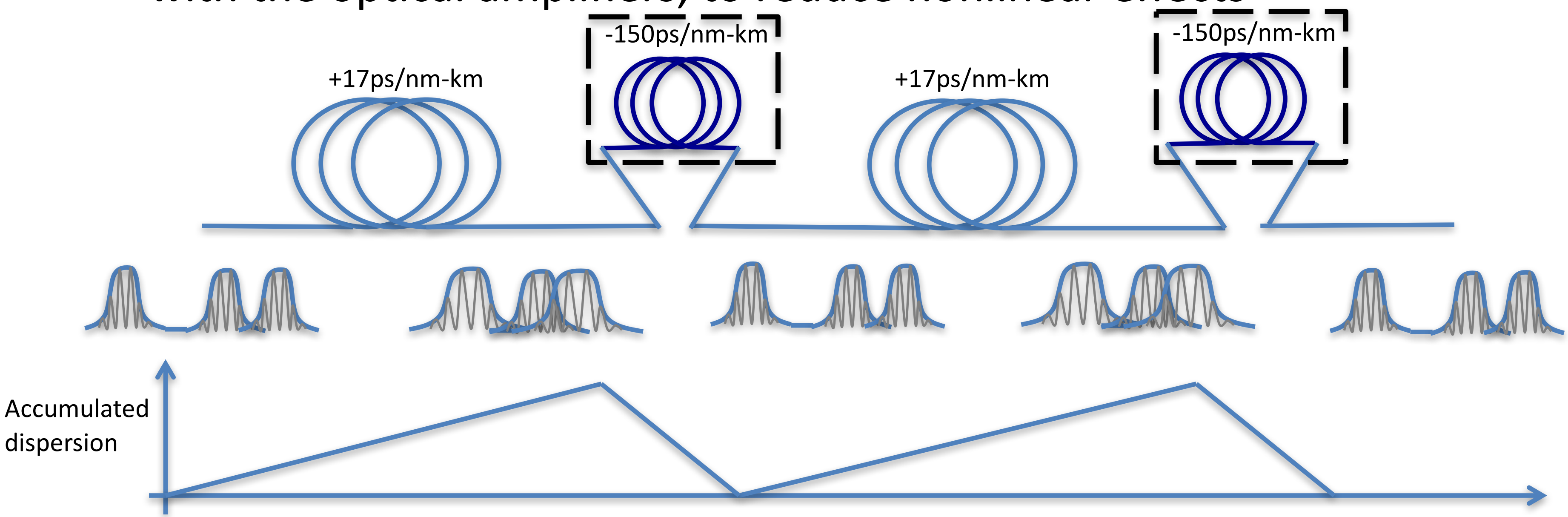
Chromatic dispersion calculation

- The dispersion coefficient D is $D = -\frac{\lambda}{c}\frac{\partial^2 n}{\partial \lambda^2}$ and is measured in $\frac{ps}{nm \cdot km}$
- We see it depends on the variation of the refractive index with wavelength, as well as to the wavelength itself
- In fibre the refractive index decreases as the wavelength increases (= frequency decreases), thus higher wavelength (= lower frequencies) travel faster than lower frequencies.

- The dispersion increases with the signal bandwidth.
- The pulse broadening increases with the distance.
- D is positive (17 $\frac{ps}{nm \cdot km}$, at 1550 nm) in optical fibre, meaning that a pulse of bandwidth 1 nm, will spread by 17 ps after 1km distance

Chromatic dispersion compensation

- If the dispersion accumulated is too large it will make pulses overlap, thus it needs to be compensated.
- Up to a few years ago, a typical way of compensating chromatic dispersion consists on adding a length of fiber with opposite dispersion characteristic, called Dispersion compensating Fibre (DCF)
- If done with DCF, compensation can be done at the end of the link. However it is usually distributed over multiple stages and co-located with the optical amplifiers, to reduce nonlinear effects



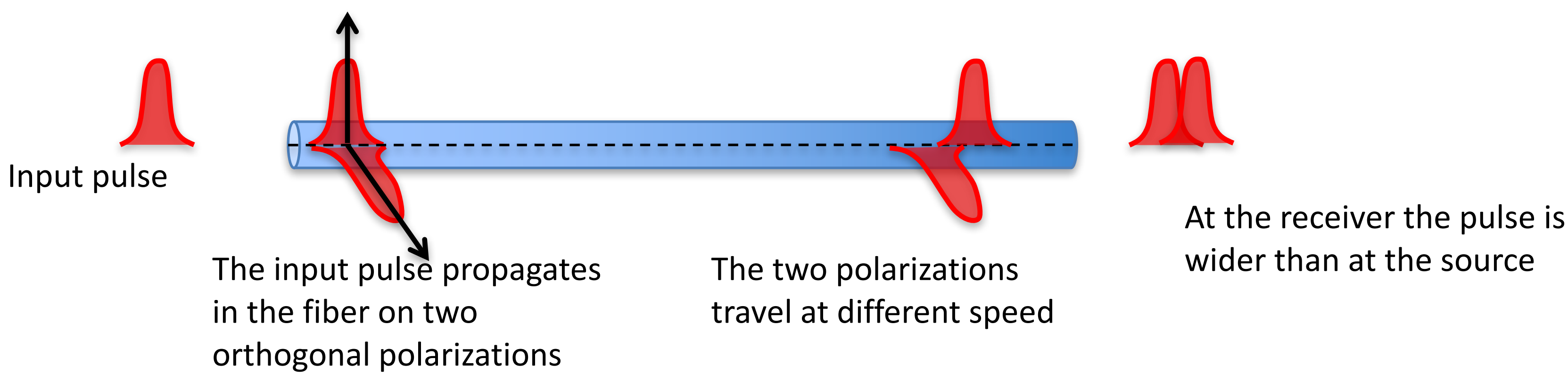
Modern Dispersion compensation

- Today coherent transmission systems can digitally compensate for all dispersion at the receiver.
- Since the receiver has both amplitude and phase information of the received signal, and the dispersion of fibre is well know, the receive can fully compensate it by applying a digital filter.
- In this module, as far as exercises are concerned, we'll assume that the dispersion can be compensated at the receiver.

Polarization-mode dispersion (PMD)

- The electric field in a single mode fibre propagates with two orthogonal polarization
- Because of imperfect production techniques, the fiber is not completely symmetrical

    ➔ The two orthogonal components of the electric field have different propagation characteristics



- PMD is less severe than chromatic dispersion: about 0.5 ps/km

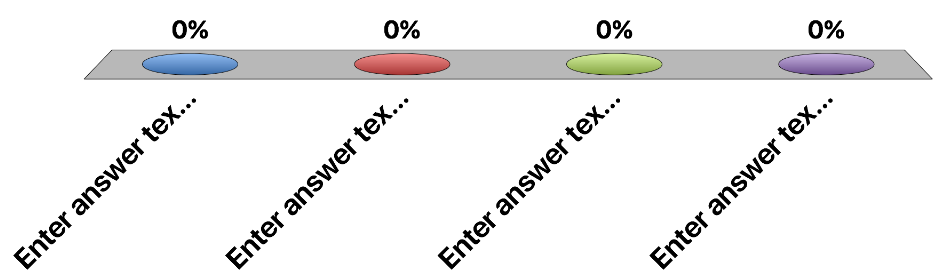
Distortion caused by non-linear effects

- Nonlinearity implies that the transfer function of the fiber depends on the signal being transmitted. Their effects increase with the transmitted power.

- Mentioning a few effects:
  - Self-phase modulation (SPM): since the refractive index depends on the intensity of the traveling light, an amplitude-modulated signal sees different values of n, and is subject to a different propagation constant
  - Cross-phase modulation (CPM): if there are multiple wavelengths in a fiber (WDM), the modulation of other wavelengths produce changes in the refractive index that affects (re-modulate) the signal
  - Both SPM and CPM produce a broadening of the pulse, so create additional dispersion and are more problematic at higher rates
  - Four-wave mixing (FWM): the refractive index nonlinearity also generates new frequencies (e.g. $2\omega_i - \omega_j, \omega_i + \omega_j - \omega_k$). This can generate noise in WDM systems. It does not depend on data rate, but it is worse when the waveneght spacing is small

What is the largest cause of dispersion in single-mode fibre

A. Modal dispersion
B. Chromatic dispersion
C. Polarisation-mode dispersion



In single mode fibre

A. Propagation speed increases with frequency
B. Dispersion is not compensated in modern coherent systems
C. Multiple wavelengths can propagate in parallel
D. modal dispersion is 100 times less severe than chromatic dispersion