Topic 5

5. Loss and dispersion limits

5.1 Introduction

5.2 Review of Fibre Properties

i) Repeater spacing (longest length without “boost”)

ii) Bandwidth

5.3 Characteristics

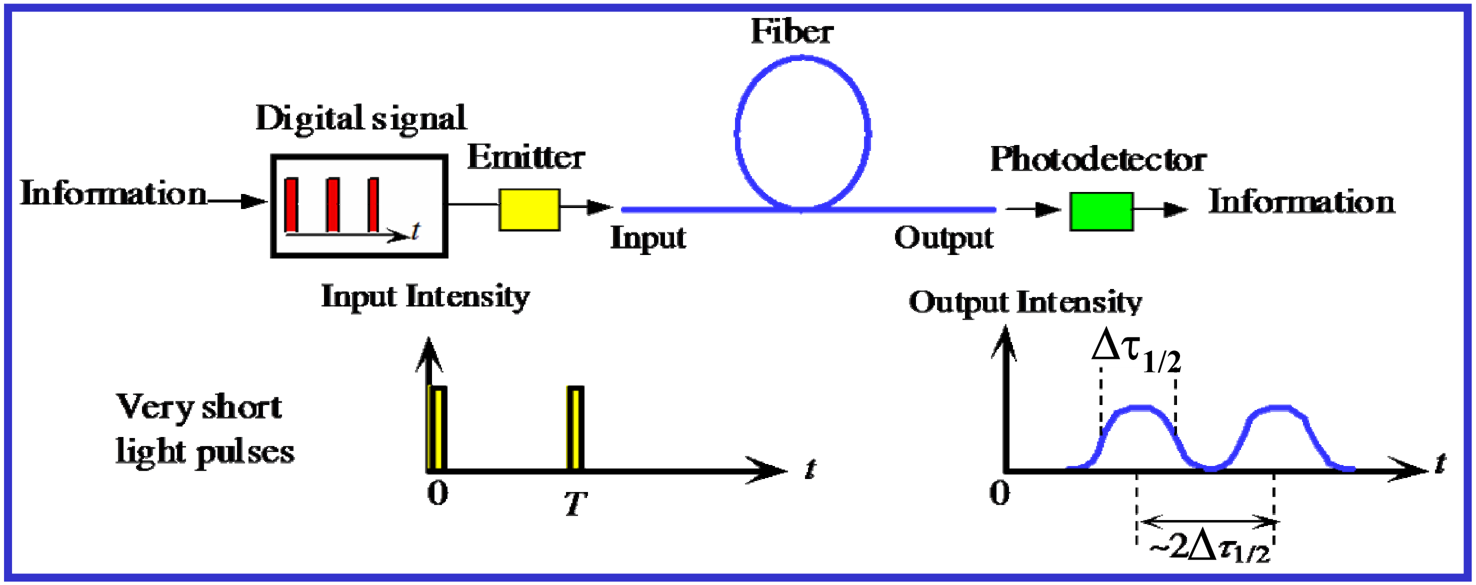
i) Attenuation

ii) dB and dBm

iii) Dispersion

5.4 Power Budget

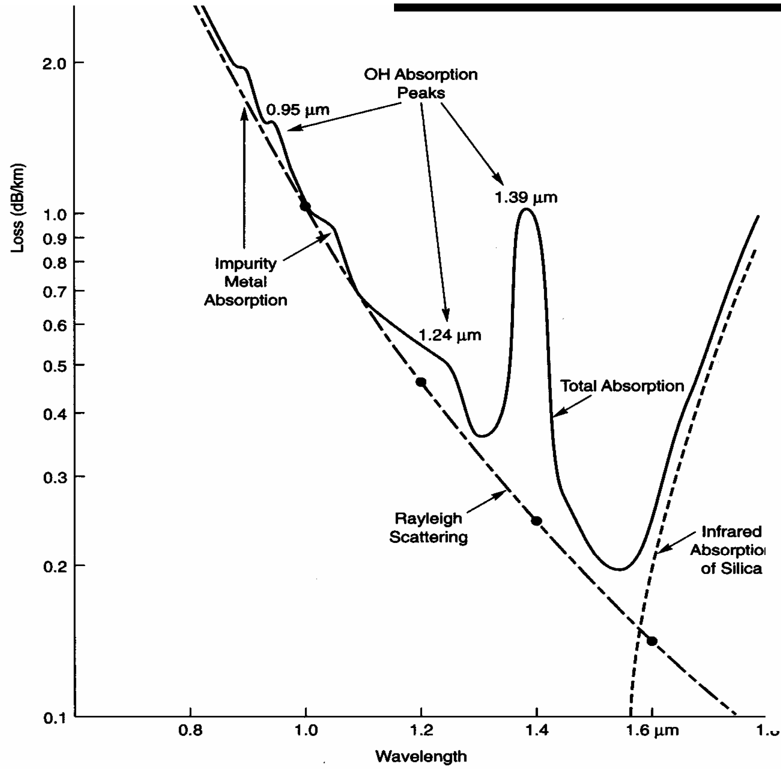
Introduction

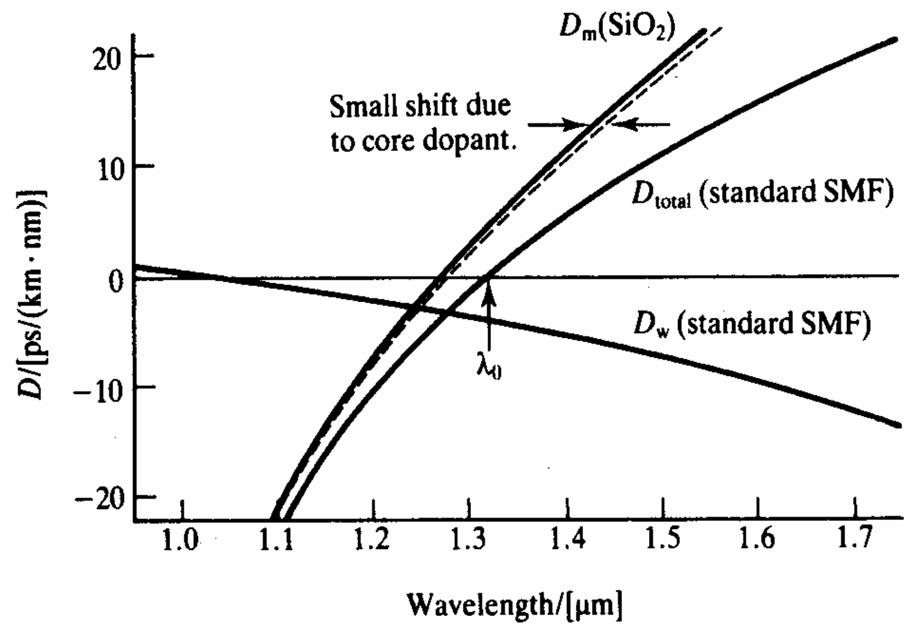


The limits in an optical communication system:

1. Signal attenuation due to optical loss: limit how far the signal can travel (longest distance without "boost")
2. Signal distortion due to optical dispersion: limit signal resolution (bit-rate)

Review of Fibre Properties





Optical loss: 5 major reasons (see Slide 3 in Topic 4)

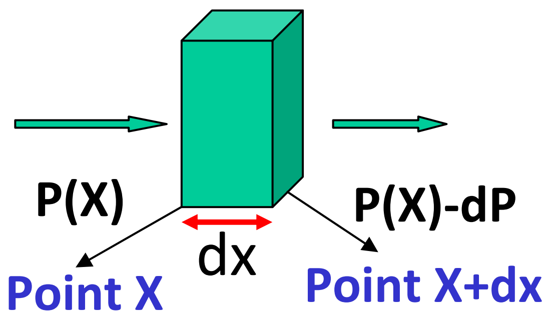
Optical dispersion: Intermodal and Intermodal (material, waveguide)

Minimising optical loss and optical dispersion: longest length of optical fibre and highest bit-rate

Attenuation coefficient

- Definition of attenuation coefficient (α): fractional decrease in optical power per unit distance

$$\boxed{\alpha = -\frac{1}{P}\frac{dP}{dx}}$$



P(x): optical power in the fiber at a location X from the input

- Unit dB: **Number of Decibels for loss**

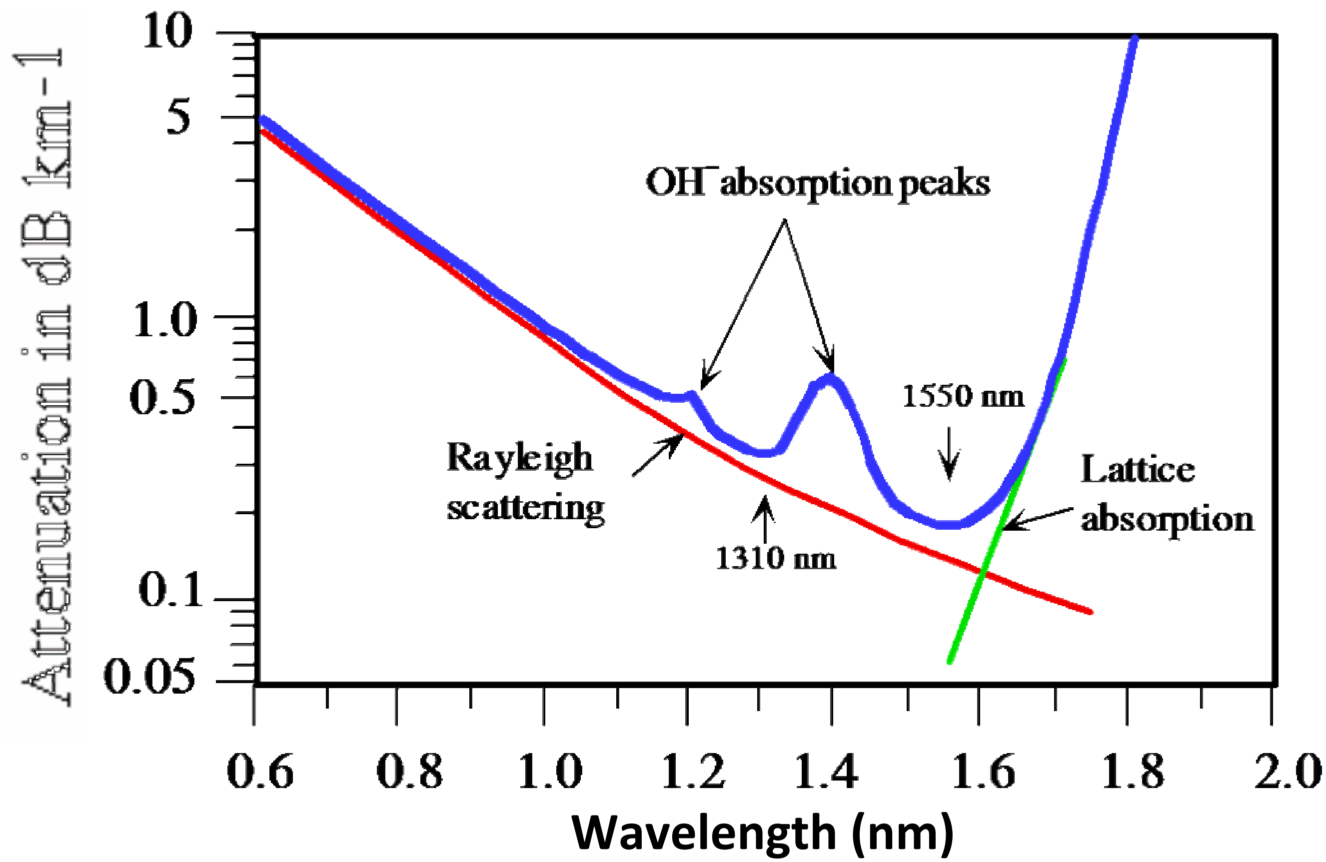
$$\boxed{dB = 10\log\left(\frac{P_{in}}{p_{out}}\right)}$$

- Number of Decibels for loss per unit distance (kilometre)

$$\boxed{dB = \frac{10}{L}\log\left(\frac{P_{in}}{p_{out}}\right)}$$

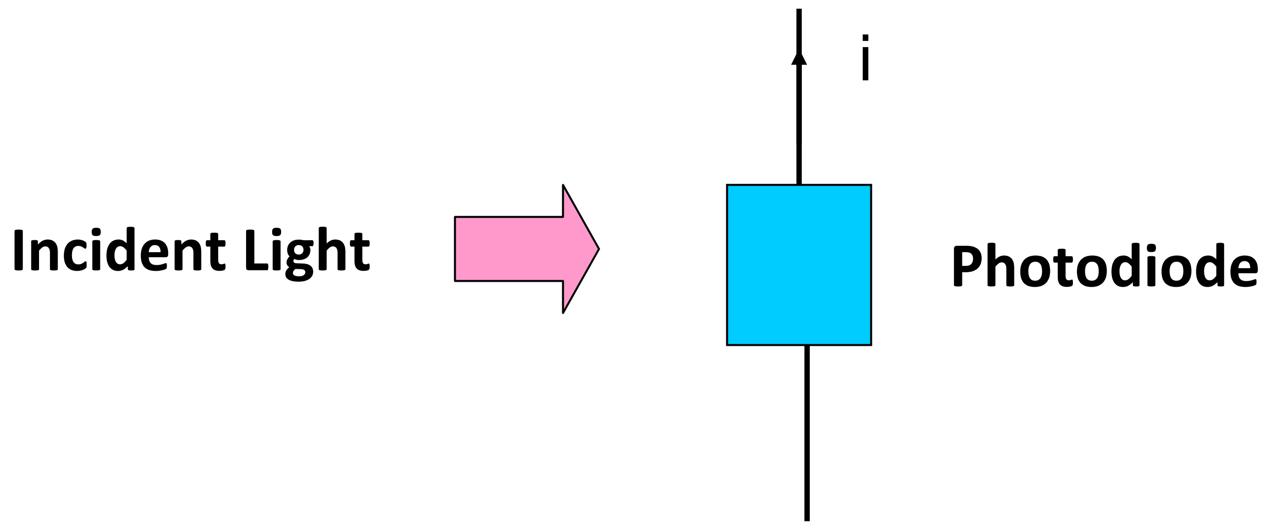
- Optical fibre loss (1000 dB/km~ 1dB/meter) in 1953, meaning **2mW** laser will drop to **1.58 mW** in only a meter distance
- Optical fibre loss (20 dB/km~ 0.02dB/meter) in 1970, meaning **2mW** laser will drop to **1.99 mW** in a meter distance.

Attenuation coefficient of a silica fiber



- Sharp increase at $\lambda > 1.6\ \mu m$ (***infrared*** *region*)
- Strong absorption due to the OH- mainly at 1.2 and 1. 4 μm.
- Latest progress on a new kind of fiber (plastic), eliminating absorption due to OH-

Electrical vs. Optical dBm



- If we double the incident optical power

(1) Optical Power x2 gives – Electrical power x4 as Power $\propto i^2$

(2) 3dB of Optical power gives 6 dB electrical power

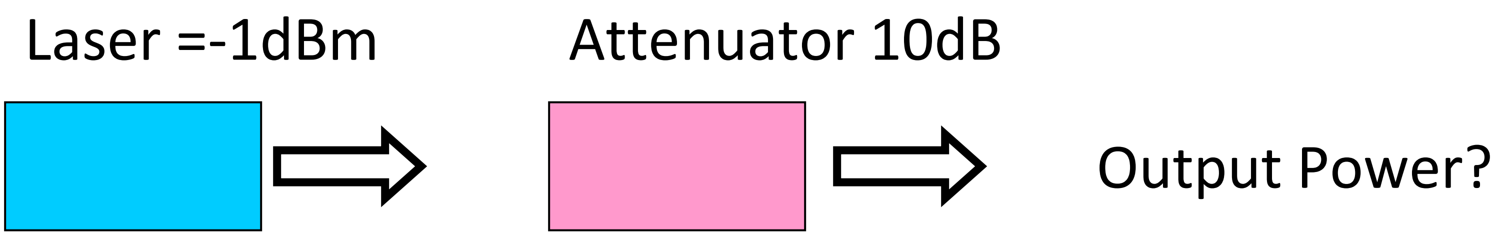
In the rest of this course we only deal with $dB_{opt,}$ unless indicated

Why bother with dBm ? (1)

For convenience, we introduce dBm, which is based on a fixed output power of 1 mW

$$dB = 10\log(\frac{P}{p_{ref}})$$

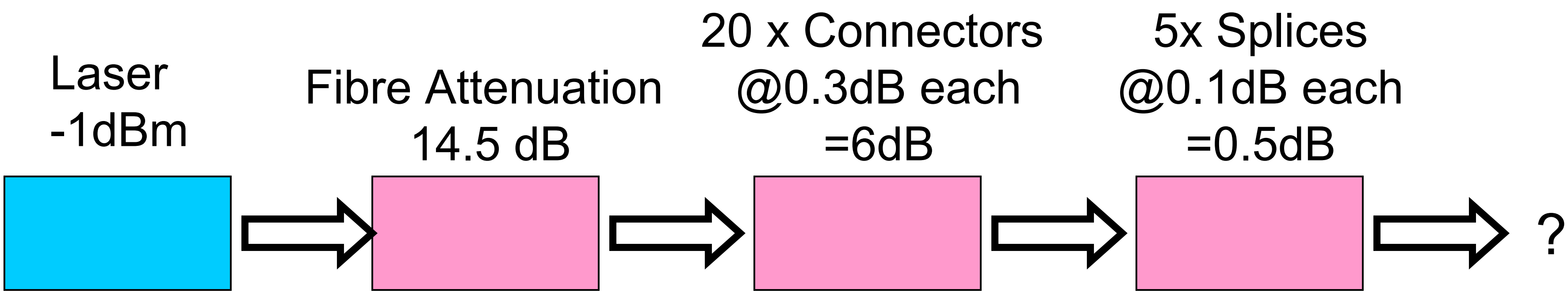
$$dBm = 10\log(\frac{P}{1mW})$$



-1dBm meaning $-1 = 10\log(\frac{P_{in}}{1mW})$

Therefore, P_{out} = 0.7943 mW,
For a 10 dB attenuator, 10 dB means $(P_{in}/P_{out}) = 10^{10/10}$, and thus P_{out} = 0.0794 mW (-11 dBm, i.e., -1dBm-10dB=-11dBm)

Why bother with dBm ? (2)



$$dB = 10\log(\frac{P_{in}}{p_{out}})$$

$$dBm = 10\log(\frac{P_{in}}{1mW})$$

(1) Easy – Total loss = 21dB

$(P_{in}/P_{out}) = 10^{21/10} = 126$

$P_{out} = 0.795mW/126 = 0.63\mu W$

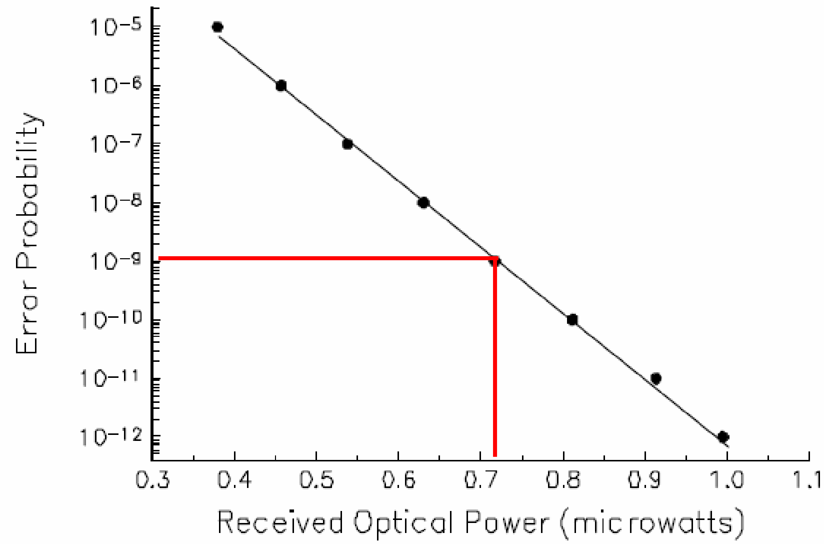
(2) Easier way $\Rightarrow$ -1dBm-21dB = -22dBm = 0.63μW

- Important when we have many sources of gain and loss!
- Remember attenuation is –ve, amplification is +ve

dBm level	Power
80 dBm	100 kW
60 dBm	1 kW = 1000 W
50 dBm	100 W
40 dBm	10 W
37 dBm	5 W
36 dBm	4 W
33 dBm	2 W
30 dBm	1 W = 1000 mW
27 dBm	500 mW
26 dBm	400 mW
25 dBm	316 mW
24 dBm	250 mW
23 dBm	200 mW

22 dBm	160 mW
21 dBm	125 mW
20 dBm	100 mW
15 dBm	32 mW
10 dBm	10 mW
6 dBm	4.0 mW
5 dBm	3.2 mW
4 dBm	2.5 mW
3 dBm	2.0 mW
2 dBm	1.6 mW
1 dBm	1.3 mW
0 dBm	1.0 mW = 1000 μW
−1 dBm	794 μW
−3 dBm	501 μW
−5 dBm	316 μW
−10 dBm	100 μW
−20 dBm	10 μW
−30 dBm	1.0 μW = 1000 nW
−40 dBm	100 nW

Attenuation Limitation-1



• Optical signal is too low, and the correct data cannot be received
(1) An optical communication system: Bit Error Ratio (BER) < 10^{-9}.
(2) The minimum number of photons required depends on receiver sensitivity

• Assuming that the minimum number of photon required is N_p per bit, the bit rate is B, and the wavelength is λ, the minimum optical power requested is given :

$$\boxed{p_{\min} = h \tfrac{c}{\lambda} N_p B}$$

Attenuation Limitation-2

- If we know the optical power of the input optical source P_i and the minimum optical power requested by a photo-detector

$$\boxed{p_{\min} = h\tfrac{c}{\lambda}N_p B}$$

the total optical losses are allowed:

$$\boxed{dB_{total} = 10\log(\frac{p_i}{p_{\min}})}$$

- Assuming that α : loss coefficient of the fiber (in dB/km)

the maximum fiber length would be

$$\boxed{L_{\max} = \frac{dB_{total}}{\alpha} = \frac{10}{\alpha}\log(\frac{p_i}{p_{mim}}) = \frac{10}{\alpha}\log(\frac{p_i}{N_p Bhc/\lambda})}$$

Attenuation and Bit-Rate

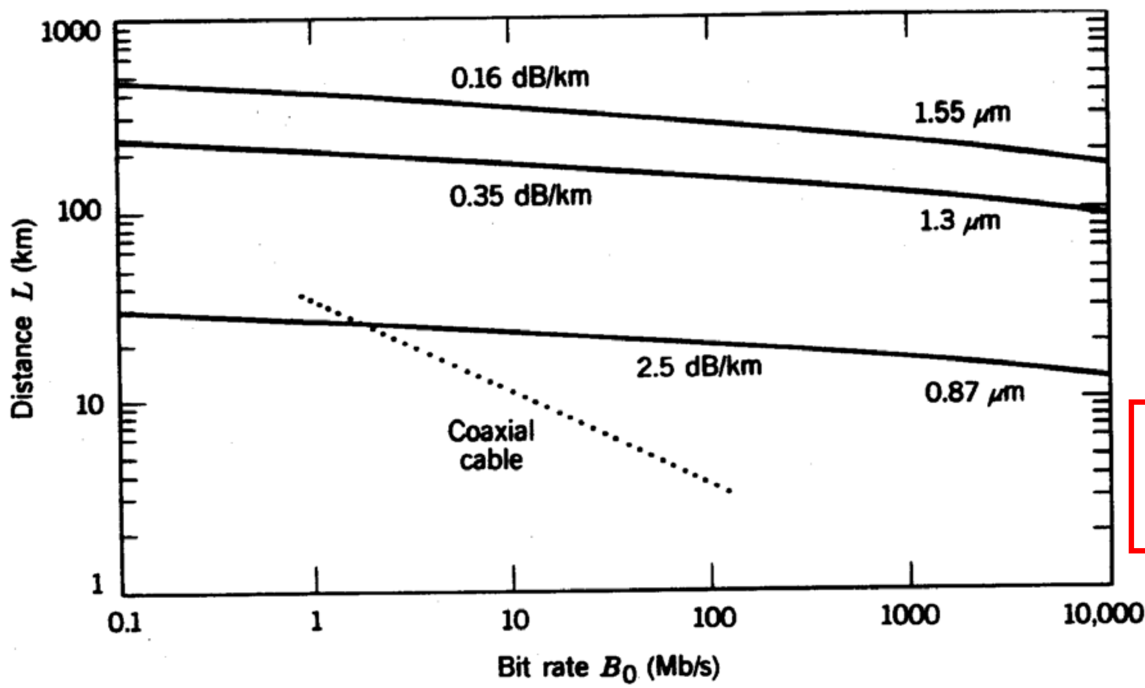


Figure 22.3-4 Maximum fiber length L as a function of bit rate B_0 under attenuation-limitec conditions for a fused silica glass fiber operating at wavelengths $\lambda_o = 0.87$, 1.3, and 1.55 μn assuming fiber attenuation coefficients $\alpha = 2.5$, 0.35, and 0.16 dB/km, respectively; source powe $P_s = 1$ mW ($\mathscr{P}_s = 0$ dBm); receiver sensitivity $\bar{n}_0 = 300$ photons/bit for receivers operating a 0.87 and 1.3 μm and $\bar{n}_0 = 1000$ for the receiver operating at 1.55 μm; and $P_c = P_m = 0$. Fo comparison, the L–B_0 relation for a typical coaxial cable is also shown.

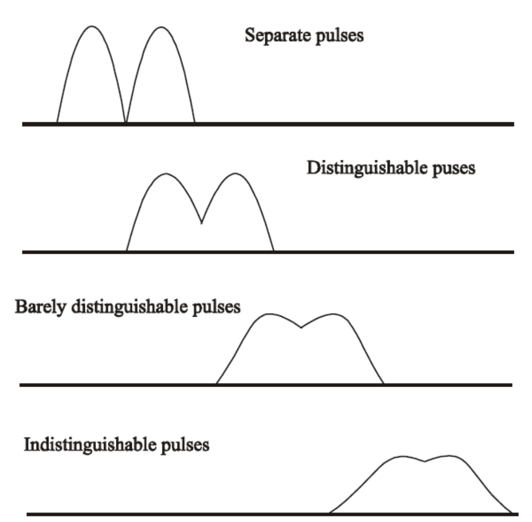
$$L_{\max} = \frac{10}{\alpha}\log\left(\frac{p_i}{N_p Bhc/\lambda}\right)$$

Bit (binary digit): basic capacity of information in telecommunications;
a bit can have the value of either one or Zero only

Bit rate: number of bits that are transmitted or processed per unit of time.

Bit-Rate Capacity

- **Bit rate capacity** is directly related to the **dispersion characteristics.**
- **Bit rate capacity *B*** (bits per second) of the fiber: The maximum rate at which the digital data can be transmitted along the fiber.

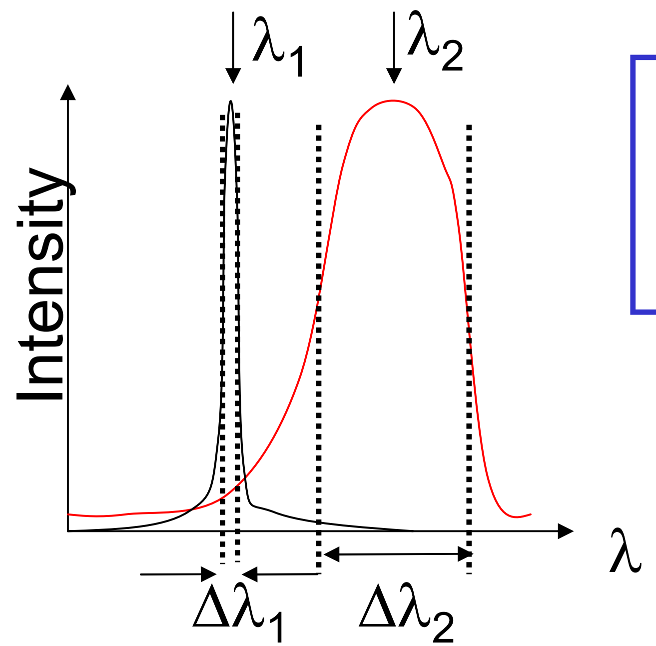


For a particular wavelength, if the length of an optical fibre increases, optical dispersion will increase as well, **limiting the bit-rate capacity.**

Therefore, a compromise between length and bit-rate will be made
i) Long length and low bit-rate; or ii) short length and high bit-rate

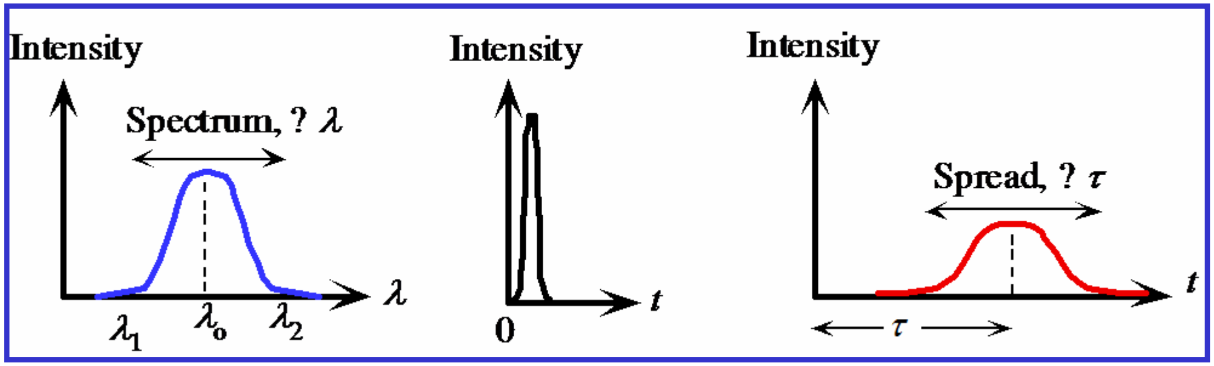
Simple characteristics describing the overall capability:
product of bit-rate (B) and length of optical fibre (L), i.e., BL product

Light source - Wavelength and Linewidth



Operating wavelength (λ): Peak wavelength

Linewidth ($\Delta\lambda$): Full Width at Half Maximum



$\Delta\lambda$: linewidth of intensity between the half-intensity points (wavelength spectrum).

$\Delta\tau$: linewidth of the output light intensity between the half-intensity points (vs. time)

$\Delta\tau = L\Delta\lambda\, D(\lambda)_{total}$

D : ps km^{-1}nm^{-1}

- **No perfectly monochromatic light source**
- **Optical pulse with various components**
- **Each component with a different λ will propagate at a different group velocity**

⇨The different components arrives at different time at the end of fiber, leading to broadening of output light pulse.

Dispersion Limit and Bit-rate

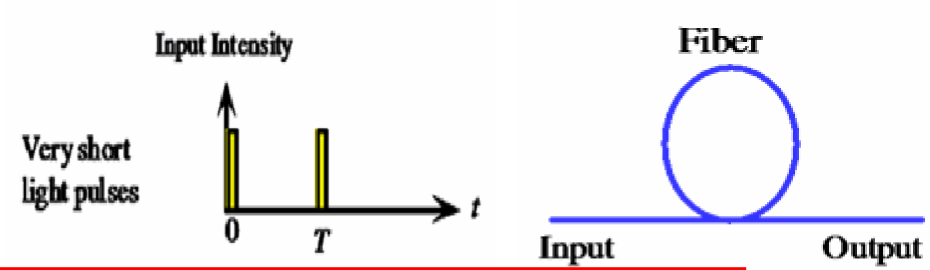
- Optical Dispersion limit
  - Optical Pulse Broadening Depends on:
    - **Fiber dispersion** (material dispersion waveguide dispersion, etc): $D(\lambda)_{total}$
    - **Linewidth** of the optical source: $\Delta\lambda$
    - **Transmission Distance**: L

$$\boxed{\Delta\tau = L\Delta\lambda\, D(\lambda)_{total}}$$

$\Delta\lambda$: the linewidth of intensity between the half-intensity points (wavelength spectrum).

$\Delta\tau$: the linewidth of the output light intensity between the half-intensity points (vs. time).

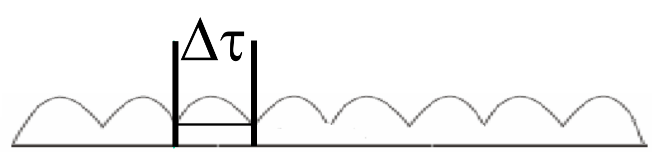
D: $\boxed{\text{ps km}^{-1}\text{nm}^{-1}}$



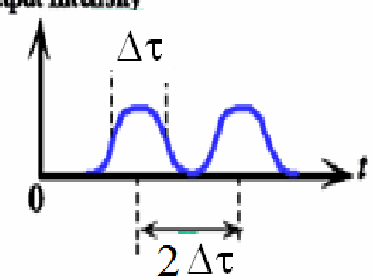
Input: very short-duration light pulse

Output: a pulse that is broadened (by $\Delta\tau = L\Delta\lambda\, D(\lambda)_{total}$)

(A)



(B)



In case A:	Bit rate $B = 1/\Delta\tau$	(bit slot: $T = \Delta\tau$)
In case B:	Bit rate $B = 1/(2\Delta\tau)$	(bit slot: $T = 2\Delta\tau$)

BL Product

Further using case B as an example, we can simply conclude the relationship between optical pulse width and bit-rate **B = 1/ 2 $\Delta\tau$,**

We have learnt: **$\Delta\tau$ = L$\Delta\lambda$D(λ),**

$$\boxed{BL = \frac{L}{2\Delta\tau} = \frac{L}{2L\Delta\lambda|D_{total}|} = \frac{1}{2\Delta\lambda|D_{total}|}}$$

- ⇨ *BL* is the **intrinsic properties** of the fiber, and only depends on D_{total} (total dispersion coefficient) and also of the linewidth of optical source.
- In specifications, the fiber length is taken as 1km.
- Ex., step-index single mode fiber @ λ = 1300 nm and excited by a laser diode source
- ⇨ Unit for *BL* ~ Gb s^{-1} km

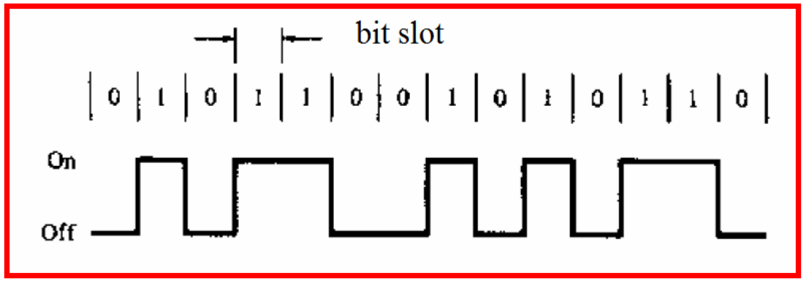
Given the fibre length required by an optical system, the maximum bit-rate allowed can be obtained
(Depends on the fibre length used)

$$\boxed{B = \frac{1}{2\Delta\lambda|D_{total}|L}}$$

Return-to-zero (RZ) and Nonreturn-to-zero (NRZ)

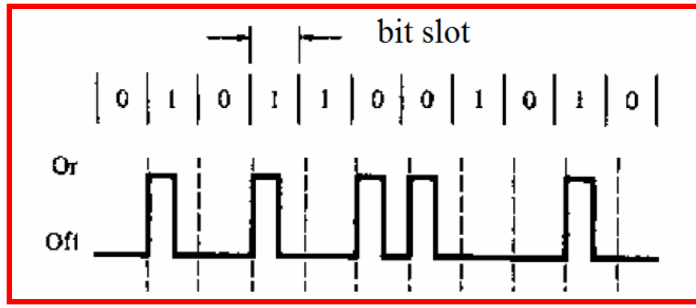
- **Nonreturn-to-zero (NRZ) optical pulse**

  The binary 1 level is hold for the whole bit period



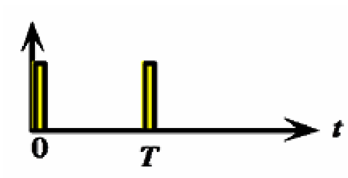
- **Return-to-zero (RZ) optical pulse**

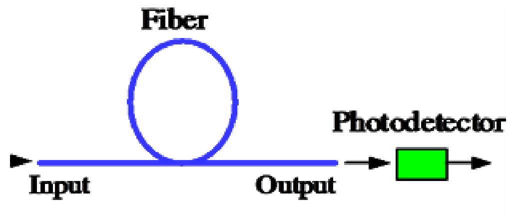
  (1) The binary 1 level is hold for only part (half) of the bit period; and 0 level for the rest part of the bit period

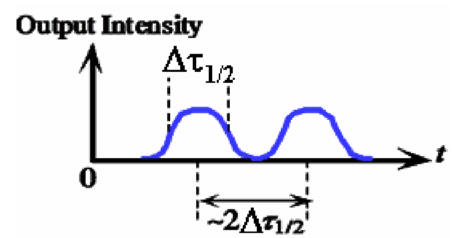


- **In practical applications, Bit rate *B*(NRZ) > *B*(RZ)** (generally speaking a factor of two, i.e., *B*(NRZ) =2 *B*(RZ)

Summary of Bit rate *B* and *BL* product







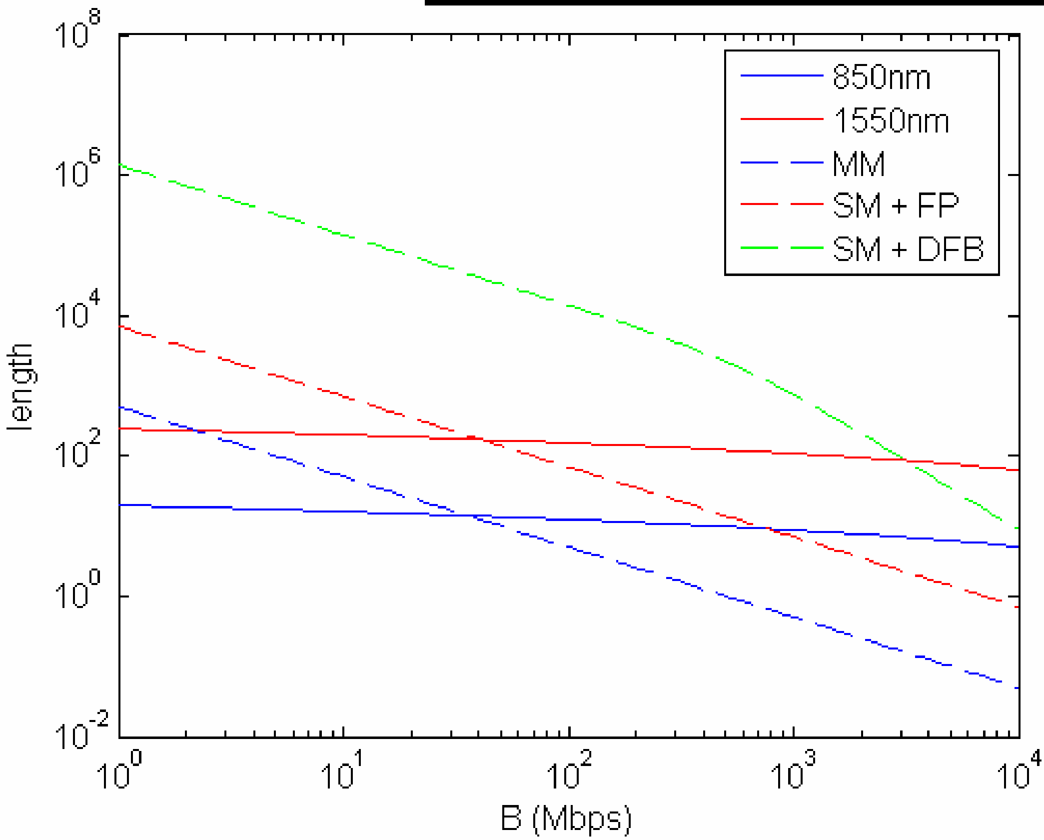
- Bit rate $B \propto 1/\Delta\tau$
- Dispersion increases with fiber length L and also with the linewidth of source wavelength $\Delta\lambda$ (related to $\Delta\tau$ **= L$\Delta\lambda$D(λ)**)

⇨ Dispersion $\Delta\tau \uparrow$, as $L \uparrow$ and $\Delta\lambda \uparrow$

⇨ Bit rate $B \propto 1/\Delta\tau \downarrow$, as $L \uparrow$ and $\Delta\lambda \uparrow$

- It is customary to specify the product of the bit rate B with the fiber length L at the operating wavelength for a given emitter.
- The *BL* product, called the **bit-rate** $\times$ **length product**, describe the intrinsic properties of an optical fibre

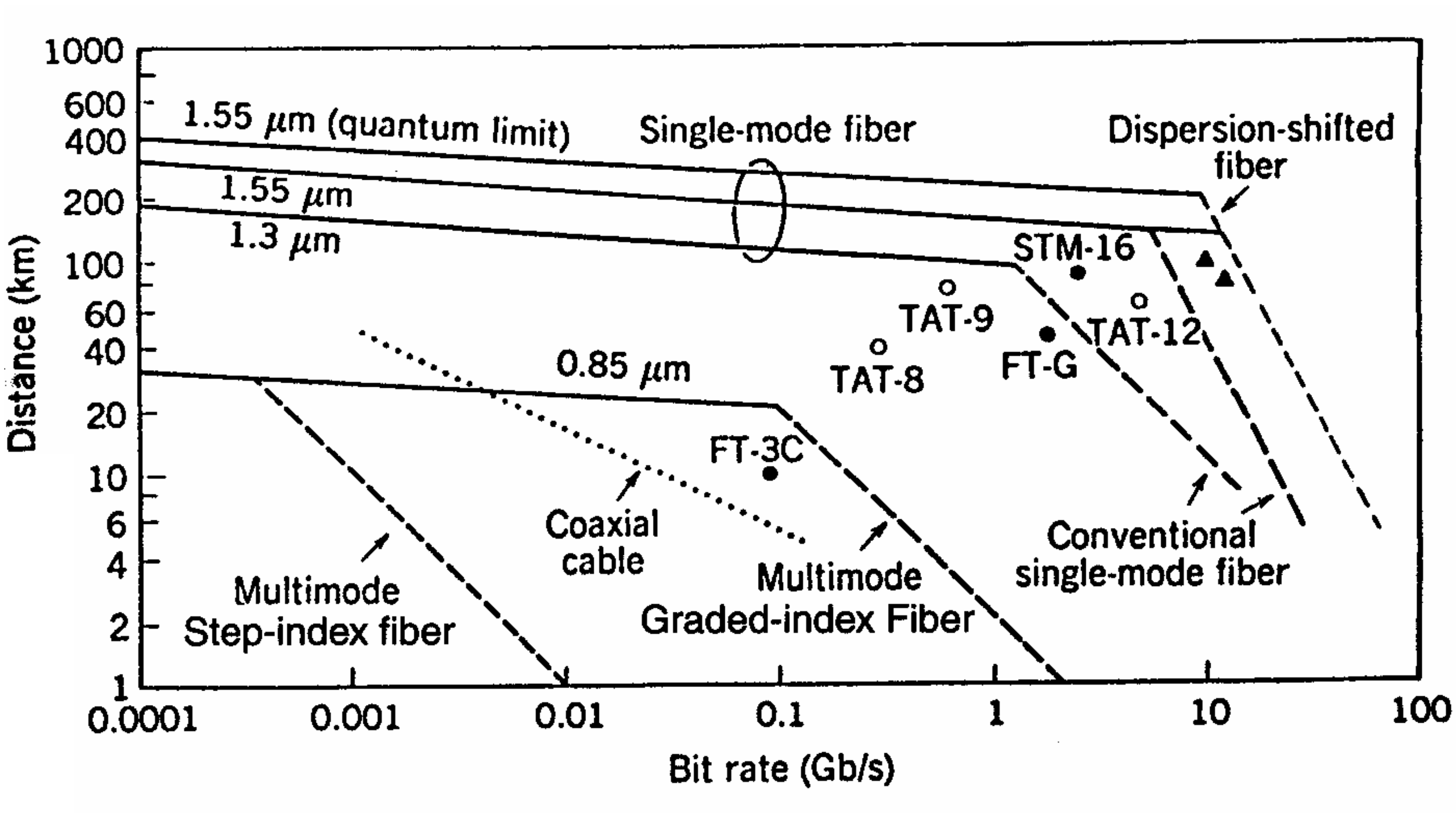
Length Limitations



- Solid lines: attenuation limit
- Dashed lines: dispersion limit

- Length of Optical fibre without "boost" is limited
  (1) Attenuation and detection limitation of detector
  (2) **Dispersion**: transmitted signals need to be identified
- Both are related to Bit-rate
  (1) Bit-rate is too **less**, leading the signal intensity below detection
  (2) Bit-rate is too **high**, leading to merge of two consecutive signals

Typical Systems – Attenuation and Dispersion Limits



Solid – Loss limited
Dashed – dispersion limited

Fibre Properties: Effect on Transmitter and Receiver

Operating Wavelength – Minimum for attenuation or dispersion?

•Dispersion limited transmission;

•Linewidth of Transmitter – Minimise Dispersion

Loss Limited Transmission:-

•Power of Transmitter – Turn power up and up! (maximum limit exists)

•Receiver sensitivity – Function of Bit-rate,

Power Budget

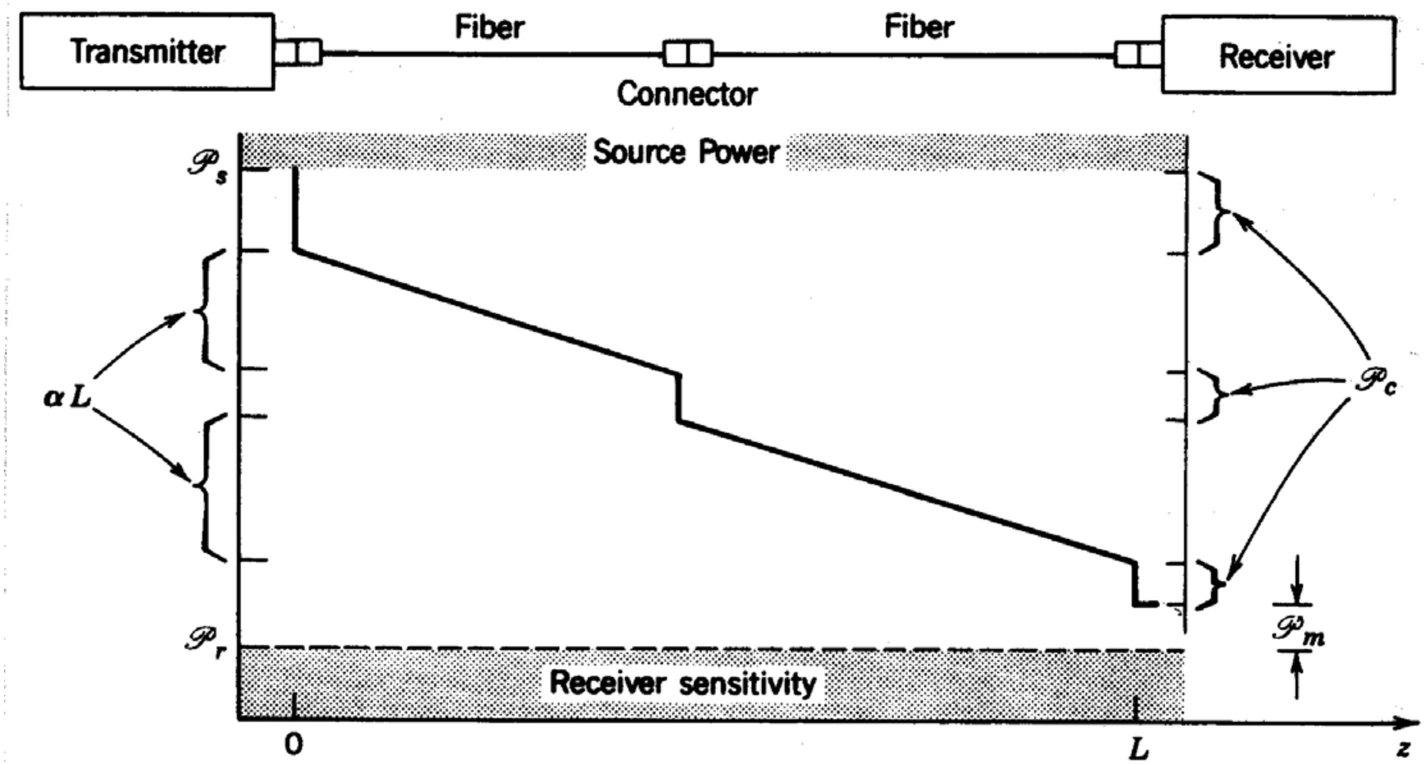


Figure 22.3-2 Power budget of an optical link.

•**Power budget**:

Allocation of available optical power from transmitter considering a number of optical losses, such as fiber attenuation, coupling loss, splice losses, and connector losses, in order to ensure that adequate signal strength (optical power) is available at the receiver.

• **Unit of Power budget**: usually expressed in dB.

Losses In A System

Loss:

(1) Fibre: few tenths of dB/km

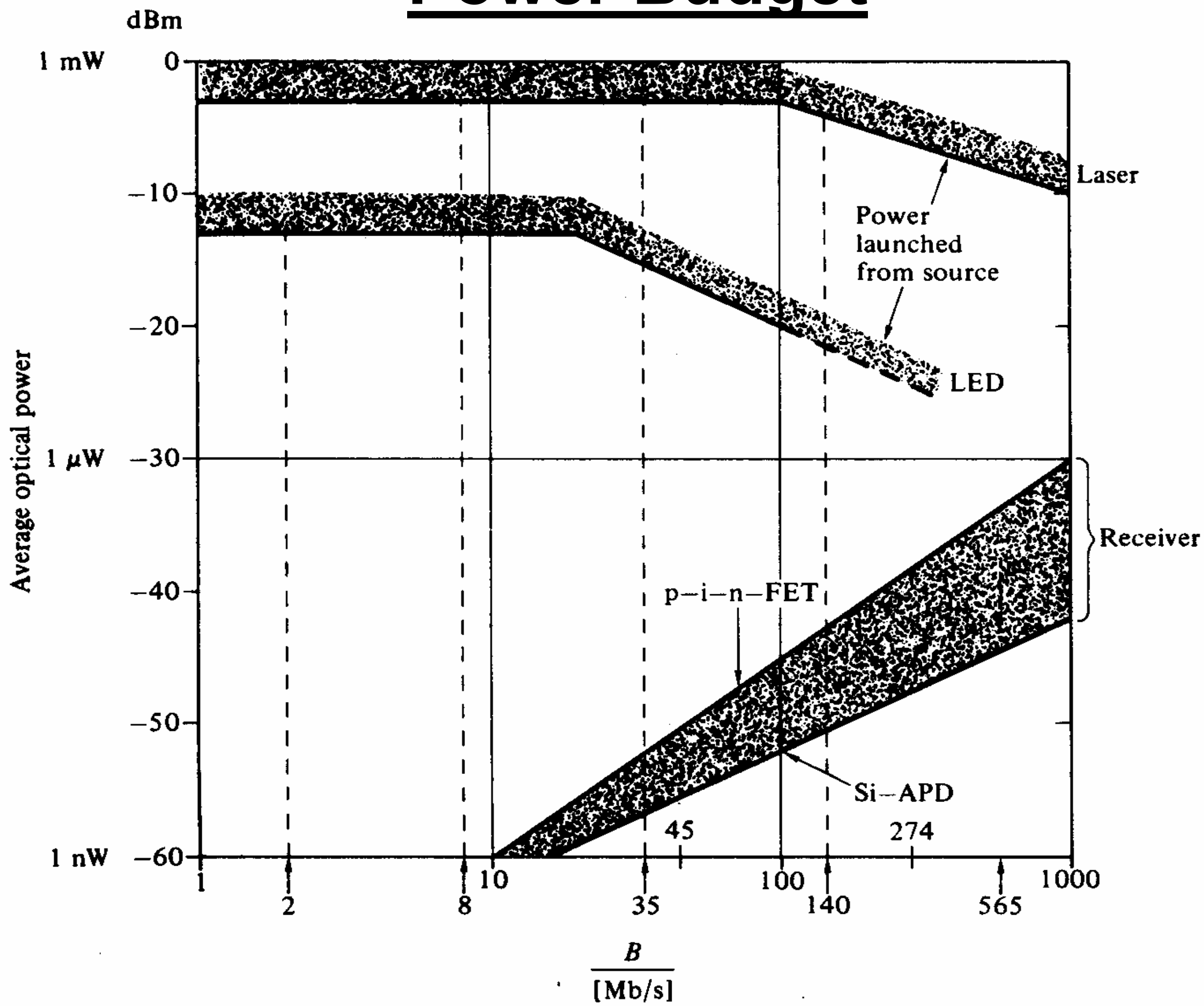
(2) Splice: 0.1 dB each

(3) Connector: 0.3 dB each

If we just budget for fibre loss in designing our system we will be in big trouble if we have to repair the fibre or add and additional components..

A smart engineer will leave some slack or "**margin**", meaning the input provided is slightly higher than the minimum power required.

Power Budget



Power (input or transmitter) - total loss + amplification = margin + sensitivity (Receiver)

Power Budget Example

1GHz system

-10 dBm Transmitter Power
-30 dBm Receiver Sensitivity
10 dB gain EDFA (Amplifier)
Need loss of 20 dB for connectors/splices/unexpected losses etc
What is total loss I can tolerate?
Loss of fibre is 0.2 dB/km – how far can I transmit?

Power (input or transmitter) - total loss + amplification = margin + sensitivity (Receiver)

T5 – Summary

- **Amplitude Modulated Bits**
- Loss and Dispersion Characteristics are key in determining how far and at what data rate we can transmit data
- Dispersion – broadens bit within it's bit-slot – if too severe get inter-symbol interference and errors
- Loss – if not enough photons in a pulse cannot differentiate between "0" and "1" at receiver
- Later gives rise to a "power budget"
- Power budget – determined by power required at receiver (fn Data rate), launch power, margin, other factors e.g. Dispersion penalty, Extinction ratio penalty, etc

T5 Tutorial Questions

T5.1 Sketch the variation of optical power with time for a digital NRZ bit stream 010111101110 assuming a bit rate of 10Gb/s. What is the duration of the shortest and widest optical pulse? What is the peak power when an average power of 2mW is launched into the fibre?

T5.2 Draw a schematic of the attenuation and dispersion of a standard single mode fibre as a function of wavelength. Explain how these characteristics affect the transmission of an amplitude modulated bit stream.

T5.3 Consider a fiber link operating at 1300 nm with a fiber loss of α = 0.4 dB/km. The input optical power is 1 mW and the minimum number of photons per bit of information Np is 1000. If the data rate is 2.5 Gbit/s, what is the maximum fiber length limited by fiber attenuation

$$L_{\max} = \frac{10}{\alpha}\log\left(\frac{p_i}{N_p B h \gamma}\right) = \frac{10}{0.4}\times\log\frac{10^{-3}}{10^{3}\times 2.5\times 10^{9}\times 0.9537\times 1.602\times 10^{-19}} = 85km$$

T5 Tutorial Questions

T5.4 A laser source launches 120 μW of optical power into an optical fibre of length 8km. The mean optical output at the end of the fibre is 3μW .

Calculate:

(a) The overall signal attenuation in dB.

(b) The signal attenuation per kilometre

(c) The output power of the laser source in dBm.

(d) The output power of the fibre in dBm

Answers

(a) loss = 10 $\mathrm{Log}_{10}\, P_i/P_o$ = 16.dB

(a) attenuation per kilometre = 16/8 = 2dB/km

(b) –9.2 dBm

(c) –25.2 dBm

T5 Tutorial Questions

T5.5 Confirm the following table (do a few mW to dBm, a few dBm to mW)

Power (mW)	Power (dBm)
100	20
10	10
1.6	2.04
1	0
0.32	-5
0.1	-10
0.01	-20

T 5.6 An 800nm optical receiver needs at least 1000 photons to detect 1 bits accurately. What is the maximum possible length of the fibre link for a 100Mb/s lightwave system designed to transmit -10dBm of average power? Fibre loss is 2dB/km at 800nm. Assume an NRZ format and 1:1 mark space ratio for the optical pulse.