Fiber Optic Communications

Ch 1. Optical Fiber

Titular : lec. dr. eng. Păun Adrian Florin

- **Evaluation:**
  - Project **30 pcts**
  - Homework **20pcts**
  - Final exam **50 pcts** (minimum 20 pcts for pass)
  - Pass the course – **total pcts > 50**

Contents

Optical Fiber properties

- Optical fiber is used to contain and guide light waves
  - Typically made of glass or plastic
  - similar to cable guiding electromagnetic waves
- Capacity comparison
  - Microwave at 10 GHz
  - Light at 100 Tera Hz (10^{14})

Optical Fiber

Historical Developments

- 1930 - Experiments with silica fibers, by Lamb (Germany)
- 1950-55 - The birth of clad optical fiber, Kapany et al (USA)
- 1962 - The semiconductor laser, by Natan, Holynal et al (USA)
- 1960 - Line of sight optical transmission using laser:
- - Beam diameter: 5 m
- - Temperature change will effect the laser beam

(therefore, not a viable option)

- 1966 - A paper by C K Kao and Hockham :
  - Loss < 20 dB/km
  - Glass fiber rather than crystal (because of high viscosity)
  - Strength: 14000 kg /m2.

Historical Developments – contd'

- 1970 - Low attenuation fiber, by Apron and Keck (USA) from 1000 dB/km - to - 20 dB/km

  - Dopent added to the silica to indecrease fiber refractive index

- 1976 - Japan, Graded index multi-mode fiber

  - Bandwidth: 20 GHz, but only 2 GHz/km

  - 800 nm Graded multimode fiber: 2 Gbps·km

- 1980's - 1300 nm Single mode fiber 100 Gbps·km

  - 1500 nm Single mode fiber: 1000 Gbps·km

  - Erbium Doped Fibre Amplifier

- 1990 - Soliton transmission (exp): 10 Gbps over 106 km no err

  - Optical amplifiers

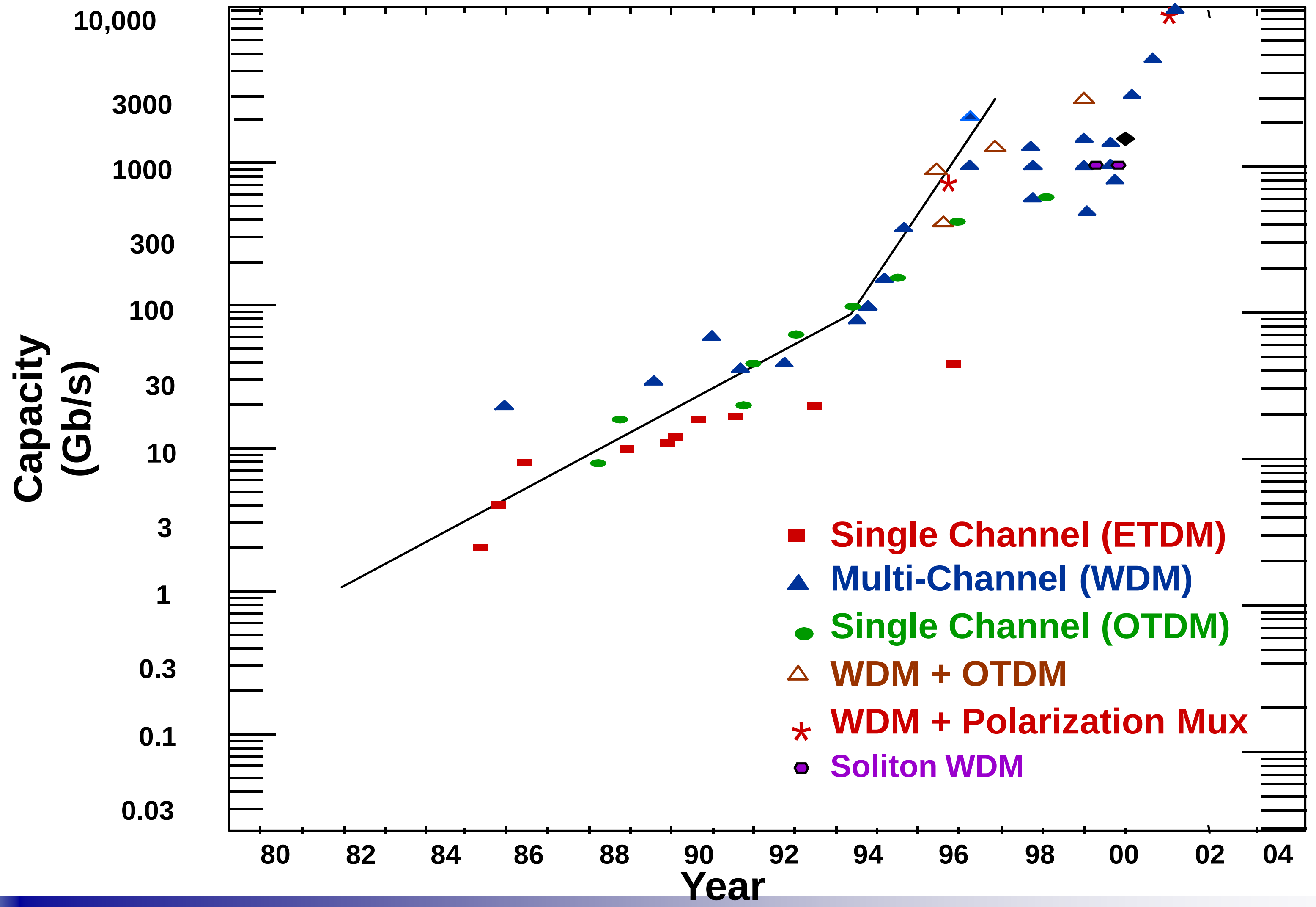
  - Wavelength division multiplexing (experimental OTDM)

Historical Developments – contd’

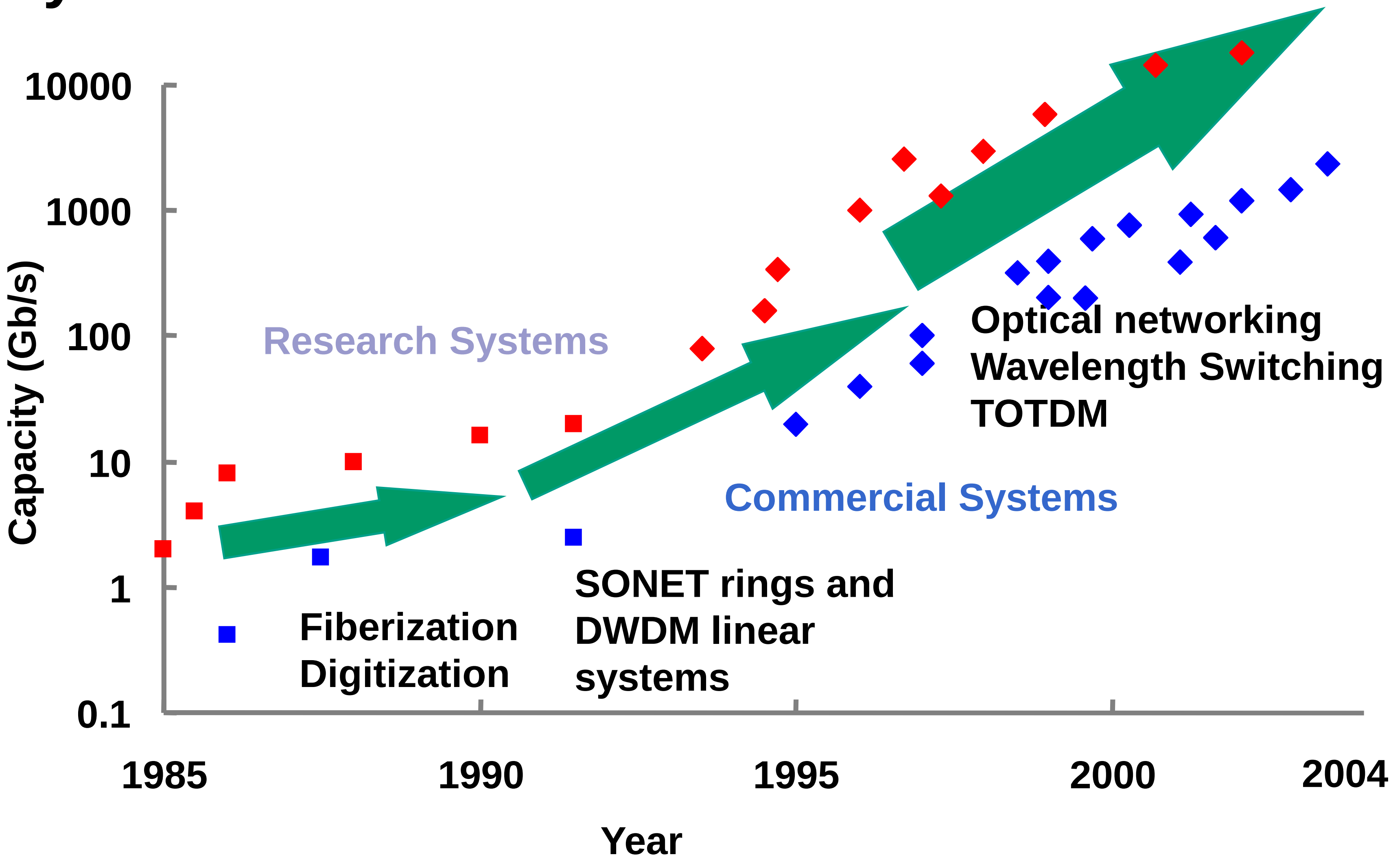
- 2000 and beyond
  - Optical Networking
  - Dense WDM: 40 Gbps/channel, 10 channels
  - Hybrid DWDM/OTDM
  - ~ 50 THz transmission window
  - > 1000 Channels WDM
  - > 100 Gbps OTDM
  - Polarisation multiplexing
  - Intelligent optical networks

Optical Fiber

Lightwave Evolution



System Evolution

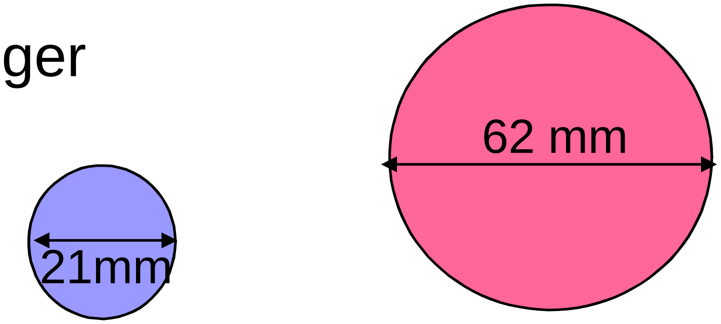


Communications Technologies

Year	Service	Bandwidth distance product
1900	Open wire telegraph	500 Hz-km
1940	Coaxial cable	60 kHz-km
1950	Microwave	400 kHz-km
1976	Optical fibre	700 MHz-km
1993	Erbium doped fibre amplifier	1 GHz-km
1998	EDFA + DWDM	> 20 GHz-km
2001-	EDFA + DWDM	> 80 GHz-km
2001-	OTDM	> 100 GHz-km

Optical Technology – Advantages

- High data rate, low transmission loss and low bit error rates
- High immunity from electromagnetic interference
- Bi-directional signal transmission
- High temperature capability, and high reliability
- Avoidance of ground loop
- Electrical isolation
- Signal security
- Small size, light weight, and stronger



64 optical fibres
363 kg/km

448 copper pairs
5500 kg/km

Optical Fiber

Applications

- **Electronics and Computers**
- **Broad Optoelectronic**
- **Medical Application**
- **Instrumentation**
- **Optical Communication Systems**

  High Speed Long Haul Networks

  (Challenges are transmission type)
- **Metropolitan Area Network (MAN)**
- **Access Network (AN)**

  Challenges are:

  - Protocol and Multi-service capability

  - Cost

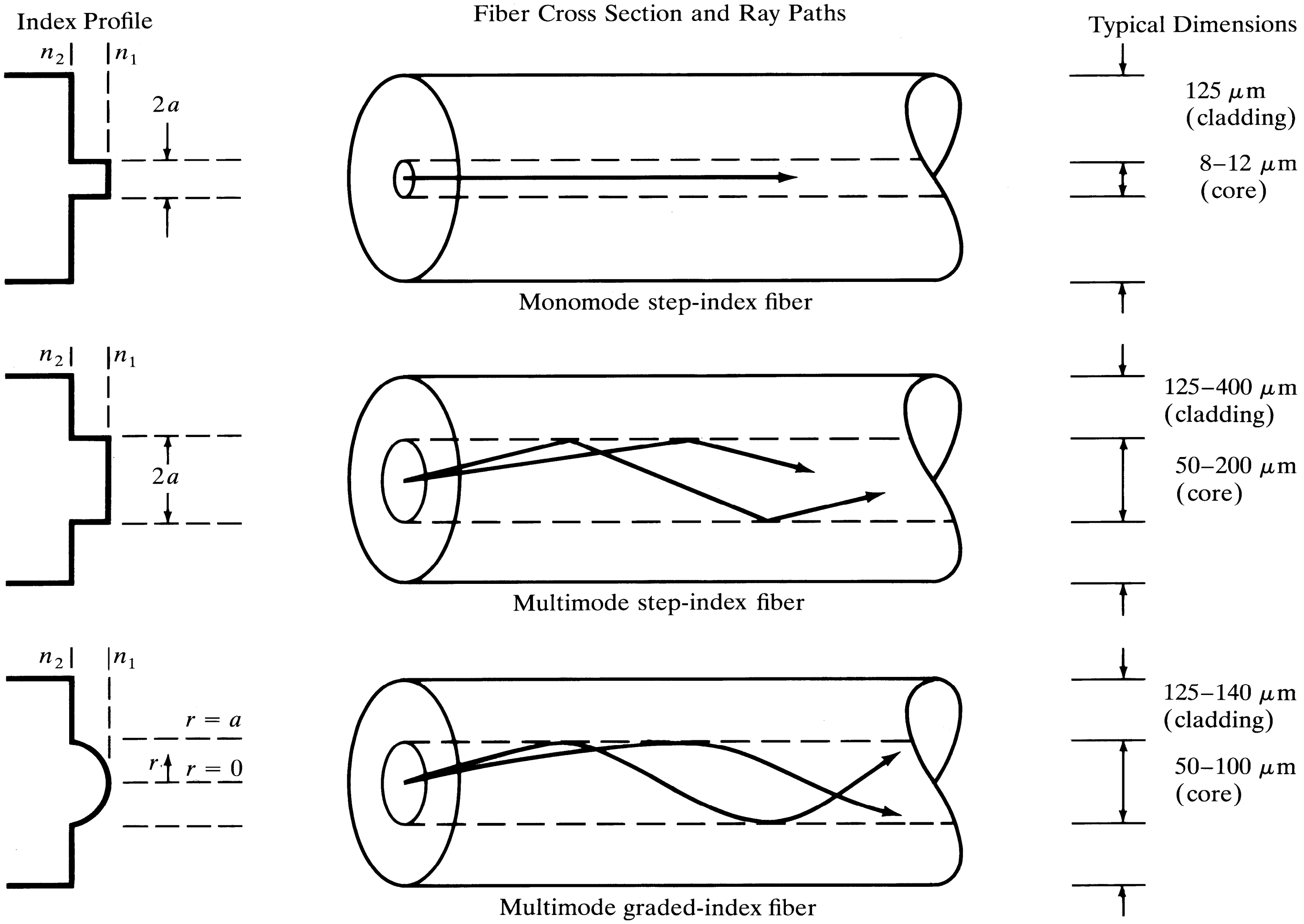
Optical Fiber

Geometrical description

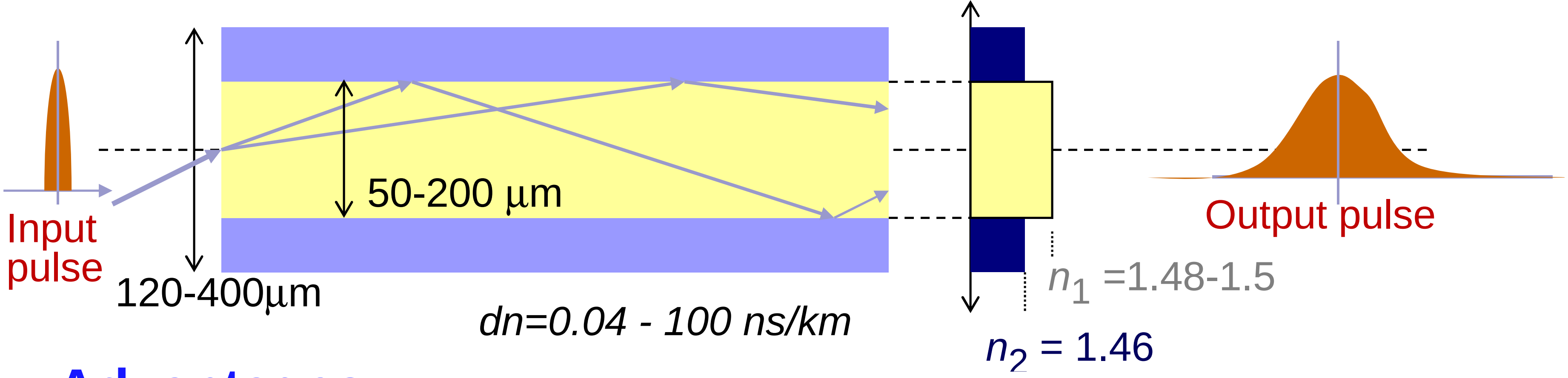
Comparison of fiber structures:

- core (n_1)
- cladding (n_2)
- buffer

coating



Step-index Multi-mode Fiber



Advantages:

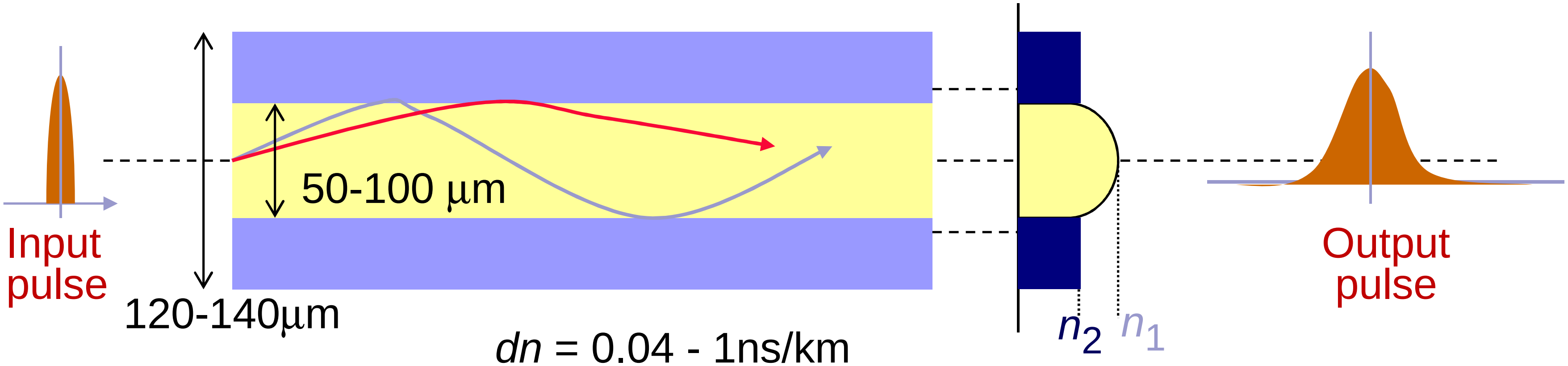
- Allows the use of non-coherent optical light source, e.g. LED's
- Facilitates connecting together similar fibres
- Imposes lower tolerance requirements on fibre connectors.
- Cost effective

Disadvantages:

- Suffer from dispersion (i.e. low bandwidth (a few MHz)
- High power loss

Optical Fiber

Graded-index Multi-mode Fibre



dn = 0.04 - 1ns/km

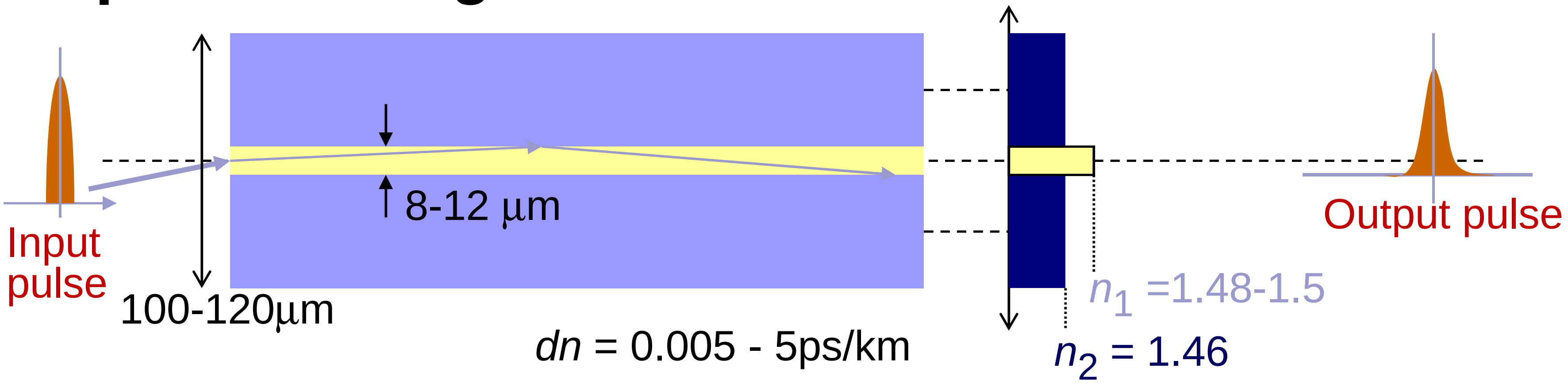
Advantages:

- Allows the use of non-coherent optical light source, e.g. LED's
- Facilitates connecting together similar fibres
- Imposes lower tolerance requirements on fibre connectors.
- Reduced dispersion compared with STMMF

Disadvantages:

- Lower bandwidth compared with STSMF
- High power loss compared with the STSMF

Step-index Single-mode Fibre



Advantages:

- Only one mode is allowed due to diffraction/interference effects.
- Allows the use high power laser source
- Facilitates fusion splicing similar fibres
- Low dispersion, therefore high bandwidth (a few GHz).
- Low loss (0.1 dB/km)

Disadvantages:

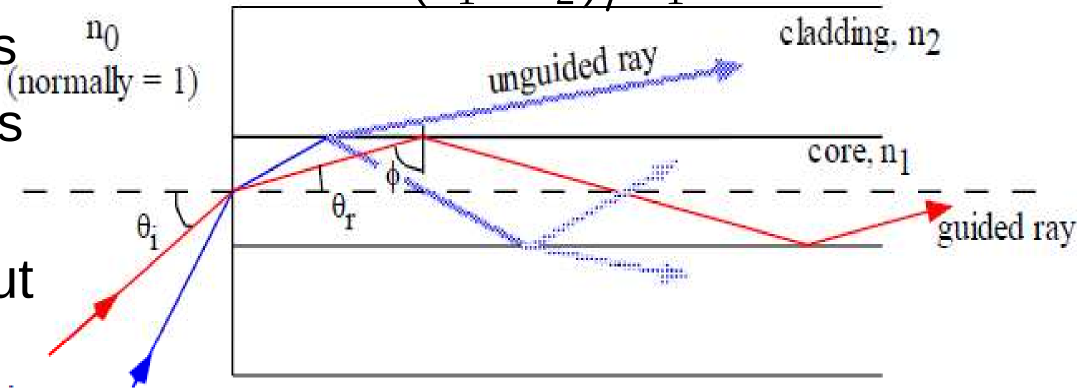
- Cost

Optical Fiber

Geometrical description

- The fractional index change is $\Delta = (n_1 - n_2)/n_1 << 1$
  - $\Delta \approx$ 1–3% for MM fibers
  - $\Delta \approx$ 0.1–1% for SM fibers
  - $n_2 = n_1(1 - \Delta)$
  - Apply Snell's law at input

$$n_0 \sin(\theta_i) = n_1 \sin(\theta_r)$$



  - Minimum critical angle φ_c for total internal reflection (TIR)

$$n_1 \sin(\phi_c) = n_2 \sin(\pi/2) \;\Rightarrow\; \sin(\phi_c) = n_2/n_1$$

  - Relate to maximum entrance angle

$$n_0 \sin(\theta_{i,\max}) = n_1 \sin(\theta_{r,\max}) = n_1 \cos(\phi_c) = n_1 \sqrt{1 - \sin^2 \phi_c} = \sqrt{n_1^2 - n_2^2}$$

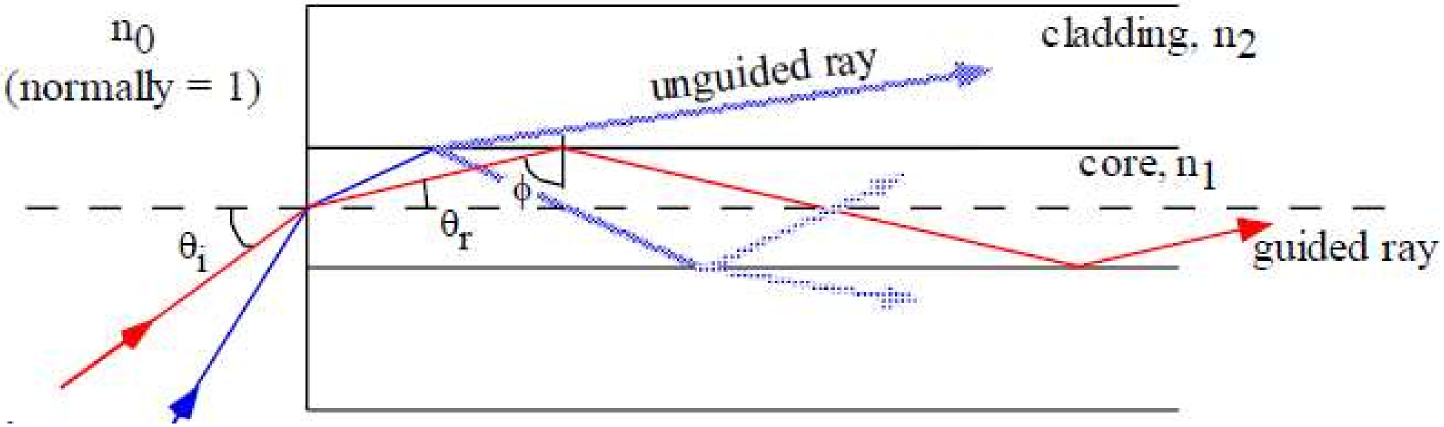
Optical Fiber

Numerical aperture

- The ***numerical aperture*** (NA) is a measure of the light-gathering power of an optical system
  - The term originates from microscopy
- For fibers, we have

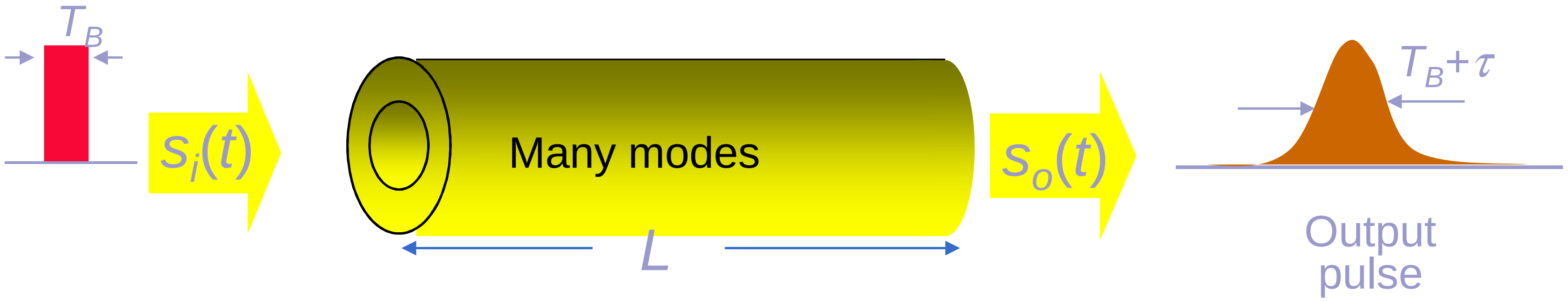
$$NA = n_0 \sin(\theta_{i,\max}) = \sqrt{n_1^2 - n_2^2} \approx n_1 \sqrt{2\Delta}$$

- Clearly, a higher NA is always better!?!
  - No, we get problems with dispersion



Fiber Dispersion

- Data in an optical fiber → pulses of light energy with a large number of frequencies travelling at a given rate.
- ***Dispersion*** → phenomenon of pulse spreading, that limits the highest data rate ("Bandwidth") of the fiber.

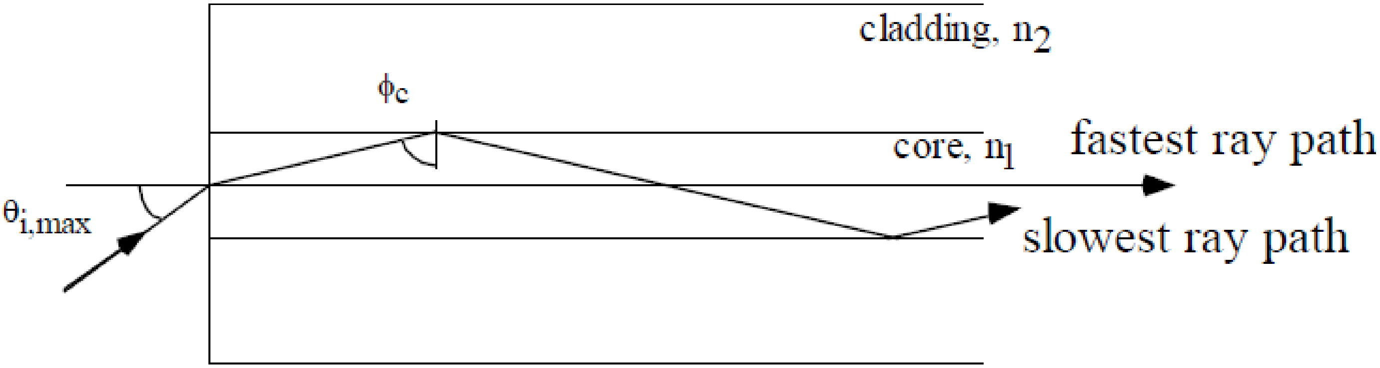


Dispersion types:

- **Modal (Intermodal) Dispersion** → multimode fiber (MMF)
- **Chromatic (Intramodal) Dispersion** → MMF and single mode fiber
  - **Material dispersion** - different wavelengths => different speeds
  - **Waveguide dispersion** - different wavelengths => different angles

Modal dispersion (MMF) - Step Index Fiber

- Compare the propagation times along the slowest and the fastest path



Maximum broadening:

$$\Delta T = \frac{L_{long} - L_{short}}{c/n_1} = \left(\frac{L}{\sin\phi_c} - L \right) \cdot \frac{n_1}{c} = L\left(\frac{n_1}{n_2} - 1 \right) = \frac{L\, n_1^2}{c\, n_2^2} \Delta \approx \frac{L(NA)^2}{2cn_1}$$

- For a rectangular input pulse (and uniform delays distribution), the RMS pulse broadening due to modal dispersion at the output is: $\tau_{\text{modal}} = \frac{Ln_1^2\Delta}{\sqrt{3}\cdot n_2^2 c} \approx \frac{L(NA)^2}{3.5 \cdot n_1 c}$

Optical Fiber

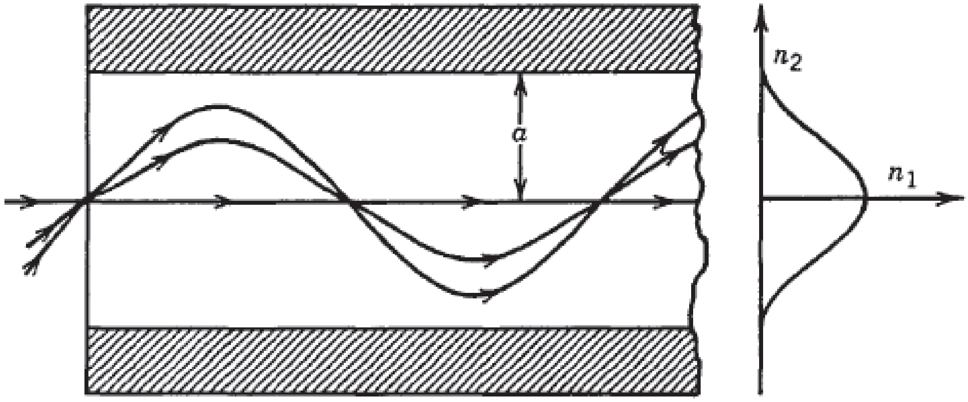
Graded-index Fibers

ρ - radial distance of the ray from the axis

a – core radius

α =2 for graded-index fiber

$$n(\rho) = \begin{cases} n_1\left[1-\Delta\left(\rho/a\right)^{\alpha}\right] \\ n_1(1-\Delta) = n_2 \end{cases}$$



$$\frac{d^2\rho}{dz^2} = \frac{1}{n}\frac{dn}{d\rho} \Rightarrow \rho(z) = \rho_0\cos(pz) + \left(p_0'/p\right)\sin(pz)$$

where $p = \sqrt{2\Delta}/a$ and ρ_0, ρ' - initial position and direction of ray

- all rays recover their initial positions and directions at distances

$$z = 2m\pi/p$$

Optical Fiber

Modal dispersion - Graded-index Fibers

Δ*T* – maximum multipath delay in a fiber with length *L*

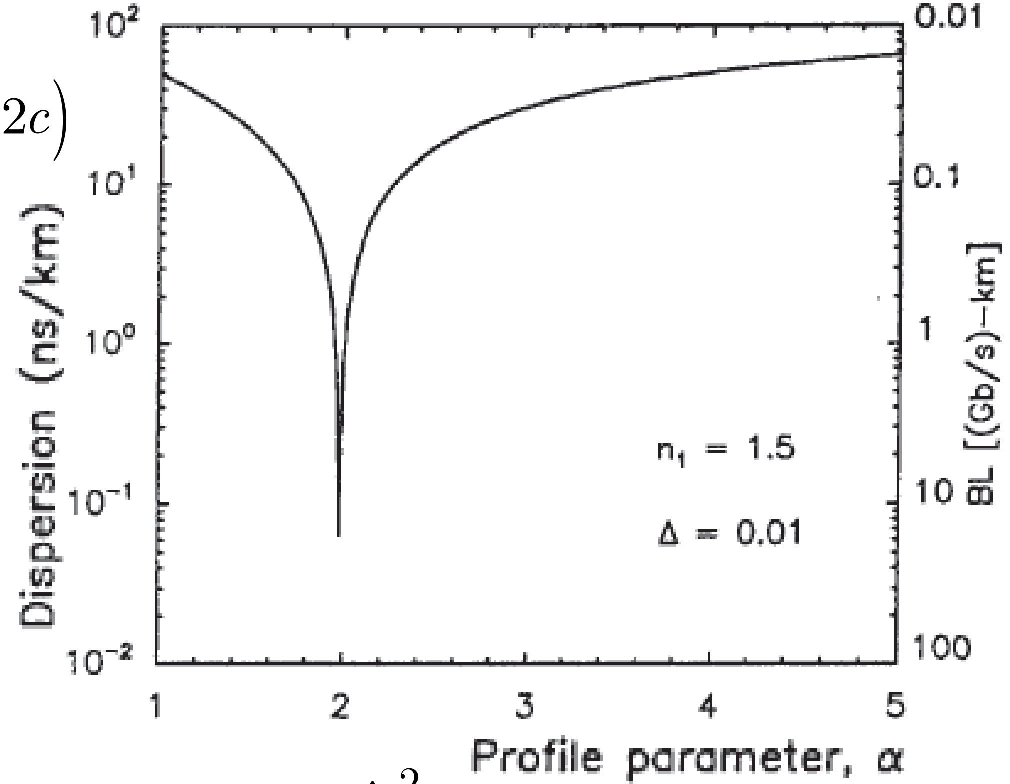
- Δ*T* vary with *α*

Exp: *α* = 2 → $\Delta T / L = \left(n_1 \Delta^2\right) / \left(2c\right)$

- Minimum value:

$$\frac{\Delta T}{L} = \frac{n_1 \Delta^2}{8c}$$

for $\alpha = 2\left(1 - \Delta\right)$



- Minimum dispersion = the RMS pulse broadening (for a rectangular input pulse and uniform delays distribution): $\tau_{\text{mod}} = \dfrac{n_1 \Delta^2}{8\sqrt{3}c}$

Dispersion - MMF

Material Dispersion: Since *n* is a function of wavelength, different wavelengths travel at slightly different velocities.

Total Dispersion:

$$\tau_{\text{total}} = \sqrt{\tau_{\text{mod}}^2 + \tau_{\text{mat}}^2} \approx \tau_{\text{mod}} \quad ; \quad \tau_{\text{mod}} >> \tau_{\text{mat}}$$

Optical Fiber

Step-index single mode Fibers (SMF)

- isn't affected by modal dispersion

Total dispersion: $\tau_{\text{total}} = \sqrt{\tau_{GVD}^2 + \tau_{pol}^2}$

Chromatic Dispersion (Group Velocity Dispersion – GVD):

Material Dispersion (τ_{mat}) - different wavelengths travel at slightly different velocities (due to *n(λ)*); Input pulse has many *λ*.

Waveguide Dispersion (τ_{wave}) - Signal in the cladding travels with a different velocity than the signal in the core. This phenomenon is significant in single mode conditions.

$$\tau_{\text{GVD}} = \tau_{mat} + \tau_{wave}$$

Polarization Dispersion (PMD) – Each polarization state has a different velocity $\rightarrow$ PMD

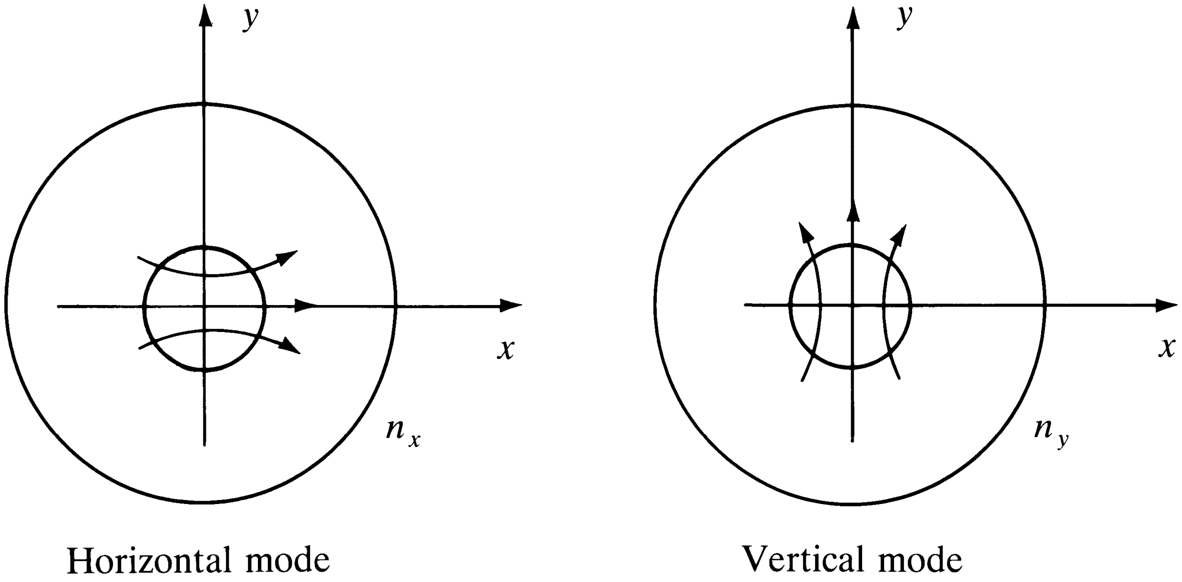
$$\tau_{PMD} = D_{PMD} \cdot \sqrt{L} \quad ; \quad D_{PMD} = 0.1 - 1 \text{ ps}/\sqrt{\text{km}}$$

Polarization Dispersion Fibers (PMD)

- optical fiber has a single axis of anisotropy, differently polarized light travels at slightly different velocity

- a Linear Polarized wave will always have two orthogonal components: x and y polarization components

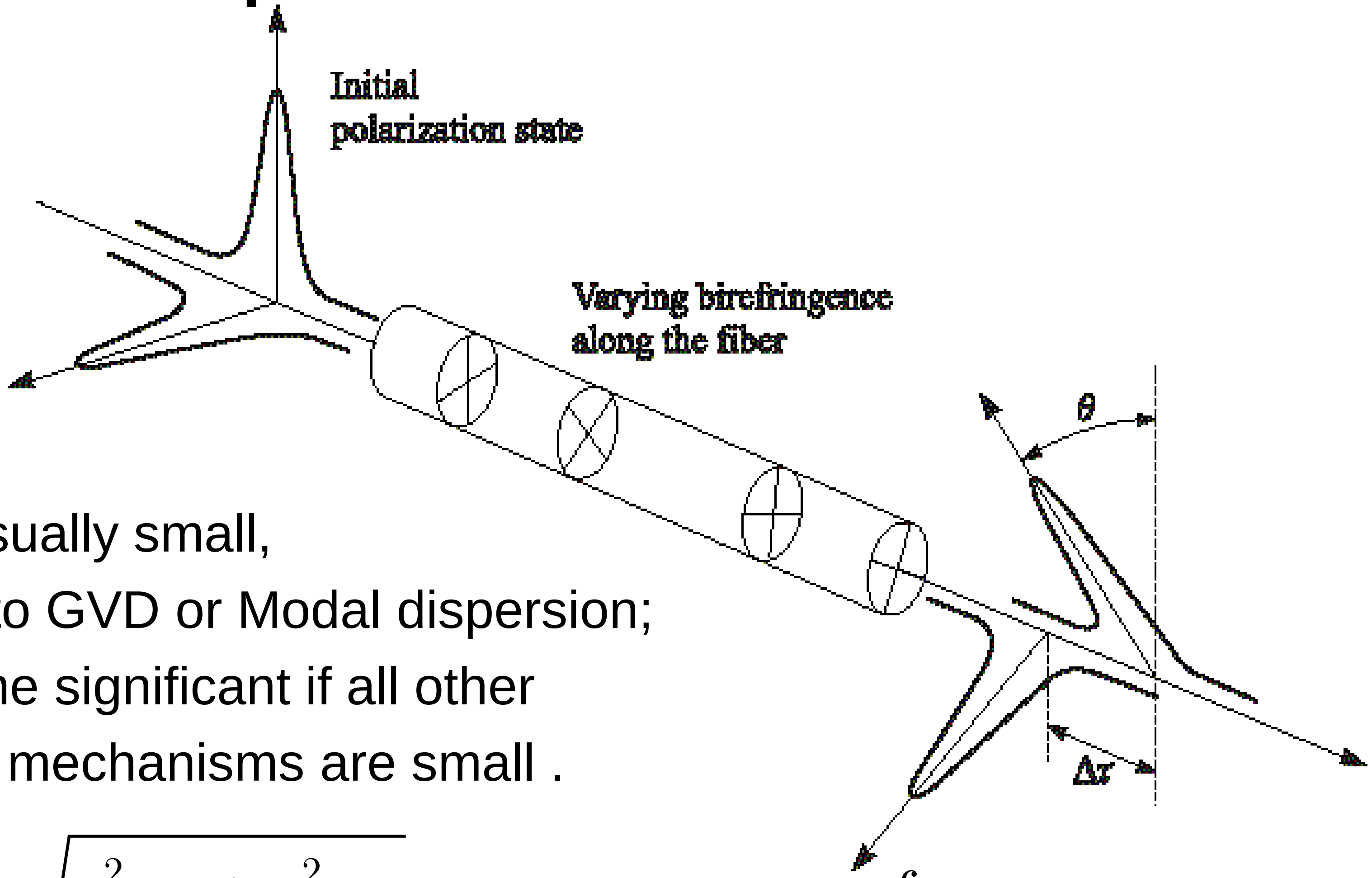
- each component can be individually handled if polarization sensitive components are used



Birefringence

- Birefringence is the decomposition of a ray of light into two rays types of (anisotropic) material
- In optical fibers, birefringence can be understood by assigning two different refractive indices n_x and n_y to the material for different polarizations.
- In optical fiber, birefringence happens due to the asymmetry in the fiber core and due to external stresses
- There are *Hi-Bi, Low-Bi* and *polarization maintaining* fibers.

Polarization Dispersion Fibers



- PMD is usually small,
compared to GVD or Modal dispersion;
may become significant if all other
dispersion mechanisms are small .

$$\tau_{\text{total}} = \sqrt{\tau_{GVD}^2 + \tau_{PMD}^2} \approx \tau_{GVD} \quad ; \qquad \text{for } \tau_{GVD} \gg \tau_{PMD}$$

Permissible Bit Rate

As a practical rule of thumb the permissible total dispersion (including electro-optical conversion) can be up to 70% of the bit period.

- for NRZ pulses $$B = \frac{0.7}{\tau_{\text{total}}}$$

- for RZ pulses $$B = \frac{0.35}{\tau_{\text{total}}}$$

- Global performances: ***Bandwidth – Length Product*** (BL)

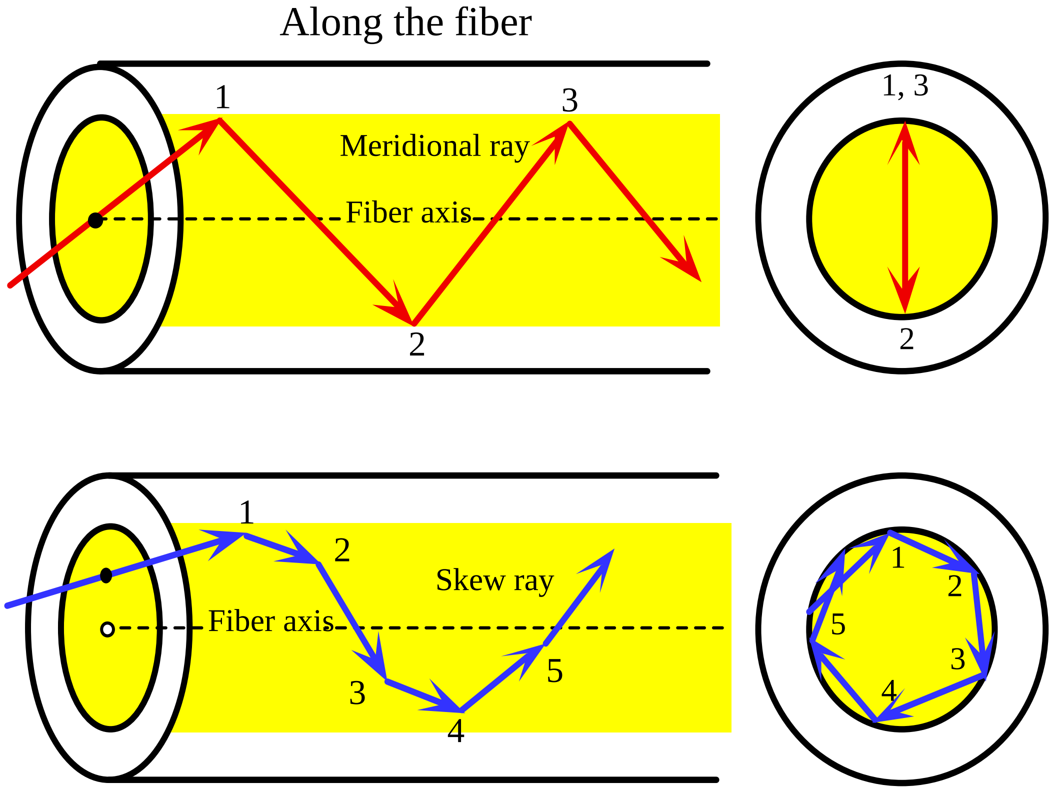
Optical Fiber

Exp: EIA/TIA 568 50/125 FO

Fiber Type	Wavelength (nm)	Max Atten. (dB/km)	Bandwidth Distance (MHz-km)
50/125 (OM2, OM3, OM4)	**850**	**3.5**	500 (OM2), 2000 (OM3), 3500 (OM4)
	1300	**1.5**	**500**
62.5/125 (OM1)	**850**	**3.5**	**160**
	1300	**1.5**	**500**
Singlemode (OS1, OS2)(Premises)	**1310**	**1.0**	**NA**
	1550	**1.0**	**NA**
Singlemode (OS1, OS2)(Outside Plant)	**1310**	**0.5**	**NA**
	1550	**0.5**	**NA**

Optical Fiber

Skew Rays



(a) A meridiona
ray always
crosses the fibe
axis.

(b) A skew ray
does not have
to cross the
fiber axis. It
zigzags around
the fiber axis.

Ray path along the fiber

Ray path projected
on to a plane normal
to fiber axis

Illustration of the difference between a meridional ray and a skew ray.
Numbers represent reflections of the ray.

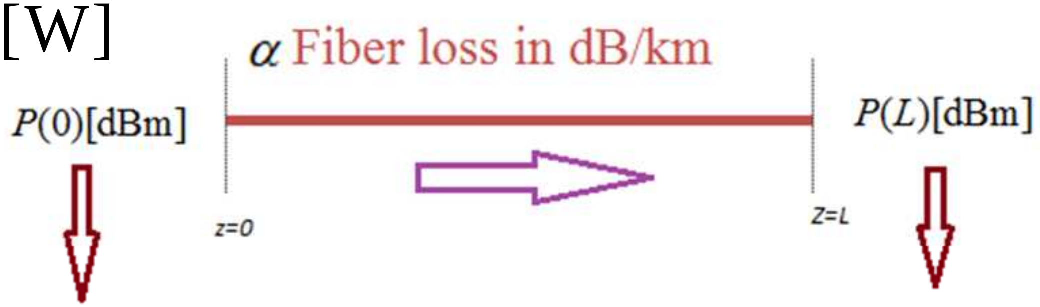
Optical Fiber

Fiber Loss

$$P_{\text{out}} = P_{\text{in}} \cdot e^{-\alpha_p \cdot L} \quad [\text{W}]$$

$$\alpha[\text{dB/km}] = \frac{10}{L} \log\left[\frac{P(0)}{P(L)}\right]$$

$$P(L) = P(0) \cdot e^{-\alpha_p \cdot L} \quad [\text{W}]$$



$$P(0)[\text{dBm}] - \alpha[\text{dB/km}] \times L[\text{km}] = P(L)[\text{dBm}]$$

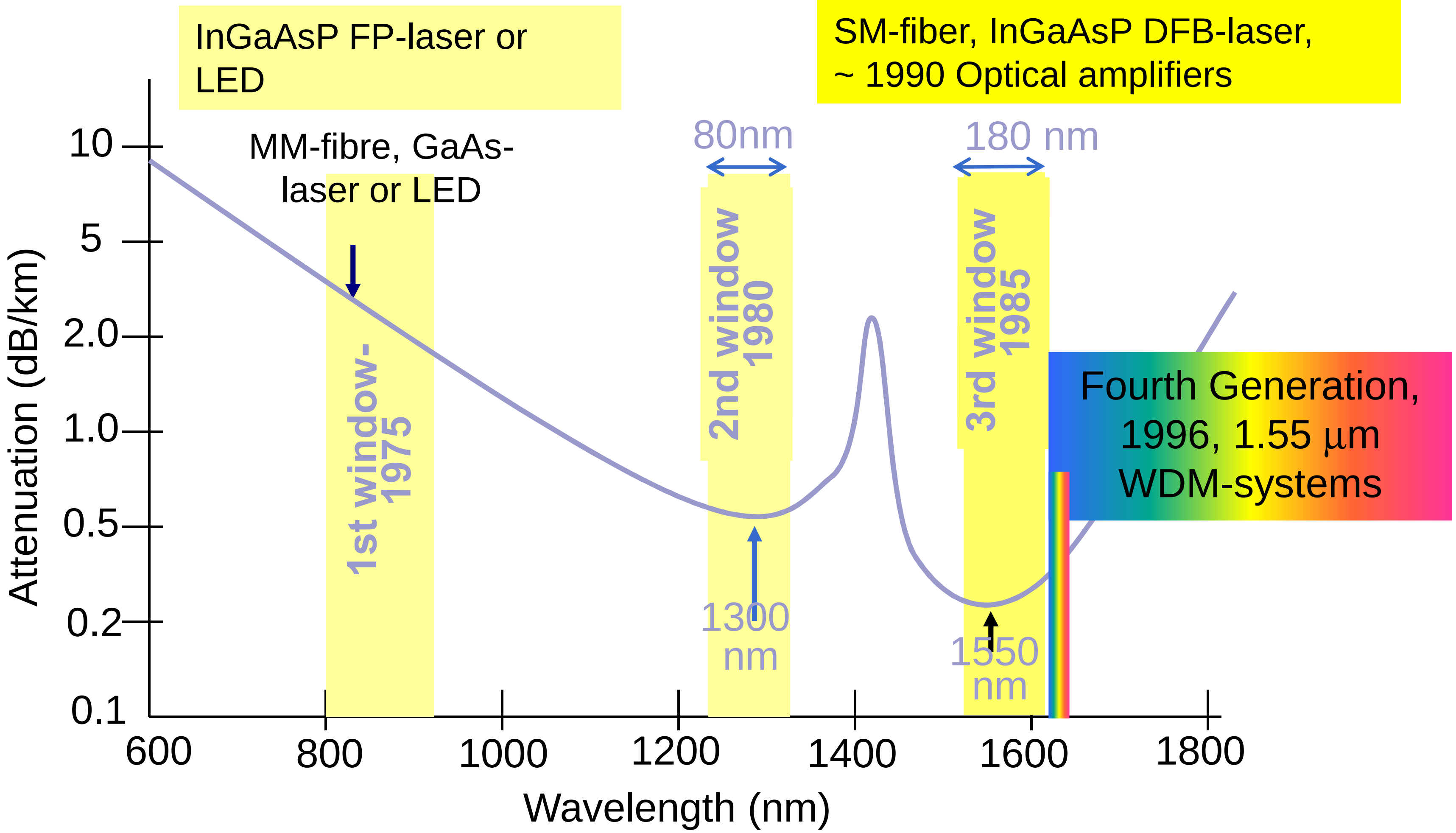
Fibre attenuation coefficient

($\alpha_p = \alpha_{scattering} + \alpha_{absorption} + \alpha_{bending}$)

Attenuation along the fibre link can be measured using **Optical Time Domain Reflectometer**

Optical Fiber

Fiber Loss



InGaAsP FP-laser or LED

MM-fibre, GaAs-laser or LED

SM-fiber, InGaAsP DFB-laser, ~ 1990 Optical amplifiers

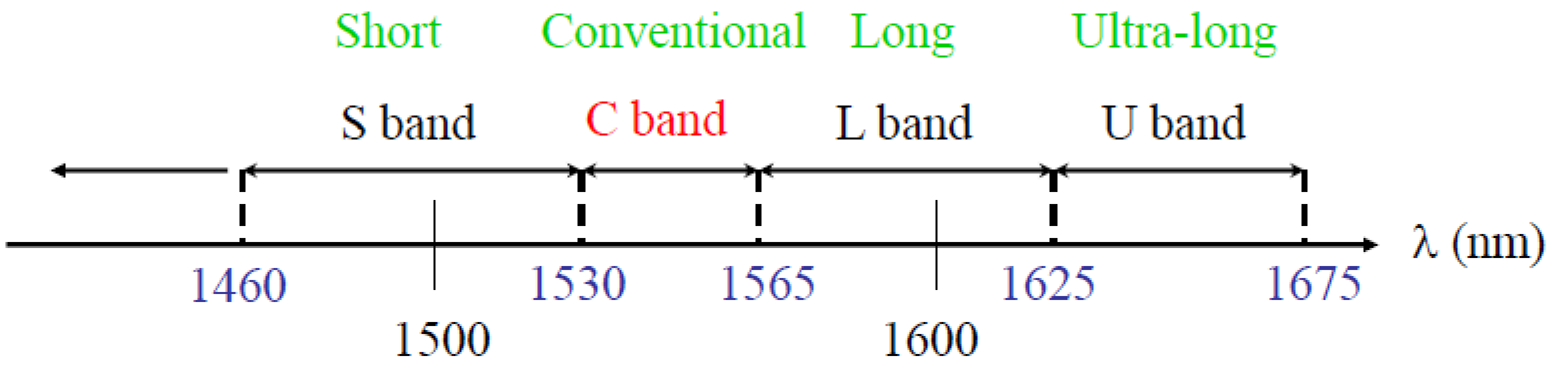
Fourth Generation, 1996, 1.55 µm WDM-systems

Fiber Loss

Three major spectral windows where fiber attenuation is low :

- the 1st window: 850 nm, attenuation 2 dB/km
- the 2nd window: 1300 nm, attenuation 0.5 dB/km
- the 3rd window: 1550 nm, attenuation 0.3 dB/km

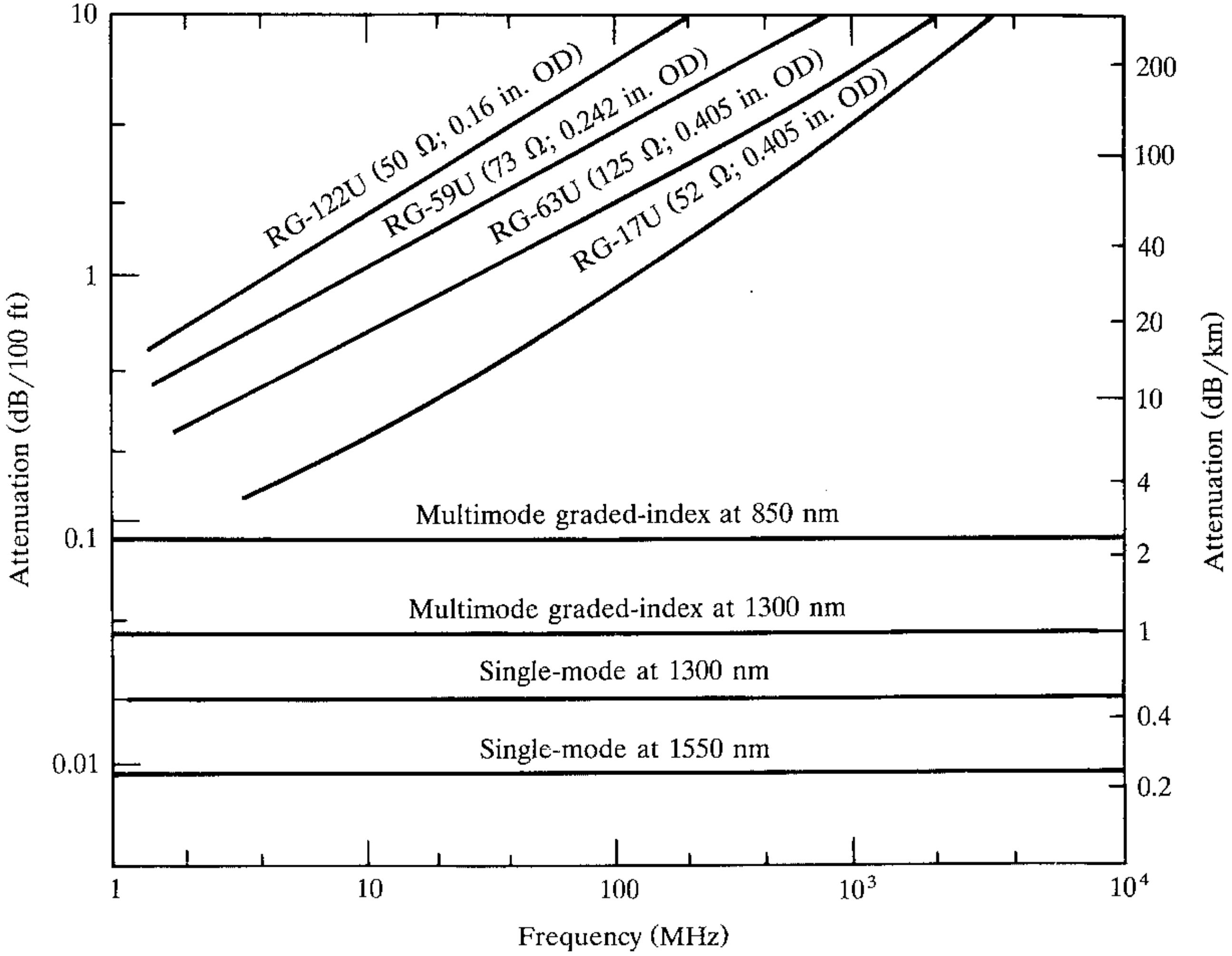
1550 nm window is today’s standard long-haul communication wavelengths



Optical Fiber

Attenuation vs Modulation Frequency (Bandwidth)

Fiber attenuation does not depend on modulation frequency



Fiber Loss

Fiber attenuation mechanisms:

1. Material absorption
2. Scattering loss
3. Bending loss
4. Radiation loss (due to mode coupling)
5. Leaky modes

Material absorption losses in silica glass fibers

- Material absorption - a loss mechanism related to
  - the material composition
  - the fabrication process for the fiber.

The optical power is lost as *heat* in the fiber.

- The light absorption
  - intrinsic (due to the material components of the glass)
  - extrinsic (due to impurities introduced into the glass during fabrication).

Intrinsic absorption

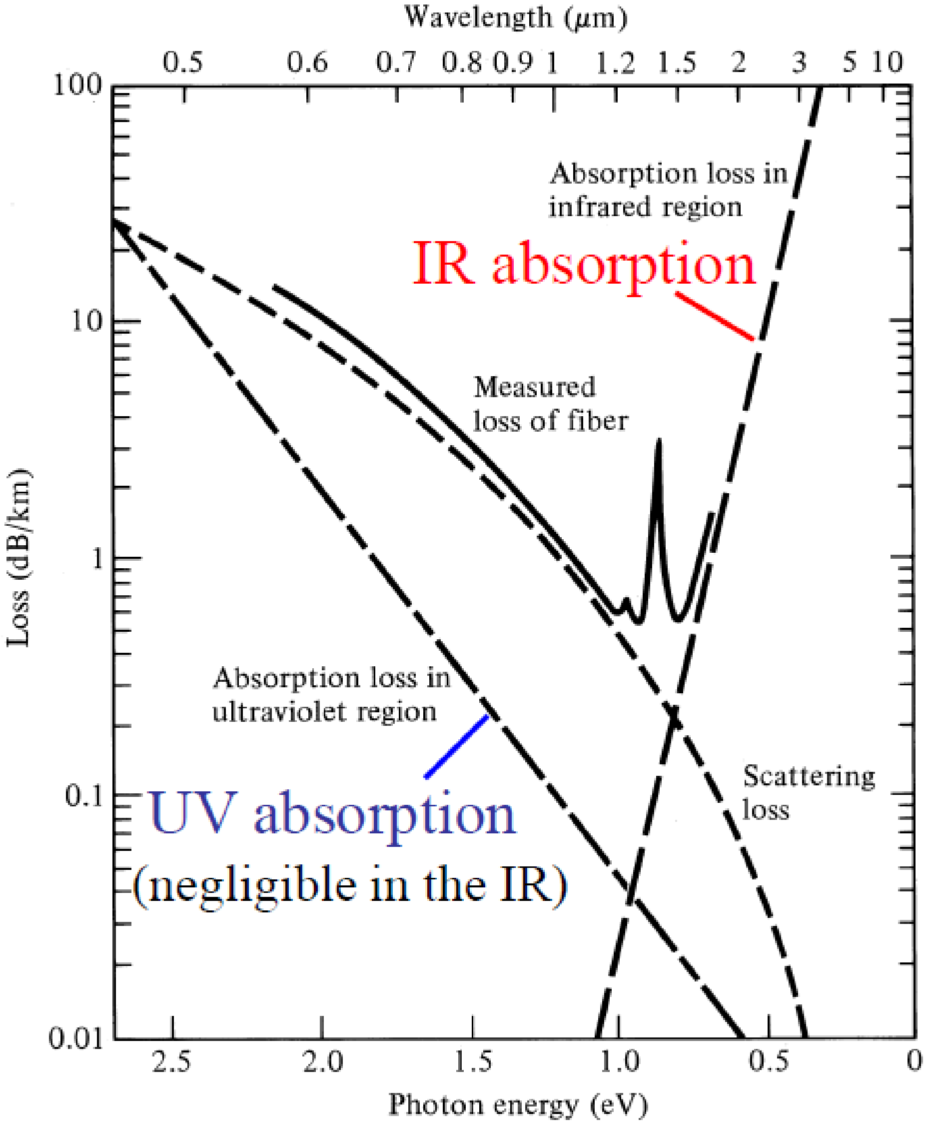
Pure silica-based glass has two major intrinsic absorption mechanisms at optical wavelengths:

(1) a fundamental UV absorption edge, the peaks are centered in the ultraviolet wavelength region. This is due to the electron transitions within the glass molecules. The tail of this peak may extend into the the shorter wavelengths of the fiber transmission spectral window.

(2) a fundamental infrared and far-infrared absorption edge, due to molecular vibrations (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

Optical Fiber

Fundamental fiber attenuation characteristics



Extrinsic absorption

- Major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH^- ions).
- These OH^- ions are bonded into the glass structure and have absorption peaks (due to molecular vibrations) at 1.38 mm.
- Since these OH^- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 mm and 1.55 mm which are essentially unaffected by OH^- absorption.
- The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 mm at about 0.2 dB/km, approaching the minimum possible attenuation at this wavelength.

Scattering loss

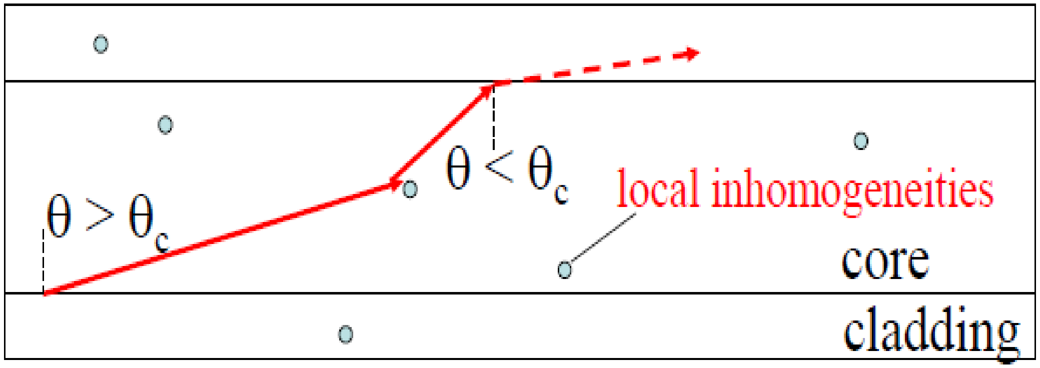
Scattering results in attenuation (in the form of radiation) as the scattered light may not continue to satisfy the total internal reflection in the fiber core - Silica glass is amorphous.

One major type of scattering is known as Rayleigh scattering - results from random non-homogeneities that are small in size – generate refractive index fluctuations

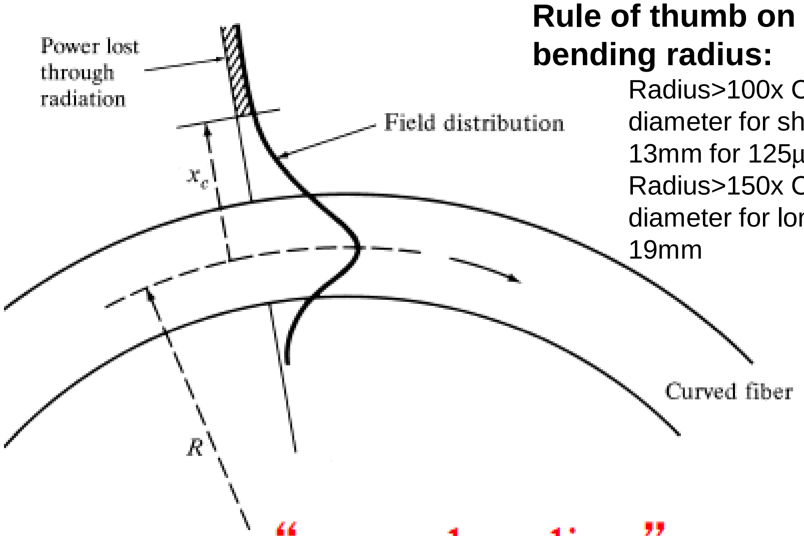
Rayleigh scattering results in an attenuation (dB/km): $\alpha_R = C / \lambda^4$

$$C = 0.8 - 0.9 \ \ [\mathrm{dB/km} \cdot \mu\mathrm{m}^4]$$

$$\alpha_R = 0.12 - 0.16 \ \mathrm{dB/km} \ ,$$
$$\text{for} \quad \lambda = 1.55 \mu\mathrm{m}$$



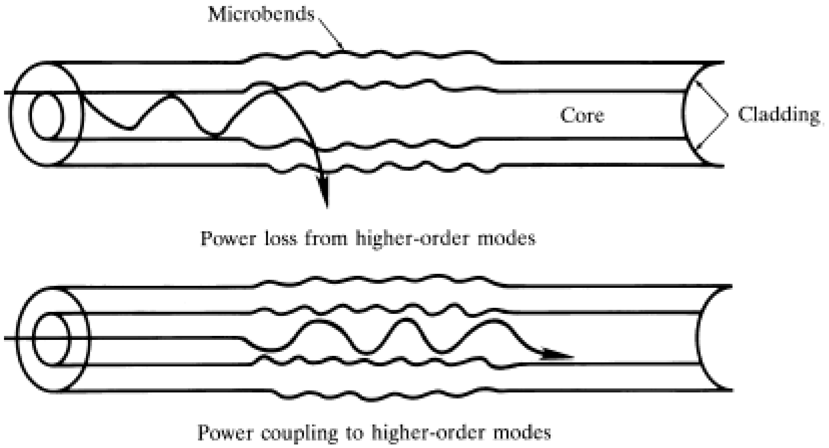
Fiber bending loss and mode-coupling to higher-order modes



Rule of thumb on minimum bending radius:

Radius>100x Cladding diameter for short times
13mm for 125µm cladding
Radius>150x Cladding diameter for long times
19mm

“macrobending”



“microbending”

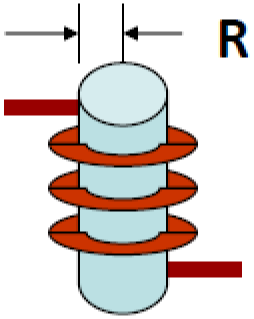
“microbending” – power coupling to higher-order modes that are more lossy

The total number of modes supported by a curved fiber is less than in a straight fiber:

$$M_{\text{eff}} = M_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR}\right)^{2/3}\right]\right\}$$

Bending Losses in Fibers

- Optical power escapes from tightly bent fibers
- Bending loss increases at longer wavelengths
  - Typical losses in 3 loops of standard 9-mm single-mode fiber (from: Lightwave; Feb 2001; p. 156):
  - 2.6 dB at 1310 nm and 23.6 dB at 1550 nm for R = 1.15 cm
  - 0.1 dB at 1310 nm and 2.60 dB at 1550 nm for R = 1.80 cm
- Progressively tighter bends produce higher losses
- Bend-loss insensitive fibers have been developed and now are recommended
- Improper routing of fibers and incorrect storage of slack fiber can result in violations of bend radius rules



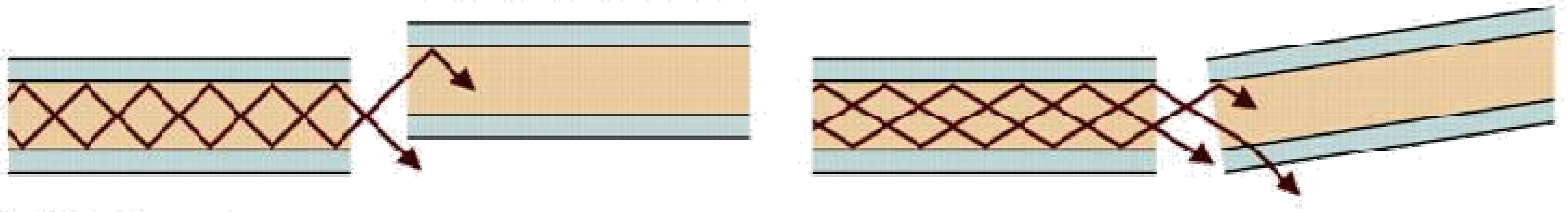
Test setup for checking bend loss:
N fiber loops on a rod of radius R

Splices and Connectors attenuations

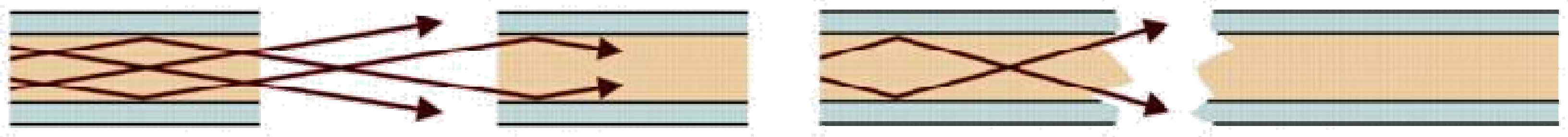
In fiber-optic systems, there are more losses sources: splices and connections. Their attenuation can be more than in the cable itself

Losses result from:

- Axial or angular misalignment
- Air gaps between the fibers
- Rough surfaces at the ends of the fibers



(a) Misalignment

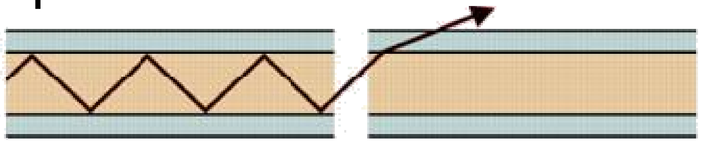


(b) Air gap

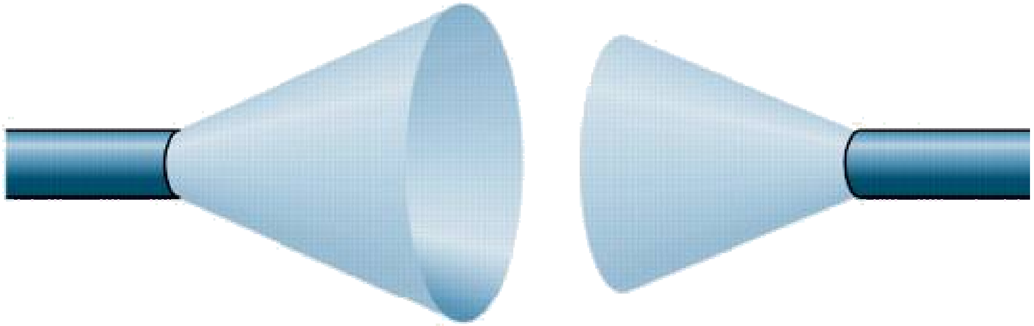
(c) Rough ends

Fiber-Optic Connectors

- Coupling the fiber to sources and detectors creates losses as well, especially when it involves mismatches in numerical aperture or in the size of optical fibers
- Good connections are more critical with single-mode fiber, due to its smaller diameter and numerical aperture
- A splice is a permanent connection and a connector is removable



(a) Path of escaping ray



(b) Different cones of acceptance

Optical Fiber

Loss of the fiber to source coupling

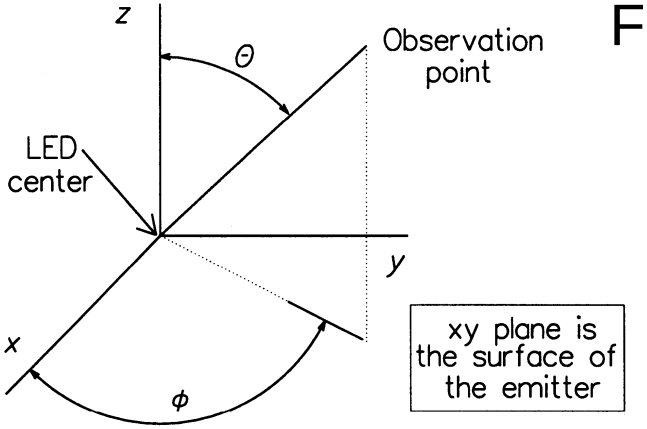
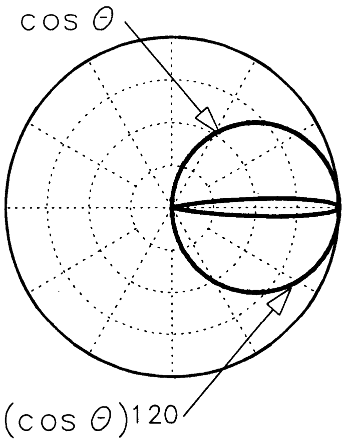


Figure 5.27 Emitter coordinate system.



For Lambertian source radiance distribution

$$B(\theta,\phi) = B_0 \cos\theta \, ,$$

Generalized *Coupled Power*

$$P_f = \int_0^{r_u} \int_0^{2\pi} \left(\int_0^{2\pi} \int_0^{\theta_{\max}} B(\theta,\phi) \sin\theta \, d\theta \, d\phi \right) d\phi_s \, r \, dr \, .$$

$$P_f = \pi B_0 \int_0^{r_u} \int_0^{2\pi} \sin^2(\theta_{\max}) \mathrm{d}\phi_s \; \rho \; \mathrm{d}\rho$$

$$= \pi B_0 \int_0^{r_u} \int_0^{2\pi} (NA)^2 \, \mathrm{d}\phi_s \; \rho \; \mathrm{d}\rho$$

$$\text{where N.A.} : \quad (NA)^2 = \sin^2(\theta_{\max})$$

Optical Fiber

Loss of the fiber to source coupling

For step index fiber NA is independent of position of *r* (inside core)

The double integral result:

$$P_f = P_s = \pi B_0 (NA)_s^2 r_s^2 \quad \text{for} \quad r_s < a \text{ , } (\mathrm{NA})_s < (\mathrm{NA})_{\mathrm{OF}} \quad (\text{source} < \mathrm{OF})$$

$$P_f = \pi B_0 (NA)_{\mathrm{OF}}^2 a^2 \quad \text{for} \quad r_s \geq a, \ (\mathrm{NA})_s \geq (\mathrm{NA})_{\mathrm{OF}} \quad (\text{source} > \mathrm{OF})$$

The *coupling efficiency*

$$\eta = \frac{P_f}{P_s} = \frac{(NA)_{OF}^2}{(NA)_S^2} \cdot \frac{a^2}{r_s^2}$$

Optical Fiber

Loss of the fiber to source coupling

For graded-index fiber NA is dependent of position of *r*

$$NA(r) = NA(0)\sqrt{1-(r/a)^{\alpha}}$$

So, integral for power coupled into fiber becomes

$$P_f = \pi B_0 \int_0^{r_u} \int_0^{2\pi} NA(0)^2 \left(1-(r/a)^{\alpha}\right) \mathrm{d}\phi_s \; r \; \mathrm{d}r$$

Evaluating the integral for $r_S < a$

$$P_f = \underbrace{\pi^2 B_0 r_S^2}_{P_S} NA(0)^2 \left[1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right] \quad , \quad (r_S < a)$$

Resulting the

coupling efficiency :

$$\eta = \frac{NA(0)^2}{(NA)_S^2}\left[1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right]$$

Optical Fiber

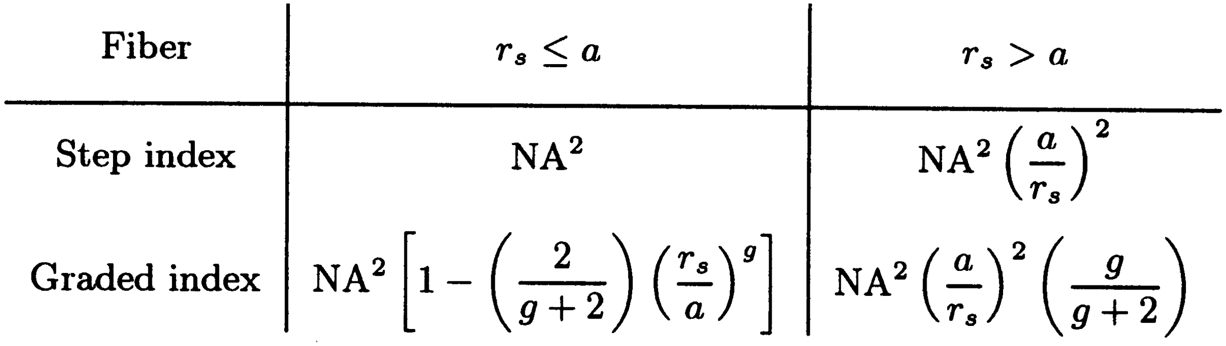
Loss of the fiber to source coupling

For the case $\left(r_S > a\right)$, the power into a fiber is

$$P_f = \frac{\pi^2 B_0 a^2 NA(0)^2 \alpha}{\alpha + 2} \quad , \quad r_s > a$$

So the coupling efficiency becomes:

$$\eta = \frac{NA(0)^2}{(NA)_S^2}\left(\frac{a}{r_S}\right)^2 \frac{\alpha}{\alpha+2} \quad , \ (r_s > a, \quad \text{graded index})$$



Fiber	$r_s \le a$	$r_s > a$
Step index	NA^2	$\mathrm{NA}^2\left(\frac{a}{r_s}\right)^2$
Graded index	$\mathrm{NA}^2\left[1-\left(\frac{2}{g+2}\right)\left(\frac{r_s}{a}\right)^g\right]$	$\mathrm{NA}^2\left(\frac{a}{r_s}\right)^2\left(\frac{g}{g+2}\right)$

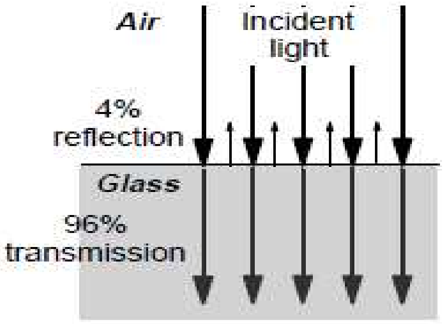
Table 5.2 Summary of coupling efficiencies (Lambertian emitter).

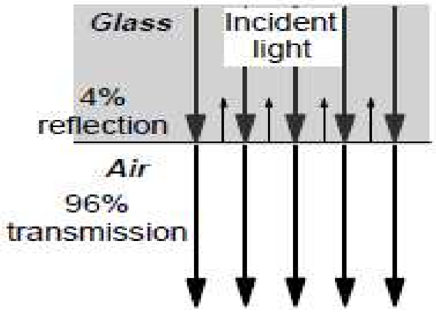
Optical Fiber

Fresnel loss

- Reflected power

$$\frac{P_{ref}}{P_{in}} = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

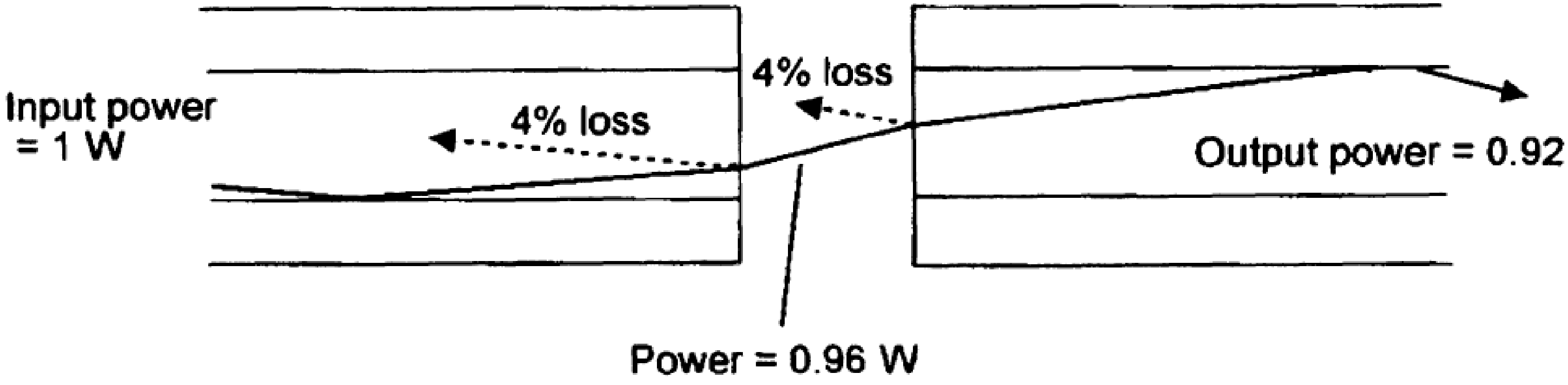




$$\frac{P_{tr}}{P_{in}} = 1 - \frac{P_{ref}}{P_{in}} = \left(\frac{2n_1 n_2}{n_1 + n_2} \right)^2$$

$$\text{for } n_1 = 1.5 \, ; \, n_2 = 1 \;\; \Rightarrow$$

$$\frac{P_{tr}}{P_{in}} \cong 92\% \quad (loss = 0.177\text{dB})$$



Bibliography

- G. P. Agrawal – Fiber Optic Communication Systems, 4th Ed, 2010

- R. Ramaswam, et. at. - Optical Networks. A Practical perspective, 3rd Ed, 2010

- J. M. Senior -Optical Fiber Communications Principles and Practice, 3rd, Ed 2009