Cours OPAT – APPING_I2

Promo 2020 – Novembre/décembre 2018

General Optics and Application to Optical Fiber Networks

Part 1 - Basics of fundamental optics - Optical fibers and cables
Part 2 - Optoelectronic components
Part 3 - Wavelength division multiplexing
Part 4 – Standards and future evolutions

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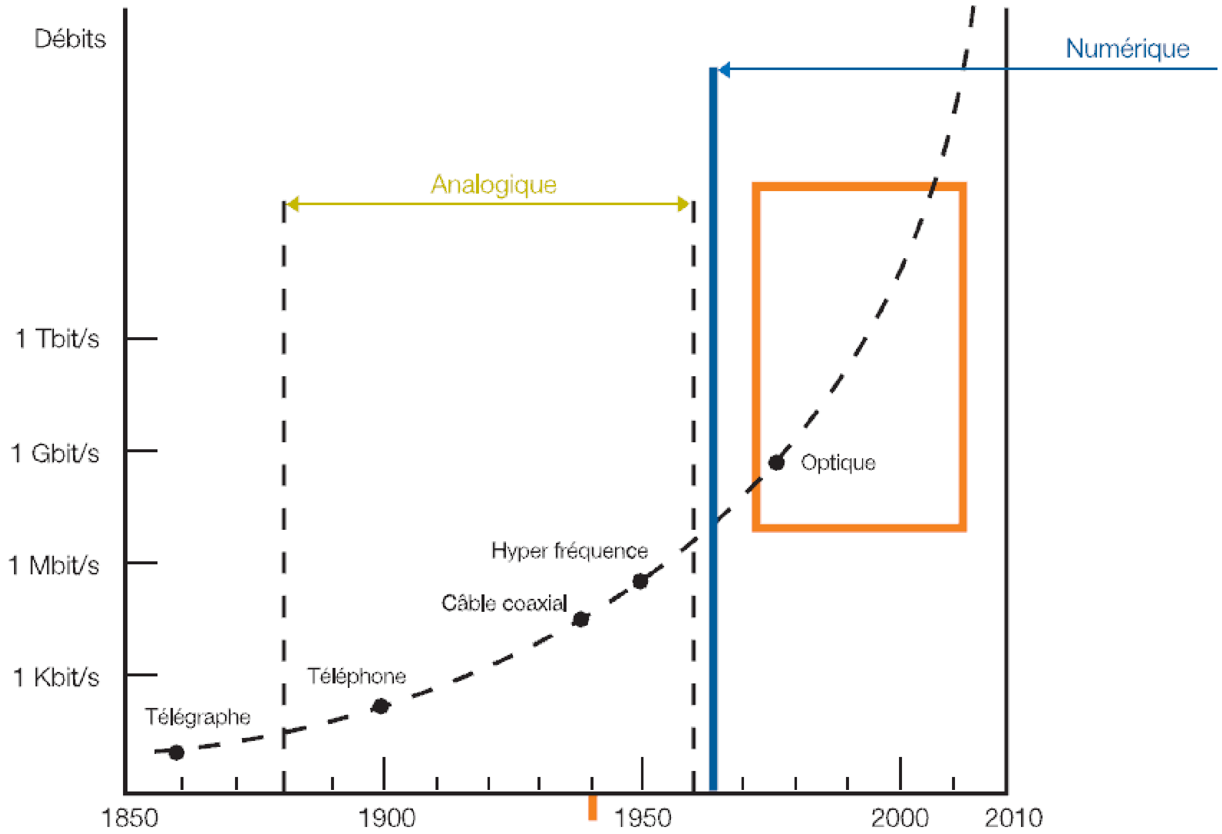
History of optical fiber development

•Development of fibers and devices for optical communications began in the early 1960s and continues strongly today
• The four major developments and inventions that have contributed to this progress :

1. The invention of the LASER (in the late 1950's)
2. The development of low loss optical fibre (1970's)
3. The invention of the optical fibre amplifier (1980's)
4. The invention of the in-fibre Bragg grating (1990's)

Needs for higher bit rates

- Increasing needs for higher bit rates



Internet applications: bit rate classes

• 3 classes of bit rates are commonly considered for the Internet applications

- Low bit rates : < 1 Mbit/s
- Medium bit rates : 1 to 10 Mbit/s
- High bit rates : 10 to > 100 Mbit/s

Internet applications: bit rate classes

- Future « Very High Bit Rate »

  - Bit rates > 100 Mbit/s will be shortly needed due to the exponential demand for higher capacity

  - Applications for VHB :
    - HD interactive television
    - High quality video-conference
    - Heavy files downloading

  - VHB only reachable using optical fibers

Potential applications of VHB

- Some applications of Very High Bit Rate
  - Medicine
    - Visio-conference between patient and doctor
    - Remote surgery using remotely-controlled robot
  - Social
    - Remote survey for old persons
  - Leisure
    - Downloading HQ pictures
    - Viewing DVD or HD quality movie films

Potential applications of VHB

- **Examples of download times**
  - **Downloading 25 pictures @ 800 Ko each**

Connection type	Download time
100 Mbit/s	2 seconds
10 Mbit/s	20 seconds
1 Mbit/s	3 minutes 20 seconds
512 kbit/s	7 minutes
128 kbit/s	30 minutes

  - **Downloading a DVD quality movie film @ 7.18 Go**

Connection type	Download time
100 Mbit/s	48 minutes
10 Mbit/s	8 hours
1 Mbit/s	16 hours
512 kbit/s	1 day 8 hours
128 kbit/s	5 days 8 hours

Advantages of optical fibers in transmission networks

- Optical fibers are today commonly used in telecommunication and networking

- Main advantages are:

  - Weight and size
  - Material cost
  - Immunity against electromagnetic interference
  - Better security : tap easy to detect
  - Very low attenuation : long distance between repeaters
  - Information capacity : some 100 Gbit/s per fiber
  - Compatible with wavelength multiplexing

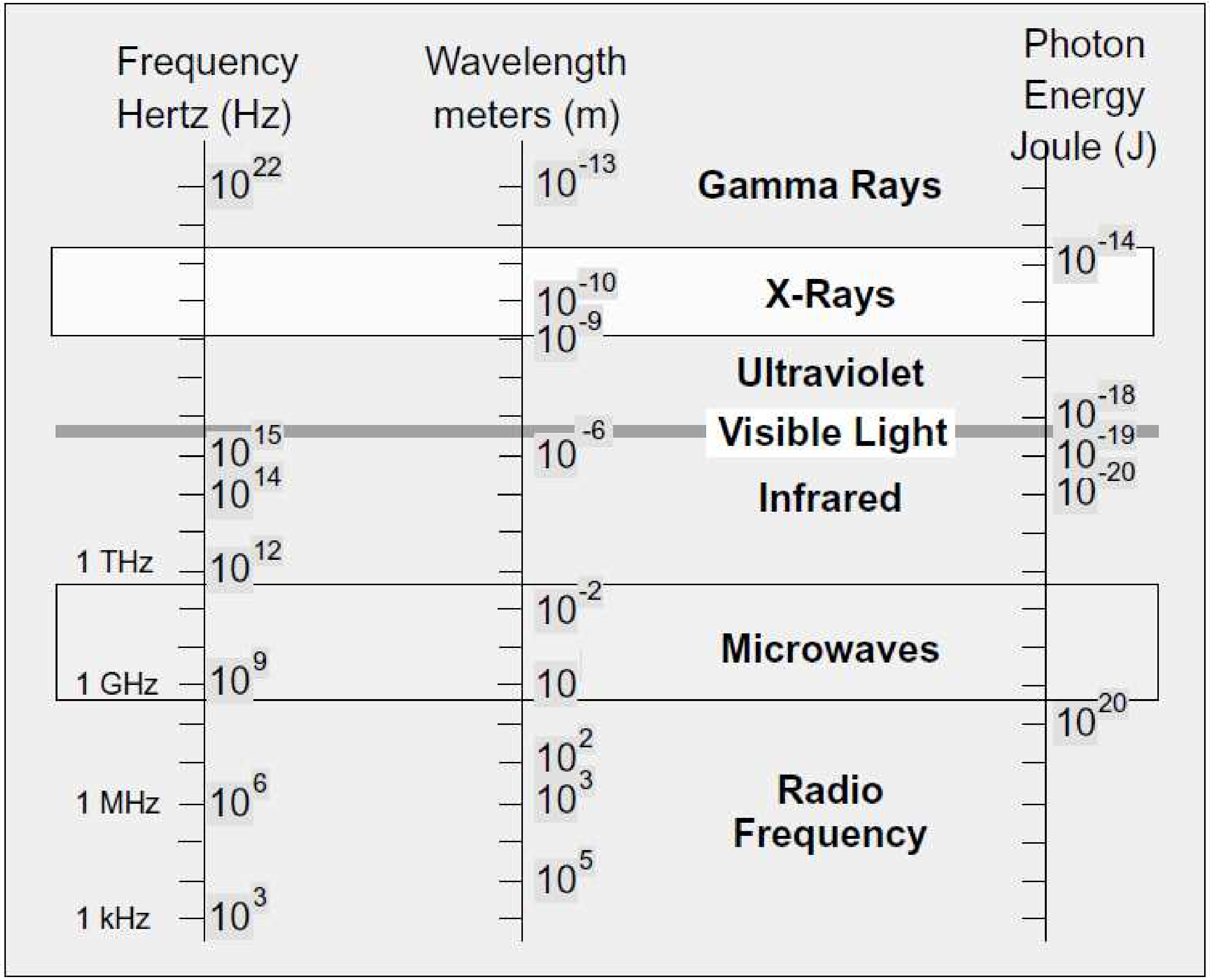
Optical fibers and cables

- **Optical fibers**
  - **Basics of fundamental optics**
    - **Nature of light**
    - **Analog and digital signals**
    - **Refraction and reflection phenomena**
  - **Optical fibers**
    - **Basic fiber structure**
    - **Multimode and single-mode fibers**
    - **Main characteristics of fibers**
      - Dispersion
      - Attenuation
    - **Manufacturing technologies**
- **Optical cables**
  - **Description of various optical cables**

The nature of light

- **THE LIGHT**
  - **The light is an electromagnetic wave**
  - **Propagation speed in vacuum : c = 300.000 km/s**
  - **Propagation speed in a transparent material**
    - **v = c / n (n = material refraction index)**
    - **In glass : n ~ 1.5 ie. v ~ 200.000 km/s**
  - **Frequency and wavelength**
    - **$f = c / \lambda$ (f in Hz, c in m/s, λ in m)**
  - **Wavelength range used in optical fibers**
    - **λ between 0.8 µm and 1.7 µm ---> Near infra-red**
  - **Corresponding frequency range**
    - **f = 175 to 375 THz (1 THz = 1000 GHz)**

The electromagnetic waves spectrum



Some useful units

- ♦ **Wavelength (representing the emitted colour)**
  - **Explained either in µm (micrometer or micron) or in nm (nanometer)**
    - **1 µm = 1 millionth meter**
    - **1 nm = 1 billionth meter**
    - **1 µm = 1000 nm**
    - **Other unit : pm (picometer) = 1 thousandth nanometer**

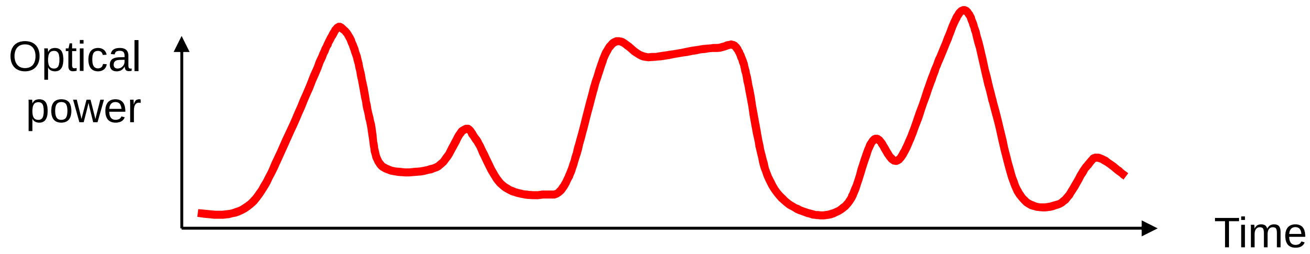
The wavelength currently used in optical fibers is in the order of 1 µm (ou 1000 nm)

- ♦ **Frequency**
  - **Explained in hertz (Hz). 1 Hz = 1 cycle per second**
    - **1 kHz (kilohertz) = 1000 Hz**
    - **1 MHz (megahertz) = 1 million Hz**
    - **1 GHz (gigahertz) = 1 billion Hz**
    - **1 THz (terahertz) = 1000 GHz = 1000 billions Hz**

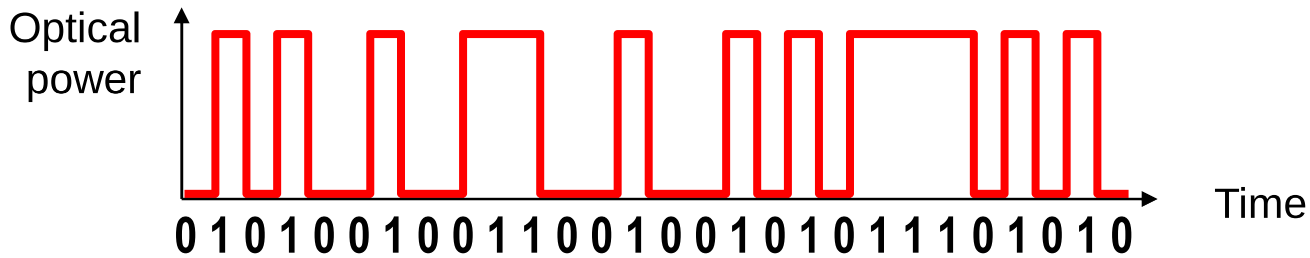
The frequency currently used in optical fibers is in the order of 200 THz (or 200,000 GHz)

Nature of transmitted signals

- **Analog signal**
  - **Optical power proportional to the amplitude of the electrical signal to be transmitted**



- **Digital signal : random series of «1s» and «0s» (binary train)**
  - **Example : 110010110001101001110010100101101001001110001100**
  - **Generalized to all transmission systems today**

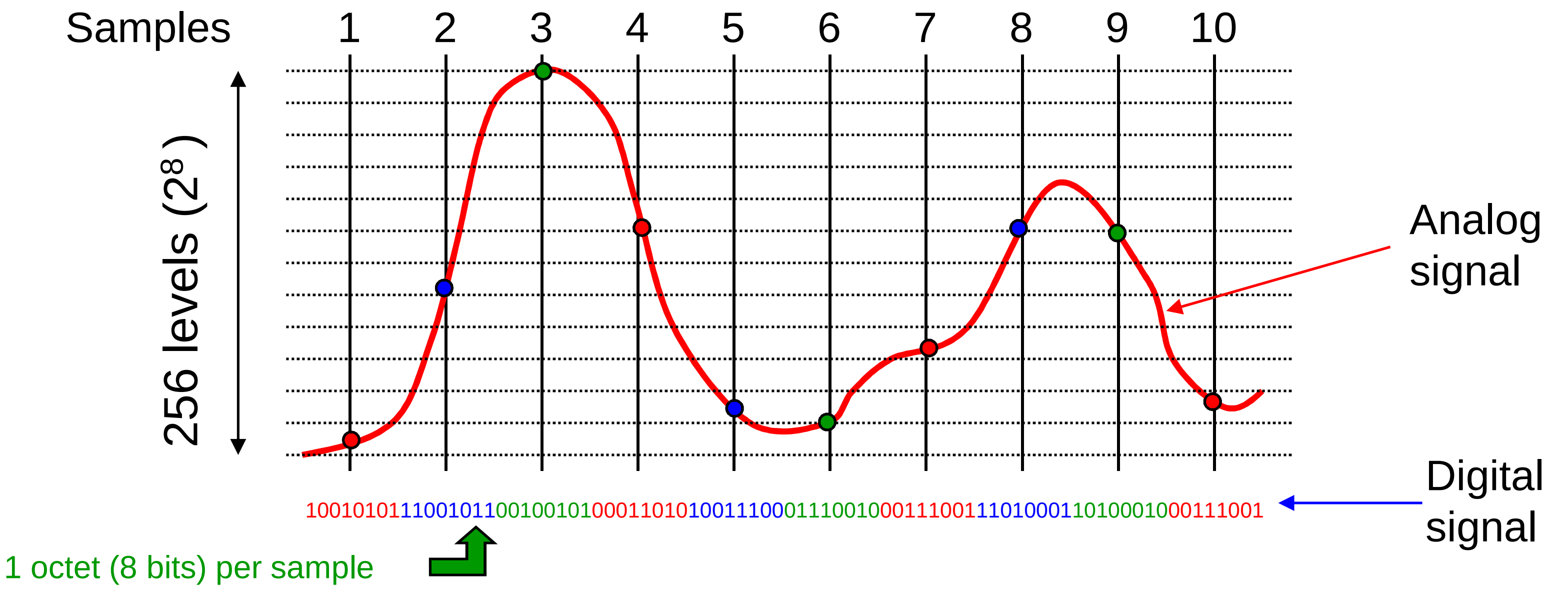


Digital signal

- **Characteristics of a digital signal**
  - **Bit (Binary Digit) = information element (1 or 0)**
    - **Level « 1 » = maximum optical power**
    - **Level « 0 » = minimum optical power**
  - **Digital bit rate = number of bits per second**
    - **Examples :**
      - Standard telephone signal = 64 kbit/s
      - CD quality signal = 800 kbit/s
      - High bit rate multiplexed signal = 2.5 Gbit/s
  - **According to international telecommunication standards**
    - **SDH (Synchronous Digital Hierarchy) -> Europe/Asia**
    - **SONET (Synchronous Optical NETwork) -> USA**

How to digitalize an analog signal

- **Example : standard telephone signal (4 kHz base band)**
  - **One sample every 125 µs (8 kHz sampling frequency)**
  - **Sample amplitude corresponds to one level among 256 (number of combinations for one octet = 8 bits)**
  - **It is given the corresponding octet value**
  - **Digital bit rate obtained : 8 bits/125 µs = 64 kbit/s**



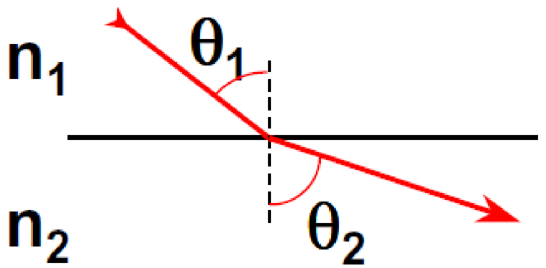
Basics of fundamental optics

- **Refraction index n**
  - **In a transparent material the light speed is lower than in vacuum**
  - **The refraction index is the ratio between light speed in vacuum (c) and light speed in the material (v)**

$$v = c/n$$

- **Snell-Descartes law**

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

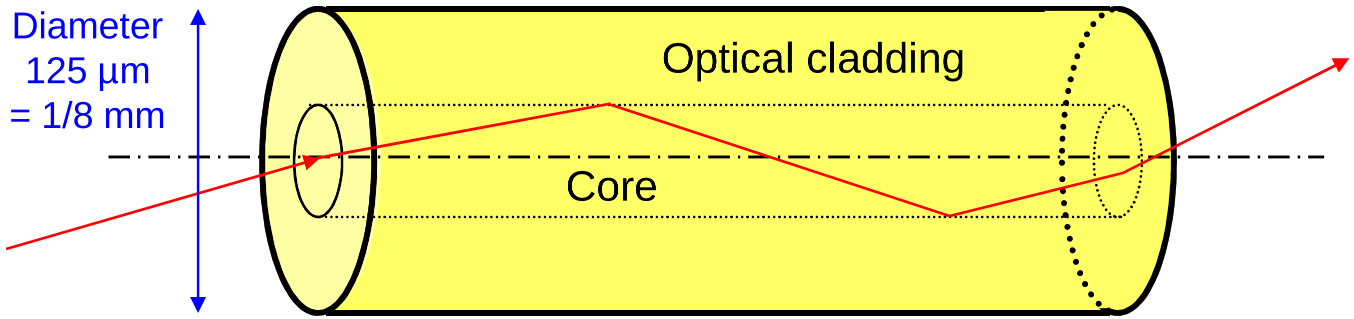


If $n_1 > n_2$ the ray goes far from the normal axis

If $\theta_1 > \arcsin(n_2/n_1)$ reflection is total

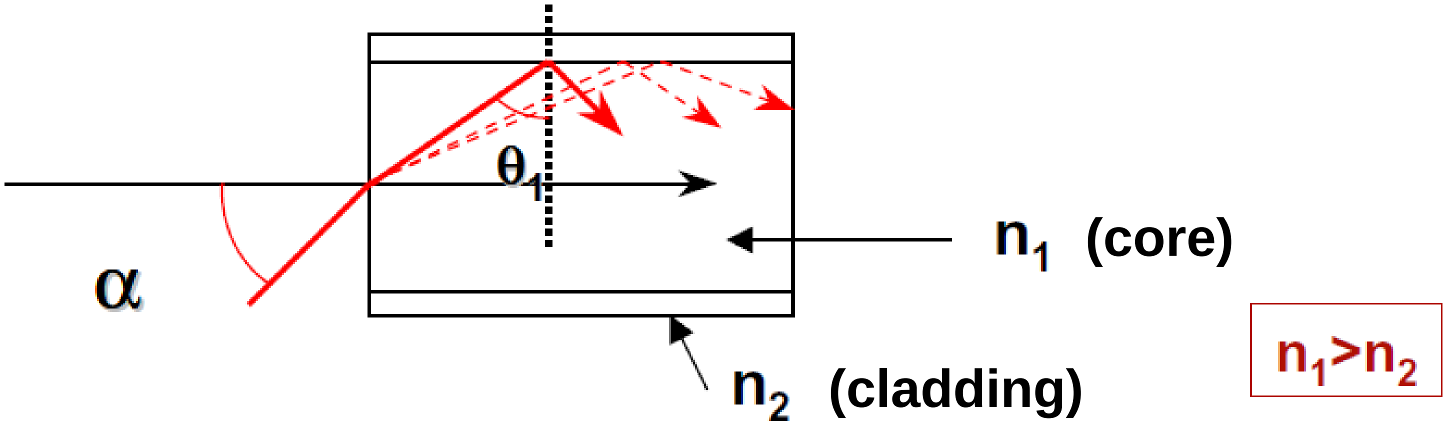
Structure of an optical fiber

- **Composed of a silica (SiO_2) optical cladding and a doped-silica core**



- **Light propagates in the core by multiple reflections on the optical cladding only if core refraction index n_1 is higher than cladding refraction index n_2 ($n_1 > n_2$)**

Propagation in the optical fiber

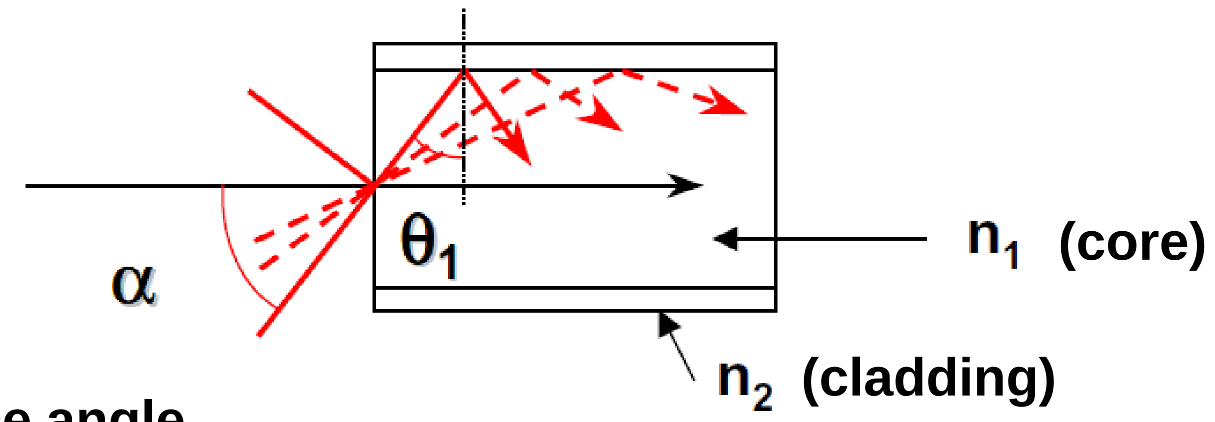


Condition of light guided in the core :

$$\theta_1 \geq \arcsin \frac{n_2}{n_1}$$

Otherwise the ray is refracted into the optical cladding

Propagation in the optical fiber



α = incidence angle

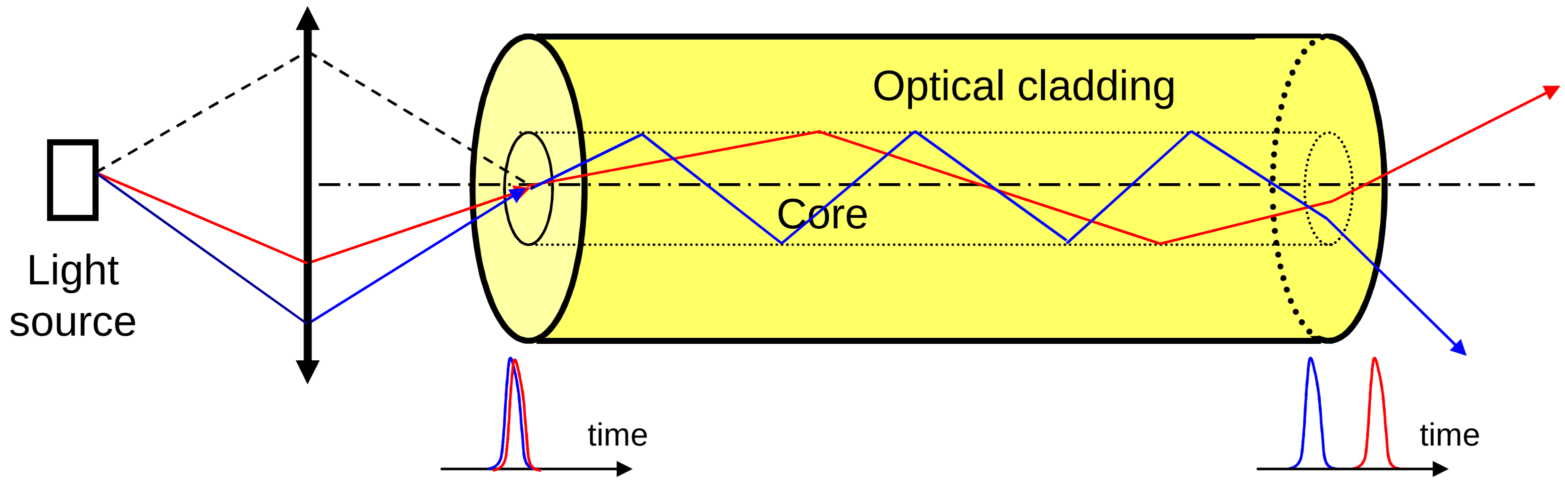
α_{max} = acceptance angle = maximum incidence angle

Numerical aperture NA (ouverture numérique ON) :

$$\text{ON} = \sin \alpha_{max} = n_1 \sin\left(\frac{\pi}{2} - \theta_{1lim}\right) = \sqrt{\left(n_1^2 - n_2^2\right)}$$

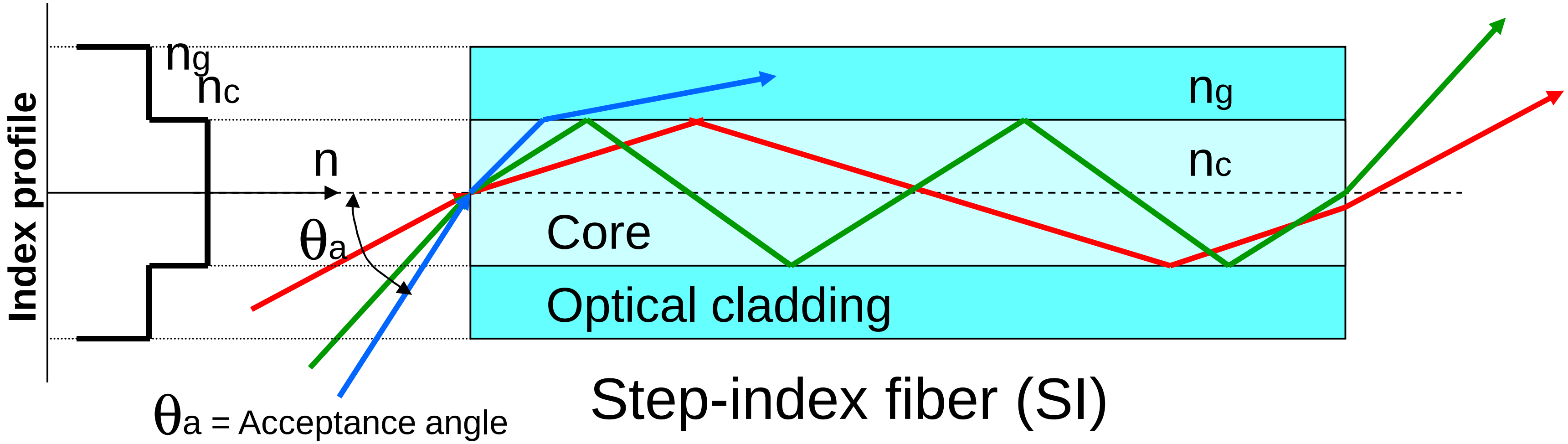
The multimode fiber

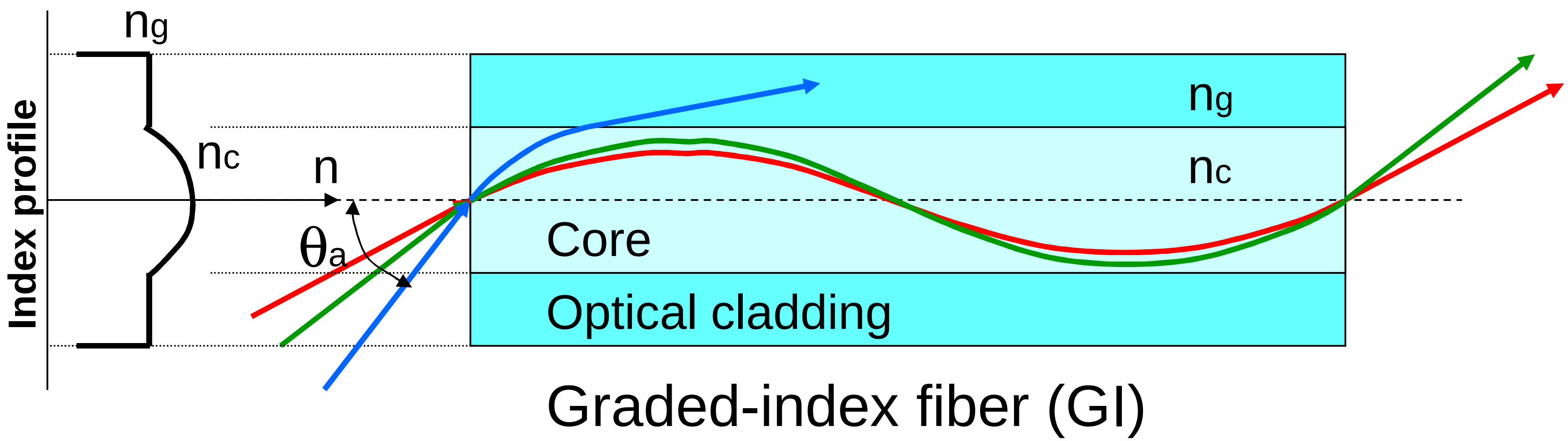
- ♦ **Large diameter core (> 50 µm)**



- ♦ **Main problem : MODAL DISPERSION**
  - **Rays with different incidence angles propagate at different speeds CONSEQUENCE : IMPORTANT DISTORTION OF SIGNALS**

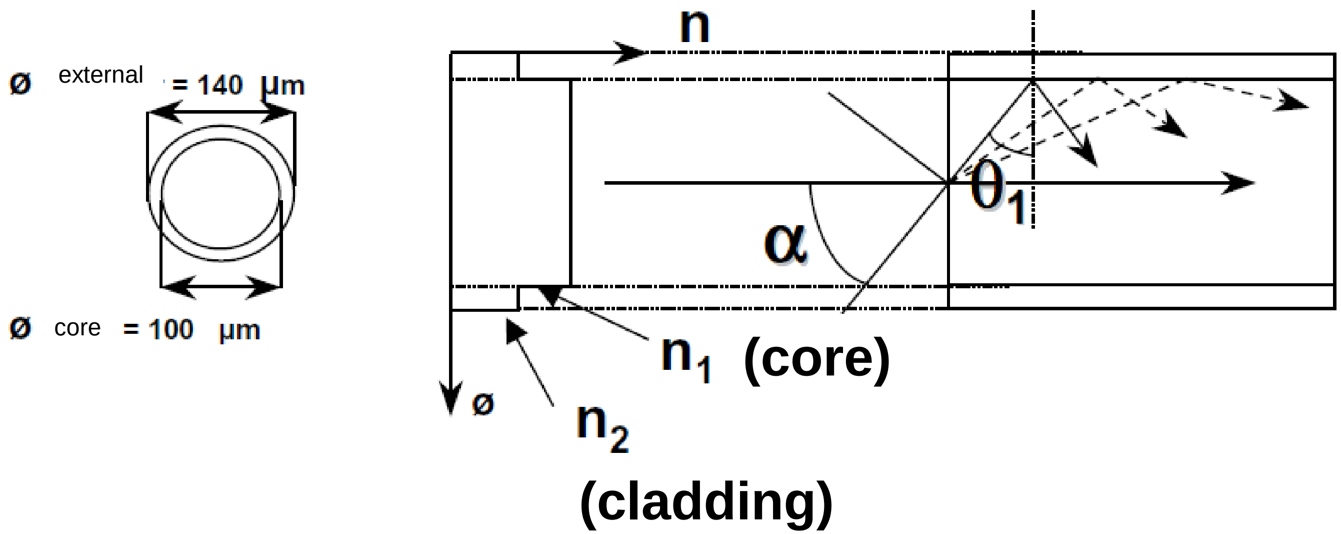
Two categories of multimode fibers





Step-index multimode fiber

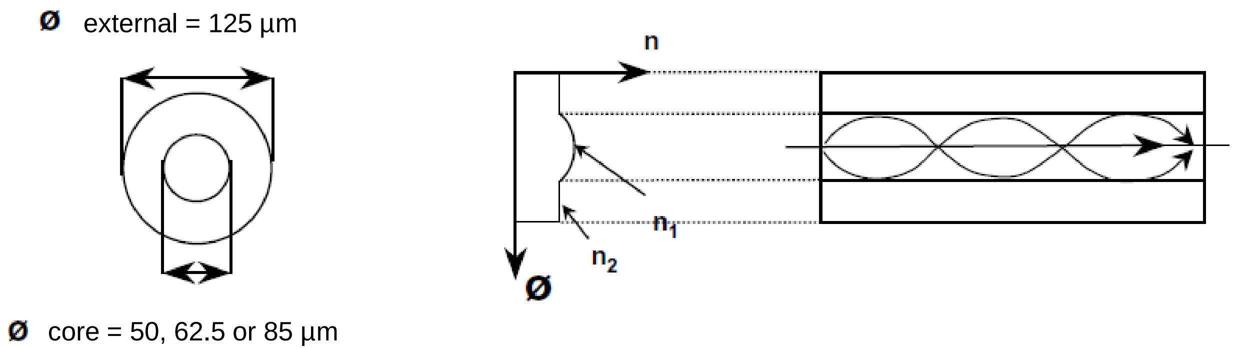
The step-index multimode fiber



Refraction index in the core (n_1) is constant

Graded-index multimode fiber

The graded-index multimode fiber



The core index decreases following a parabolic law from the axis to the core-cladding interface

The light propagates faster in lower index areas, reducing modal dispersion

Multimode propagation

V parameter = normalized frequency $$V = \frac{2\pi a}{\lambda_0}\sqrt{\left(n_1^2 - n_2^2\right)}$$

Number of propagation modes :

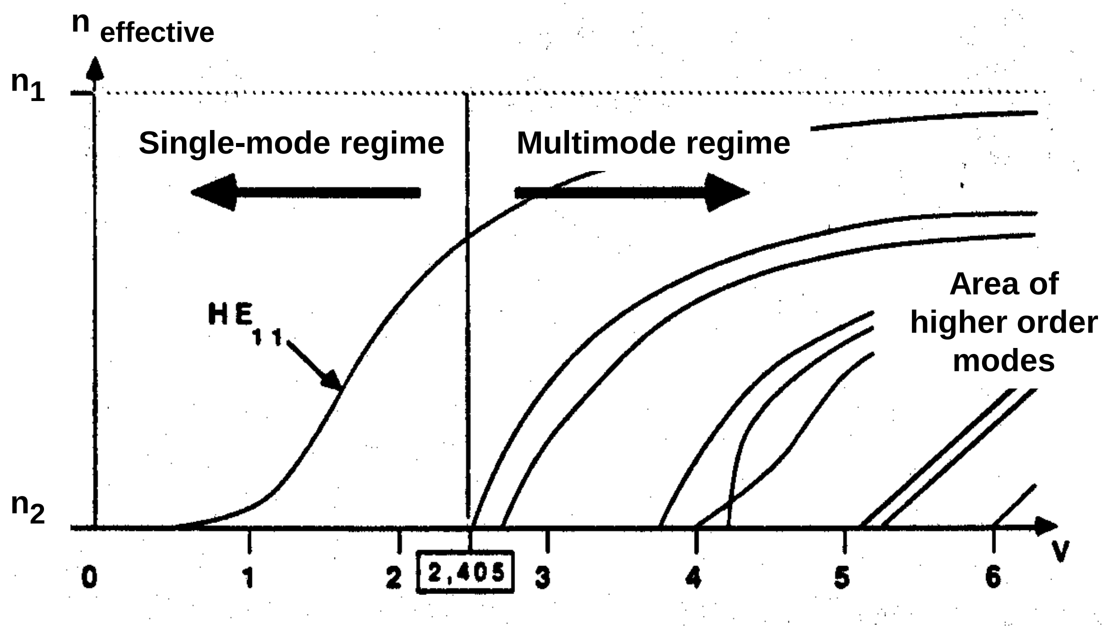
- For a step-index fiber : $$M = \frac{V^2}{2}$$

- For a graded-index fiber : $$M = \frac{V^2}{4}$$

The light ray can propagate in the fiber core in various ways each mode having its own propagation speed along the axis

Definition of single-mode regime

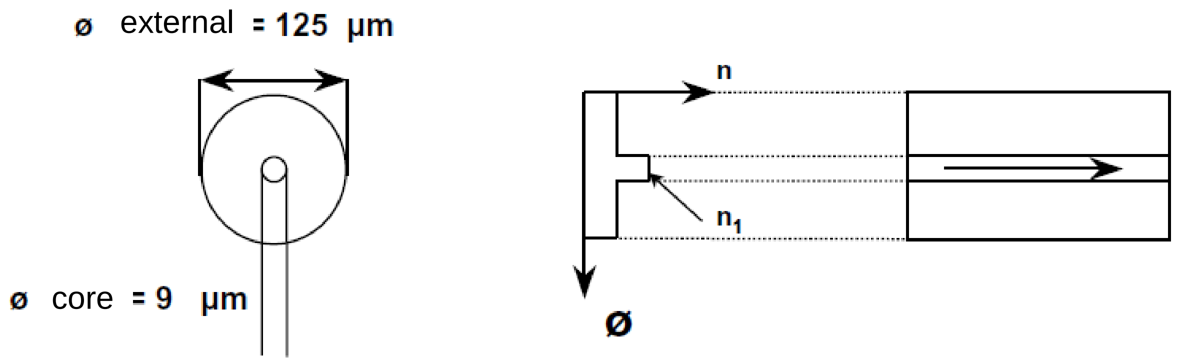
♦ **Single-mode and multimode regimes**



- **A fiber is single-mode when V < 2,405**

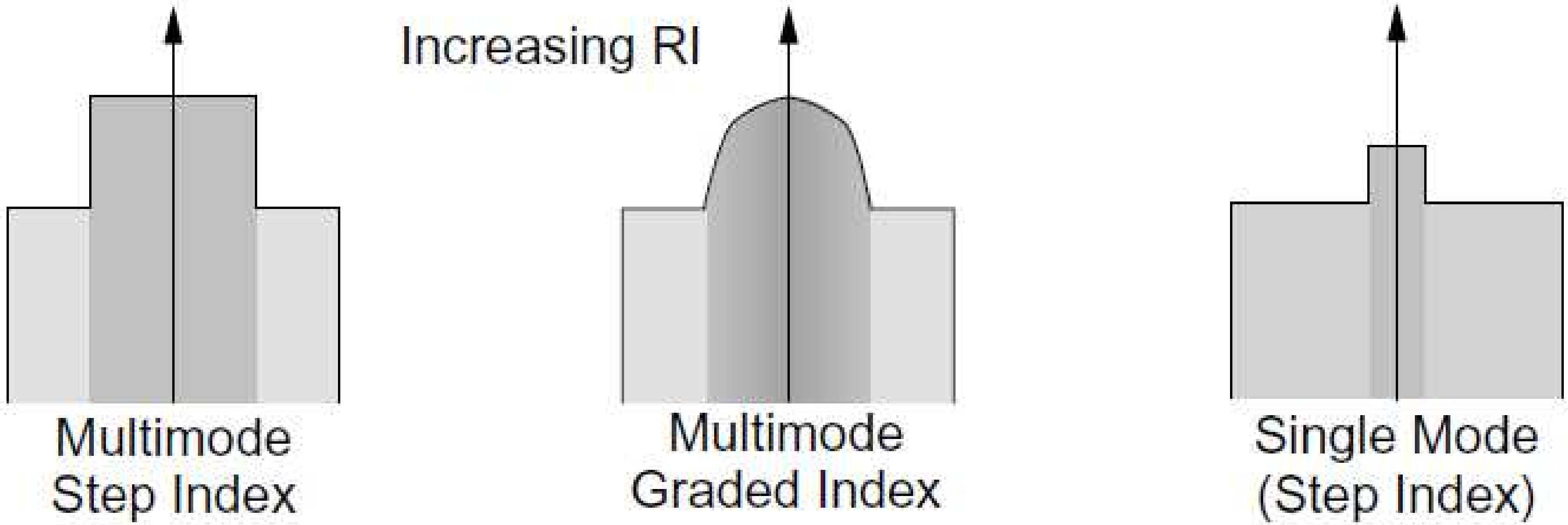
The single-mode fiber

The single-mode step-index fiber

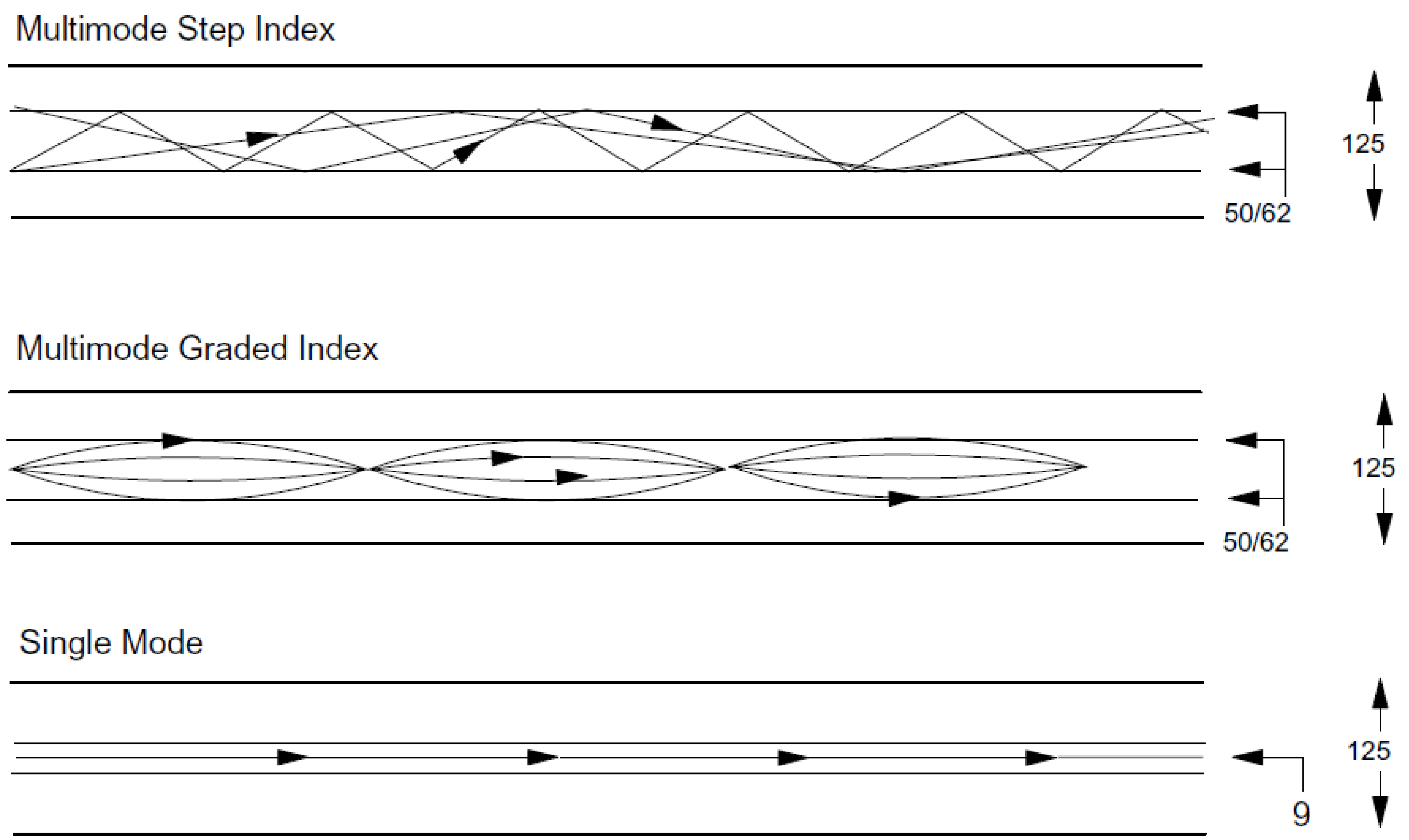


Selection of one propagation mode (fundamental mode) propagating close to the axis

Fiber refractive index profiles

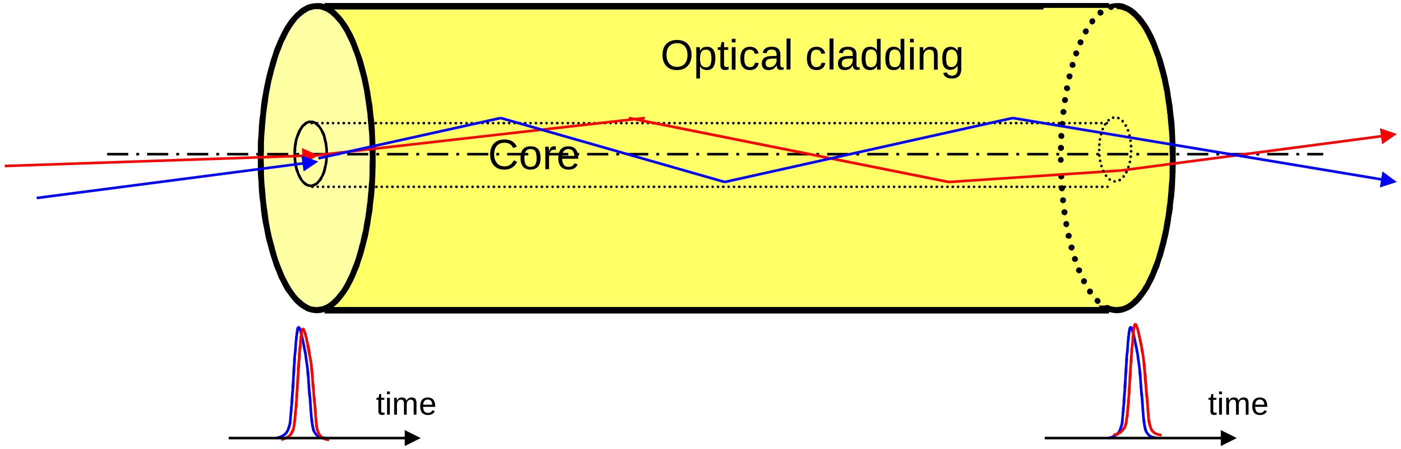


Propagation modes in optical fibers



The single-mode fiber

- **Low diameter core (8 to 10 µm)**



- **Main advantage : NO MODAL DISPERSION**
  - **All rays propagate with the same speed, whatever their incidence angle**
    - **CONSEQUENCE : VERY LOW SIGNAL DISTORTION**

Multimode vs single-mode

Multimode fiber :

- First fiber used
- Easy implementation : large core, high mechanical tolerances
- Intrinsic bandwidth limitation due to modal dispersion

  => Dedicated to short distance networks

Single-mode fiber :

- Extremely high bandwidth (no modal dispersion)
- Requires expansive components
- Low mechanical tolerances

  => Universal solution for today's telecommunication systems

Cut-off wavelength

Mode guiding varies with the wavelength :

- **At high wavelengths, only the fundamental mode is guided**
- **At short wavelengths, the fundamental mode is guided but higher order modes are also guided**
- **The cut-off wavelength is the wavelength above which the fiber becomes single-mode**

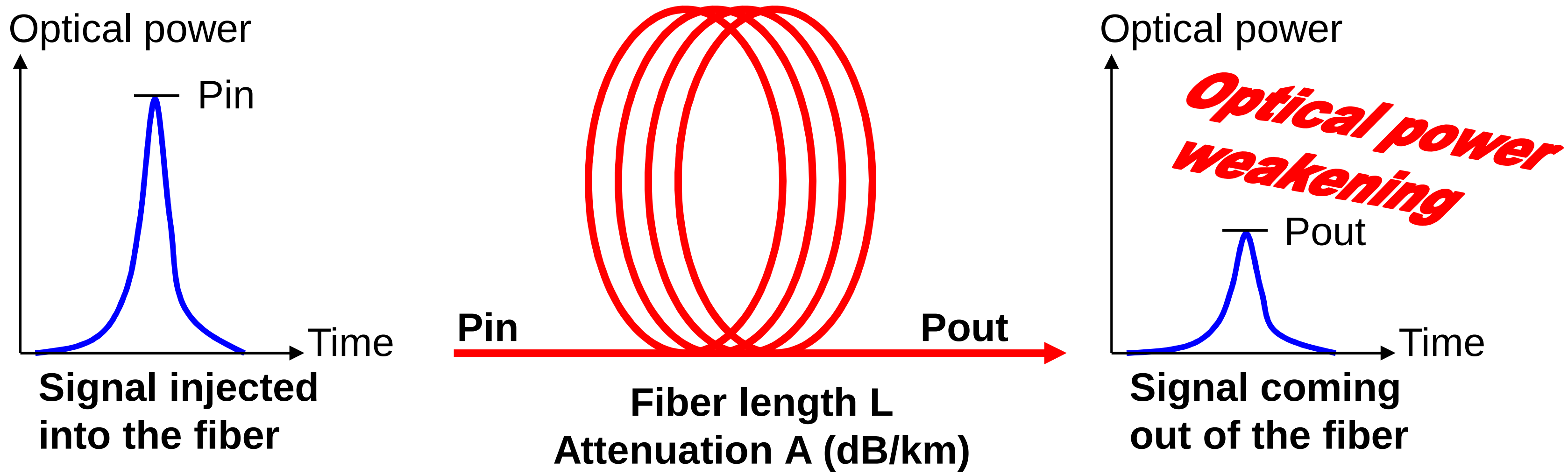
$$\lambda_c = \frac{2\pi}{2{,}405} a.ON$$

a = core radius

- **Below λ_c, the fundamental mode loses its energy to the higher order modes**

Attenuation of optical fibers

- **Linear attenuation**
  - **Mesures the weakening of the optical power propagating along the fiber**
  - **Explained in decibel per kilometer (dB/km)**



Linear attenuation of a fiber

During its propagation in the fiber core, the optical power decreases following the law :

$$\boxed{P(z) = P_{in} e^{-\alpha z}}$$

where α is the attenuation coefficient in Neper/m

But usually, the attenuation A is defined in dB/km as :

$$A = \frac{1}{L} 10 \log\left(\frac{P_{in}}{P_{out}}\right)$$

$$A_{dB/km} = 4,34.10^{3} \alpha_{m^{-1}}$$

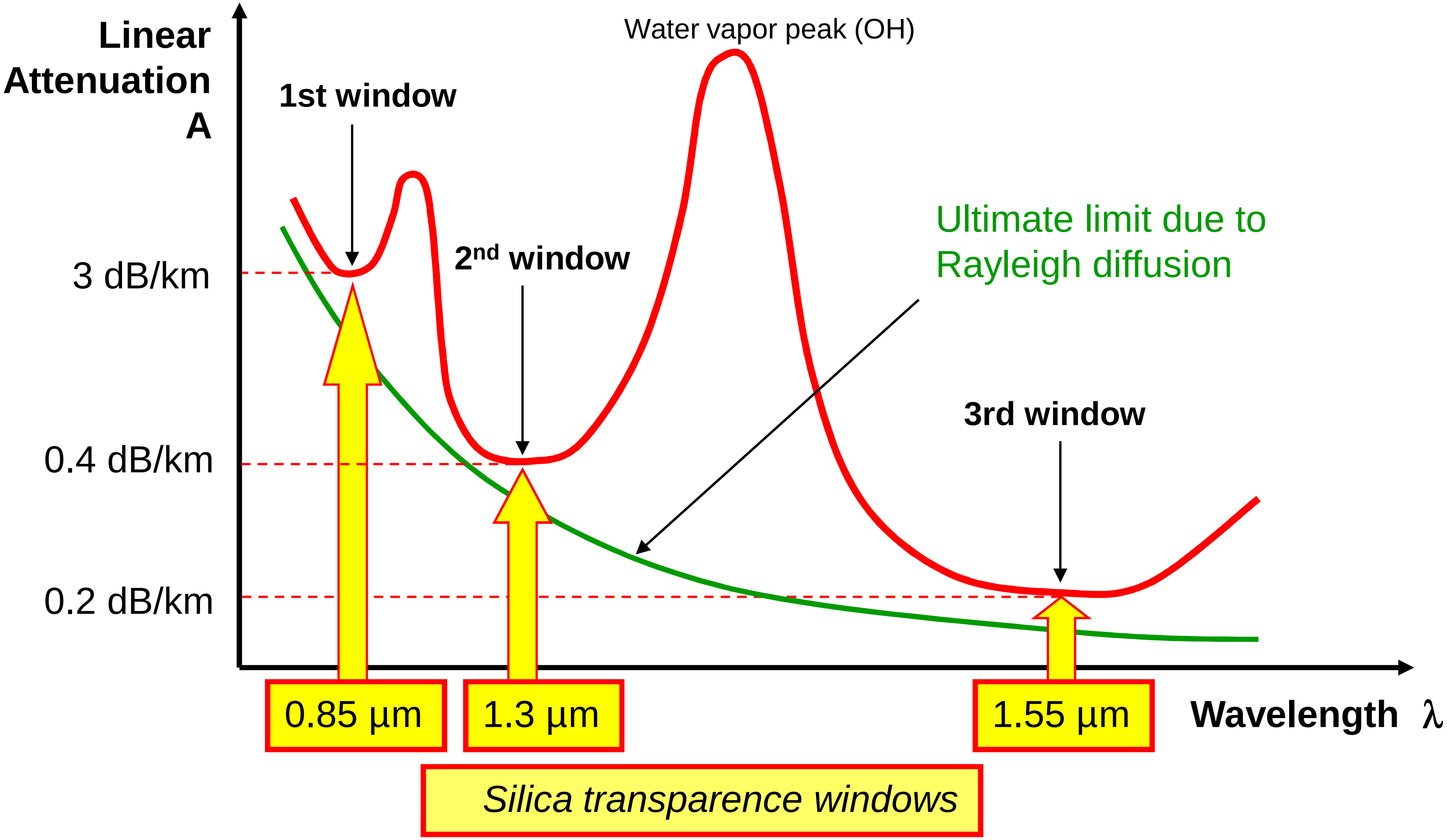
Optical fiber attenuation

- **Total attenuation (or loss) is explained in dB (decibel)**
- **Ratio between Pin and Pout explained in decimal logarithm**

$$A\ (dB) = 10 \log (Pout/Pin)$$

Pout/Pin	Attenuation A
1	0 dB
1/2	3 dB
1/4	6 dB
1/10	10 dB
1/100	20 dB
Factor of 2	+ ou - 3 dB
Factor of 10	+ ou - 10 dB

Spectral attenuation of a silica (SiO_2) fiber



Transmission windows

- **First window (0.8 to 0.9 µm) :**
  - **High attenuation (around 3 dB/km)**
  - **Very low cost components (LED sources)**

  => Only used with multimode fibers

- **Second window (1.28 to 1.33 µm) :**
  - **Low cost lasers available since a long time**
  - **Reasonable attenuation (around 0 dB/km)**
  - **Very low chromatic dispersion in single-mode fibers**

  => Still used for single wavelength operation

Transmission windows

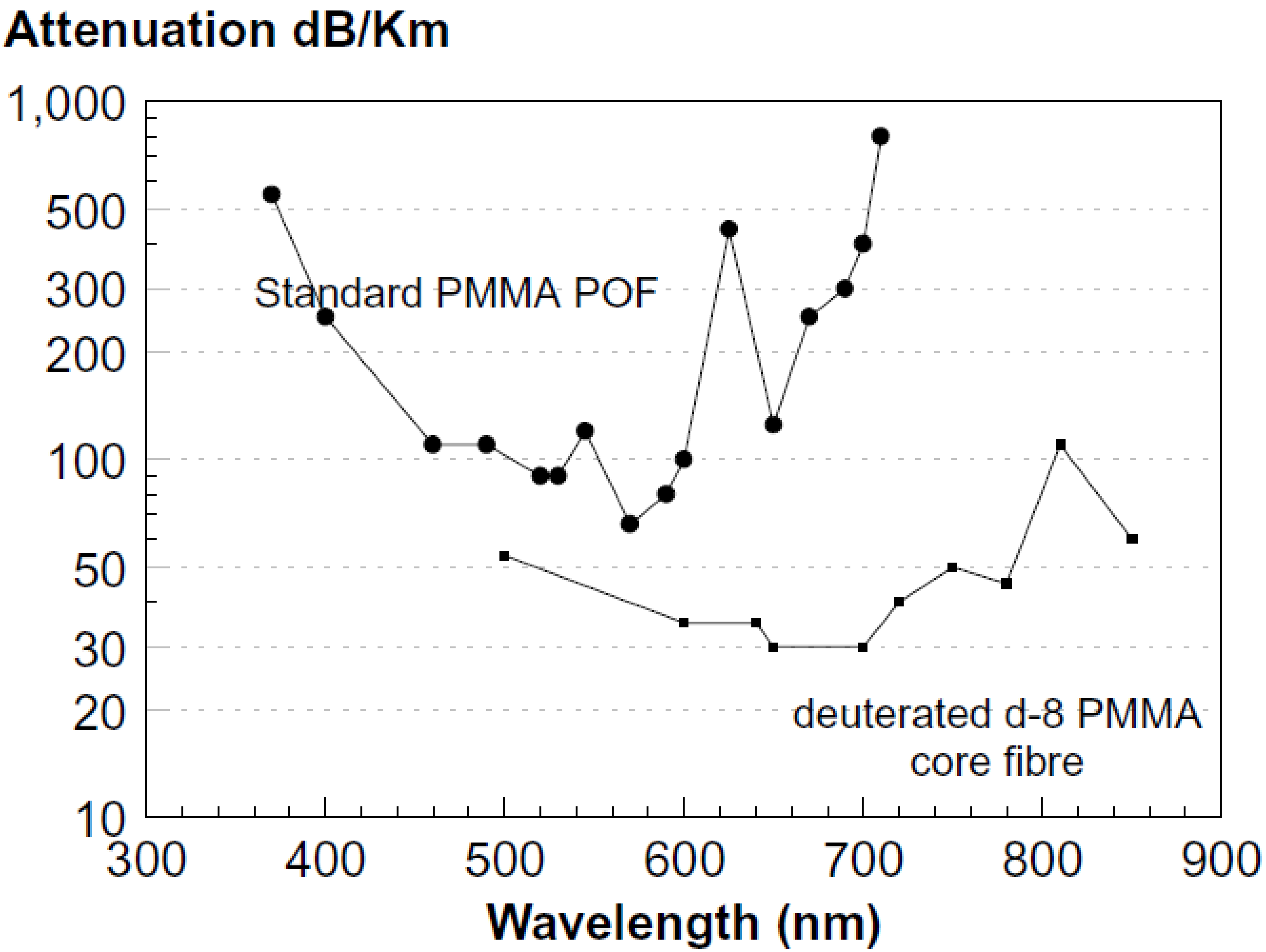
- Third window (1.530 to 1.625 µm) :
  - Very low attenuation (0.2 dB/km)
  - High performance by expansive components (laser diodes and optical amplifiers)
  - Compatible with high performance WDM systems
  - Two sub-bands : C (1530-1565 nm) and L (1565-1625 nm)

=> Today's solution for all telecommunication systems

Attenuation of various types of glasses

Matière première	VERRES	ABSORPTION en dB/km	IMPURETES Contenues dans le verre	1% d'énergie transmise (dans le proche infrarouge) sur :
Bon marché	BOUTEILLES	2.000.000	10kg/tonne	1 cm
	VITRES	200.000	1kg/tonne	10 cm
Sélection	LUNETTES	20.000	100g/tonne	1 m
Pures, traitées	OPTIQUE	2.000	10g/tonne	10 m
Ultra-pures	VERRES SODOCALCIQUES ou BOROSILICATES	20	100mg/tonne	1 km
	POUR FIBRES OPTIQUES			
	VERRES DE SILICE	0,2	10mg/tonne	100 km

Spectral attenuation of a plastic (polymer) fiber

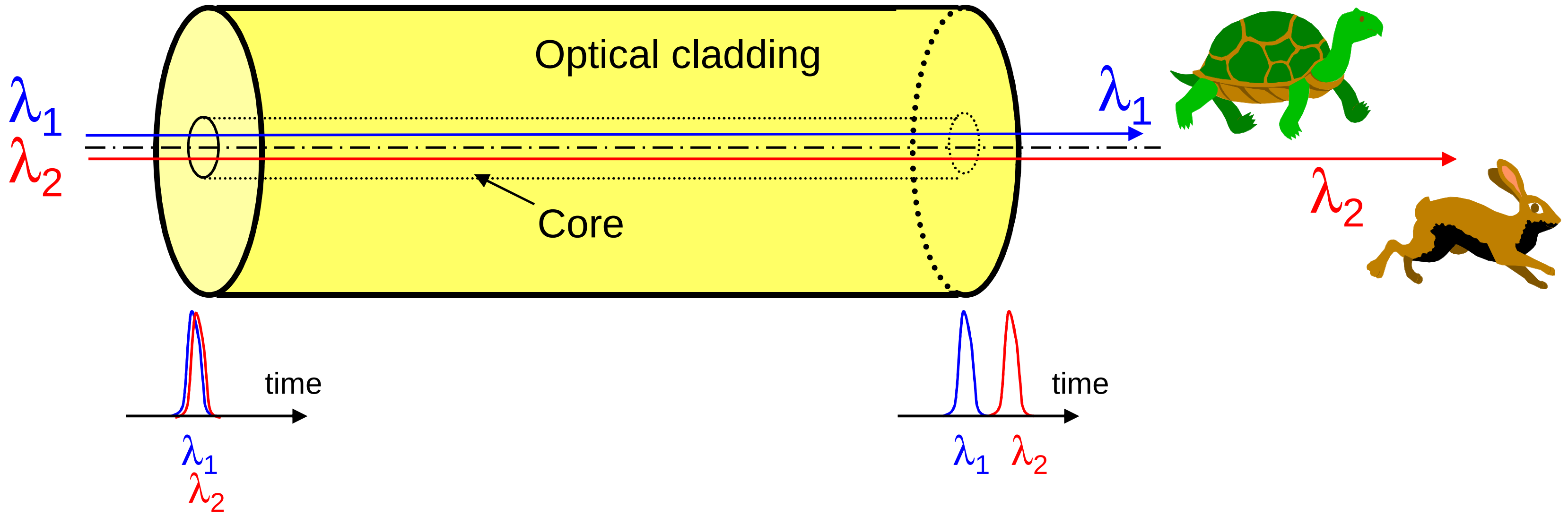


Chromatic dispersion of a silica fiber

- **Chromatic dispersion of a silica fiber**
  - **Silica is a dispersive material**
    - **Refractive index n depends on wavelength λ**
    - **Propagation speed :**

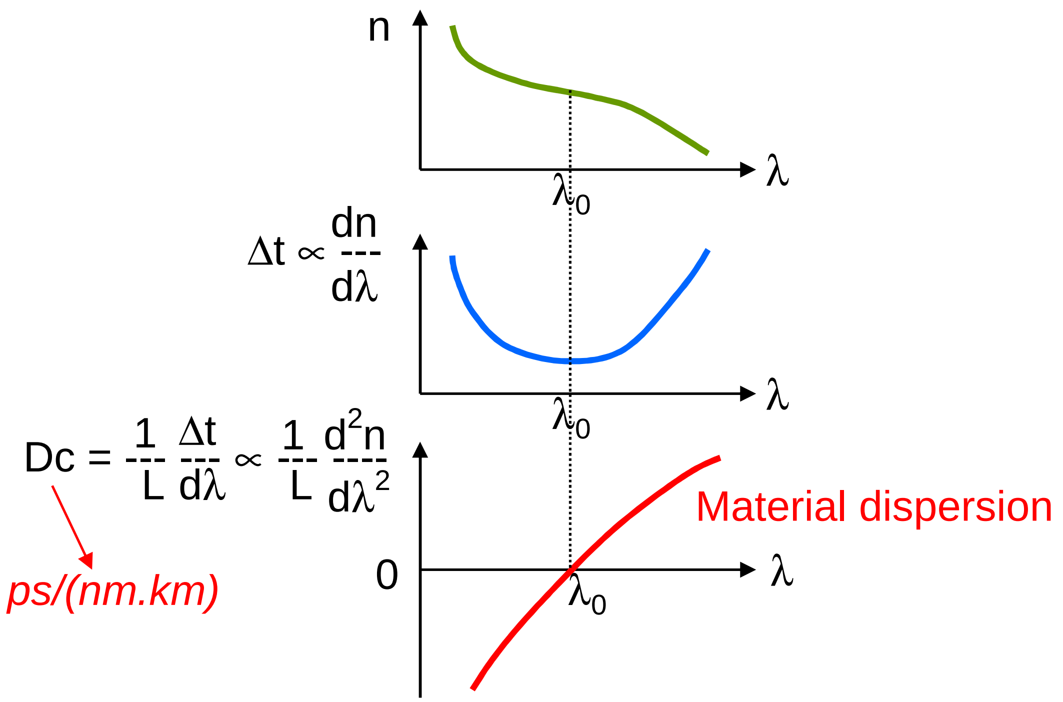
$$v = c/n$$

    - **Propagation speed v also depends on λ**



Chromatic dispersion of a silica fiber

- **Chromatic dispersion of a silica fiber**
  - **Material contribution**
    - **Silica is a dispersive material : n depends on λ**



Chromatic dispersion

The mean propagation speed of a pulse is equal to the group velocity of the fundamental mode

But the group propagation time varies with the wavelength because :

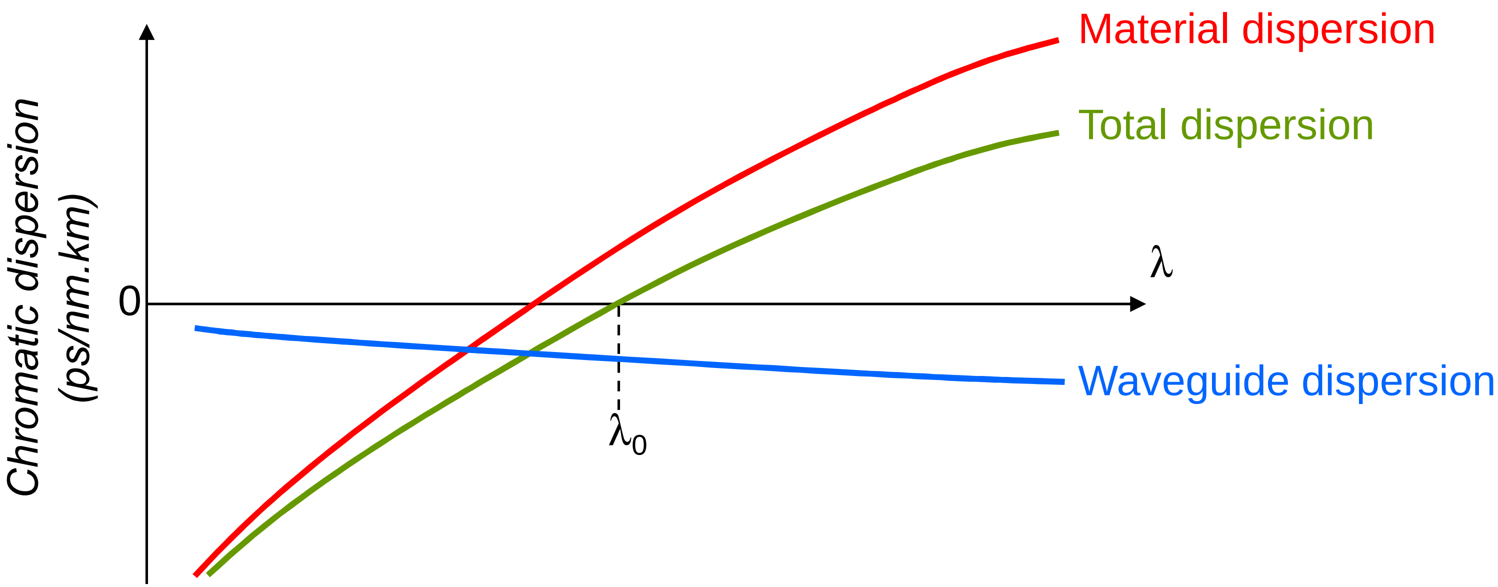
- **The refractive index varies with the wavelength (dispersive material)**
- **The group velocity is depending on the opto-geometric properties of the fiber**

As real sources are never monochromatic, these two phenomenons lead to :

- **Material dispersion**
- **Waveguide dispersion**

Chromatic dispersion of a silica fiber

- ♦ **Waveguide contribution and total dispersion**
  - **Opto-geometrical imperfections of the fiber => waveguide contribution**



Chromatic dispersion

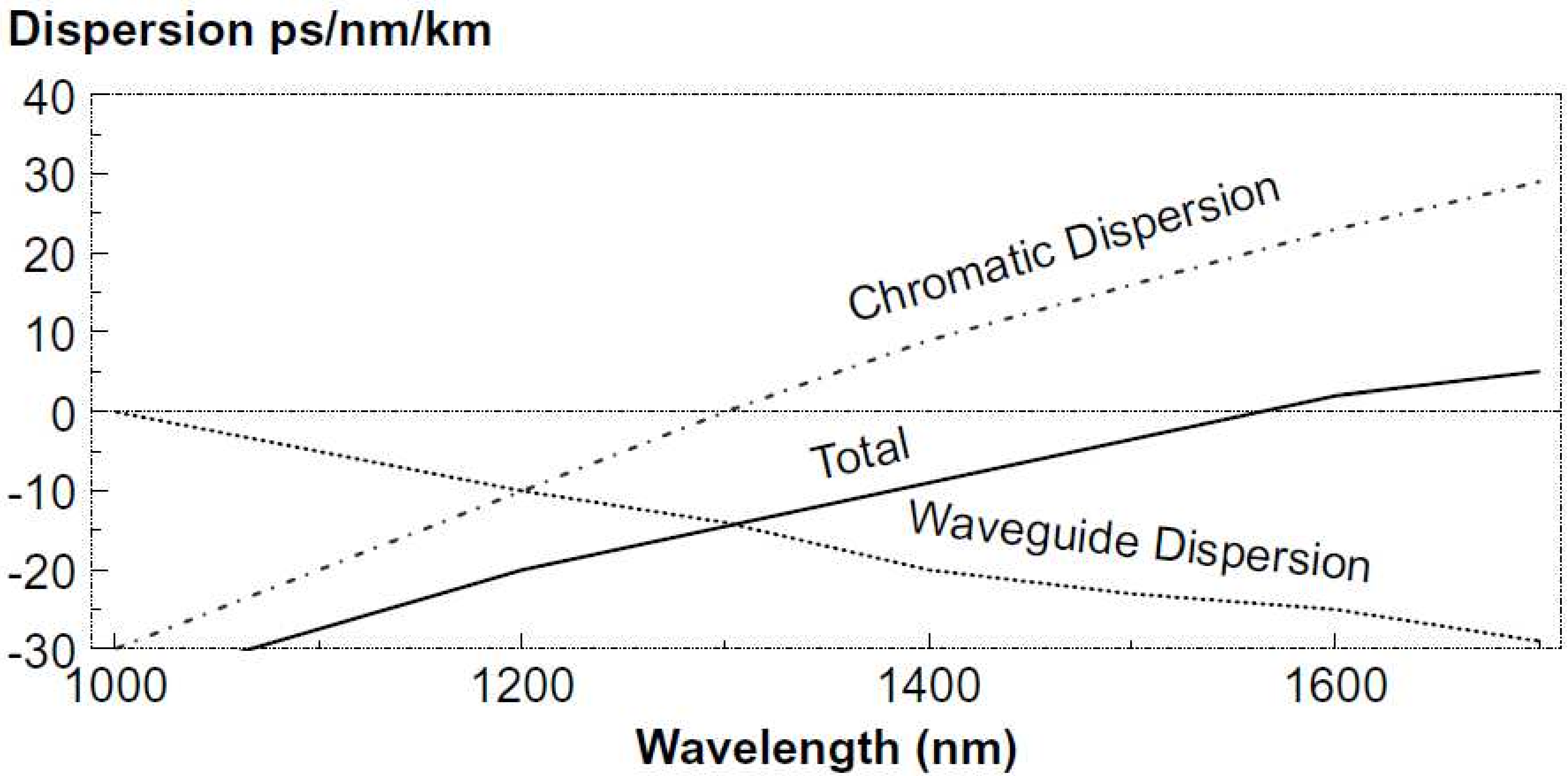
For a given spectral width $\Delta\lambda$ of the source and a given chromatic dispersion coefficient $M(\lambda)$ of the fiber, the maximum value of the (bit rate x fiber length) product is :

$$(B.L)_{max} = \frac{1}{2M(\lambda).\Delta\lambda}$$

For a standard single-mode fiber (SMF G.652) which is used in around 85% of today's infrastructure networks, we have :

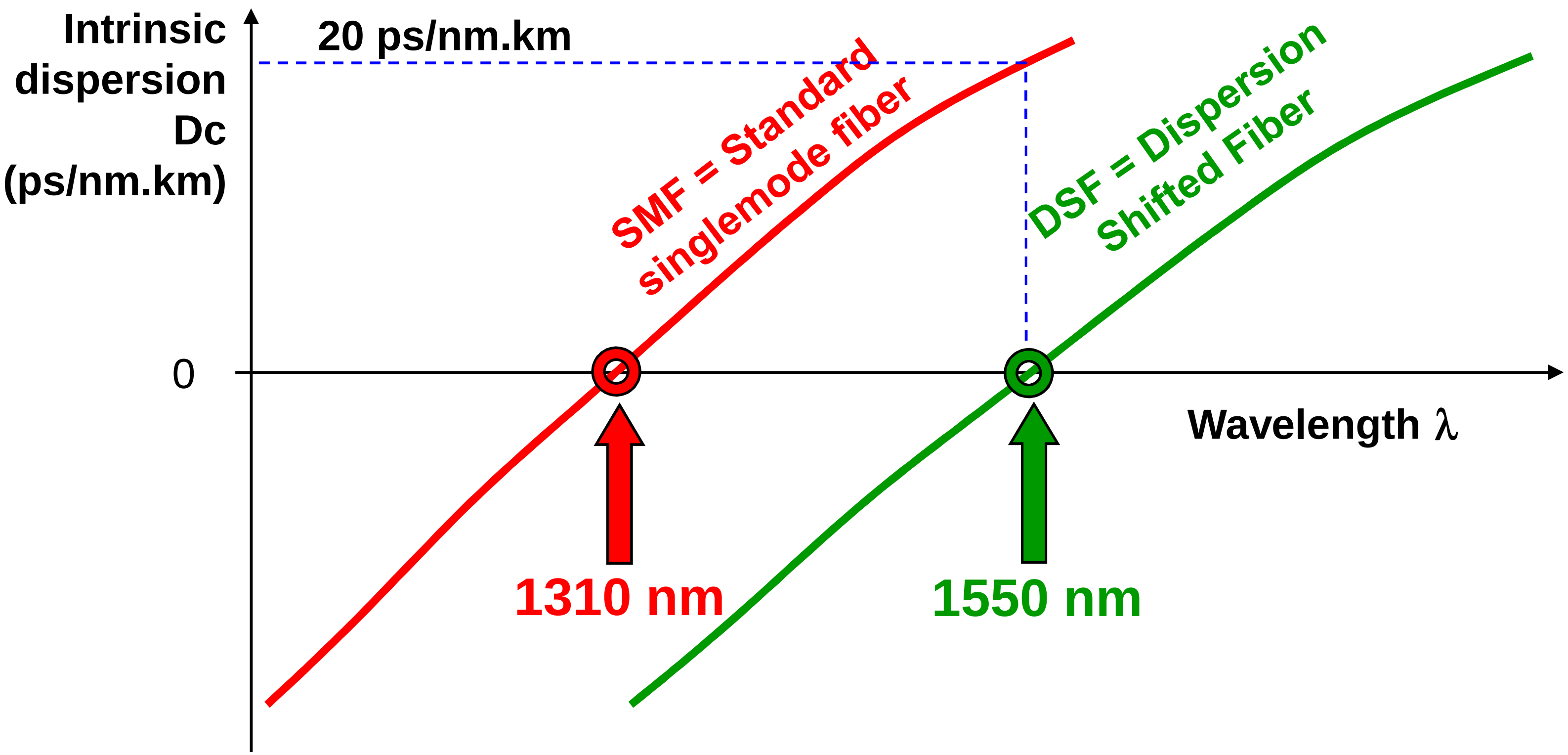
- $M(\lambda)$ = 3.5 ps/nm.km in the (1.288-1.359 µm) spectral range
- $M(\lambda)$ = 17 ps/nm.km at the 1.55 µm wavelength

Dispersion shifted fiber



Intrinsic chromatic dispersion

- **Intrinsic chromatic dispersion of a silica fiber (Dc)**



Time broadening due to chromatic dispersion

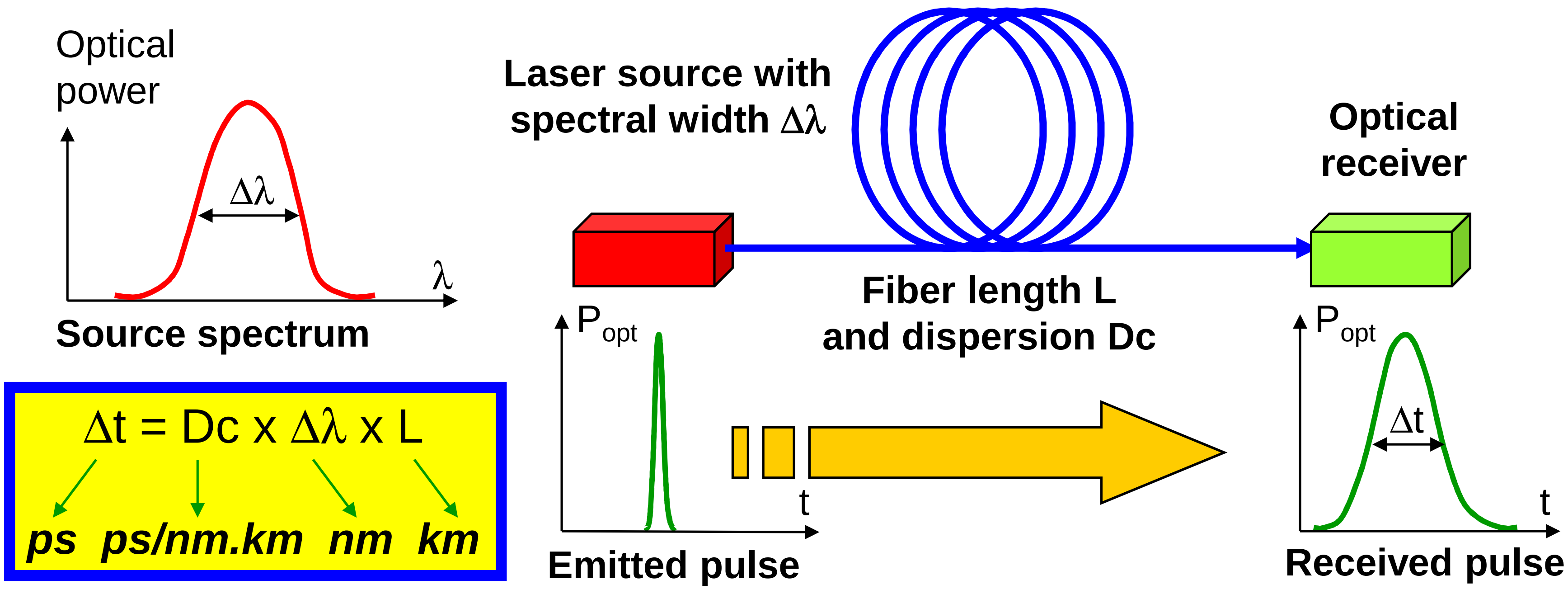
- **Chromatic dispersion of a silica fiber**
  - **Time broadening of a pulse due to chromatic dispersion**
    - **For a $\Delta\lambda$ shift between wavelengths (nm)**
    - **For a fiber length L (km)**
    - **Pulse broadening Δt (ps) is :**

$$\underbrace{\Delta t}_{ps} = \underbrace{Dc}_{ps/nm.km} \times \underbrace{\Delta\lambda}_{nm} \times \underbrace{L}_{km}$$

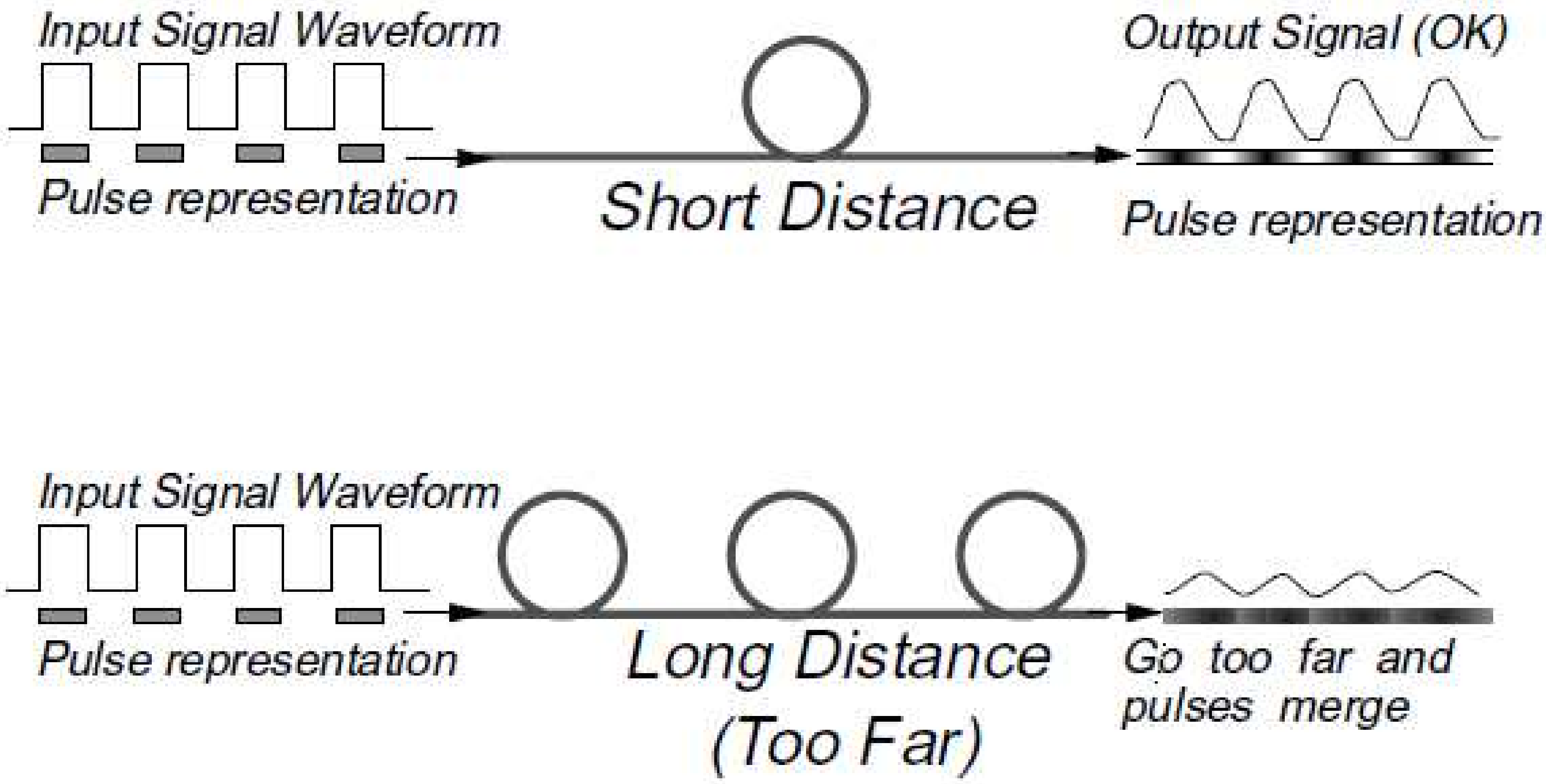
where Dc is the intrinsic chromatic dispersion of the fiber (ps/nm.km)

Total chromatic dispersion of an optical link

- **Time broadening of a pulse due to chromatic dispersion**



Dispersion limitation in a high bit rate transmission



Transmission distance limited by chromatic dispersion

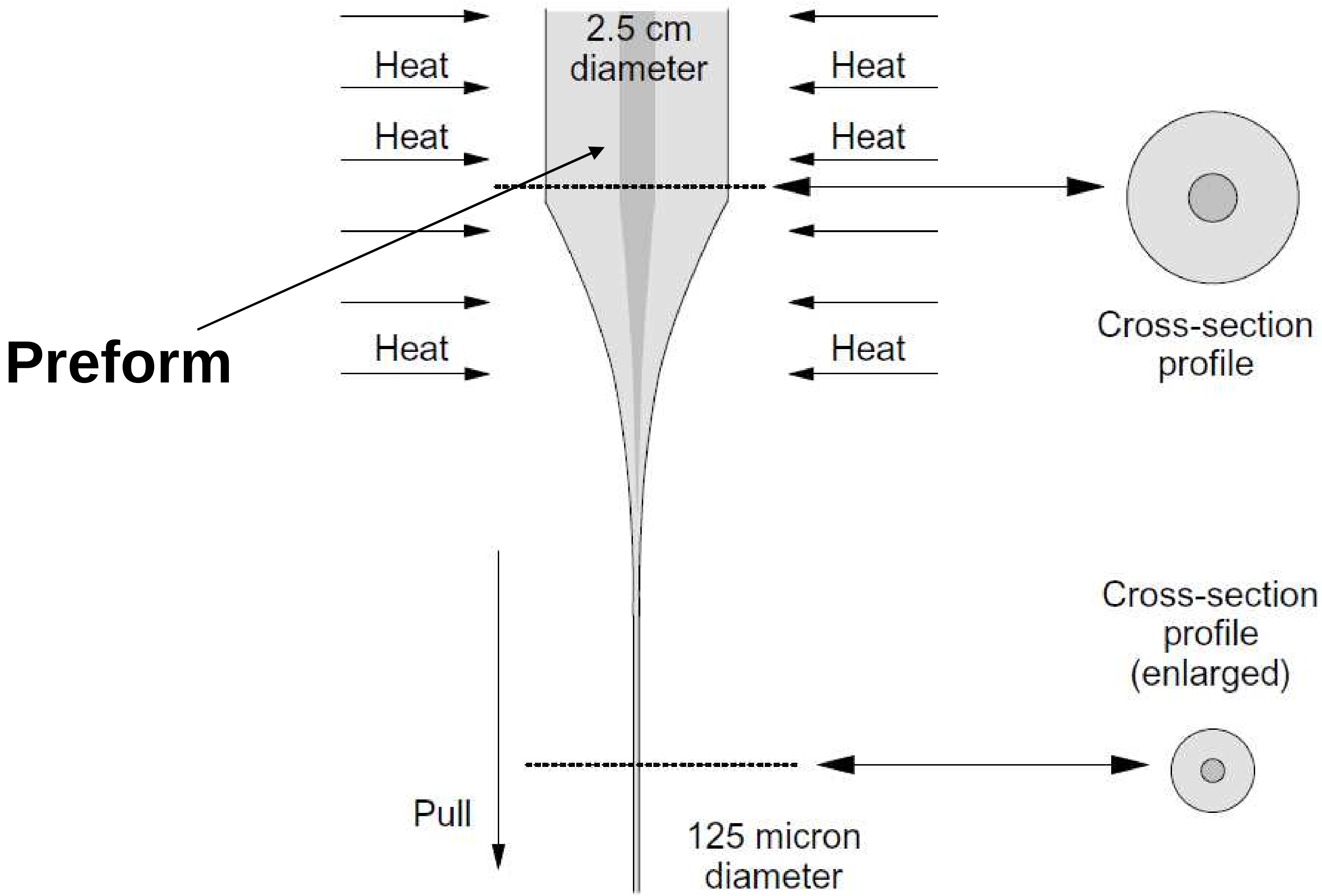
- **Maximum transmission distance :**
  - **Dispersion tolerance of the source ($\Delta t/\Delta\lambda$ in ps/nm)**
  - **Fiber type (SMF or DSF)**
  - **Light wavelength (1310 or 1550 nm)**

$$\mathbf{L\ (km) = \frac{\Delta t/\Delta\lambda (ps/nm)}{Dc\ (ps/nm.km)}}$$

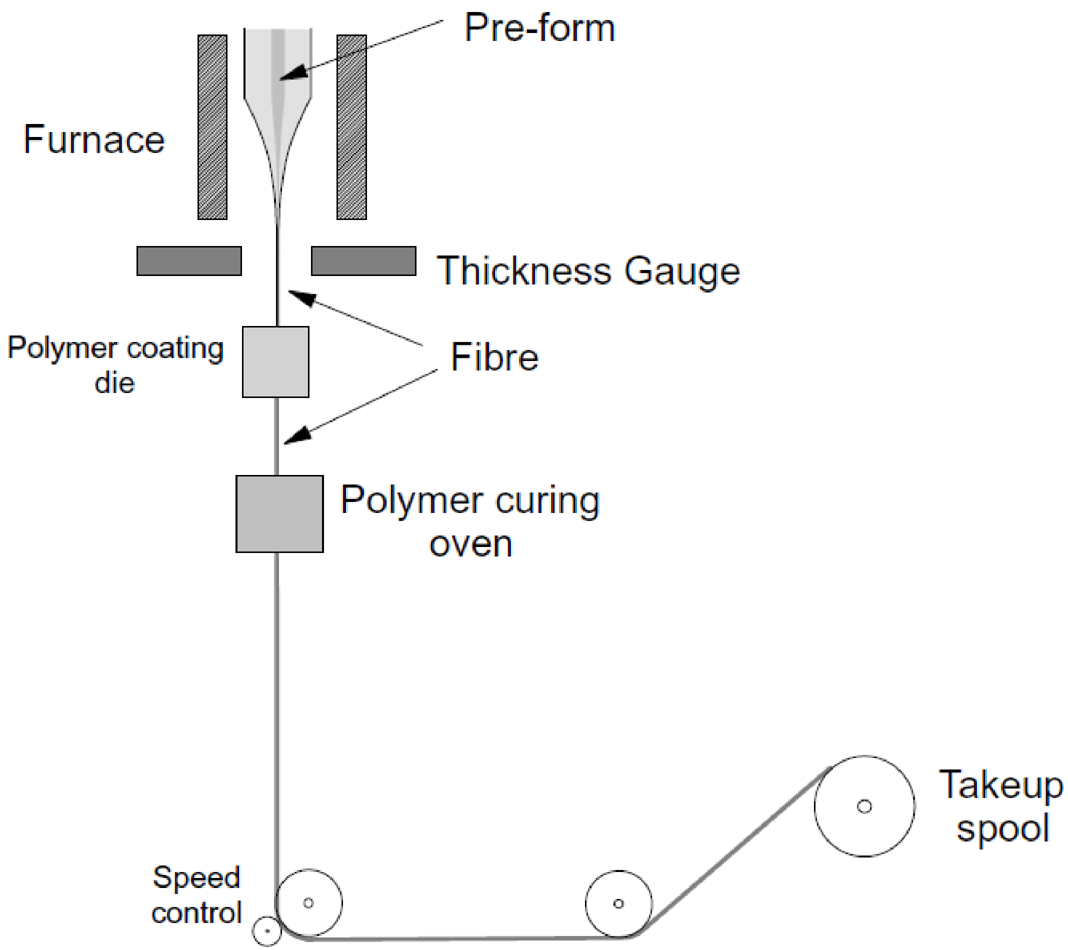
- **Example : source dispersion 1600 ps/nm coupled to a SMF fiber at 1550 nm (Dc = 20 ps/nm.km)**

$$\mathbf{L = \frac{1600\ ps/nm}{20\ ps/nm.km} = 80\ km}$$

Manufacturing technologies
Principle of fiber drawing



Manufacturing technologies
Drawing tower



Optical fibers manufacturing technologies

- **Manufacturing technologies : the PREFORM**
  - **Chemical reactions used to realize silica and dopants**
    - **Vapor phase oxydation : external heat source**

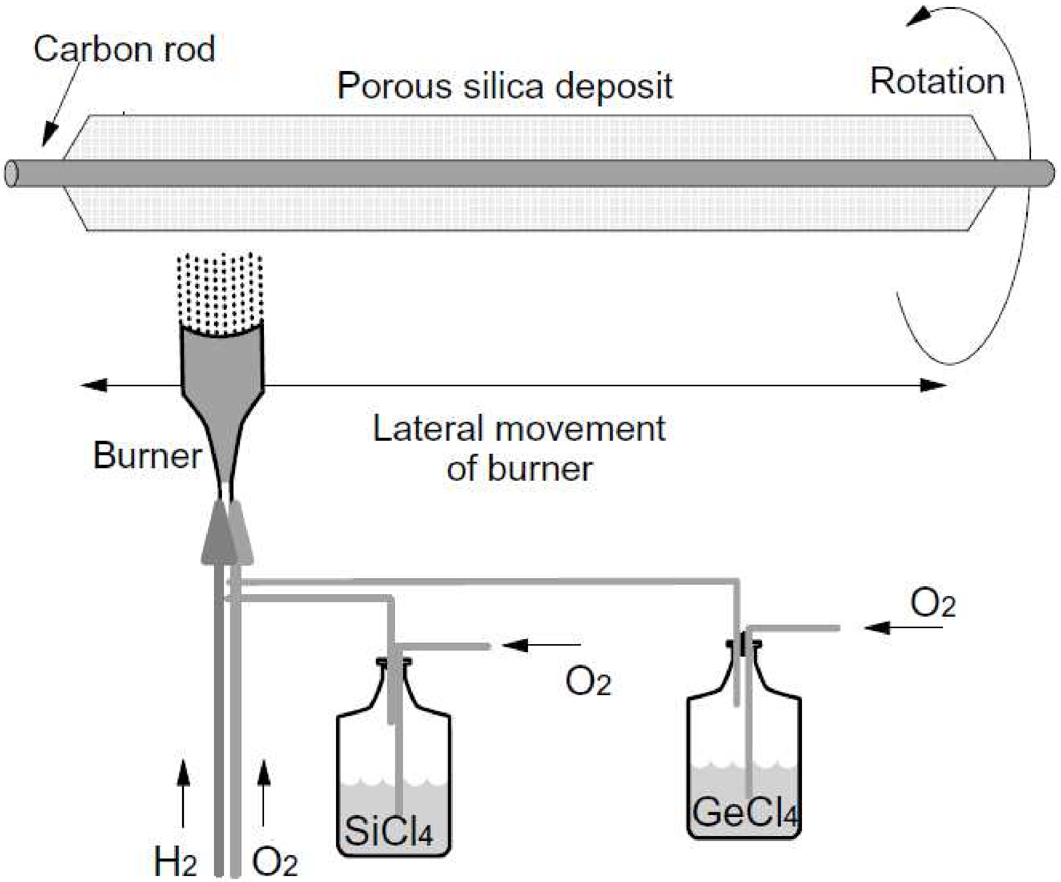
$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2$$

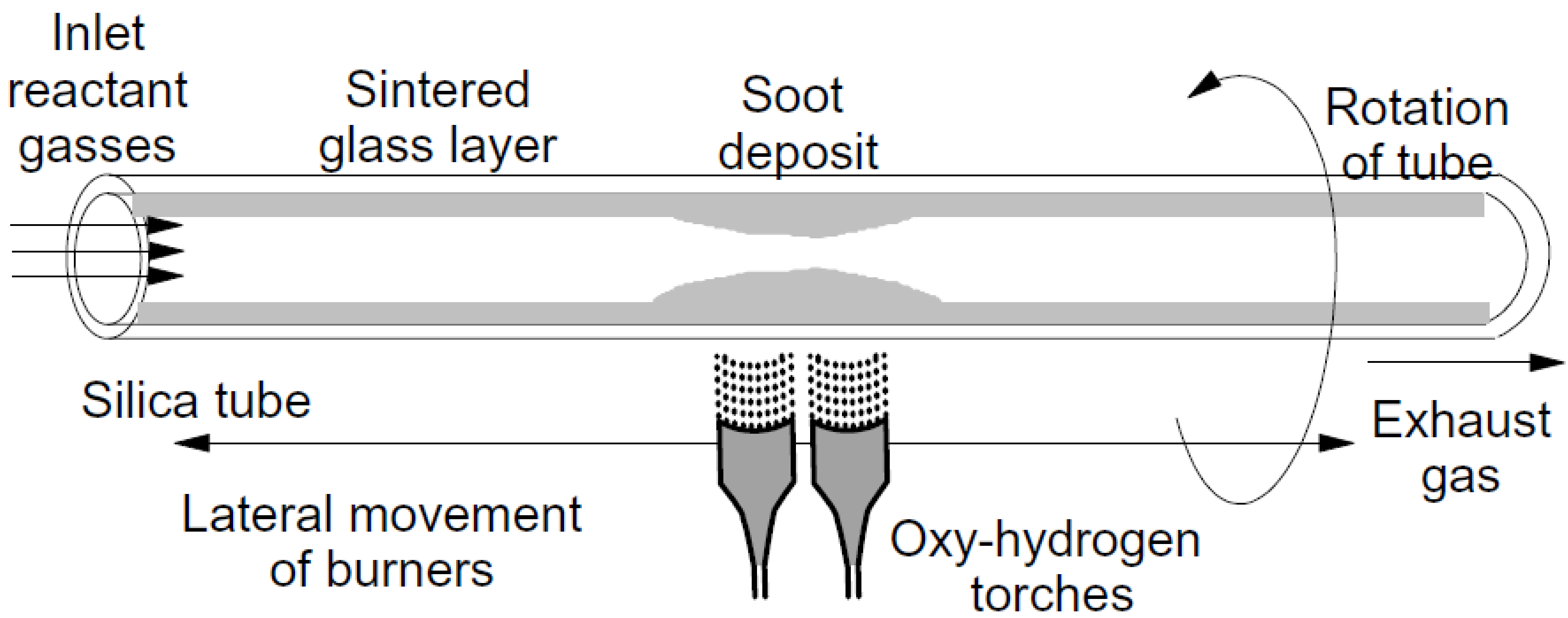
Manufacturing technologies
the PREFORM

- **Outside Vapor Deposition : OVD**



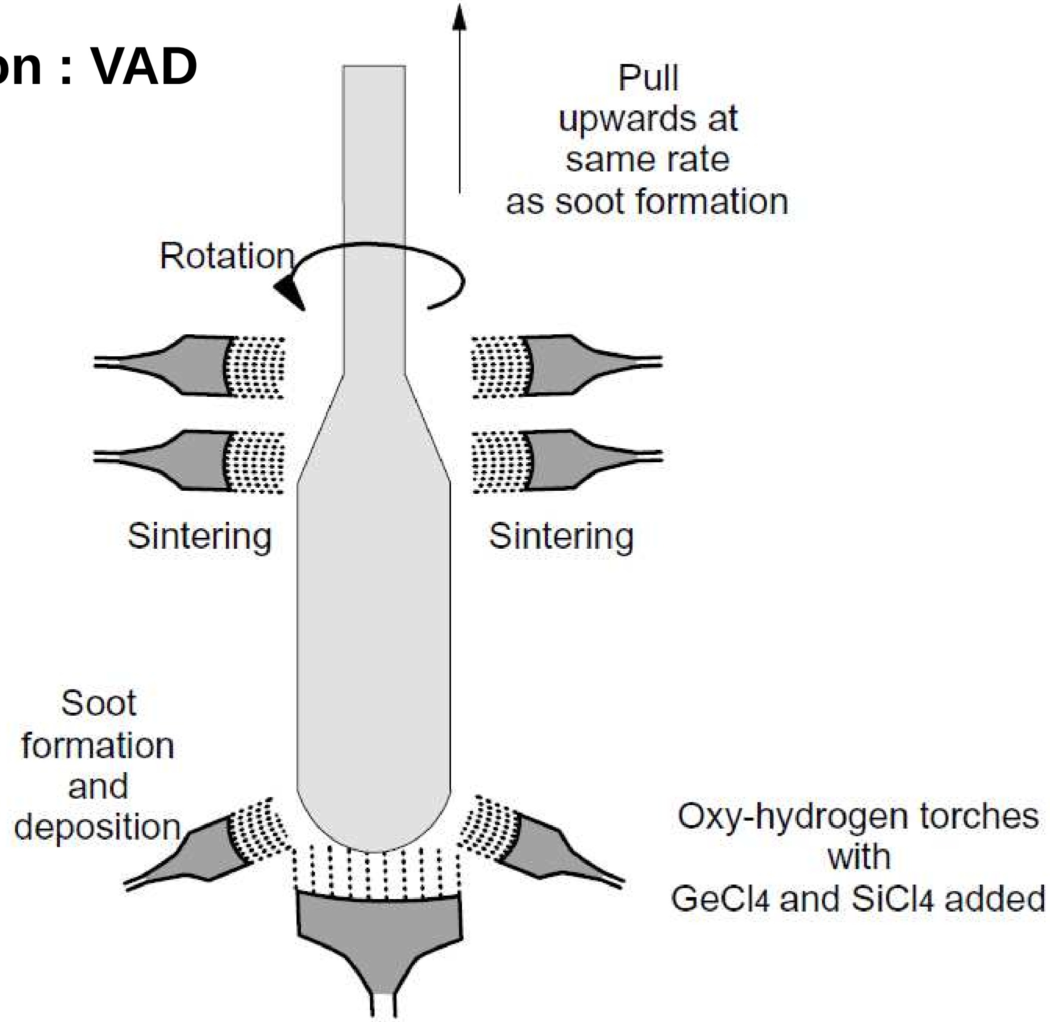
Manufacturing technologies the PREFORM

- ♦ **Chemical Vapor Deposition : CVD**



Manufacturing technologies
the PREFORM

- **Vapor Axial Deposition : VAD**



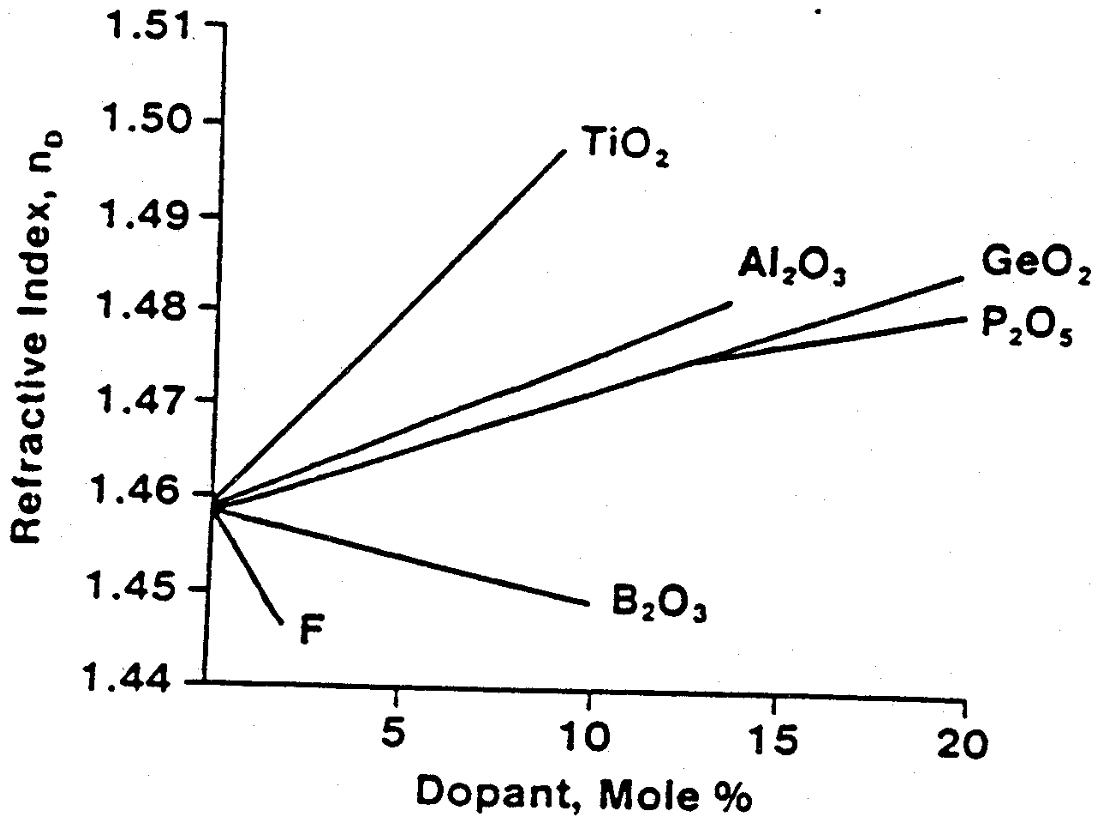
Dopants used for doping silica

- **Manufacturing technologies : effects of dopants in silica**
  - **Types of dopants used for doping silica (mainly the core) :**
    - **GeO_2, P_2O_3, B_2O_3, F, TiO_2, Al_2O_3…**
  - **Influence of dopants on silica characteristics :**

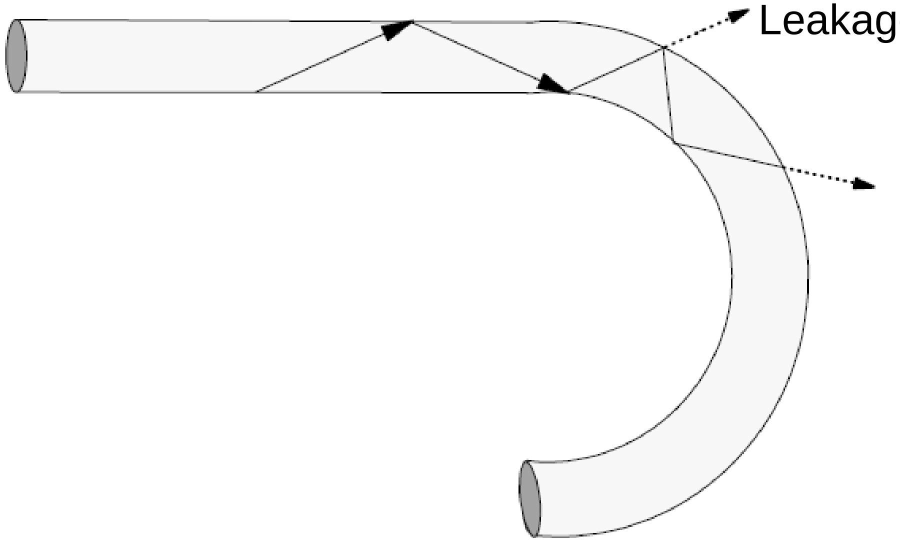
	Index n	Expansion e	Viscosity η	Stability	Durability	Dispersion λ_0	Rayleigh Scattering	IR Loss	Cost
GeO_2	↑	↑	↓	O	↓	↑	↑↑	O	↑
P_2O_5	↑	↑	↓↓	O	↓↓	O	↑	↑	O
B_2O_3	↓	↑	↓↓	O	↓↓	O	?	↑	O
F	↓↓	O	↓	O	↓↓	O	?	O	O
TiO_2	↑↑	↓	↓	↓	?	↑	?	O	O
Al_2O_3	↑	↑	↓	↓↓	?	↑	?	O	O

Effect of dopants on refractive index

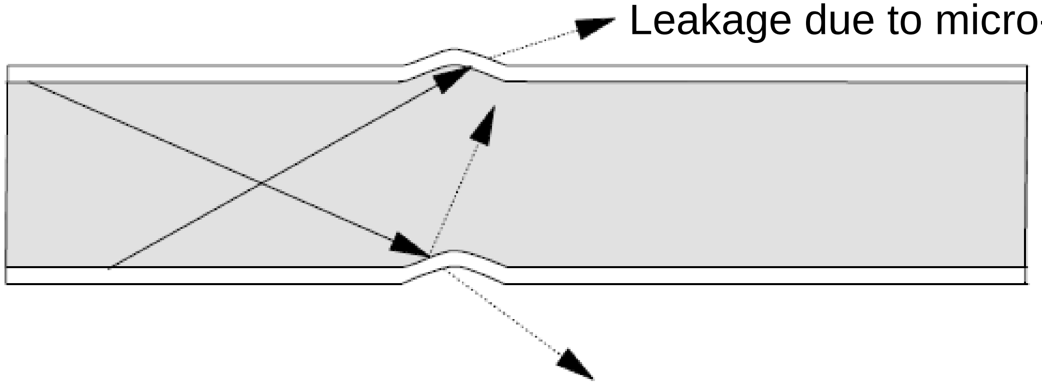
- **Manufacturing technologies : effects of dopants in silica**
  - **Effect of dopants on silica refractive index**



Cabling : bends and micro-bends in optical fibers



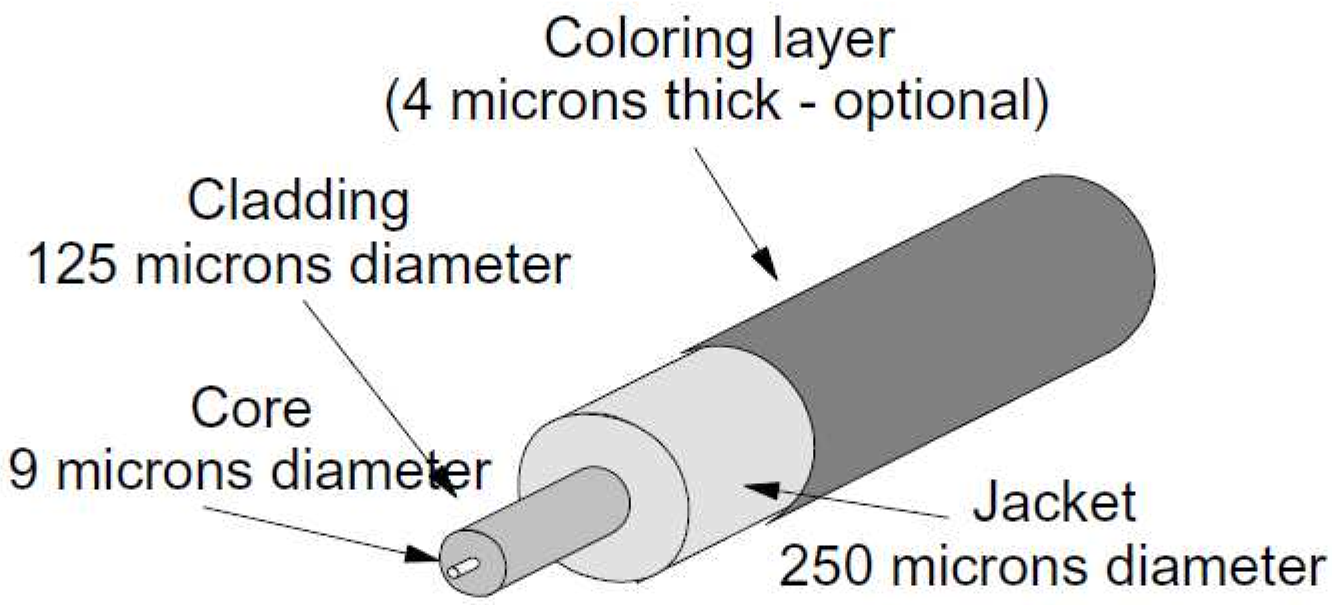
Propagation around a bend



Effect of a micro-bend

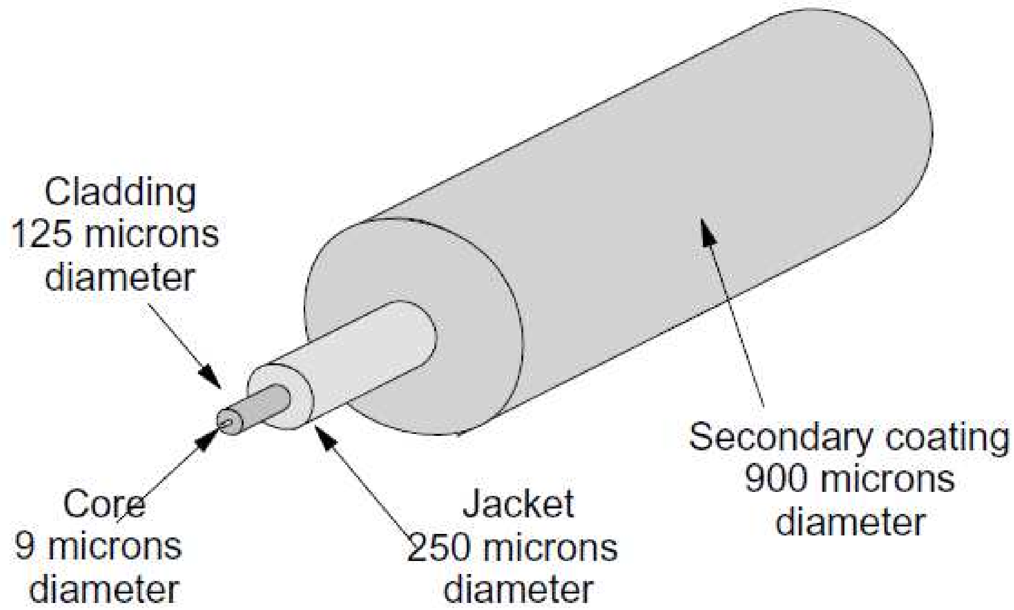
The optical cables

- **The first stage : coating the fiber**



Primary coated optical fiber (PCOF)

- **Secondary coating**
  - Forms a tight bond with the primary coating



Secondary coated optical fiber (SCOF)

Basic cable construction

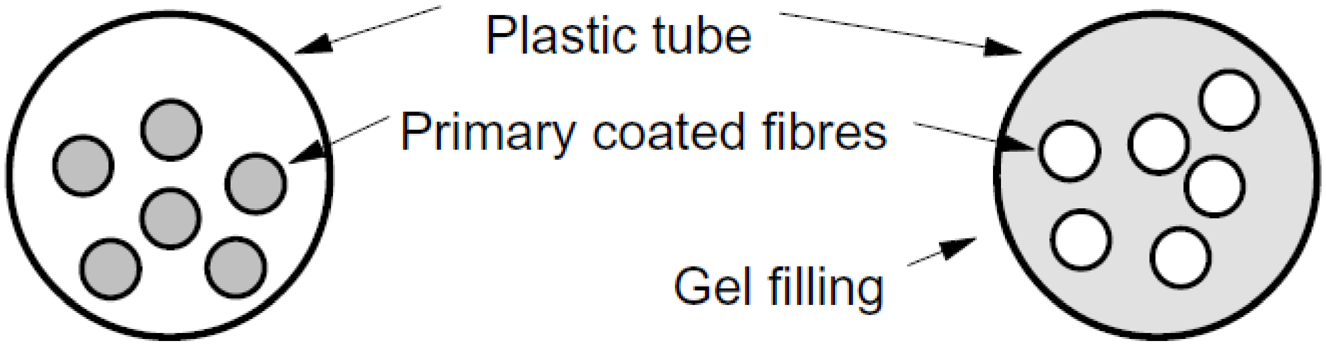
- **Two main types of cables**

  - Tight buffered cables

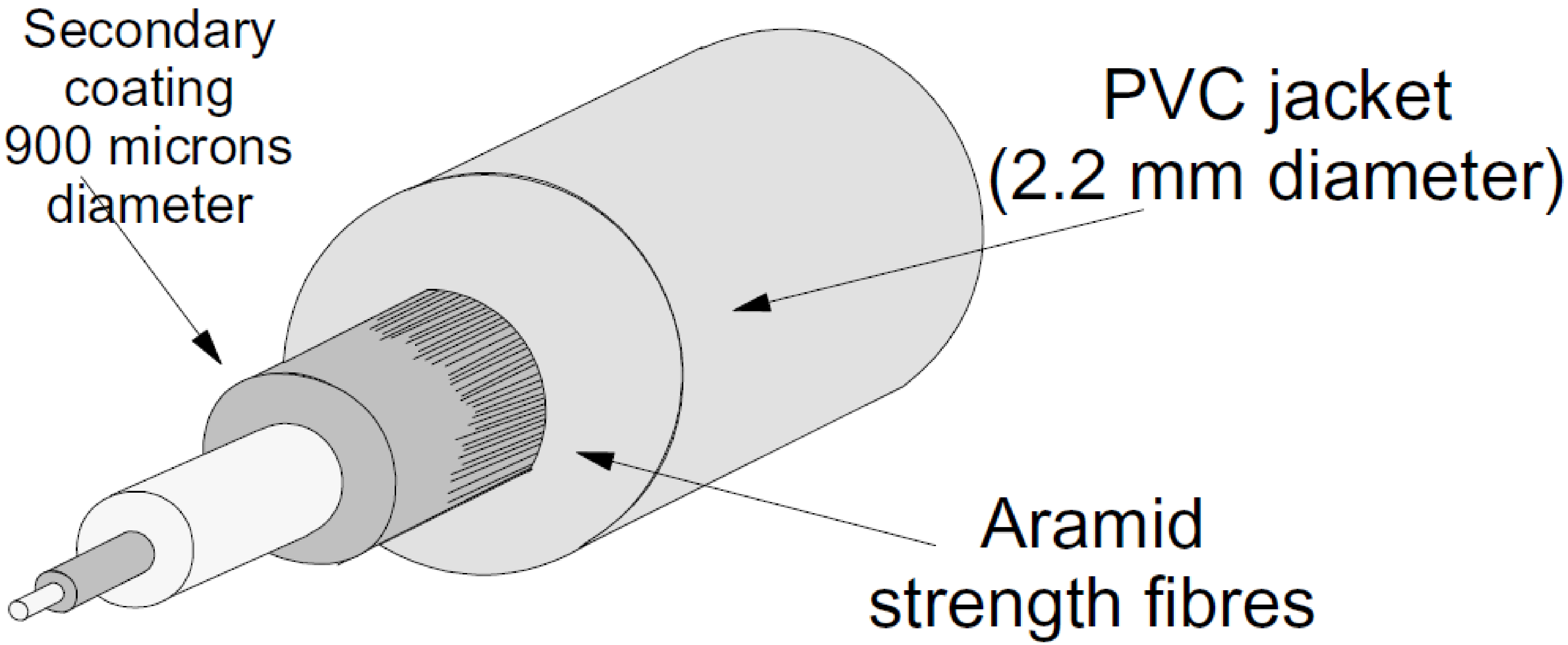
  - Secondary coated fibre (SCOF) is encased firmly in surrounding material
  - Mainly used for indoor applications with low number of fibers and short distances

  - Loose tube cables

  - A small number of PCOF fibres are carried inside a plastic (PVC) tube
  - There is plenty of room in the tube for the fibers to move loosely
  - Applications : long distance cables, as submarine links

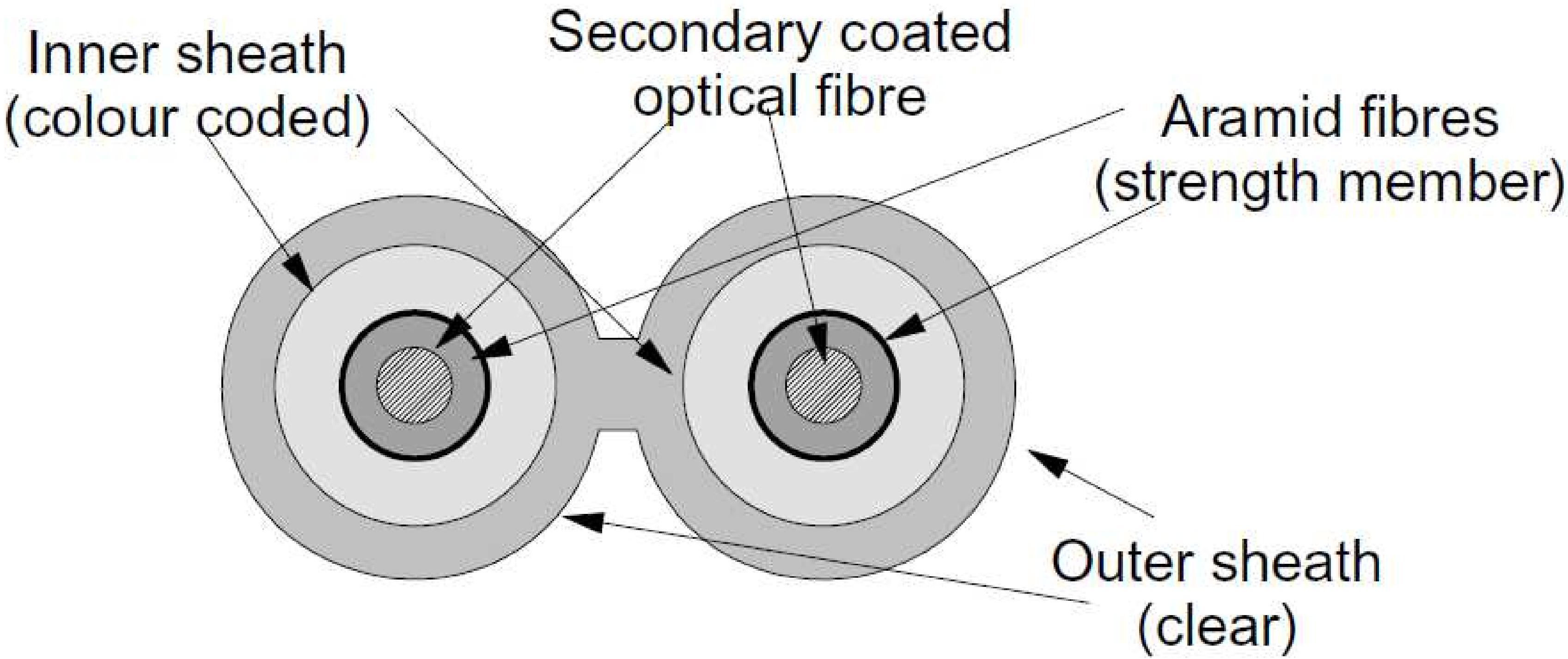


- **Single-core indoor cable**



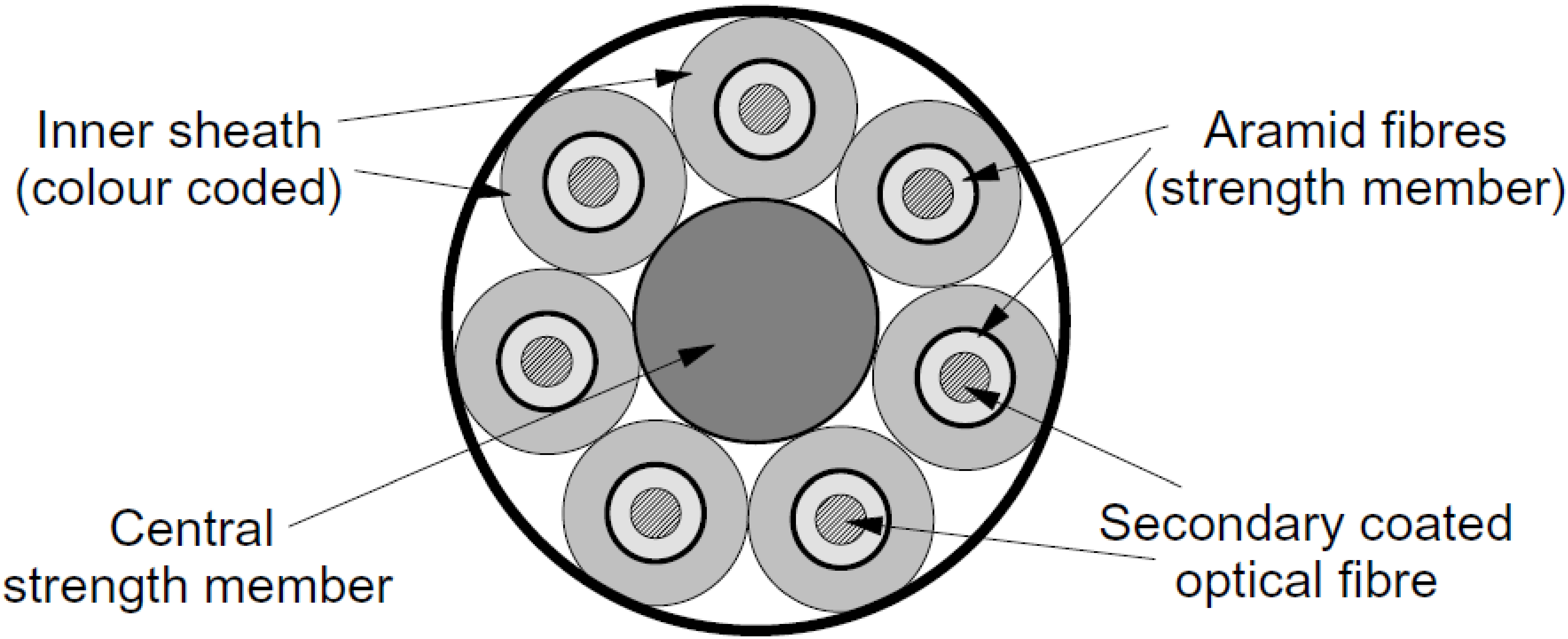
Various types of cables

- **Dual indoor cable**



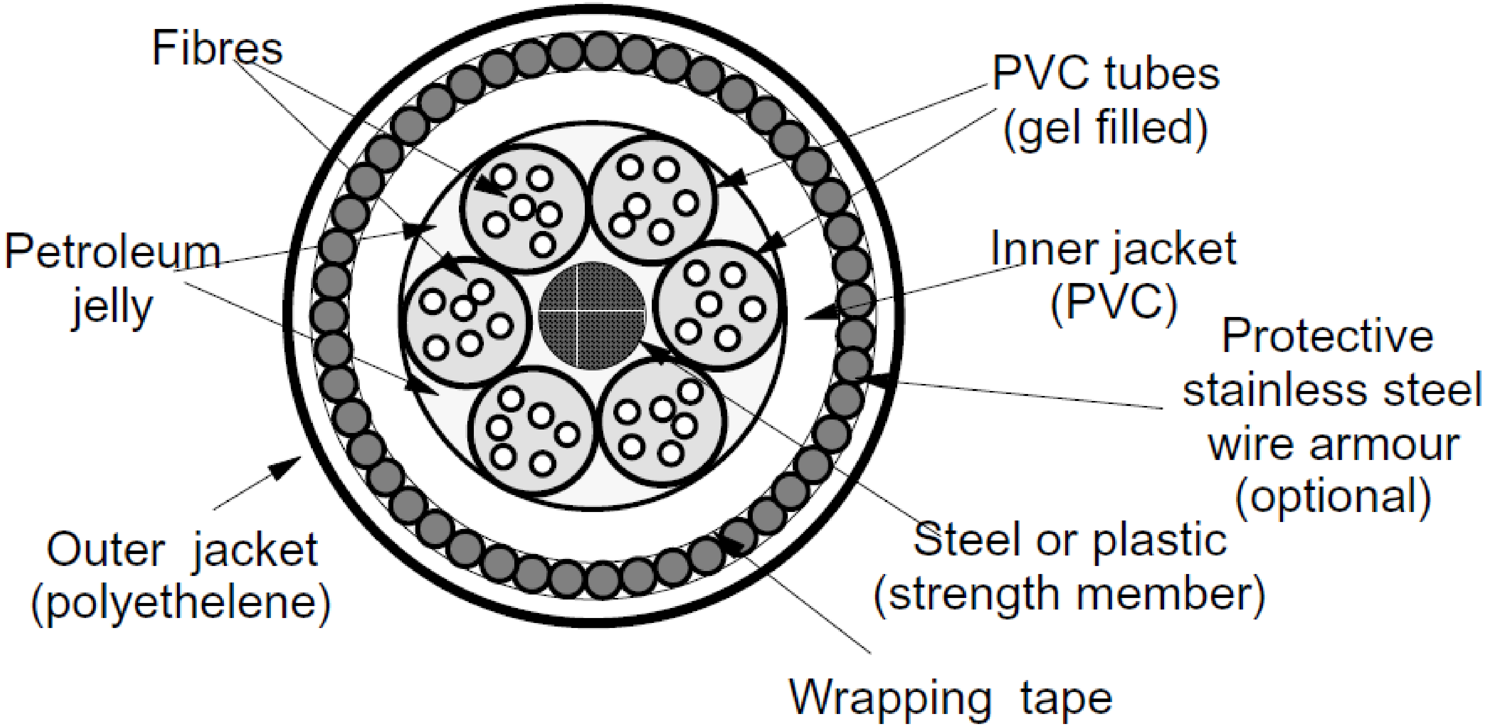
Various types of cables

- **6-core tight buffered indoor cable**



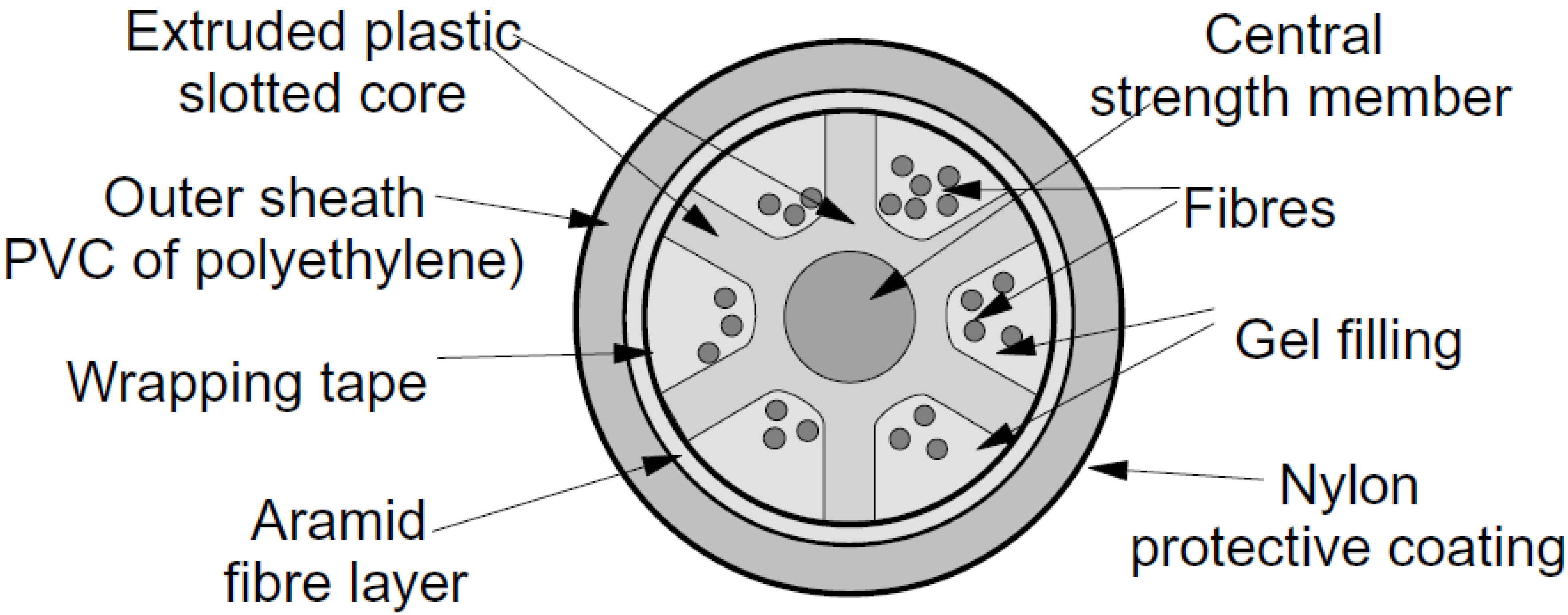
Various types of cables

- **Typical outdoor cable (loose tube – gel filled)**

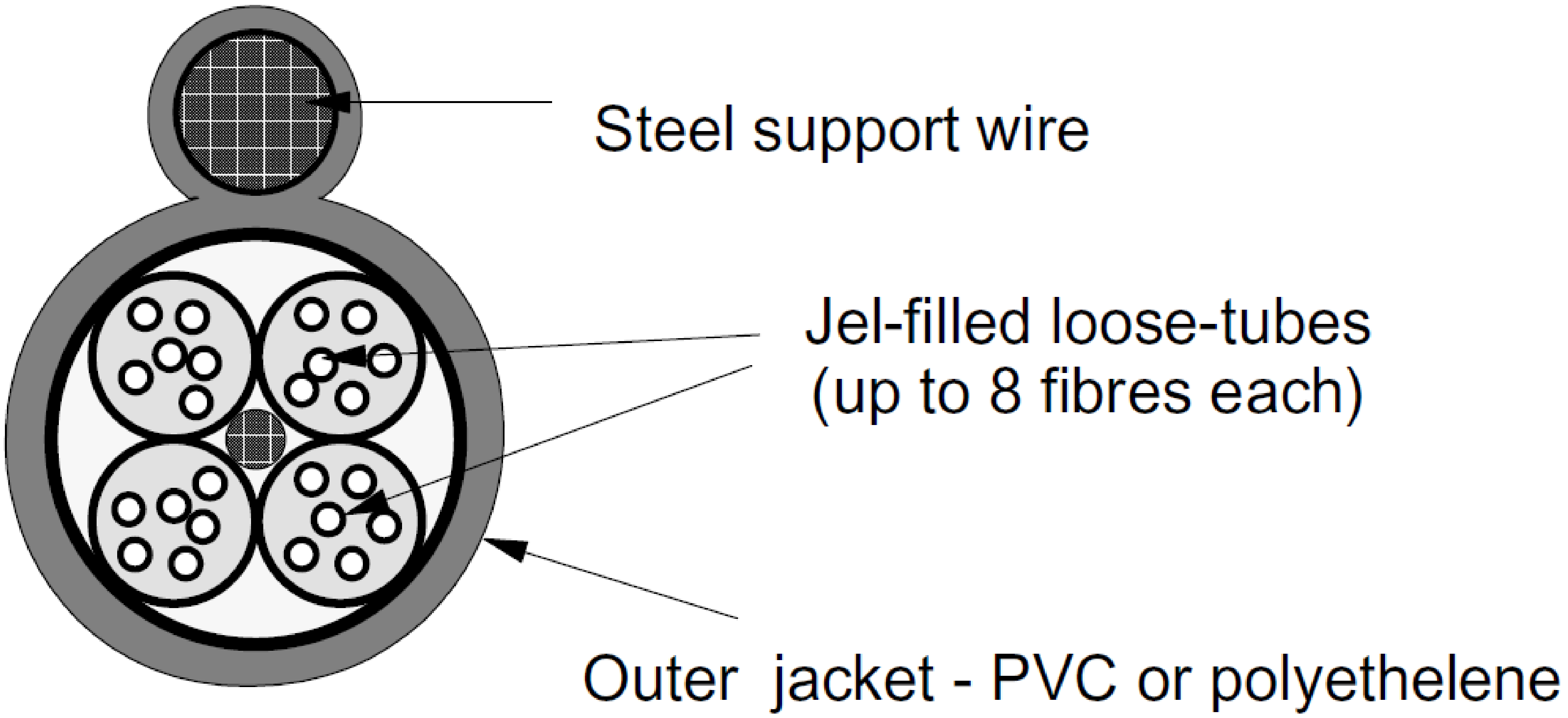


Various types of cables

- **Segmented-core cable design**

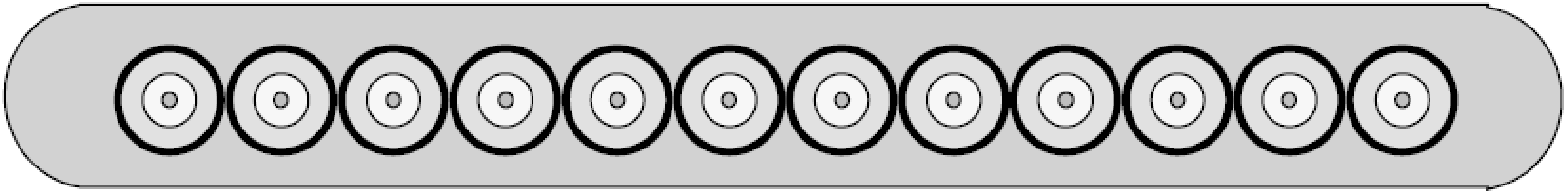


- **Outdoor aerial cable**



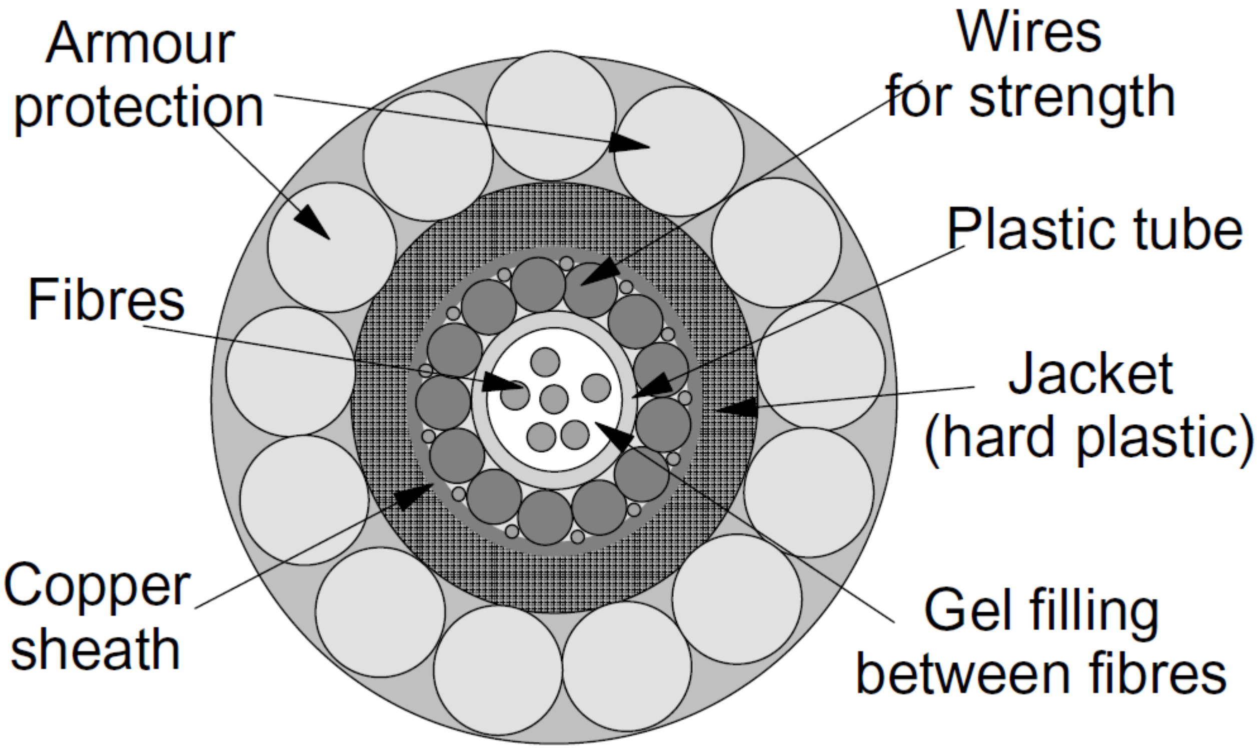
Various types of cables

- **12-core optical flat cable**



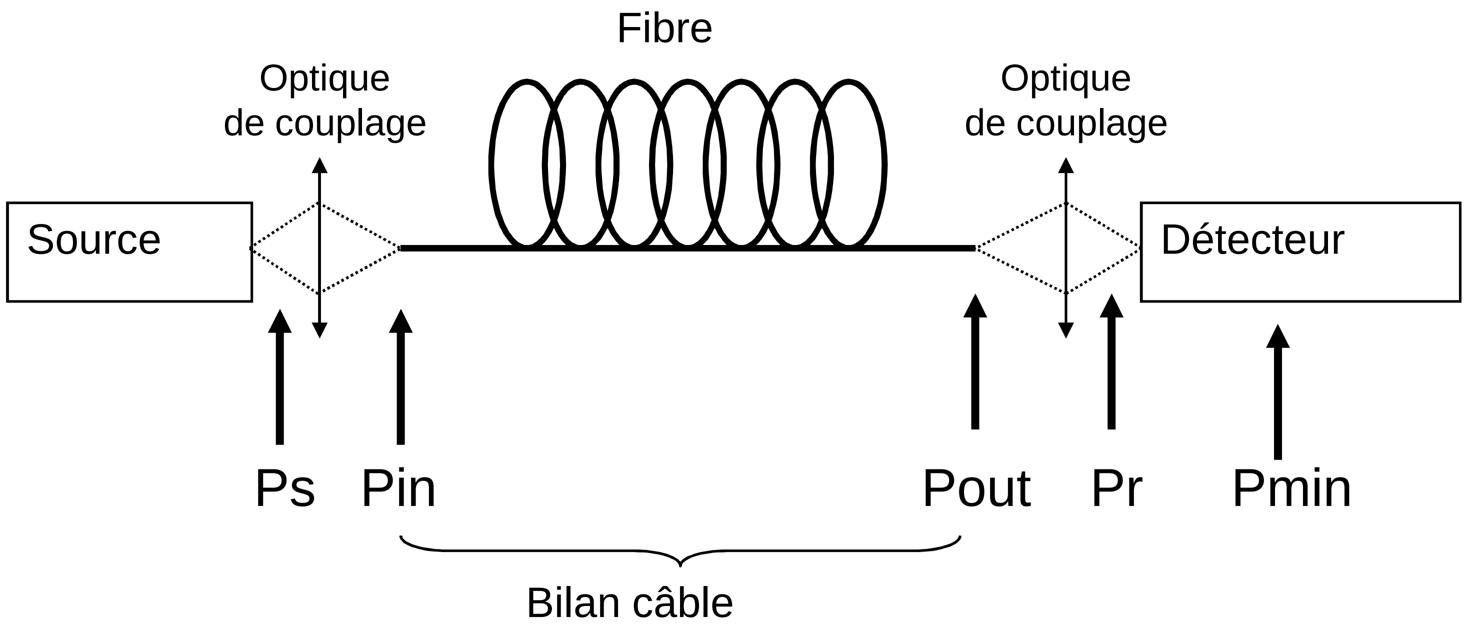
Various types of cables

- **Undersea cable**



Typical undersea cable design

Schéma de principe d'une liaison point à point



Marge système = Pr - Pmin

Diagramme du bilan en puissance

Pertes en ligne (dB)	Niveaux de puissance optique (dBm)
	Ps = puissance de la source
Perte de connexion en entrée	
	Pin = puissance injectée dans la fibre
Atténuation du câble ou bilan câble	
	Psat = puissance de saturation du détecteur
Dynamique du récepteur	
	Pout = puissance sortant de la fibre
Perte de connexion en sortie	
	Pr = puissance reçue par le détecteur
Marge système	
	Pmin = puissance minimum détectable
Rapport S/B min pour un TEB donné	
	Pb = puissance de bruit