Advanced Optical Communication

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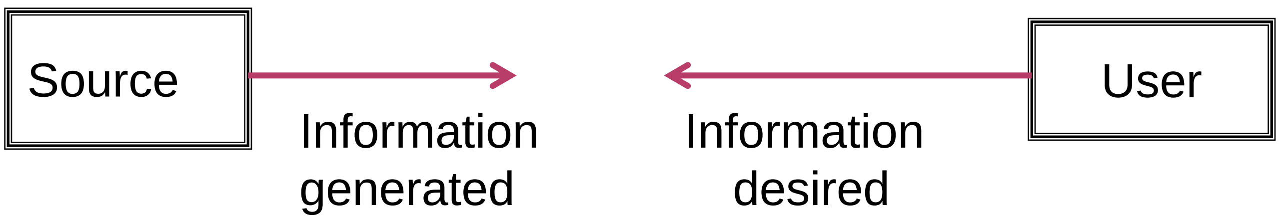
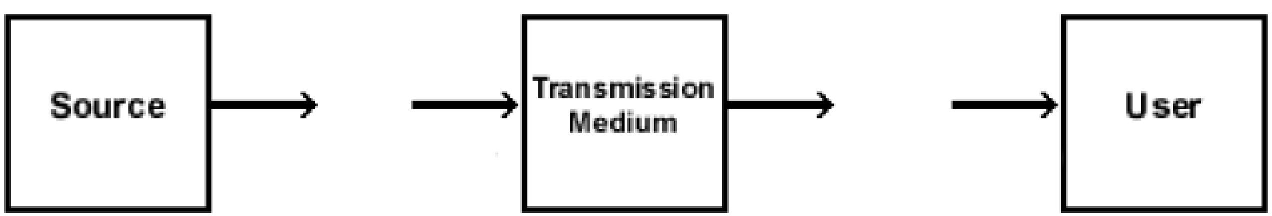
Introduction

- Source generates information
- User desires information generated by source



- To do this a medium is required in between source and user



Different Channels

Source Signal → Channel → Destination

Wired channel

(e.g. coaxial cable, twisted pair cable, etc.)

Optical Fiber

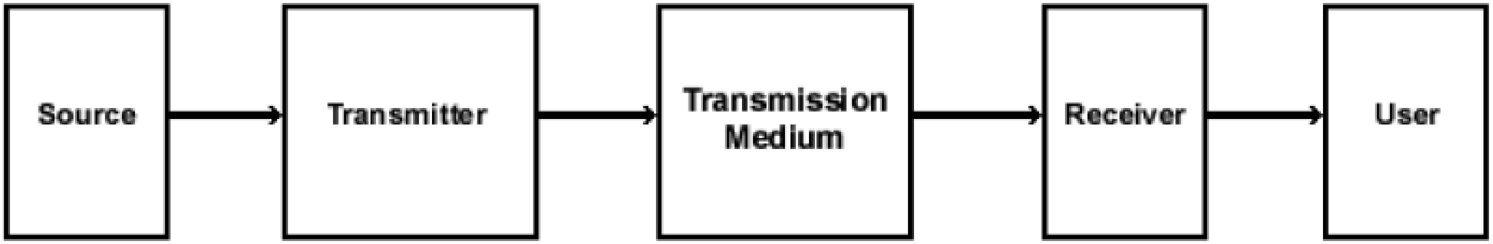
(overhead, underground, submarine cables)

Wireless

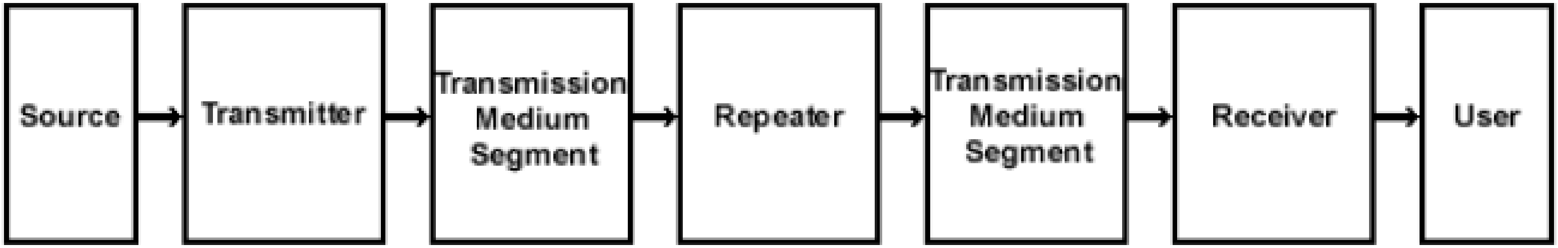
(e.g. Microwave , satellite communication, etc.

Fiber Optic Communication System

Generalized fiber optic communication system representation



Generalized fiber optic communication system representation with repeater



Elements

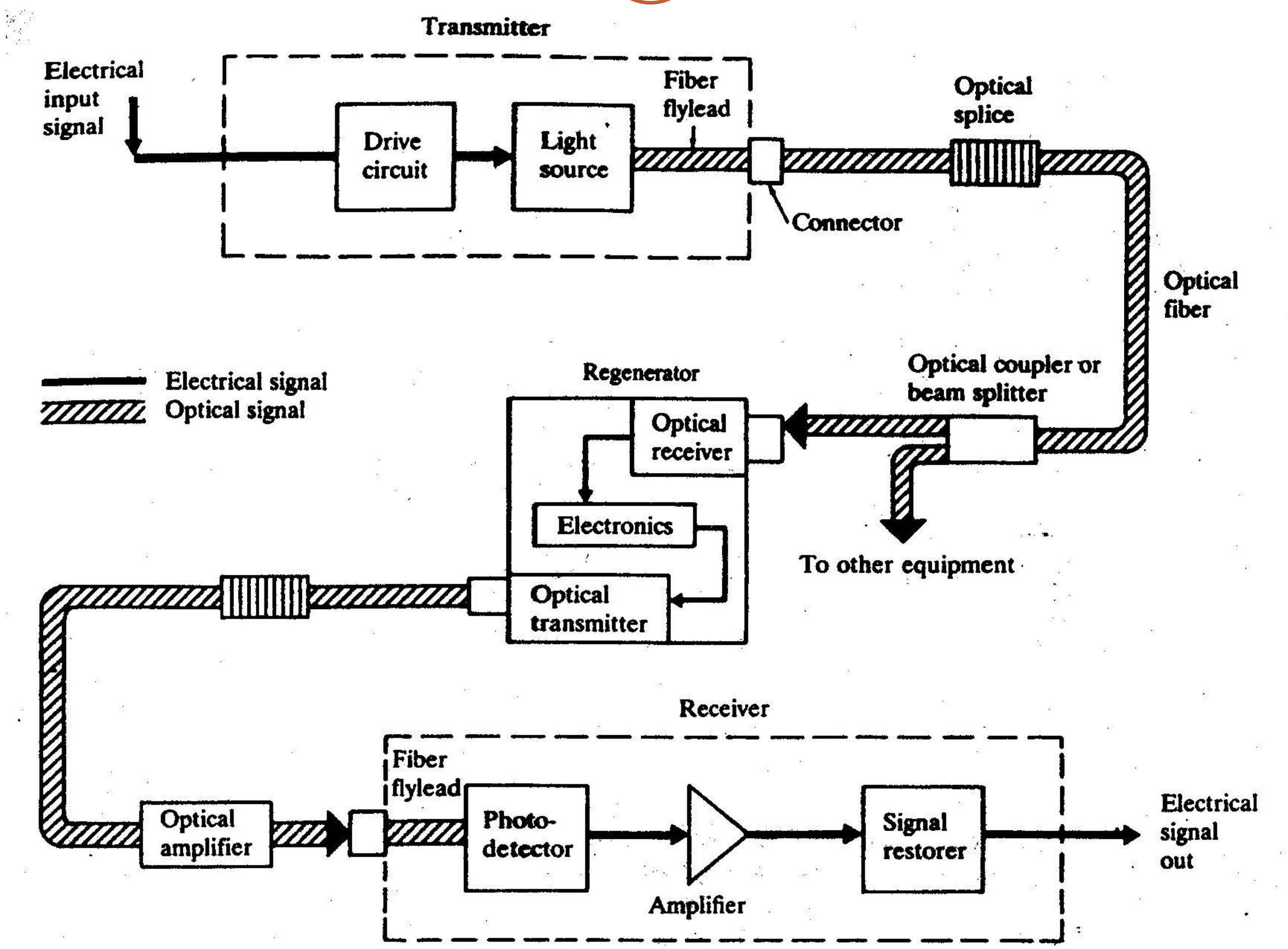
- Source & Modulators
    - LED, LD etc.
- Multiplexers & Demultiplexers
    - WDM, DWDM etc.
- Amplifiers or Repeaters
- Connectors, Couplers, Isolators, etc.
- Detectors & Demodulators
    - PD, APD, PIN etc.
- End Mile Networks

Types of Optical Communication

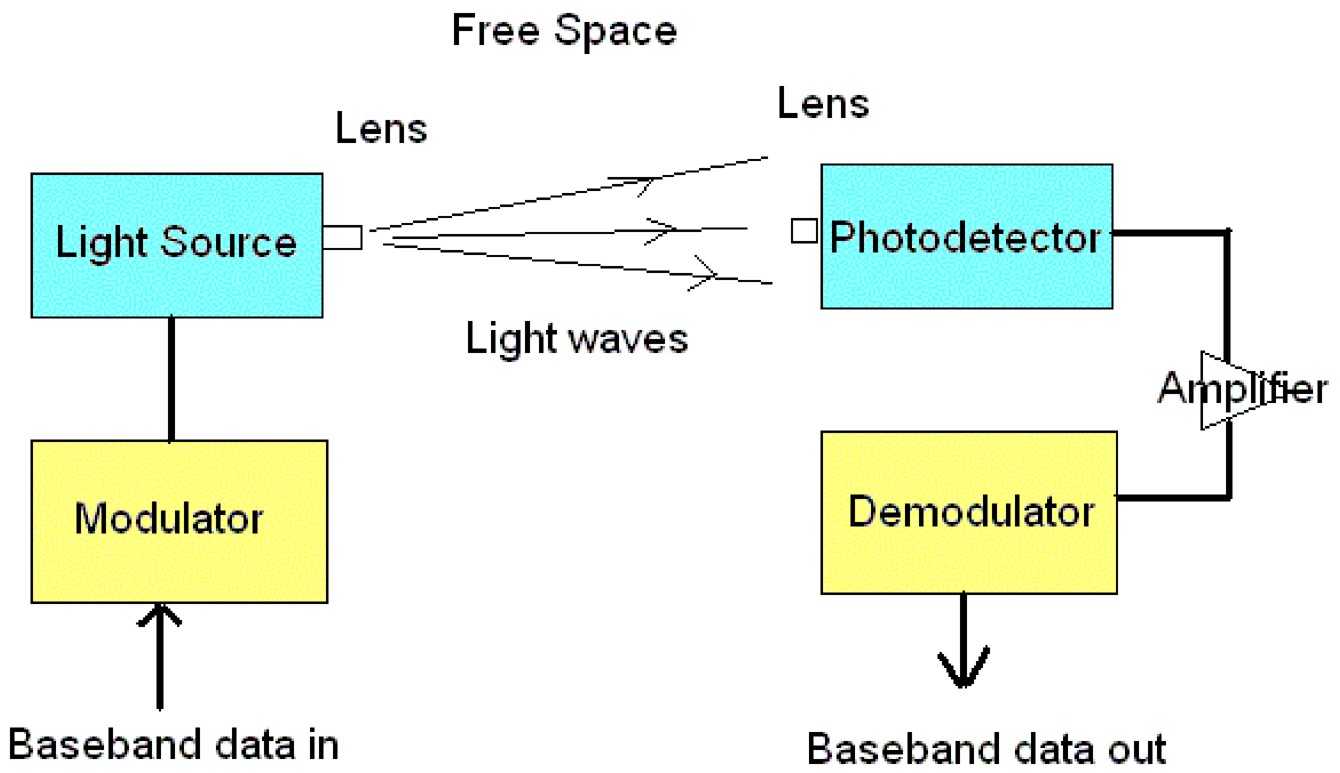
- Wired Optical Communication
    1) All Optical Communication
    2) Electro-Optical Communication
- Wireless Optical Communication

- Space Communication/ Free Space Optics (FSO)
    1) Last mile telecommunication
    2) Weather, sunlight, distance etc. affects the range

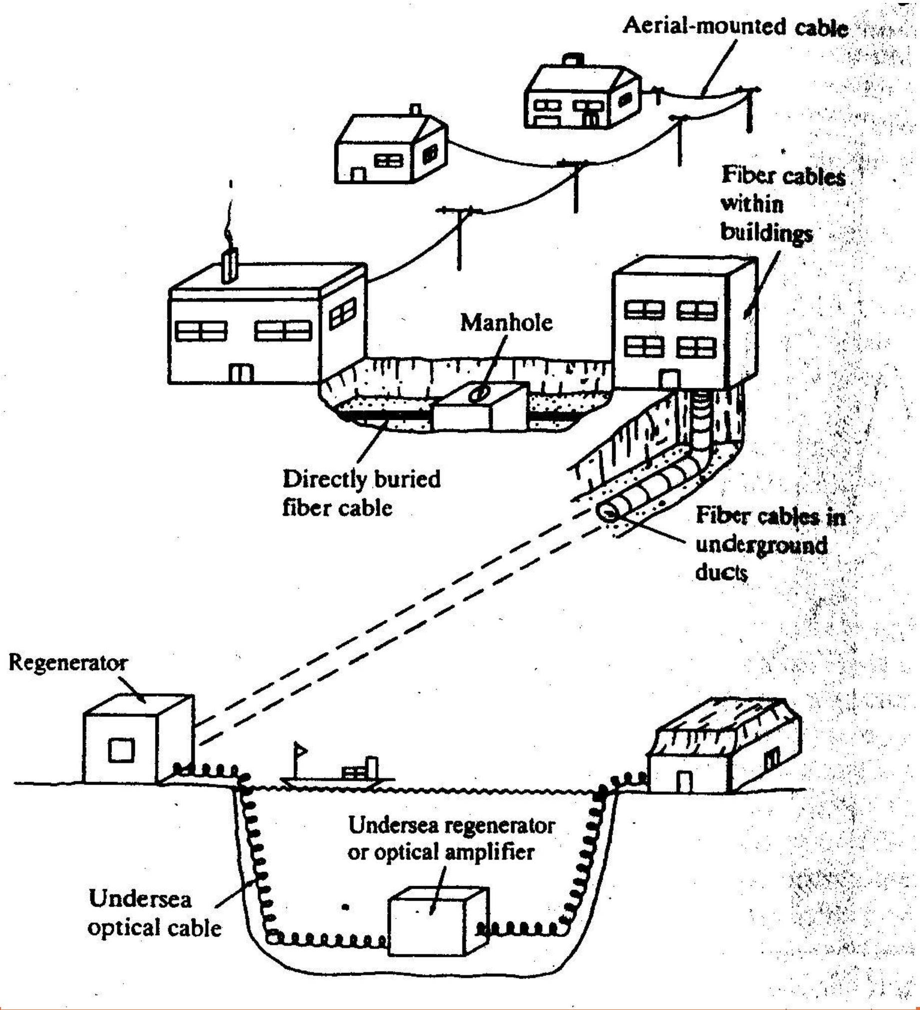
Electro-Optic Communication



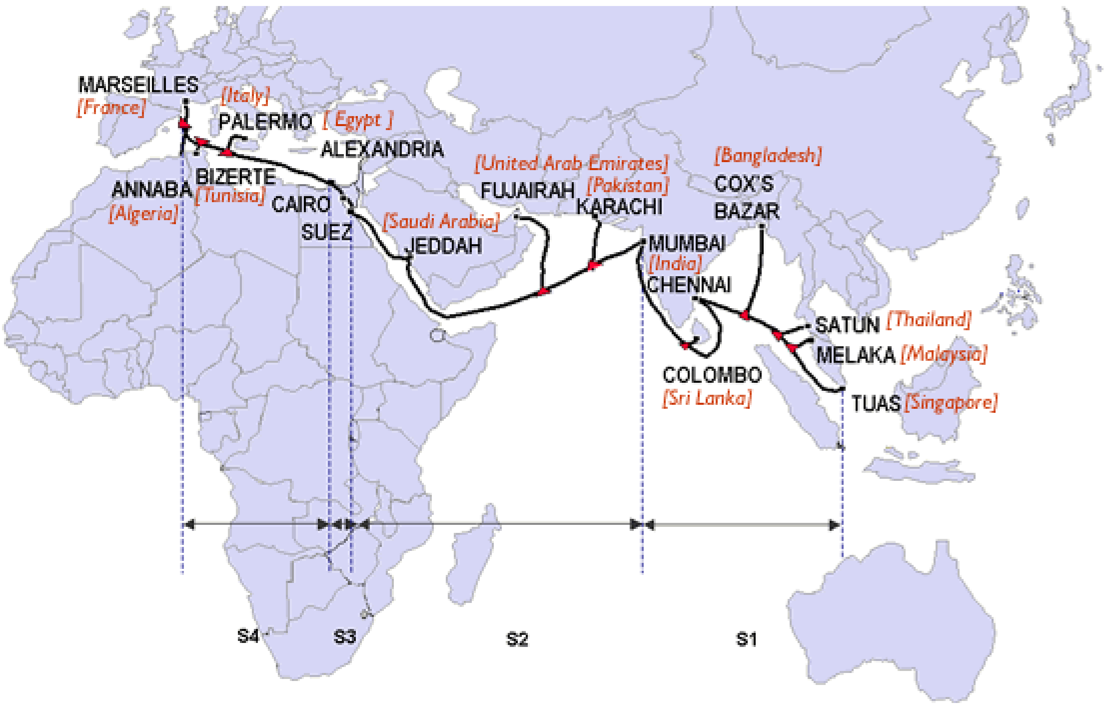
Free Space Optics



Optical Fiber Installation



SEA-ME-WE



MARSEILLES
[France]
[Italy]
PALERMO
[Egypt]
ALEXANDRIA
ANNABA
[Algeria]
BIZERTE
[Tunisia]
CAIRO
SUEZ
[Saudi Arabia]
JEDDAH
[United Arab Emirates]
FUJAIRAH
[Pakistan]
KARACHI
[Bangladesh]
COX'S
BAZAR
MUMBAI
[India]
CHENNAI
COLOMBO
[Sri Lanka]
SATUN
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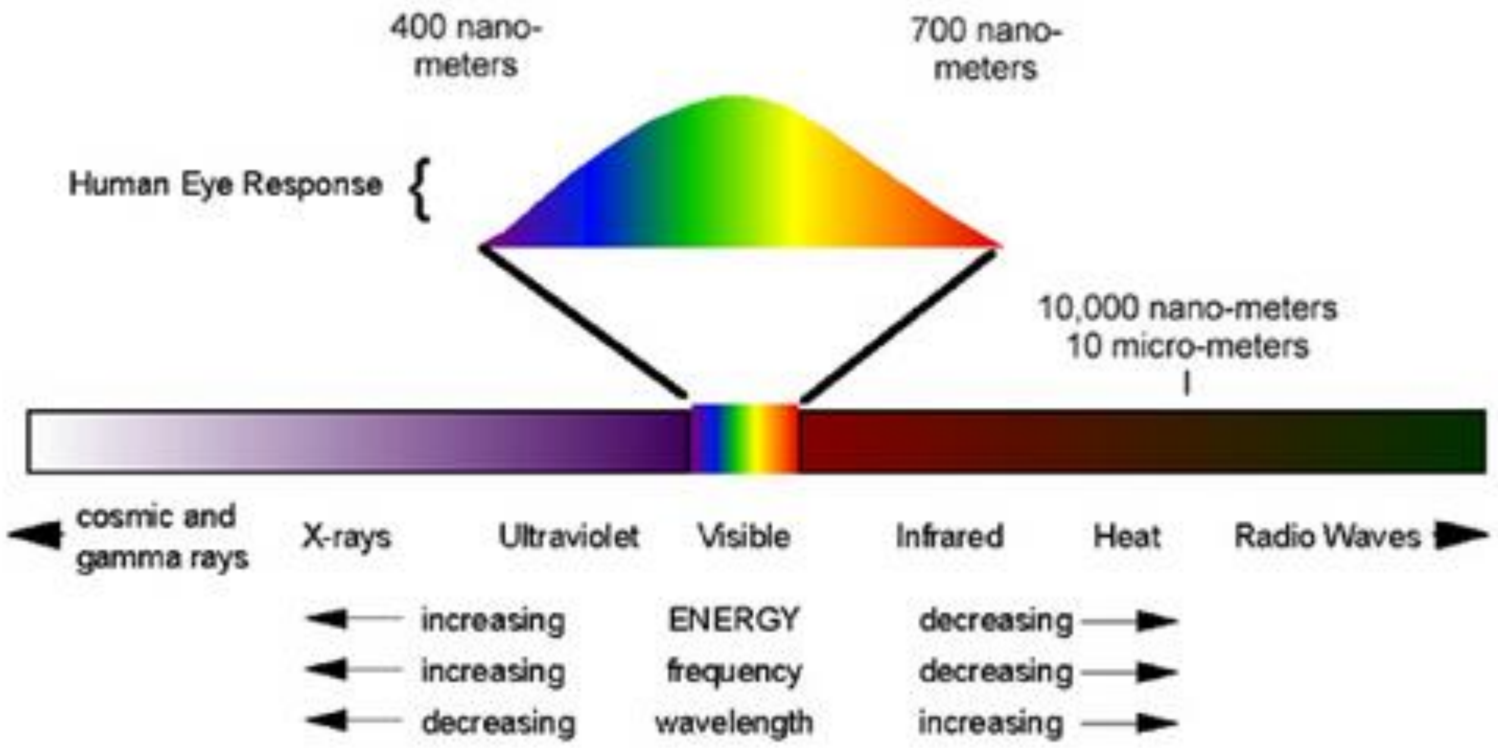
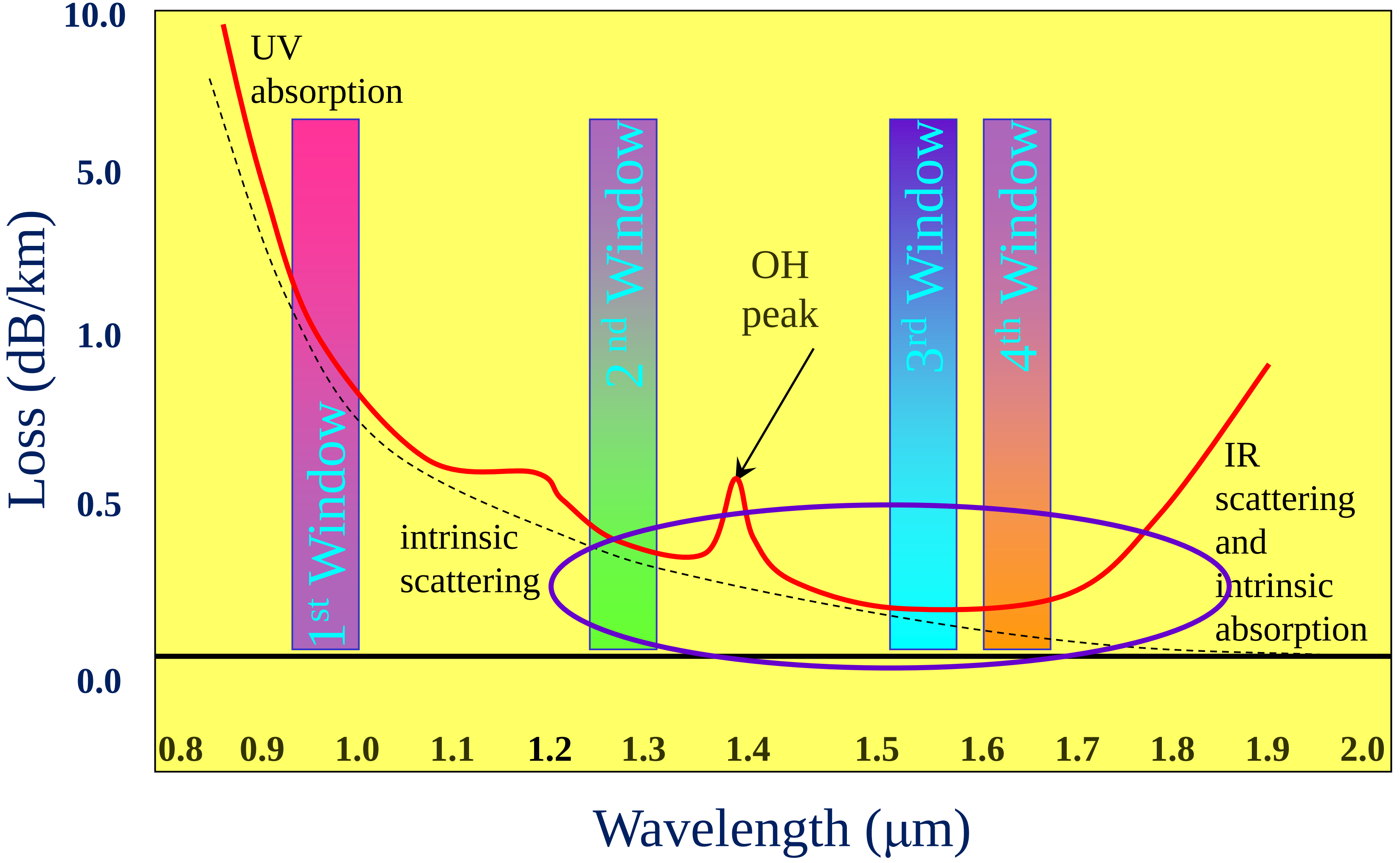
S4
S3
S2
S1

Lightwave Fundamentals



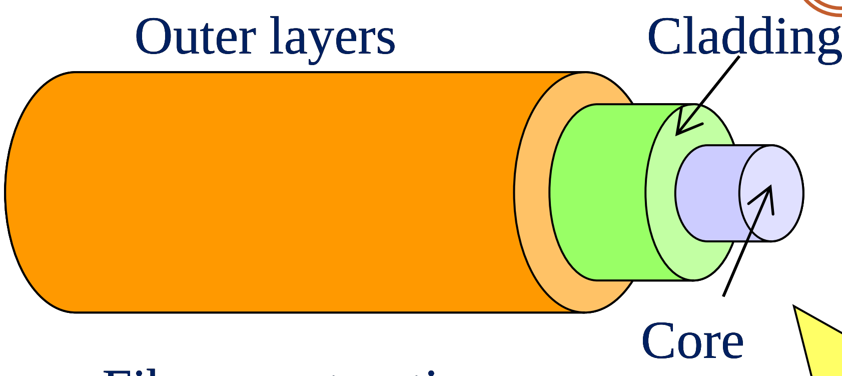
Loss & Transmission Windows



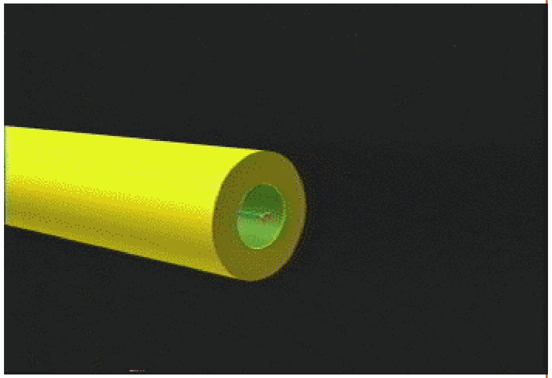
EM Bands

Band Designator	Band Descriptor	Wavelength Range (nm)
O- Band	Original	1260-1360
E- Band	Extended	1360-1460
S- Band	Short wavelength	1460-1530
C- Band	Conventional	1530-1565
L- Band	Long wavelength	1565-1625
U- Band	Ultra-long wavelength	1625-1675

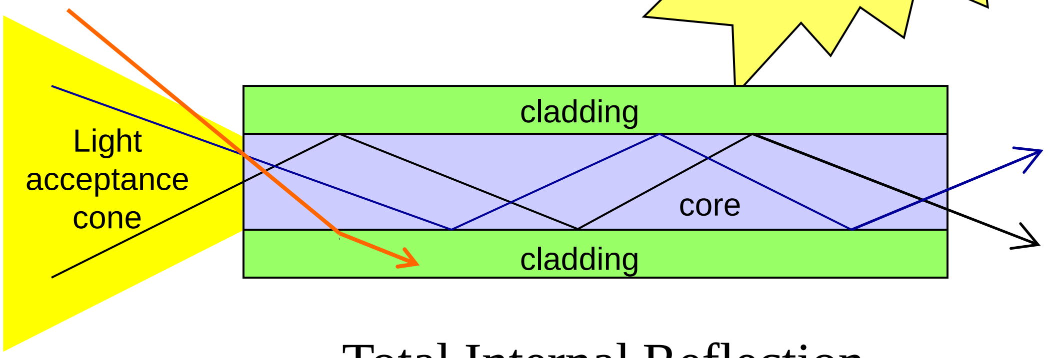
Conventional Optical Fiber



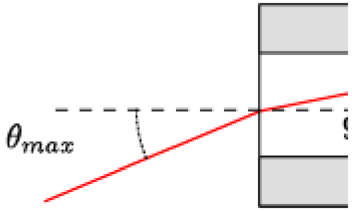
Fiber construction



TIR guiding-
$n_{core} > n_{cladding}$

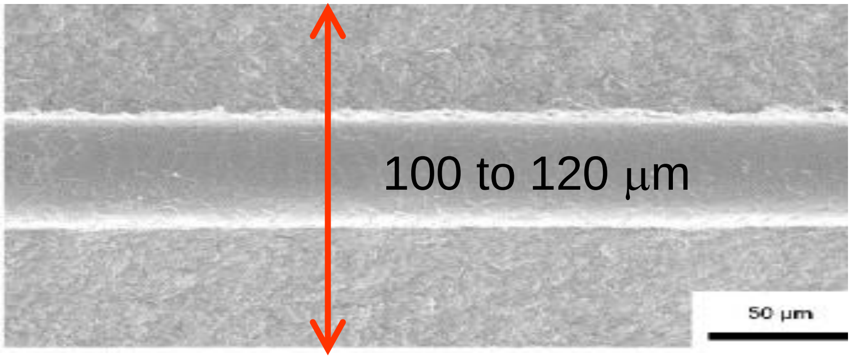


Total Internal Reflection

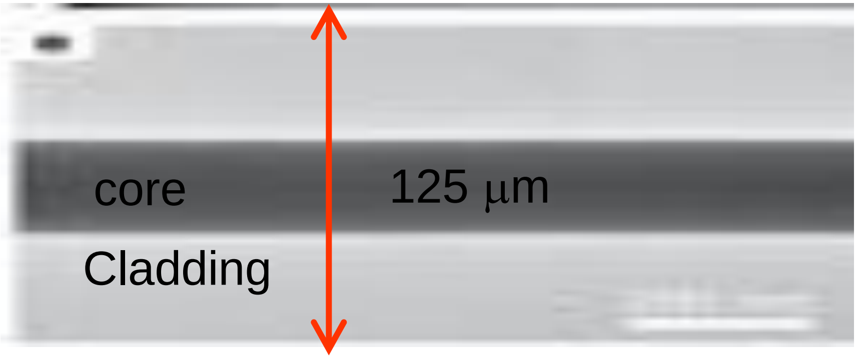


$$NA = n\sin\theta_{\max} = \sqrt{n_{core}^2 - n_{cladding}^2}$$

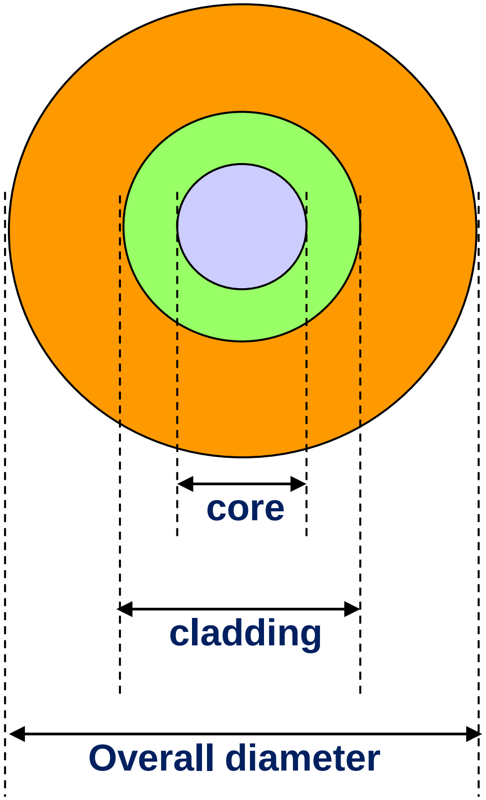
Optical Fiber Dimension



SEM Image of Human Hair



SEM Image of Optical Fiber

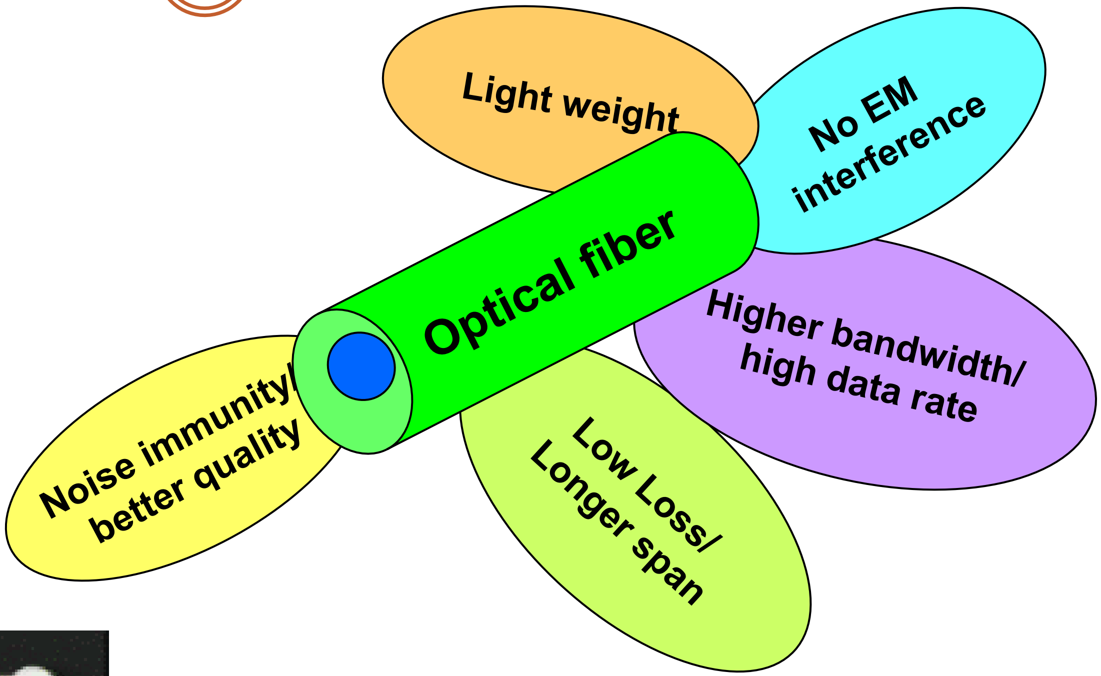


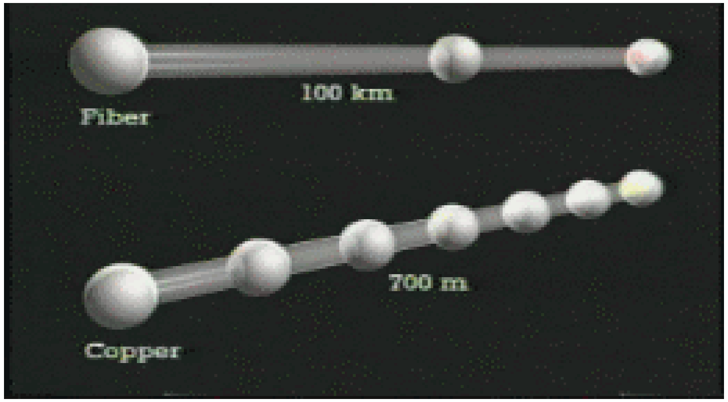
Fiber cross-section

COF vs other Conductors

Optical fiber

- Dielectric cylindrical waveguide
- Guide signals in the form of light

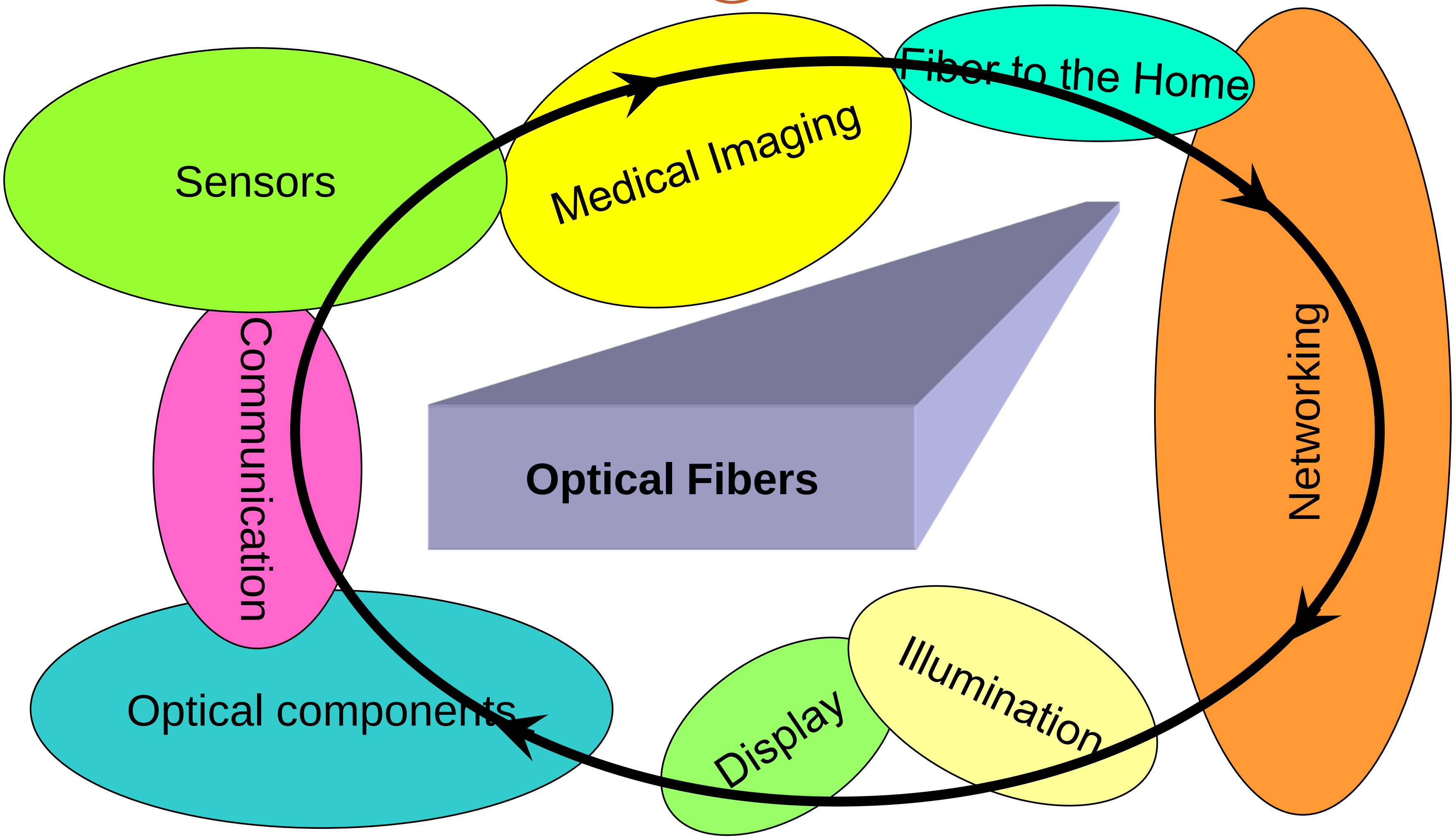




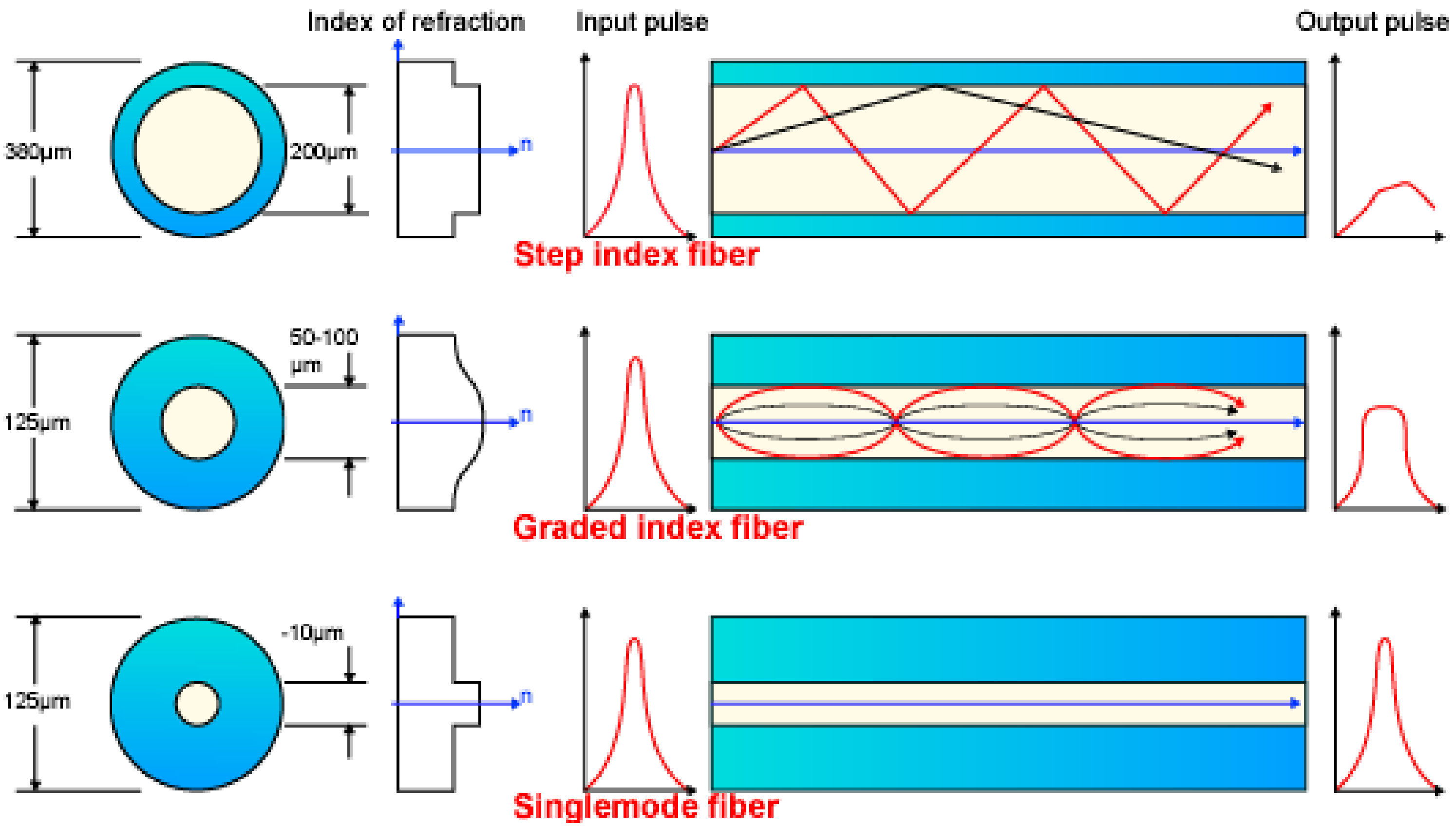
Disadvantages

- Interconnection between fibers

Applications



Single Vs Multimode



Fabrication

- Chemical Vapor Deposition
- Modified Chemical Vapor Deposition
- Stack and Draw
- Sol-gel Method etc.

Lightwave Fundamental

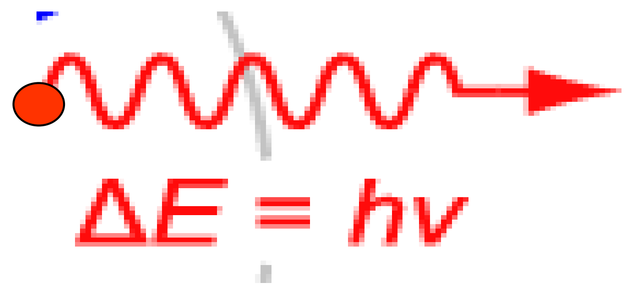
Wave ⟷ Particle

- **Light has a dual nature**
- **Wave Particle duality of light is complementary**

Geometrical Optics

• Light is represented by straight lines

Particle theory



Photon Energy

$$\mathrm{E} = h\nu = hc/\lambda \ where, c = \nu\lambda$$

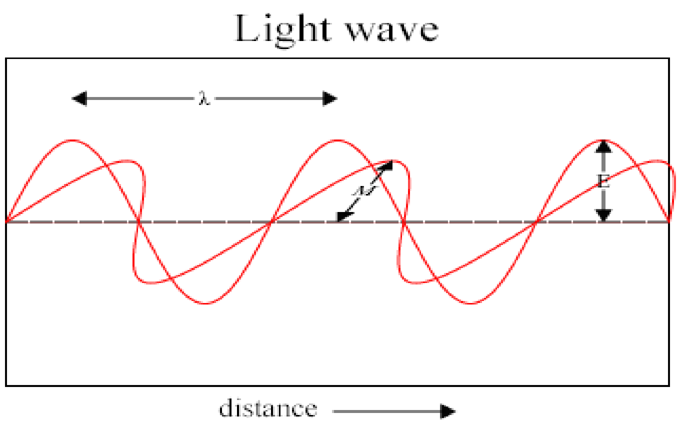
Notations: λ = wavelength; c = velocity of light; E = energy of photon, h = Planck's constant

Wave Nature

Light propagates like waves

Velocity of propagation

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} \quad \text{.........(1)}$$



A simple plane wave is given by

$$E = \hat{x} E_m Cos(\omega t - kz)$$

Where, $k = \omega / c$

In a medium other than free space

$$k = \omega / v = \omega n / c \quad where, \ v = c / n$$

Wave Equation

Maxwell's equations in a homogeneous and lossless dielectric medium are written in terms of the electric field **E** and magnetic field **H** as

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

$$\nabla \times H = -\varepsilon \frac{\partial E}{\partial t}$$

Where, $\varepsilon = \varepsilon_0 n^2$ and $\mu = \mu_0$ and
wave number = $\omega/v = \omega/\sqrt{(\mu\,\varepsilon)} = kn$ *where* $k = \omega/c$

and

$$\lambda = \frac{c}{f} = \frac{\omega/k}{f} = \frac{2\pi}{k},$$

Wave Equation

When we consider an electromagnetic wave having angular frequency and propagating in the z direction with propagation constant , the electric and magnetic fields of a fiber having axial symmetry can be expressed as

$$\tilde{\mathbf{E}} = \mathbf{E}(\mathrm{r}, \theta)\ e^{j(\omega t - \beta z)},$$
$$\tilde{\mathbf{H}} = \mathbf{H}(\mathrm{r}, \theta)\ e^{j(\omega t - \beta z)}$$

$$\begin{cases} \dfrac{\partial^2 E_z}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial E_z}{\partial r} + \dfrac{1}{r^2}\dfrac{\partial^2 E_z}{\partial \theta^2} + [k^2 n(r,\theta)^2 - \beta^2]E_z = 0 \\ \dfrac{\partial^2 H_z}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial H_z}{\partial r} + \dfrac{1}{r^2}\dfrac{\partial^2 H_z}{\partial \theta^2} + [k^2 n(r,\theta)^2 - \beta^2]H_z = 0. \end{cases}$$

In axially symmetric optical fibers, the refractive-index distribution is not dependent on θ and is expressed by n_r. The modes in an optical fiber consists of TE modes Ez = 0, TM modes Hz = 0 and hybrid modes Ez ≠ 0, Hz ≠ 0, respectively.

Wave Equation

Out of infinite possible solutions we consider those satisfying boundary conditions

$$E_t^{(1)} = E_t^{(2)}$$

$$H_t^{(1)} = H_t^{(2)}$$

There are also natural boundary conditions that require the electromagnetic fields to be zero at infinity

Group & Phase Velocity

A plane wave is given by

$$E_x = E_m \cos\omega(t - z/v)$$
$$= E_m \cos(\omega t - \omega z/v) = E_m \cos(\omega t - kz)$$

Velocity for which phase is constant is called phase velocity- $\omega t - kz = C$

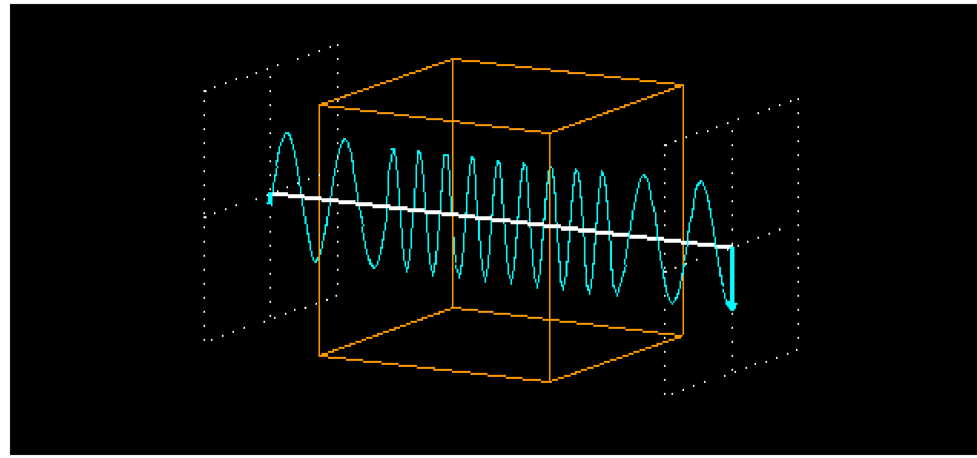
Phase velocity $v_p = dz/dt = \dfrac{\omega}{k} = f\lambda$

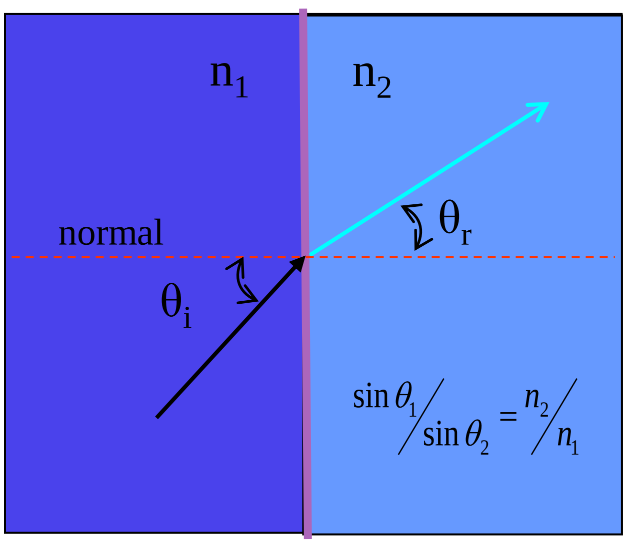
Group velocity $v_g = d\omega/dk$

Refraction

The light slows down inside the material, therefore its wavelength becomes shorter and its phase gets shifted

$$E_y = E_m \cos(\omega t - nz/\lambda)$$



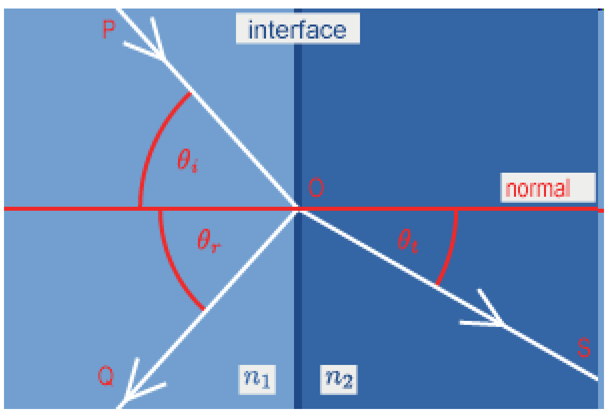


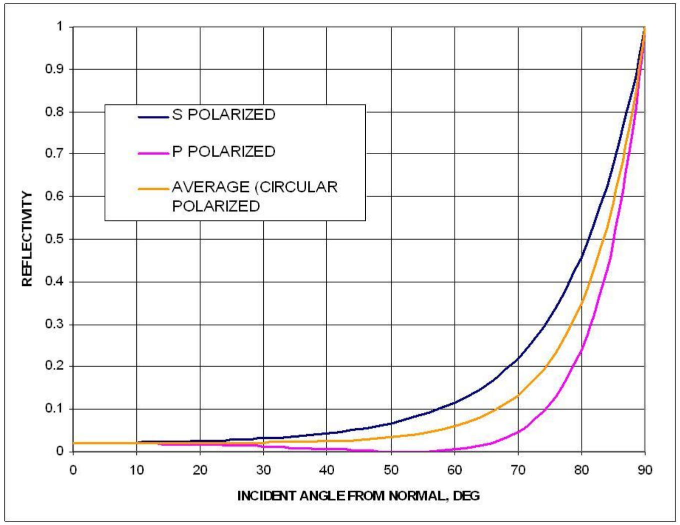
Transmission & Reflection

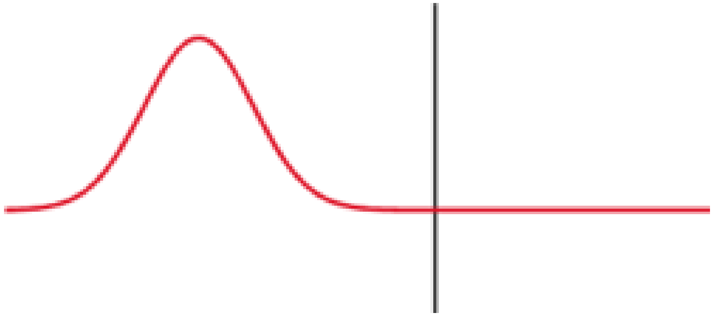
Reflectance & Transmittance

[redacted]

R = Reflectance; T = Transmittance







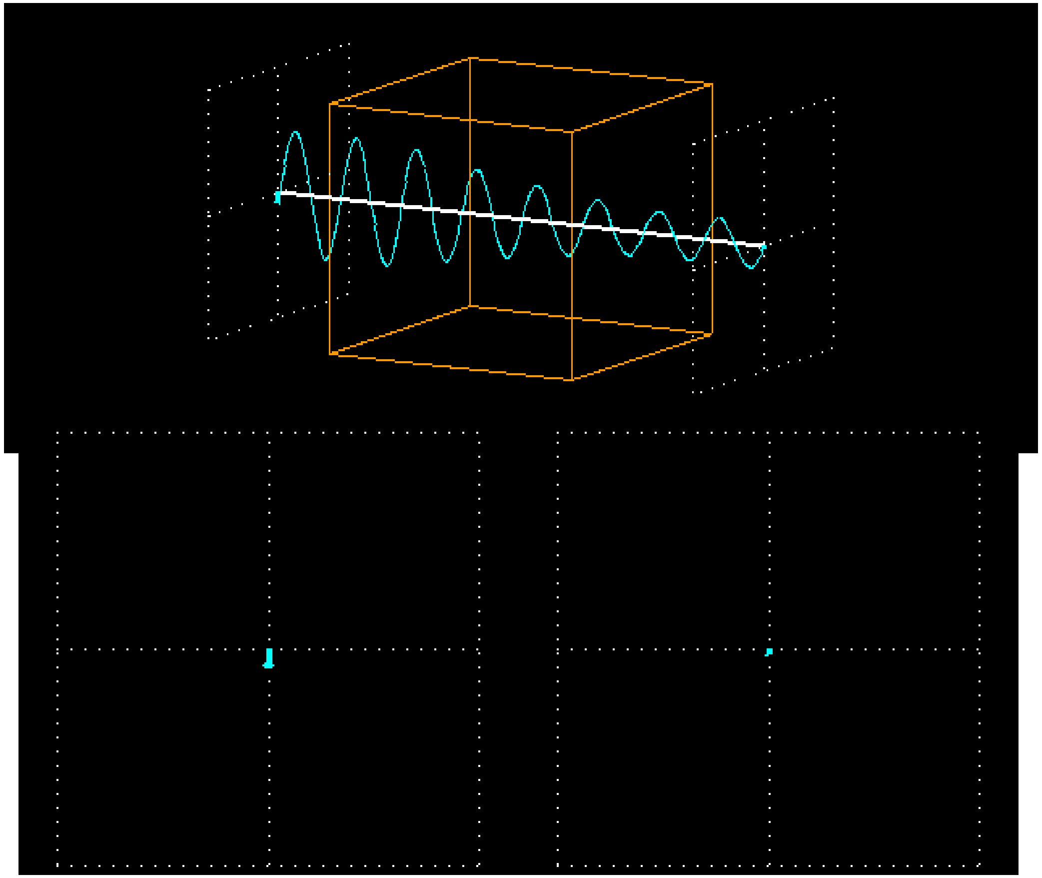
Absorption

$$E_y = E_m e^{-kz} \cos(\omega t - z/\lambda)$$

Here k is the extinction coefficient

$$\mathbf{n} = n + ik$$

Here, n is the refractive index indicating the phase speed, while k is the extinction coefficient which indicates the amount of absorption loss when the electromagnetic wave propagates through the material



$$k = \sqrt{(\varepsilon_1^2 + \varepsilon_2^2 - \varepsilon_1)/2}$$ if $$\boldsymbol{\varepsilon} = \varepsilon_1 + i\varepsilon_2$$

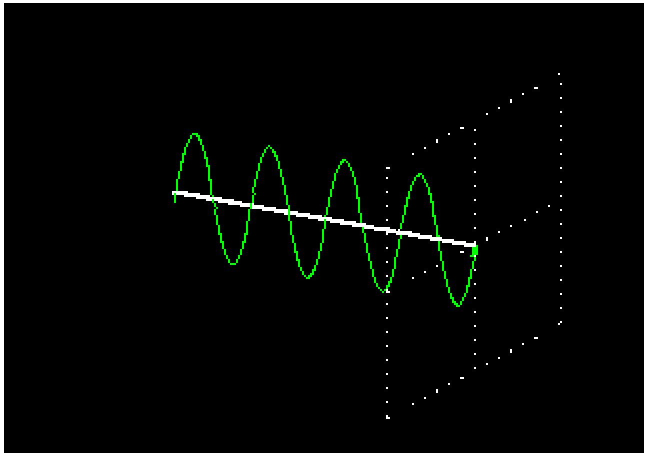
Polarization

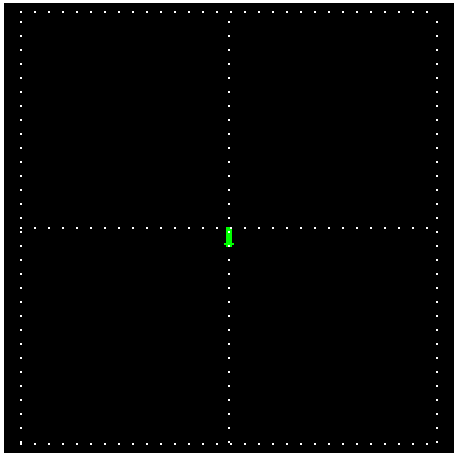
- Linear polarization
- Plane polarization
- Circular polarization
- Elliptical polarization
- Random polarization

Polarization

Vertical

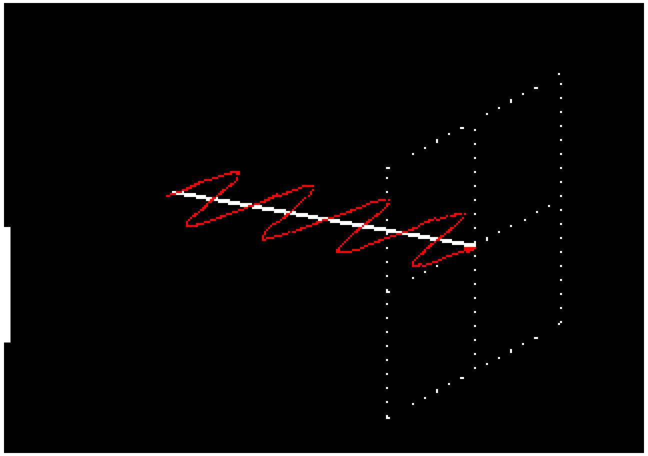
$$E_x = E_m \cos(\omega t - kz)$$

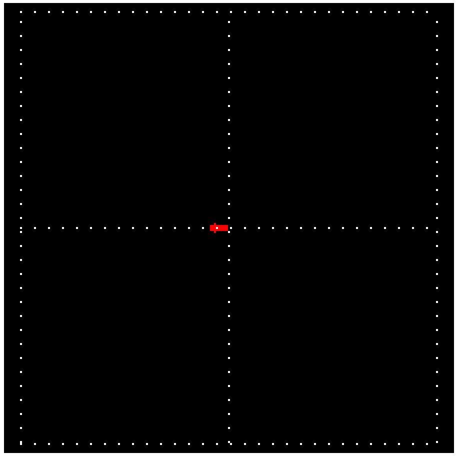




Horizontal

$$E_y = E_m \cos(\omega t - kz)$$



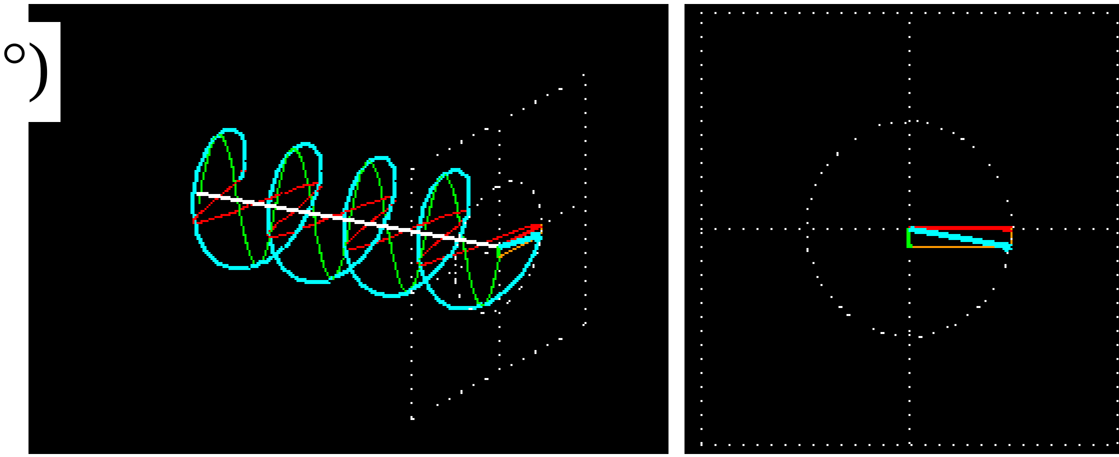


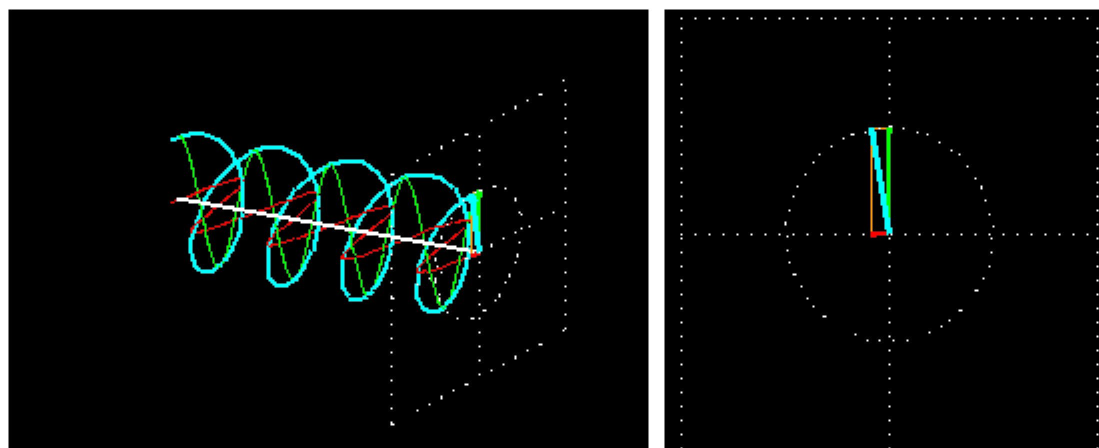
Circular Polarization

Right circular

$$E_x = E_m \cos(\omega t - kz + 90°)$$

$$E_y = E_m \cos(\omega t - kz)$$



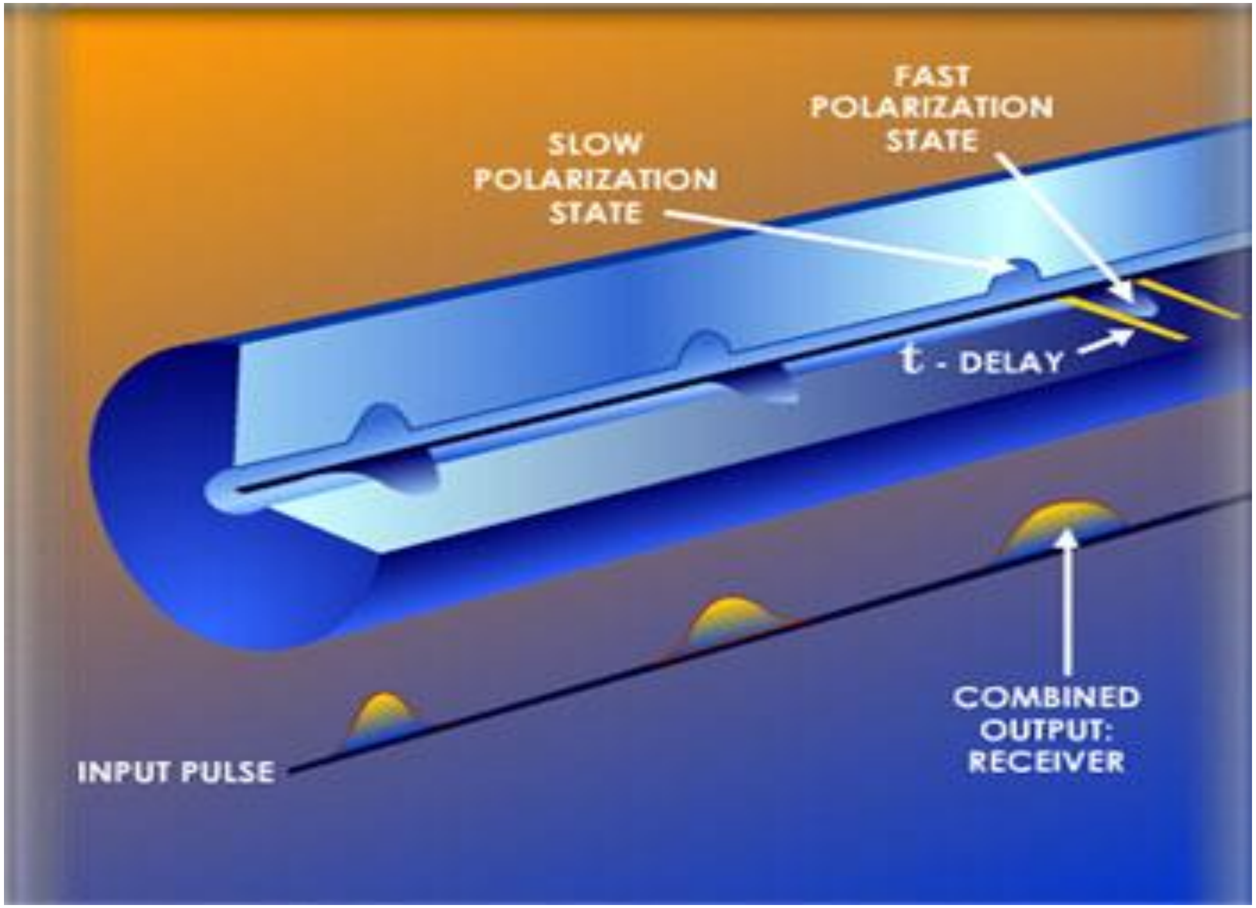


Left circular

$$E_x = E_m \cos(\omega t - kz - 90°)$$

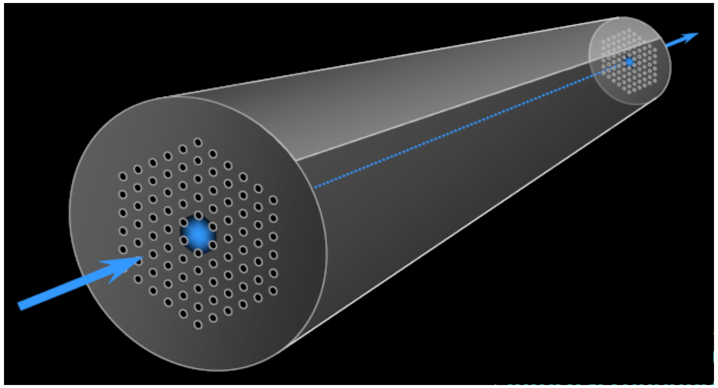
$$E_y = E_m \cos(\omega t - kz)$$

PMD


FAST
POLARIZATION
STATE
SLOW
POLARIZATION
STATE
t - DELAY
COMBINED
OUTPUT:
RECEIVER
INPUT PULSE

Microstructure Crystal Fiber

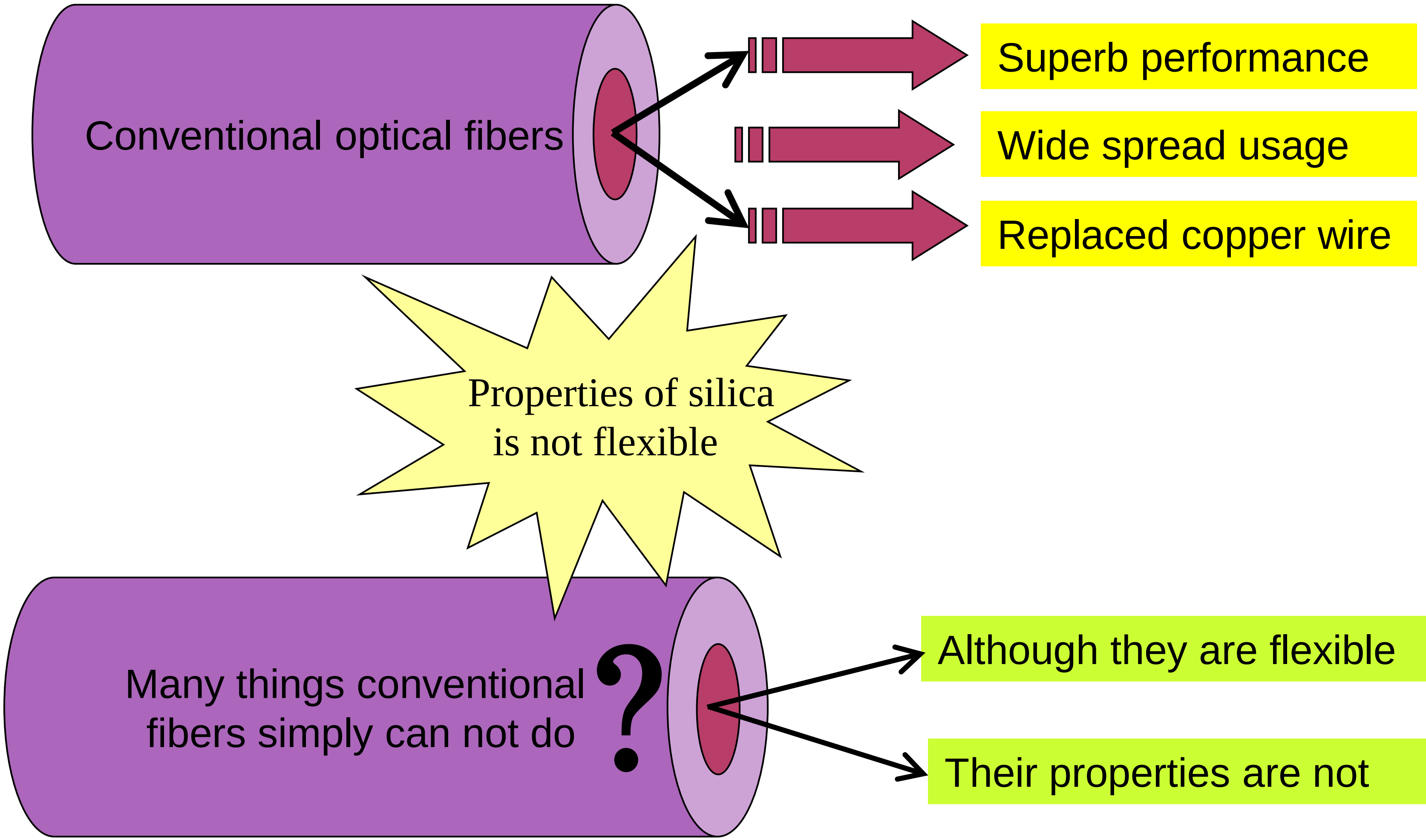
- Conventional optical fiber (COF)
- Microstructure optical fiber (MOF)
- Plastic optical fiber (POF)



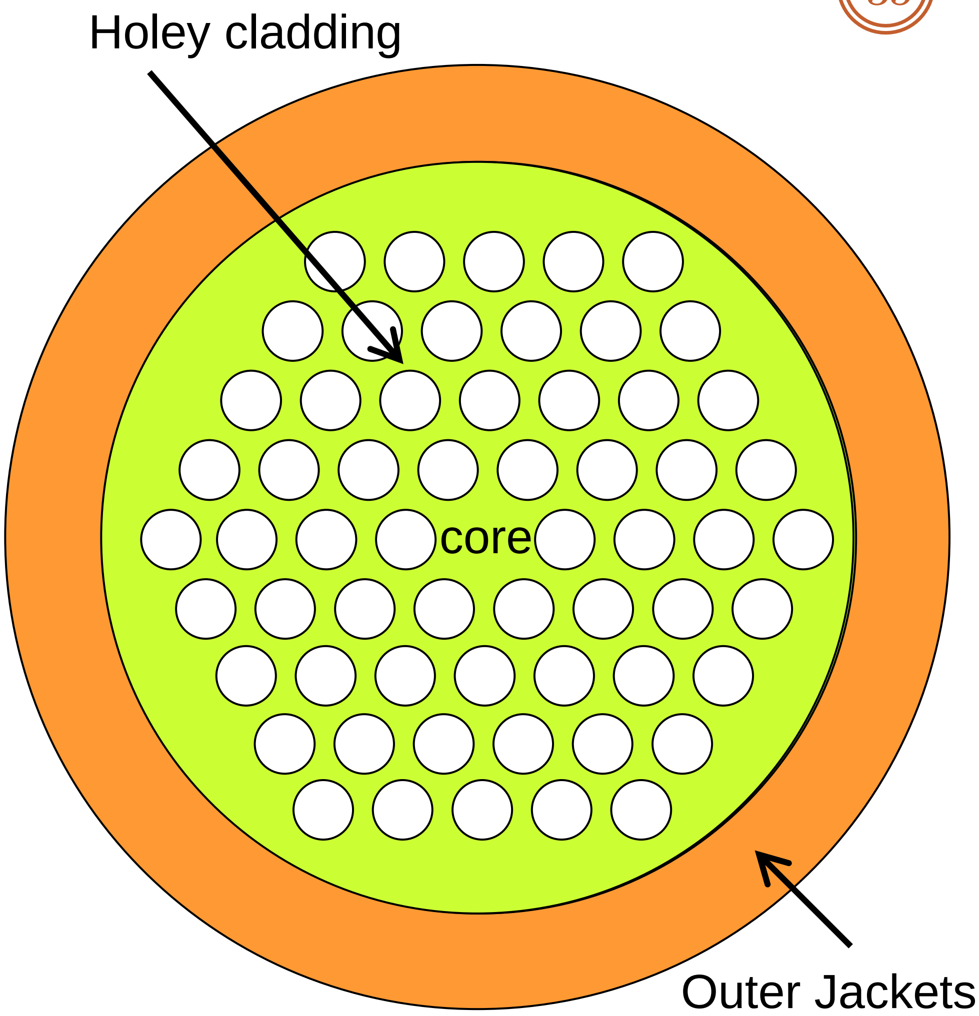
Optical Fiber

POF	MOF	COF

MOF vs PCF


Conventional optical fibers
Superb performance
Wide spread usage
Replaced copper wire
Properties of silica is not flexible
Many things conventional fibers simply can not do
?
Although they are flexible
Their properties are not

MOF Structure



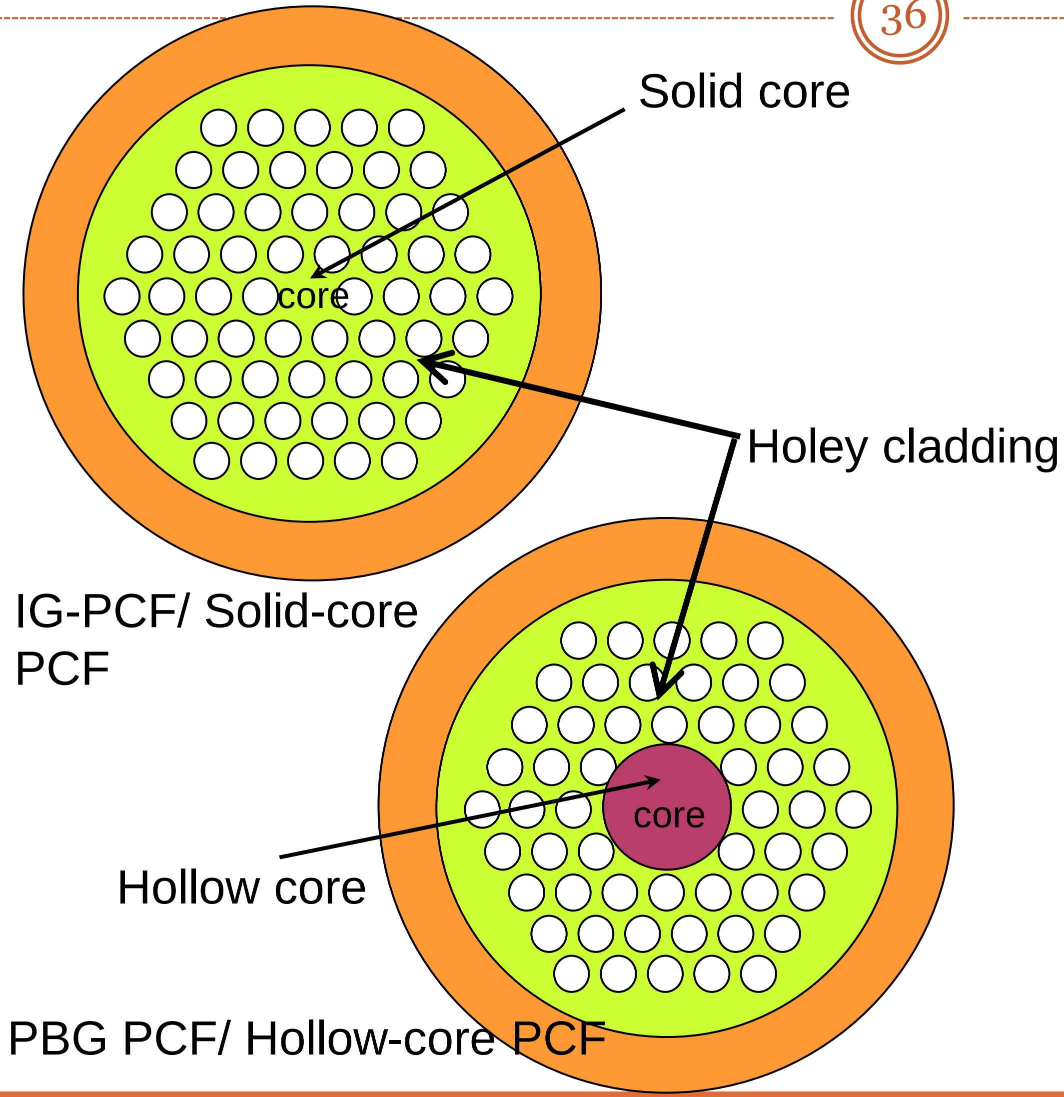
MOF/ PCF

- Core material: silica or air
- Cladding: Silica-air microstructure

Light guiding mechanisms

- TIR: high index core (silica core)
- PBG: low index core (air core)

Major MOF Types



Index-Guiding PCF

- **Guide light by TIR**
- $n_{core} > n_{cladding}$

BPG-Guiding PCF

- **Guide light by PBG**
- $n_{core} < n_{cladding}$

MOF Classification

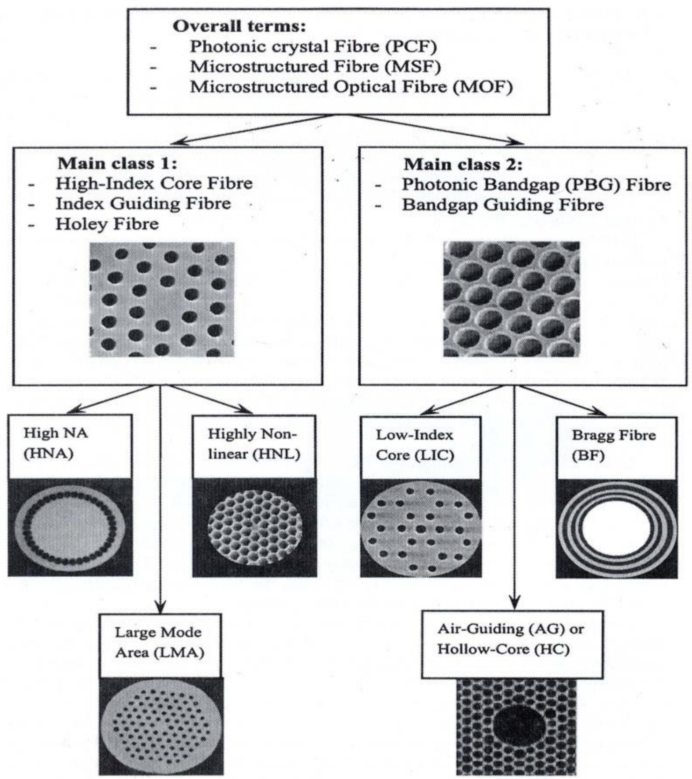
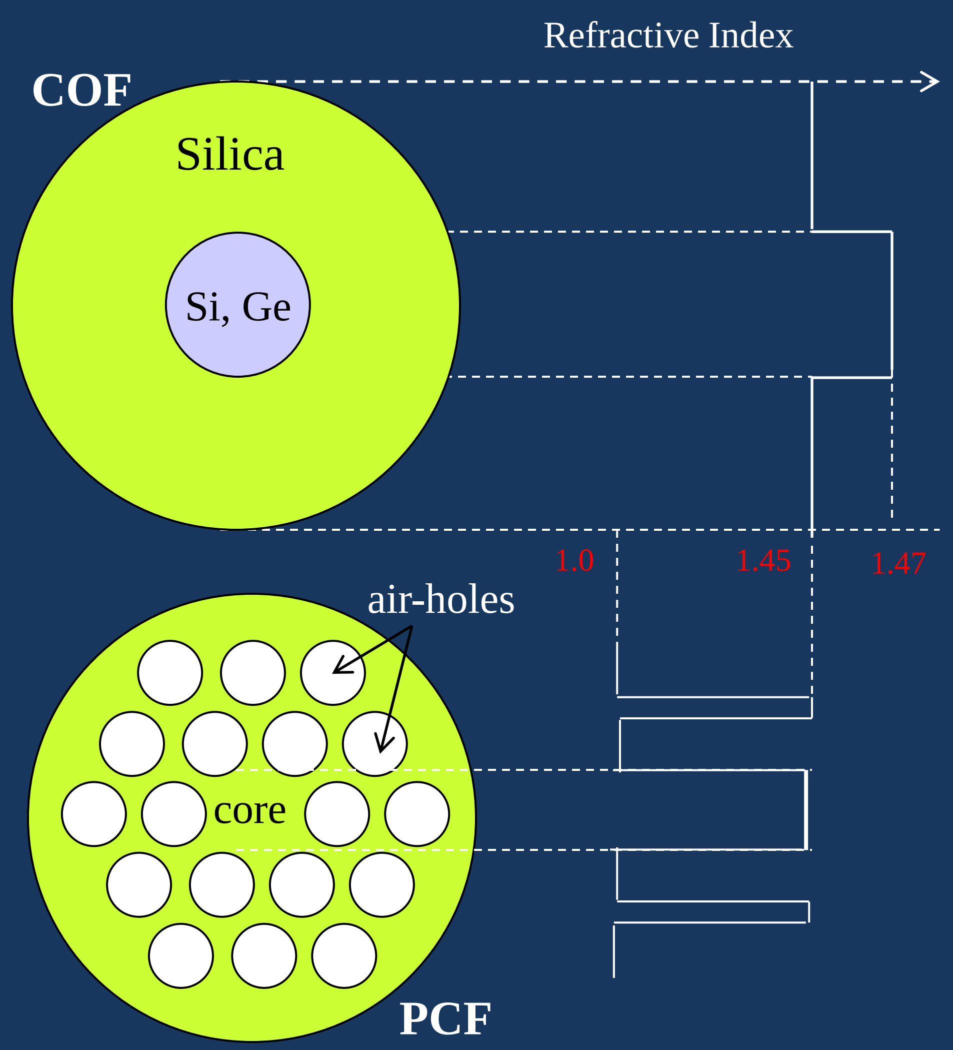


Figure 1-4. Diagram showing the most commonly used terms and typical structures for the major classes and sub-classes of photonic crystal fibres. The included photos are kindly provided by Crystal fibre A/S.

Why PCF?

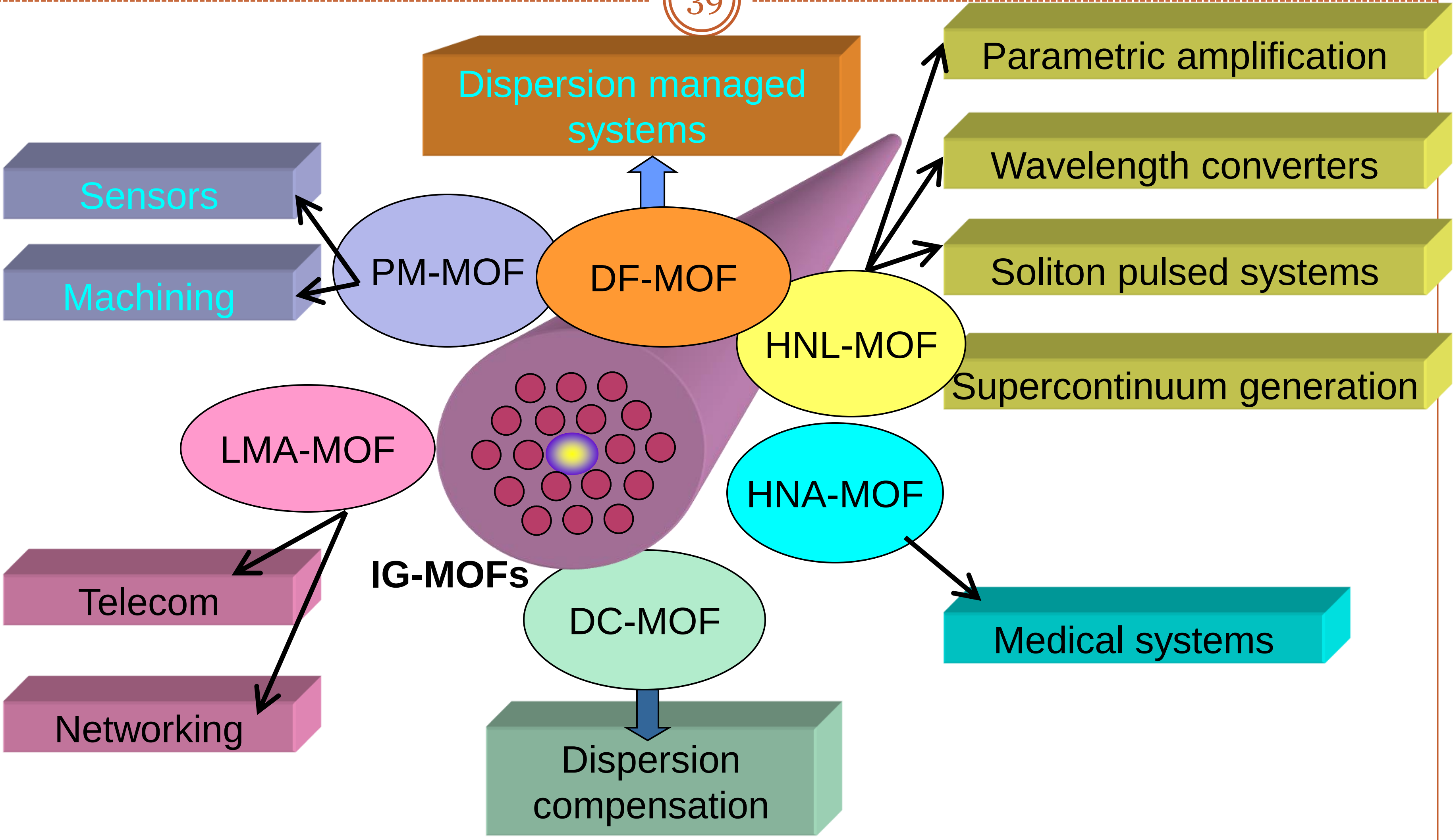


COF demerits
- Low index contrast
- Narrow design space

PCF merits
- Controlling optical properties
- Single material fiber
- High index contrast
- Wider design space

Major demerits
- Confinement losses exist
- Fabrication challenge
- Connectivity problem with other waveguides and devices
- Short manufacture length and high price of using PCF as transmission media.

MOF Applications



Applications of PCFs

Index guided PCFs:

- High power handling
- Fiber laser multi-wavelength generation
- Supercontinuum generation applied to optical coherence tomography and to spectroscopy
- Fiber sensor

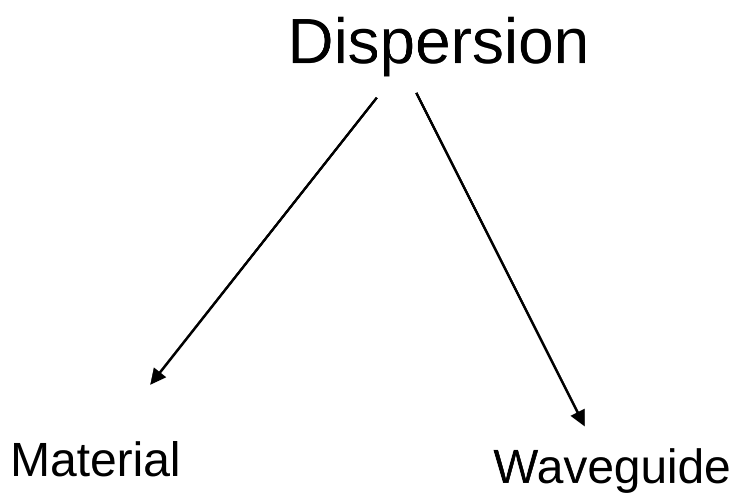
Hollow Core PCFs:

- high power transmission
- gas-based nonlinear optics
- particle guidance in liquids
- fiber sensing

Propagation Characteristics & Constraints

- Chromatic/Group velocity Dispersion
  - Material dispersion & waveguide dispersion
  - Normal & anomalous dispersion
  - Polarization mode dispersion
- Mode area/Effective mode area
- Fiber loss: Confinement, scattering, absorption, etc.
- Single/ Multimode
- Bending & Splice losses
- Nonlinearity and Nonlinear effects
  - Self phase modulation
  - Cross phase modulation
  - Four wave mixing etc.

Chromatic Dispersion



- Chromatic is used to emphasize color dependence to phase velocity
- GVD is used to emphasize wavelength dependence to group velocity

Chromatic Dispersion (Contd.)

Chromatic dispersion of second and higher order is defined via the Taylor expansion of the wave number *k* as a function of the angular frequency ω

$$k(\omega) = k_0 + \frac{\partial k}{\partial \omega}(\omega - \omega_0) + \frac{1}{2}\frac{\partial^2 k}{\partial \omega^2}(\omega - \omega_0)^2 + \frac{1}{6}\frac{\partial^3 k}{\partial \omega^3}(\omega - \omega_0)^3 + \ldots$$

- The zero-order term describes a common phase shift.
- The first-order term contains the inverse group velocity (i.e., the group delay per unit length) and describes an overall time delay without an effect on the pulse shape:

$$k' \equiv \frac{\partial k}{\partial \omega} = \frac{1}{\upsilon_g} \qquad k'' \equiv \frac{\partial^2 k}{\partial \omega^2} \qquad k''' \equiv \frac{\partial^3 k}{\partial \omega^3}$$

- The second-order (quadratic) term contains the second-order dispersion or group delay dispersion (GDD) per unit length
- The third-order (cubic) term contains the third-order dispersion (TOD) per unit length

Chromatic Dispersion (Contd.)

Second-order dispersion is the derivative of the inverse group velocity with respect to angular frequency:

$$k' \equiv \frac{\partial k}{\partial \omega} = \frac{1}{\upsilon_g} \quad \Rightarrow \quad k'' \equiv \frac{\partial}{\partial \omega}\left(\frac{1}{\upsilon_g}\right)$$

The dispersion of various orders for a medium can most conveniently be calculated if the refractive index is specified with a kind of Sellmeier formula.

In Fiber Optics, Dispersion is

$$D_\lambda = -\frac{2\pi c}{\lambda^2} \cdot \frac{\partial^2 k}{\partial \omega^2}$$

in units of picoseconds per nanometer and kilometer (ps/(nm.km)).

Normal & Anomalous Dispersion

- *Normal dispersion*
- (for $k''>0$) and *anomalous dispersion* (for $k''<0$).
- Normal dispersion, where the group velocity decreases with increasing optical frequency, occurs for most transparent media in the visible spectral region.
- Anomalous dispersion sometimes occurs at longer wavelengths, e.g. in silica (the basis of most optical fibers) for wavelengths longer than the zero-dispersion wavelength of ≈1.3 μm.

PMD

1. It arises due to interaction between two polarization modes in birefringent fibers

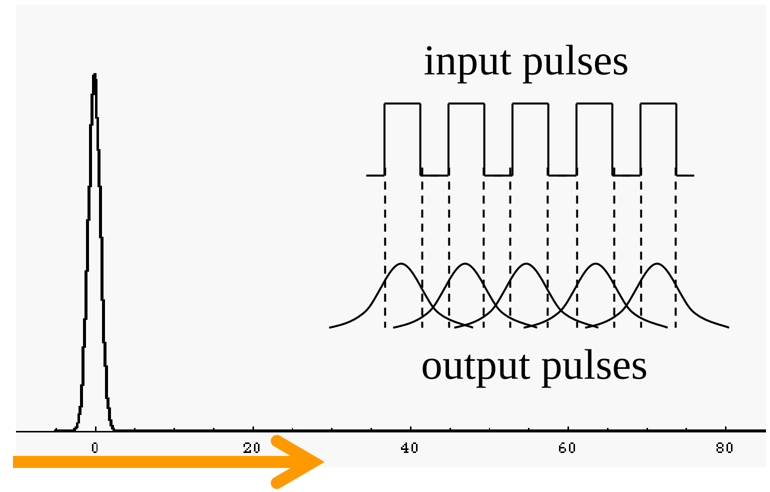
2. Becomes significant for fiber communication at very high bit rates

Dispersion Control

Spectral broadening due to transmission

Phase velocity → Refractive index

Refractive index → Wavelength



Distance

Waveguide dispersion

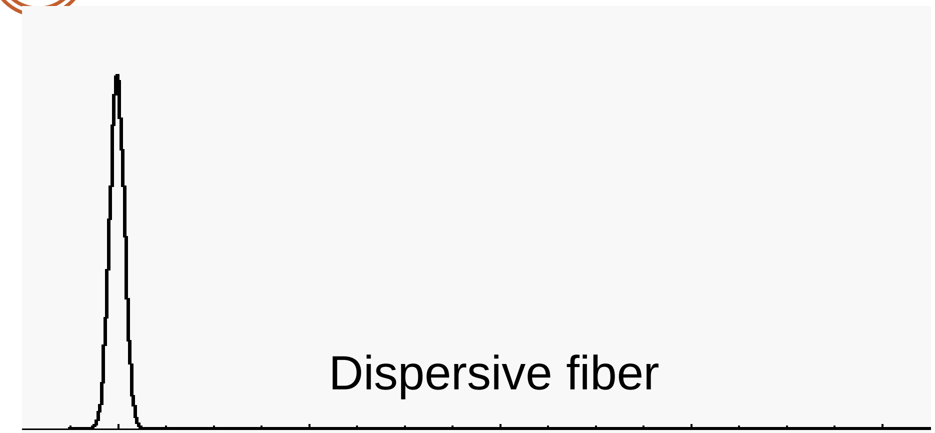
Material dispersion

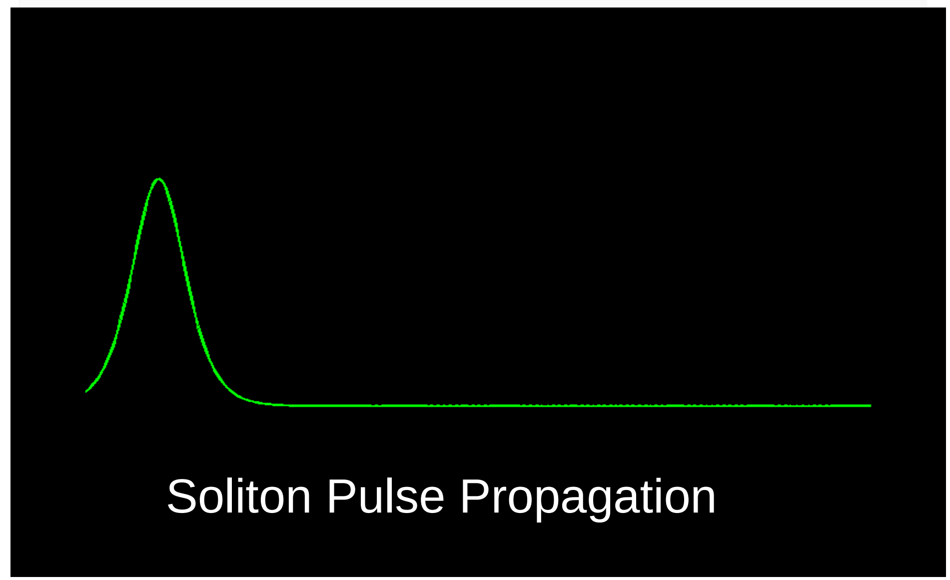
$$Dispersion,\ D(\lambda) \approx D_g(\lambda) + \Gamma * D_m(\lambda)$$

$$D(\lambda) = -(\lambda / c)(d^2 \mathrm{Re}[n_{eff}] / d\lambda^2)$$ ps/nm/km

Why Dispersion Control Necessary?

Case I: Optical Soliton



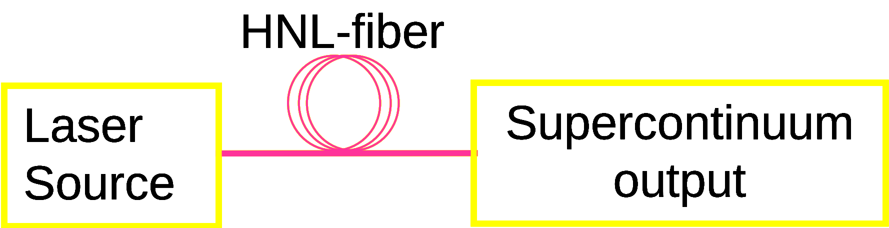


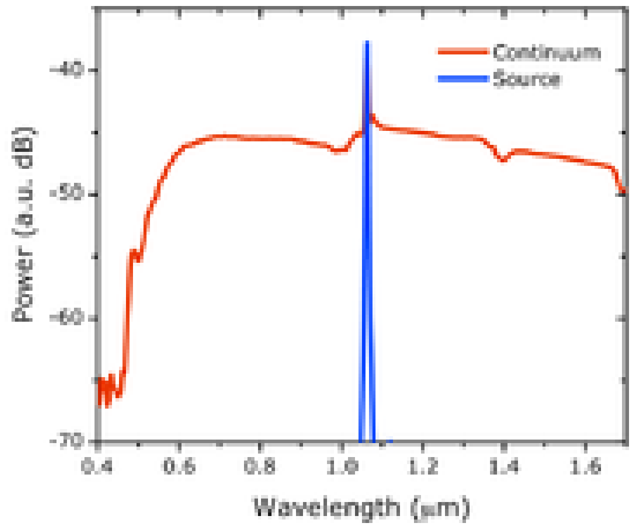
- Soliton pulse maintains its characteristics thought-out the length of transmission

- High/non-zero dispersion slope causes-
  - Instability to soliton systems
  - Destroy soliton pulse features

Why Dispersion Control Necessary?

Case II: Supercontinuum Source





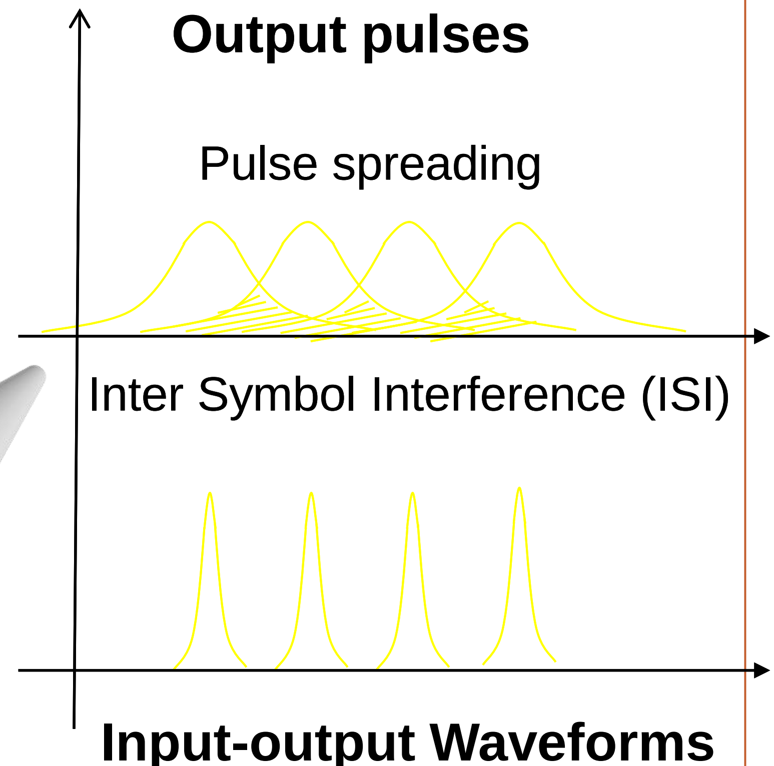
- Creation of broad visible spectrum by transmission of a short light pulse through a HNL fiber

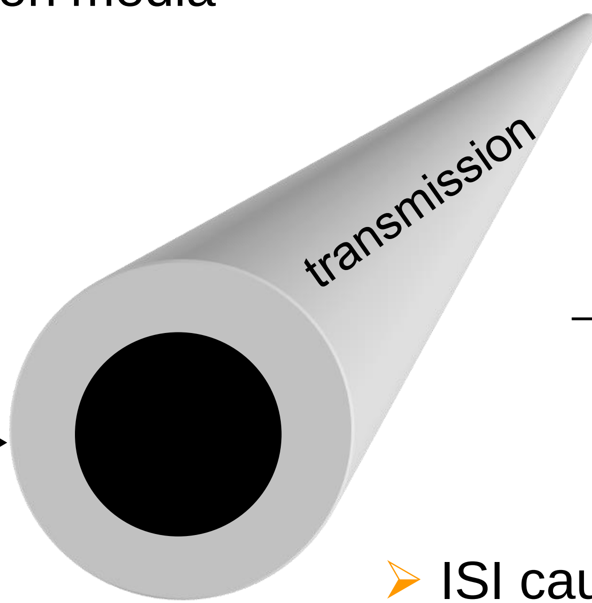
- High/non-zero dispersion slope eventually destroy-
  - Supercontinuum stability
  - Limits the bandwidth etc.

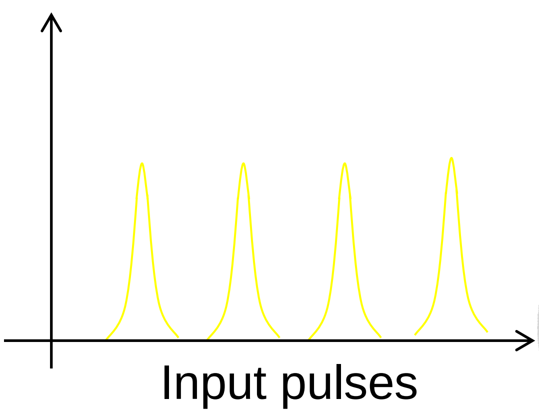
Why Dispersion Control Necessary?

Case III: WDM optical communication systems

- Dispersion is undesirable for communication media

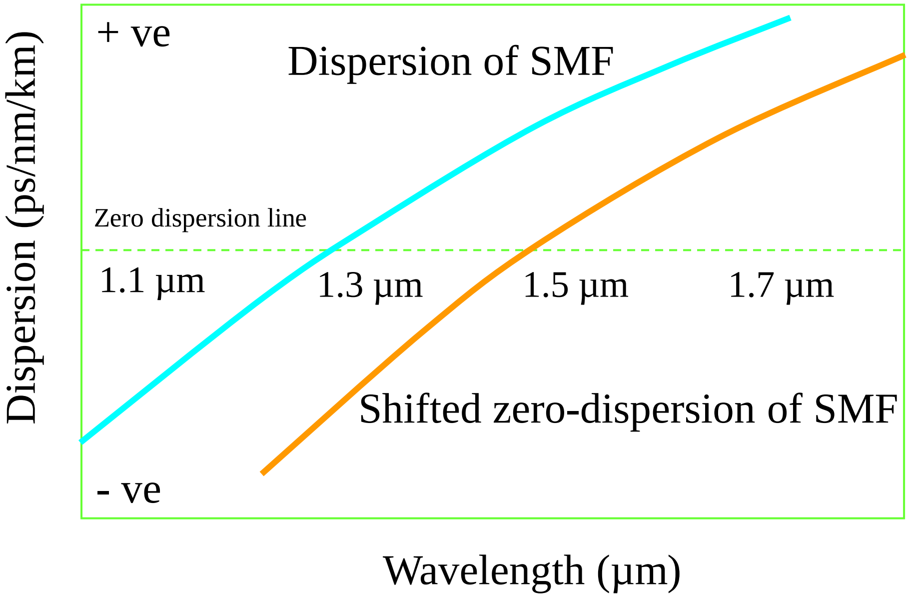






- ISI causes channel noise and bit errors

MOF's Dispersion Control Strategy

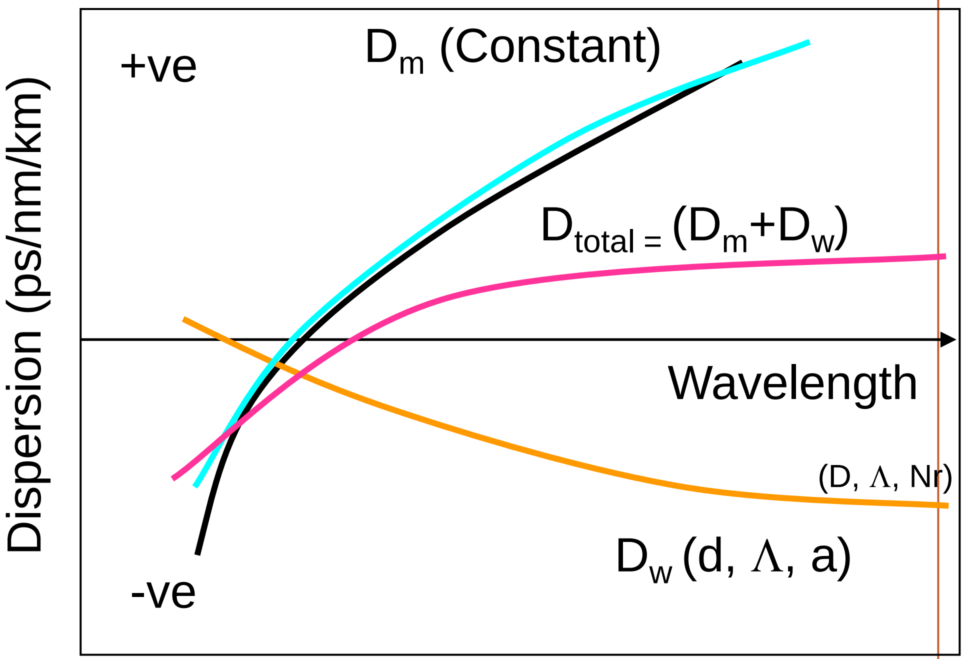


<u>COF:</u>

Flat-dispersion is not possible

<u>MOF:</u>

D_w strongly depends on waveguide parameters



Confinement Loss

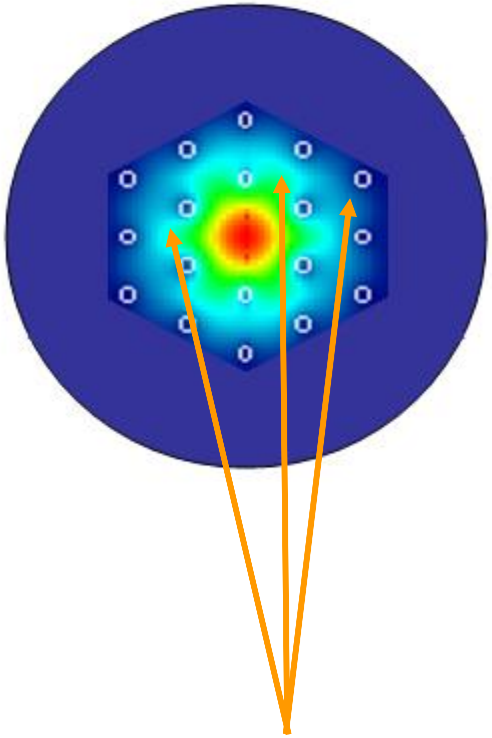
<u>Confinement loss</u>

- due to finite no of air-holes
- results in signal degradation along the channel

Confinement loss,

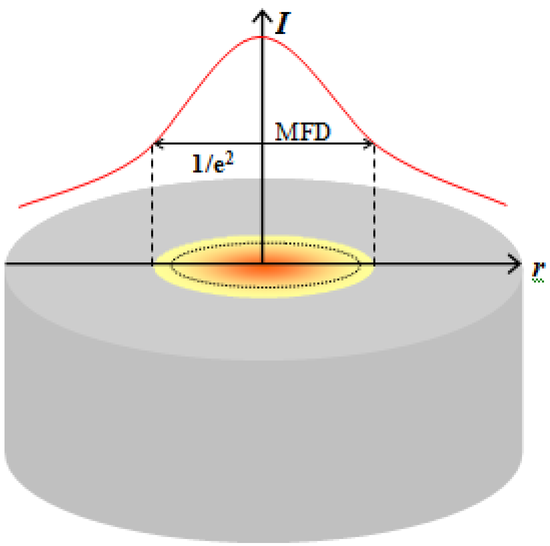
$$Lc = 8.686 \times k_0 \, \mathrm{Im}[n_{eff}] \quad \text{[dB/m]}$$

- $Im[n_{eff}]$ = Imaginary part of the effective refractive index,
- k_0 = Free space wave number = $2\pi/\lambda$, and
- λ = Wavelength



Field penetration toward cladding

Mode Area



Area of the effective core of PCFs where the intensity drops to 13.6% of the peak.

Effective area,

$$A_{eff} = \frac{\left[\iint |E^2| dxdy\right]^2}{\iint |E|^4 dxdy} \quad [\mu m^2]$$

Where, E is the calculated electric field by solving an eigenvalue problem derived from Maxwell's equations

Nonlinear coefficient,

$\gamma = 2\pi(n_2/Aeff)$ $W^{-1}km^{-1}$

Where, n_2 = nonlinear refractive index = 2.3×10^{-20} m^2/W for silica PCF

Single & Multimode Operation

<u>The V parameter for PCF:</u>

$$V_{eff} = (k\Lambda F^{1/2} / \lambda)(n_o^{\ 2} - n_a^{\ 2})^{1/2}$$

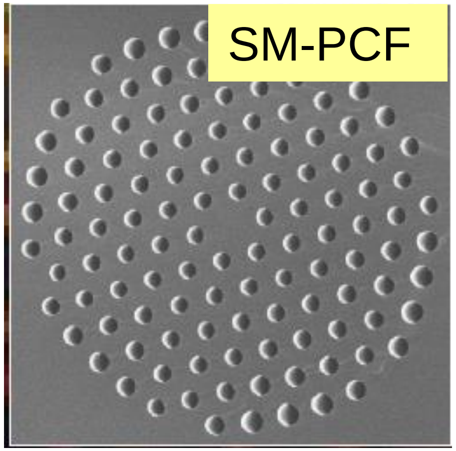
Wave number = 2π/λ

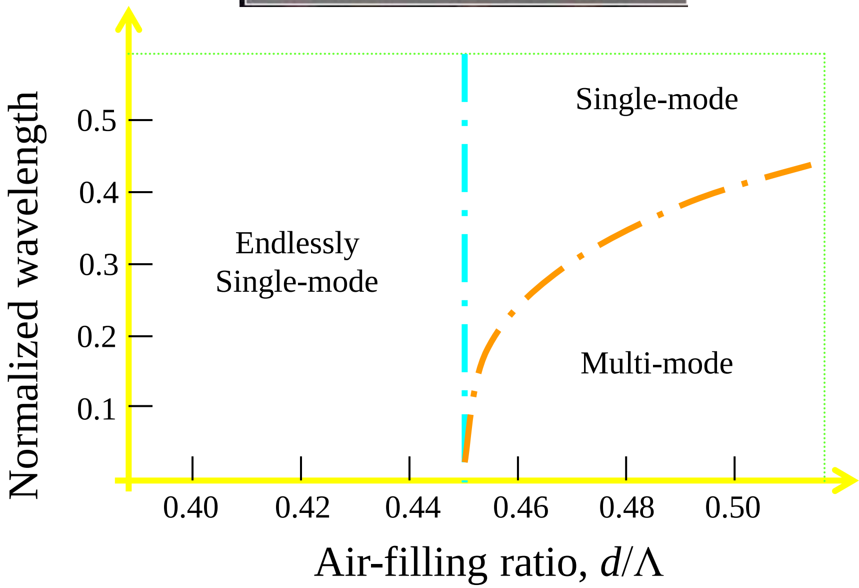
The pitch

Air-filling fraction

Core index

Index of air

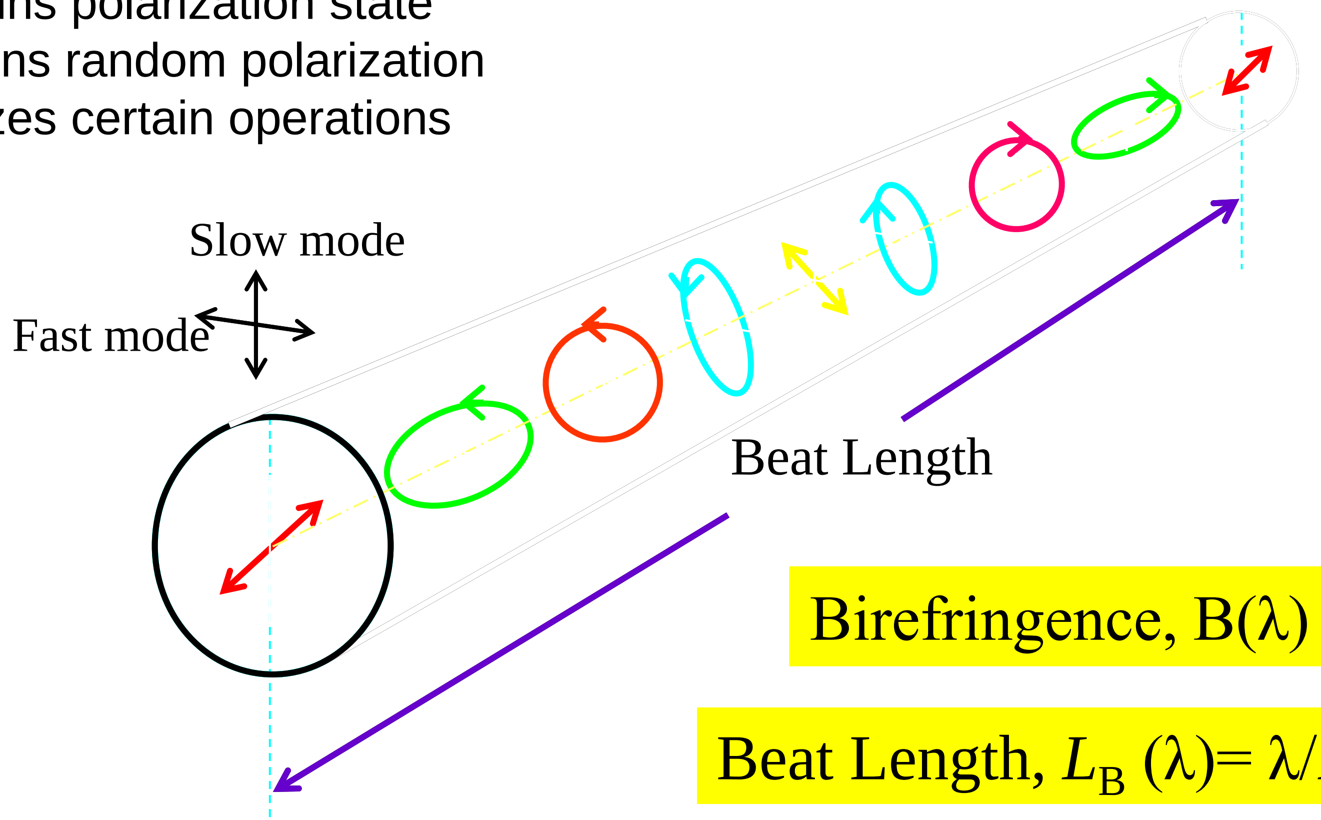




If V_{eff}<2.40, the PCF is single mode otherwise multi-mode

Birefringence

- Maintains polarization state
- Weakens random polarization
- Stabilizes certain operations



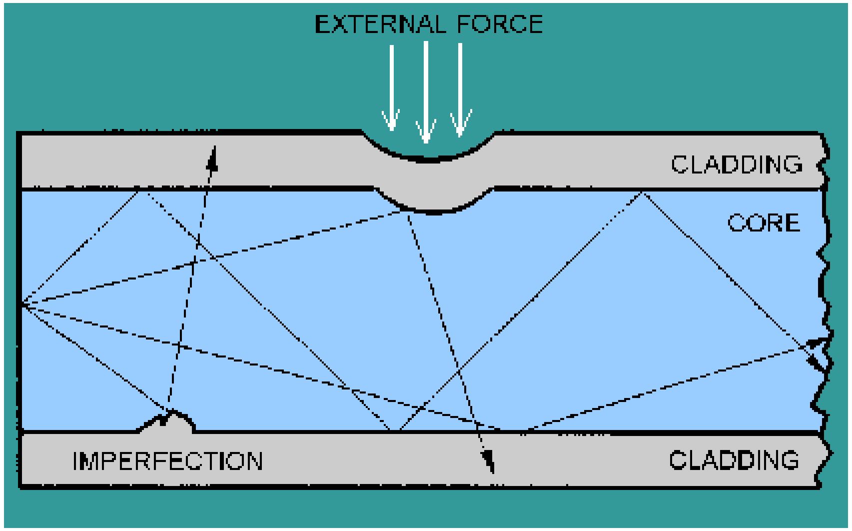
Birefringence, $B(\lambda) = |n_x - n_y|$

Beat Length, $L_B(\lambda) = \lambda / B(\lambda)$

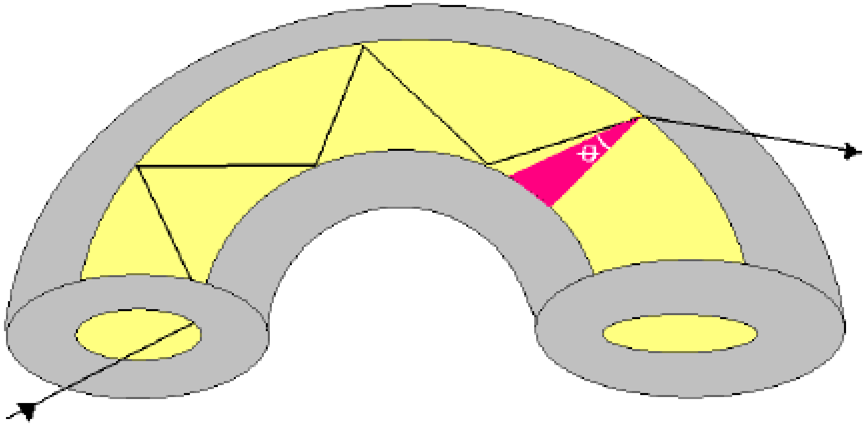
Where, n is the refractive index, λ is the wavelength, and x, y denote polarization axis.

Bending Loss and Splice Loss

- Macrobend loss
- Microbend loss



Microbend loss



Macrobend loss.

Splice Loss

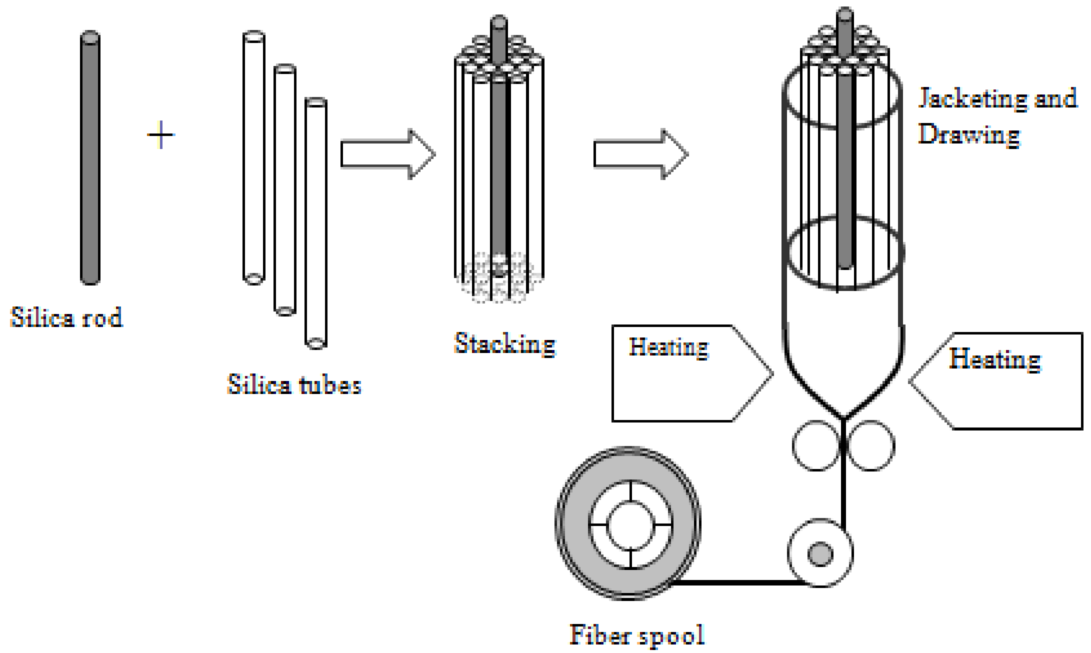
- Splice Loss between two fibers-

$$L_s = -20\log_{10}[(2w_{SMF}w_{PCF})/(w_{SMF}^2 + w_{PCF}^2)]$$

Where

w_{SMF} and w_{SMF} are the MFDs of the SMFs and the PCFs, respectively.

Stack and Draw Method



Transmission Constraints

- Attenuation
  - Absorption (wavelength selective)
    - UV absorption
    - IR absorption
  - Scattering
    - Rayleigh scattering (elastic, negligible energy x-fer)
    - Brillouin scattering (inelastic)
    - Raman Scattering (inelastic)
- Bandwidth
- Cost
- Interference & Noise

Attenuation: Absorption and Scattering

- **Rayleigh scattering -** small particle compared to wavelength of light
- **Brillouin scattering -** when light in a medium interacts with time-dependent optical density variations and changes its energy (frequency) and path.
- **Raman scattering** – photon scattered from an atom , some scattered with different frequency and energy from that of the incident photon.

Light Source

- LED, LD, etc.

Light Detectors

- PD, APD, PIN

- EDFA

Regerative Repeater

Optical Isolator

- Faraday rotation

Optical Modulators

- Analog & Digital

Splice & Connectors

Nonlinear Effects

- SPM, XPM, FWM,
- Linear effect- Pockel's effect
- Nonlinear effect- Kerr effect

Multiplexing Techniques

- WDM, DWDM

Optical Networks

- LAN, SONET, PON, AON