Optical Fiber Communications-BECE308L

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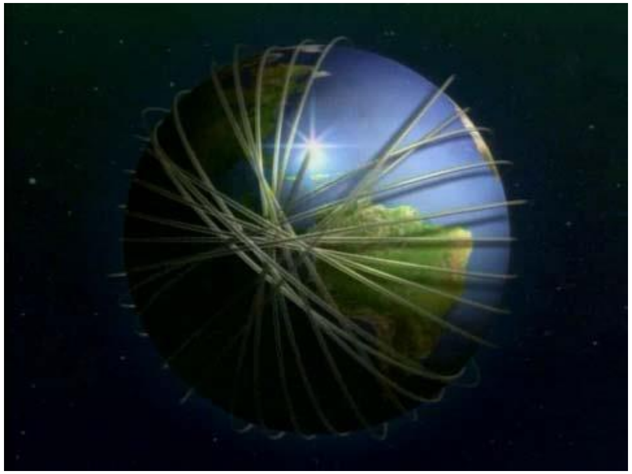


BECE308L-Optical Fiber Communications-

Aim & Objectives:

- To understand the principles of optical fibers and their signal degradation.
- To familiarize with the fundamentals of optical sources and detectors used in communications.
- To learn WDM techniques and its components in contemporary optical communication systems

Course outcome

- List the fundamental optical laws, structures and waveguides
- Comprehend the various signal degradation in the fiber optical communication.
- Design the optical transmitters and receivers and evaluate their performances.
- Estimate the system requirements for point to point communication.
- Examine the significance of WDM techniques and their applications.
- Comprehend and analyse the performance of the various optical amplifiers.

Syllabus

1. **Optical Fiber: Structures, Waveguides**
2. **Signal Degradation**
3. **Optical Transmitters**
4. **Optical Receivers**
5. **Digital links and Measurements**
6. **WDM Concepts and Components**
7. **Optical Amplifiers**
8. **Optical Contemporary Issues**

Text books and Reference Book

Text Books:

- **Gerd Keiser, "Optical Fiber Communications" 2013, 5th Edition, McGraw-Hill, India.**

Reference Books

- **Conway, E., Optical Fiber Communications Principles and Practice, 2018, 1st Edition, ED-TECH Press, United Kingdom**
- **Singal, T. L. Optical Fiber Communications: Principles and Applications, 2017, Cambridge University Press, India**
- **Optical Networks: A Practical Perspective, 3rd Edition 3rd Edition by Rajiv Ramaswami , Kumar Sivarajan, Galen Sasaki**
- **John M Senior, "Optical Fiber Communication – principle and practices", 2014, 3rd Edition, PHI, India**
- **C. Siva Ram Murthy, Mohan Gurusamy, "WDM optical networks concepts design and algorithms", 2015, 1st Edition, Pearson Education, India.**
- **G. P. Agrawal, "Nonlinear Fiber Optics", 2012, 5th Edition, Academic Press, US**

Introduction to Communication

A little bit of history

• The Morse telegraph was introduced in the 1860‘s.

Transmission rate: ~1bit/s

Distance: Due to the application of relay stations: 1000km

• Invention of the telephone 1876.

• First coaxial cable system 1940 with the capability to transmit 300 voice channels.

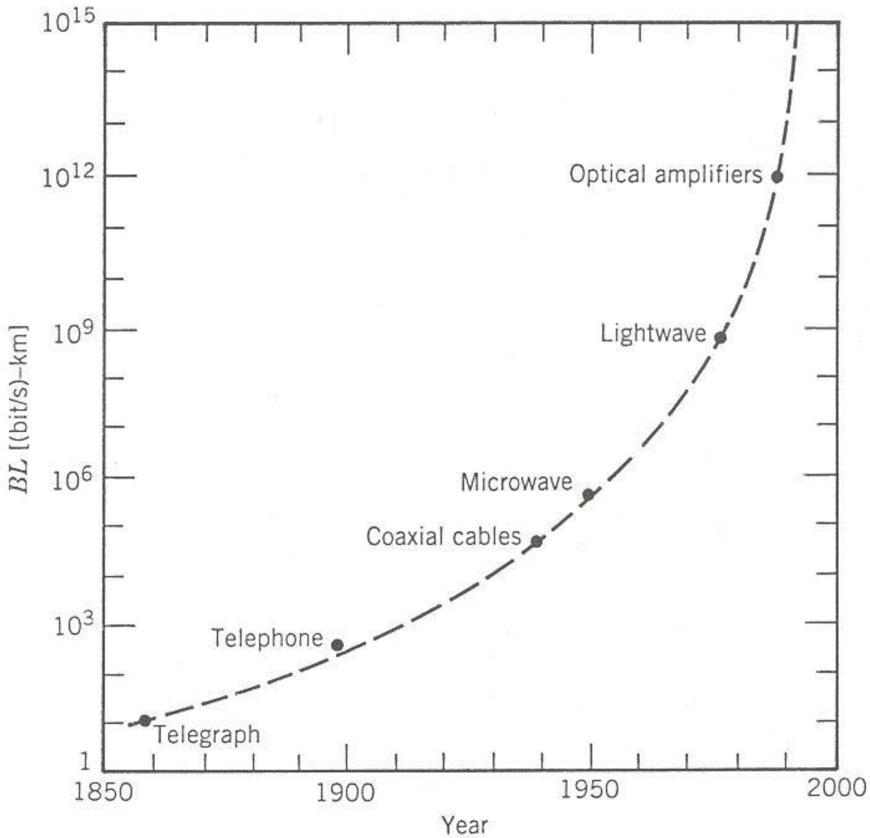
• The first microwave system was put into service in 1948 with a carrier frequency of 4GHz. Coaxial and microwave systems were operating at 100Mbit/s. High speed coaxial systems need repeater spacing of ~1km.

- The first installed optical fiber in late1970were used for telephony signals at about 6Mbs/seconds over distance around 10km

- In 1980 data rate increased beyond terabits per **seconds**

Introduction to Communication

Need for Fiber Optical Communication

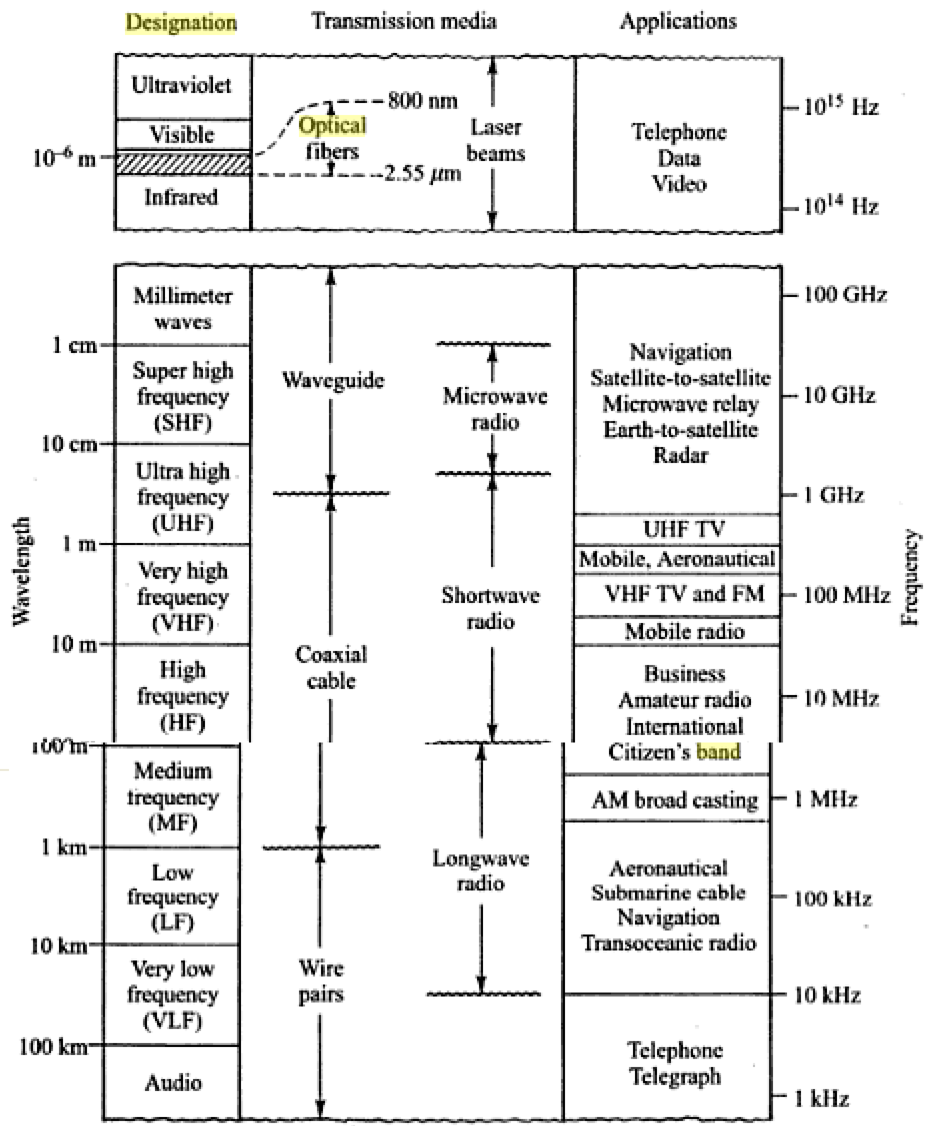


Increase of the bit rate distance product BL for different communication Technologies over time.

Ref.: G.P. Agrawal, Fiber-Optic Comm. systems

A figure of merit of communication systems is the bit rate – distance product,BL, where B is the bit rate and L is the repeater spacing.

Introduction to Optical Communication33



The regions of the electromagnetic spectrum used for radio and optical fiber communications. (Used with permission from A. B. Carlson, Communication Systems, © 1986, McGraw-Hill Book Company.)

Table 1.1 *Spectral band designations used in optical fiber communications*

Name	*Designation*	*Spectrum (nm)*	*Origin of Name*
Original band	O-band	1260 to 1360	Original (first) region used for single-mode fiber links
Extended band	E-band	1360 to 1460	Link use can extend into this region for fibers with low water content
Short band	S-band	1460 to 1530	Wavelengths are shorter than the C-band but higher than the E-band
Conventional band	C-band	1530 to 1565	Wavelength region used by a conventional EDFA
Long band	L-band	1565 to 1625	Gain decreases steadily to 1 at 1625 nm in this longer wavelength band
Ultra-long band	U-band	1625 to 1675	Region beyond the response capability of an EDFA

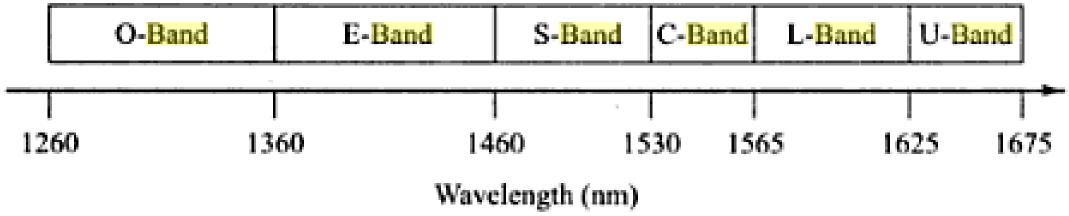
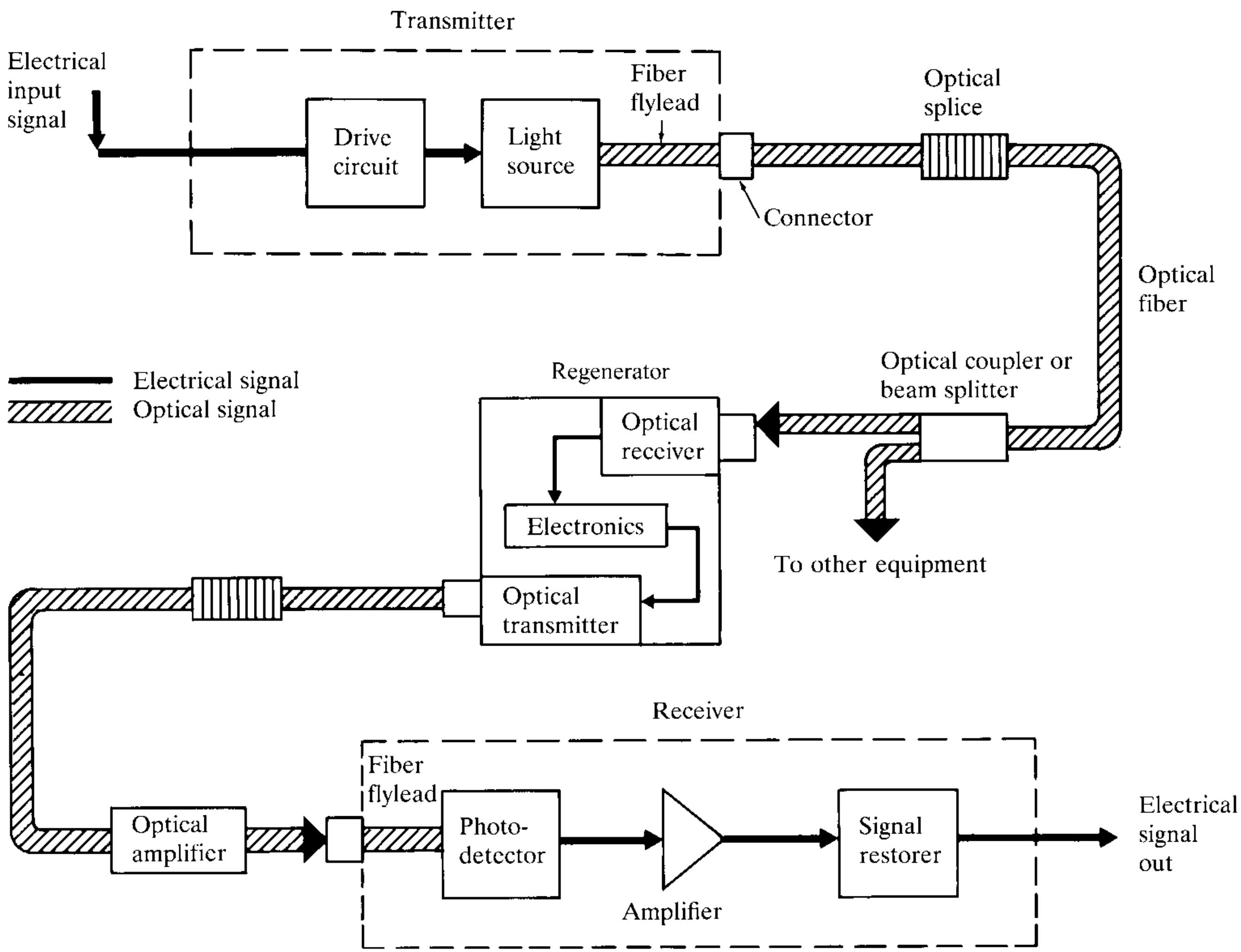


Fig. 1.3 *Designations of spectral bands used for optical fiber communications*

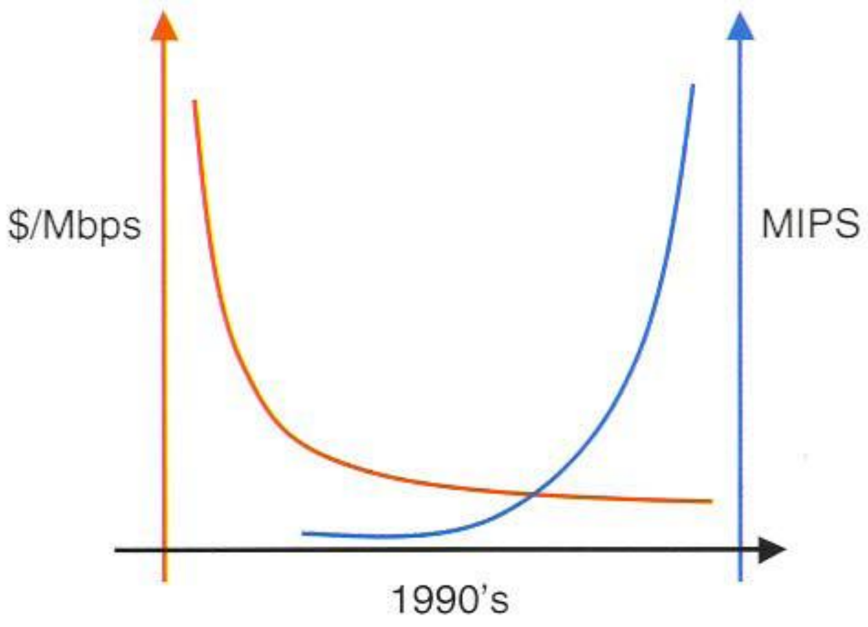
Advantages of optical fiber

1. Long Distance
2. Large information capacity
3. Small size and light weight
4. Immunity to Electrical Interferene
5. Enhanced Safety
6. Increased Signal security

Fig. 1-5: Major elements of an optical fiber link



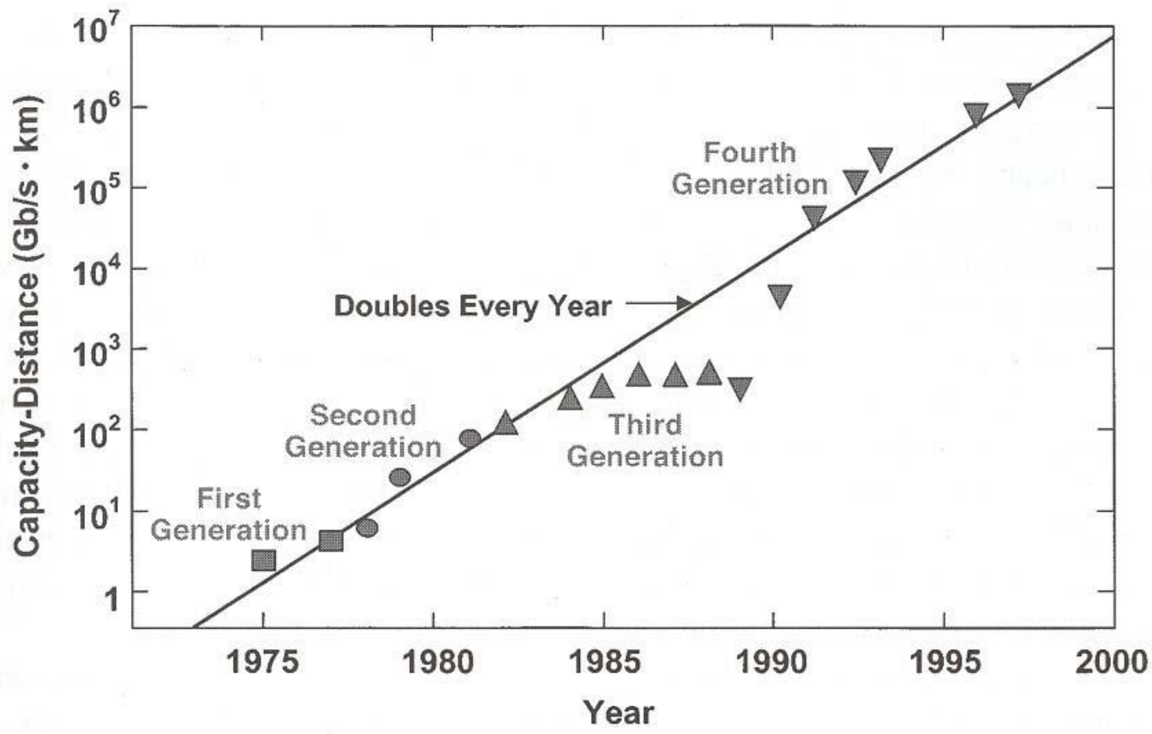
Need for Fiber Optical Communication



- Increase of the bandwidth and decreases of the cost per transmitted bit for optical communication systems during the 1990‘s.

Ref.: S. Kartalopoulos, WDWM Netorsk, Devices and Technology

Need for Fiber Optical Communication



Bit-rate distance product (BL) for different generations of optical communication systems.

Ref.: G.P. Agrawal,

Fiber-optic Communication

systems

The increase of the capacity-distance product can be explained by the four major innovations.

Evolution of Light wave systems

1. Generation: The development of low-loss fibers and semiconductor lasers (GaAs) in the 1970's.

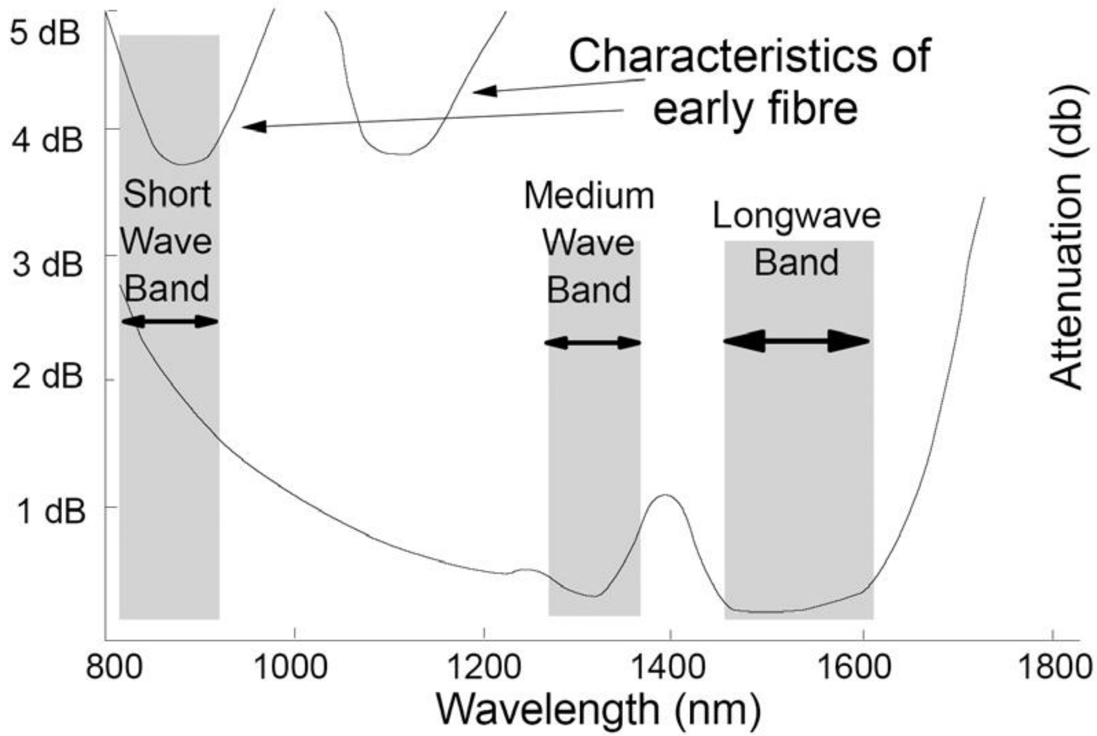
A Gallium Aresenide (GaAs) laser operates at a wavelength of 0.8 μ m. The optical communication systems allowed a bit rate of 45Mbit/s and repeater spacing of 10km.

Example of a laser diode.

(Ref.: Infineon)

Evolution of Lightwave systems

2. Generation: The repeater spacing could be increased by operating the lightwave system at 1.3 μ m. The attenuation of the optical fiber drops from 2-3dB/km at 0.8 μ m down to 0.4dB/km at 1.3 μ m. Silica fibers have a local minima at 1.3 μ m.

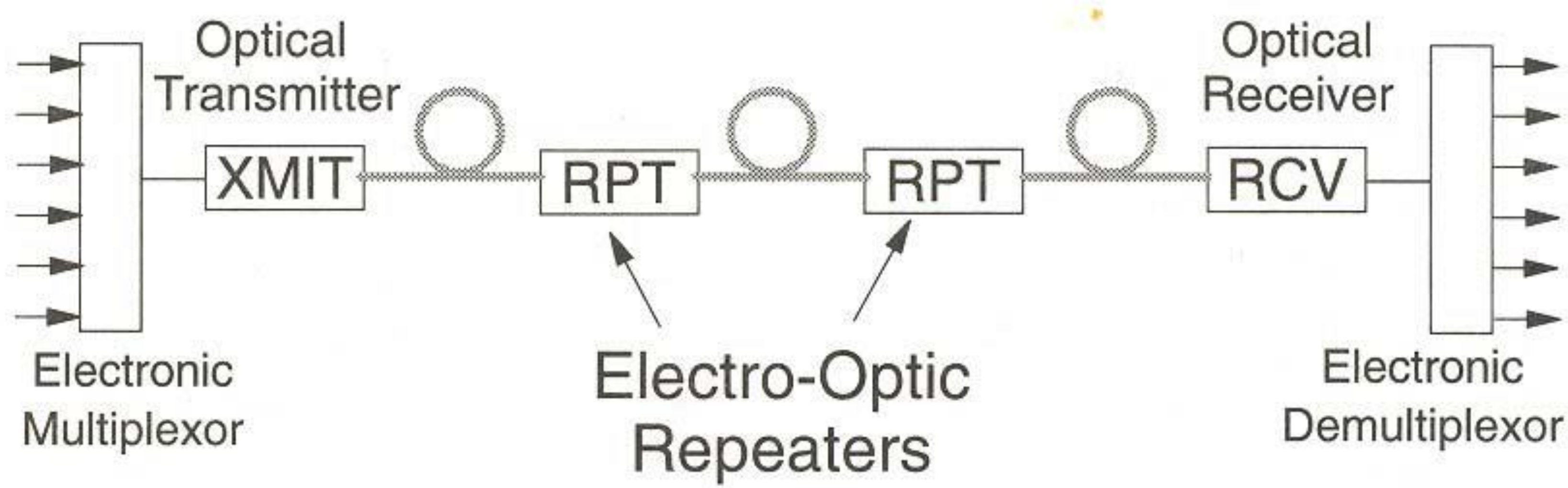


2. Generation: The transition from 0.8 μ m to 1.3 μ m leads to the 2nd Generation of lightwave systems. The bit rate- distance product can be further increased by using single mode fibers instead of multi-mode fibers.

Single mode fibers have a distinctly lower dispersion than multi mode fibers.

Lasers are needed which emit light at 1.3 μ m.

3. Generation: Silica fibers have an absolute minima at 1.55 μ m. The attenuation of a fiber is reduced to 0.2dB/km. Dispersion at a wavelength of 1.55 μ m complicates the realization of lightwave systems. The dispersion could be overcome by a dispersion-shifted fibers and by the use of lasers, which operate only at single longitudinal modes. A bit rate of 4Gbit/s over a distance of 100km was transmitted in the mid 1980‘s.

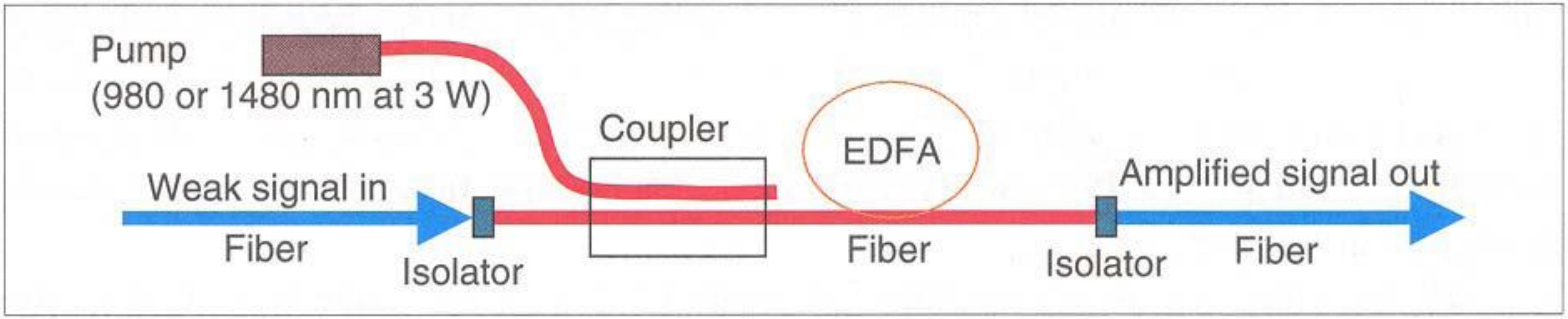


Traditional long distance single channel fiber transmission system.

Ref.: H. J.R. Dutton, Understanding optical communications

3. Generation: The major disadvantage of the 3. Generation optical communication system is the fact that the signals are regenerated by electrical means. The optical signal is transferred to an electrical signal,the signal is regenerated and amplified before the signal is again transferred to an optical fiber.

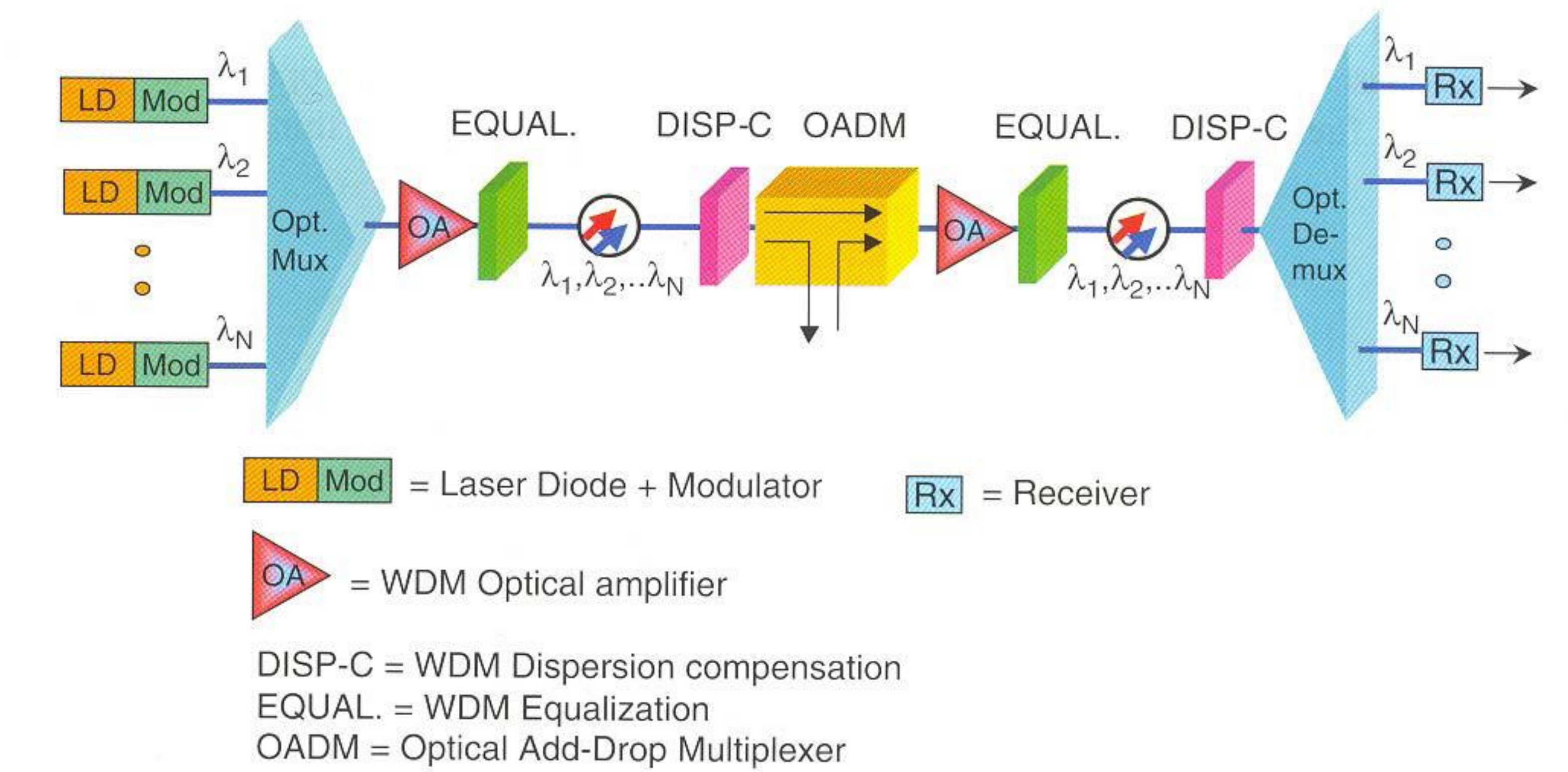
4. **Generation:** The development of the optical amplifier lead to the 4. Generation of optical communication systems.



Schematic sketch of an erbium-doped fiber amplifier (EDFA).

Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology

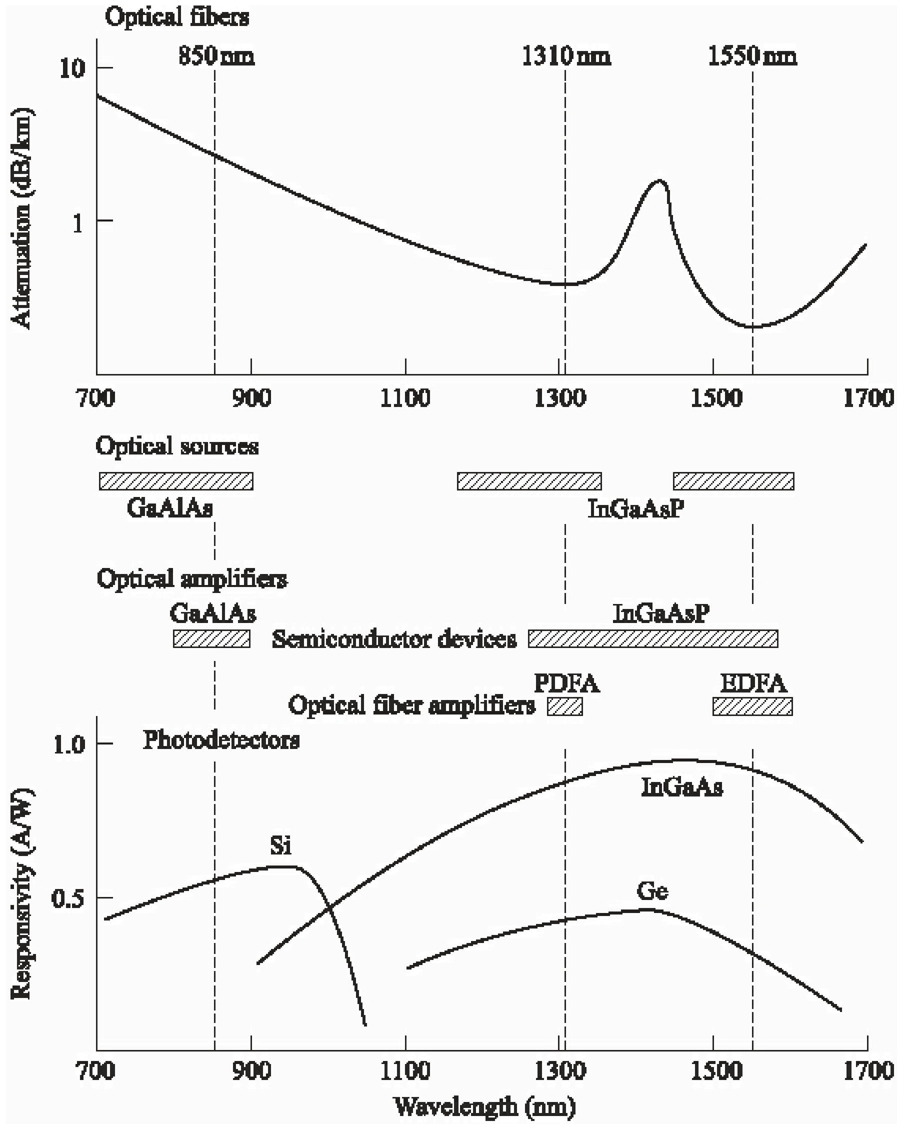
Evolution of Lightwave systems



State of the Art optical communication system: Dense Wavelength Division Multiplex (DWDM) in combination of optical amplifiers. The capacity of optical communication systems doubles every 6 months. Bit rates of 10Tbit/s were realized by 2001.

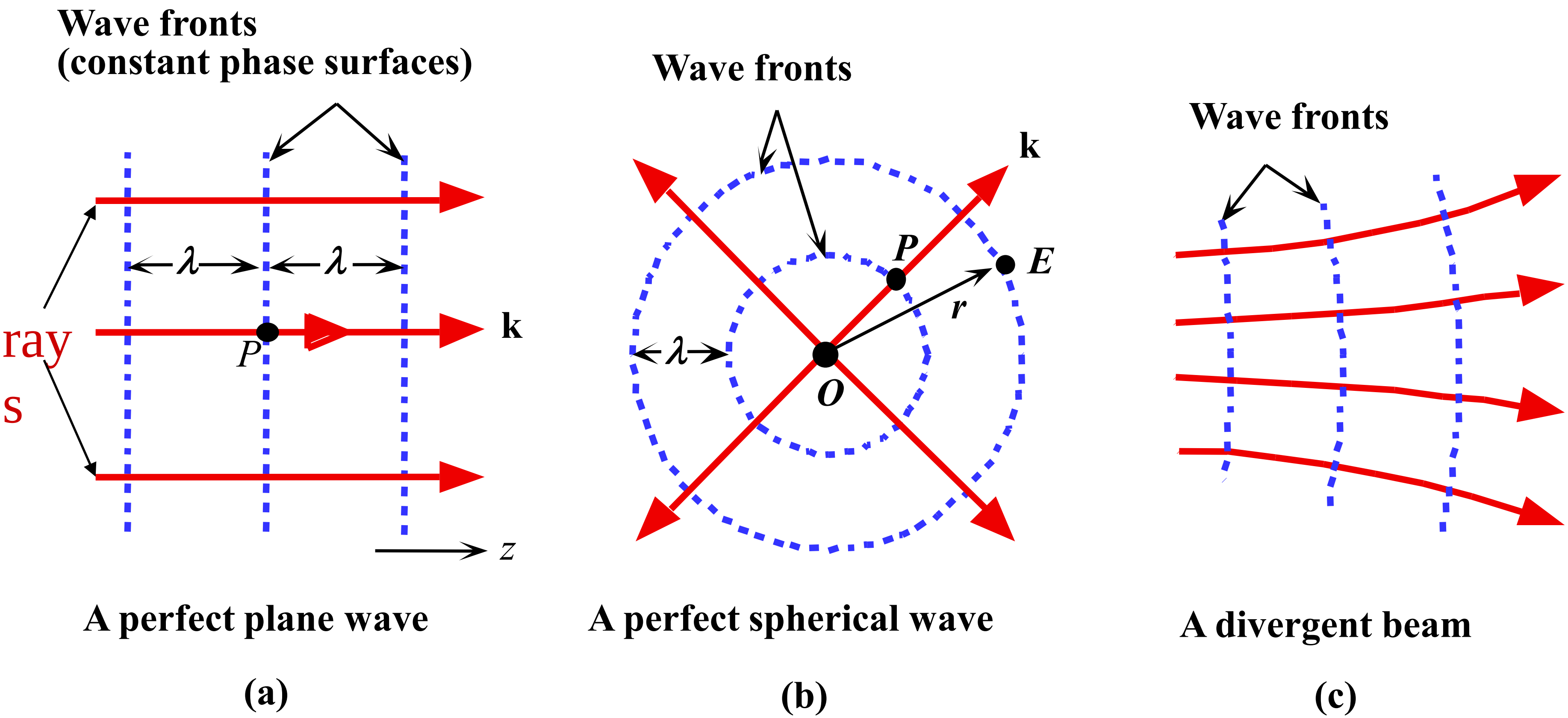
Ref.: S. Kartalopoulos, WDWM Networks, Devices and Technology

Fig. 1-3: Operating ranges of components



Theory of light

- Quantum theory ray optics
- Wave theory
- Electromagnetic wave
- In engineering discipline, we should choose the appropriate & easiest physical theory that can handle our problems



Examples of possible EM waves

Refractive Index

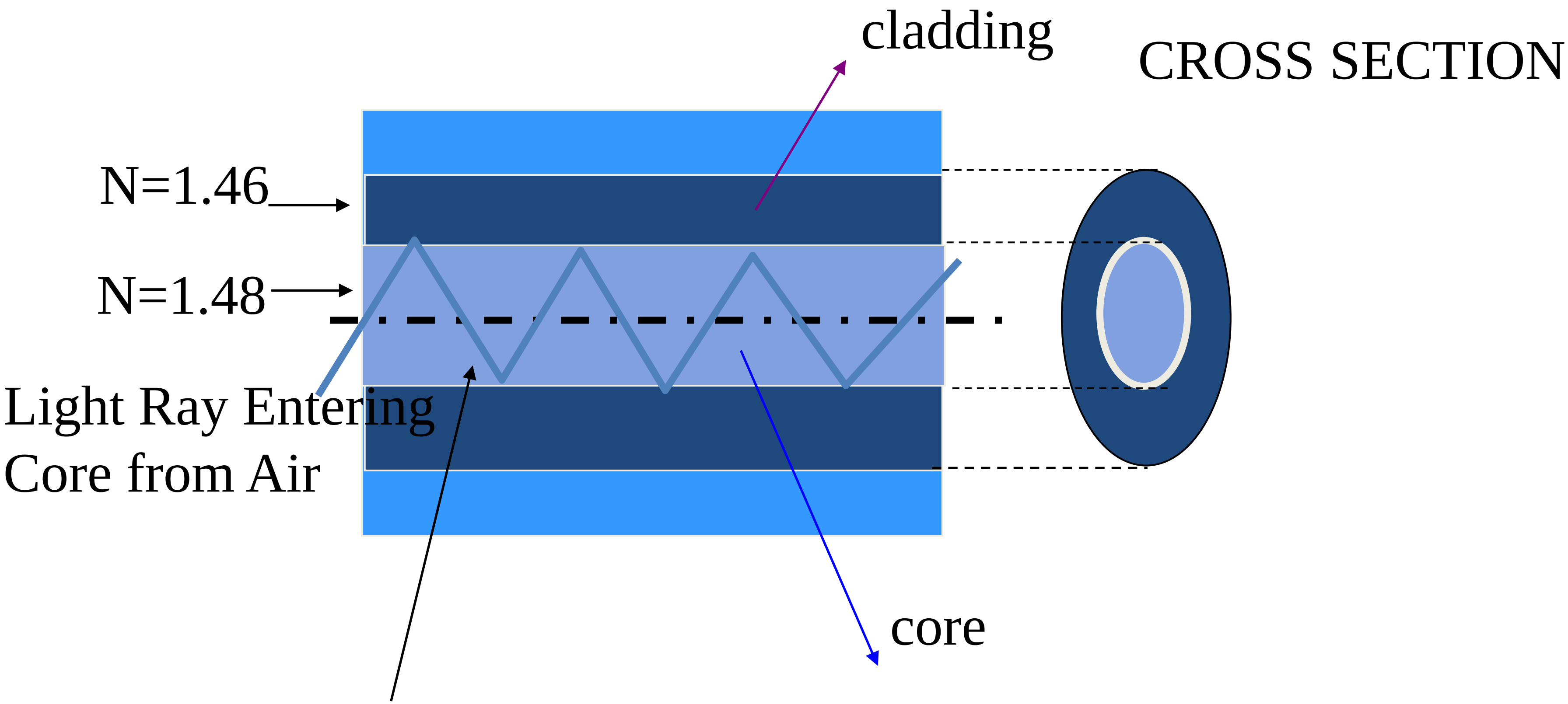
The ratio of the speed of light in a vacuum to its speed in a specific medium.

$$n = \frac{c}{v}$$

/here,

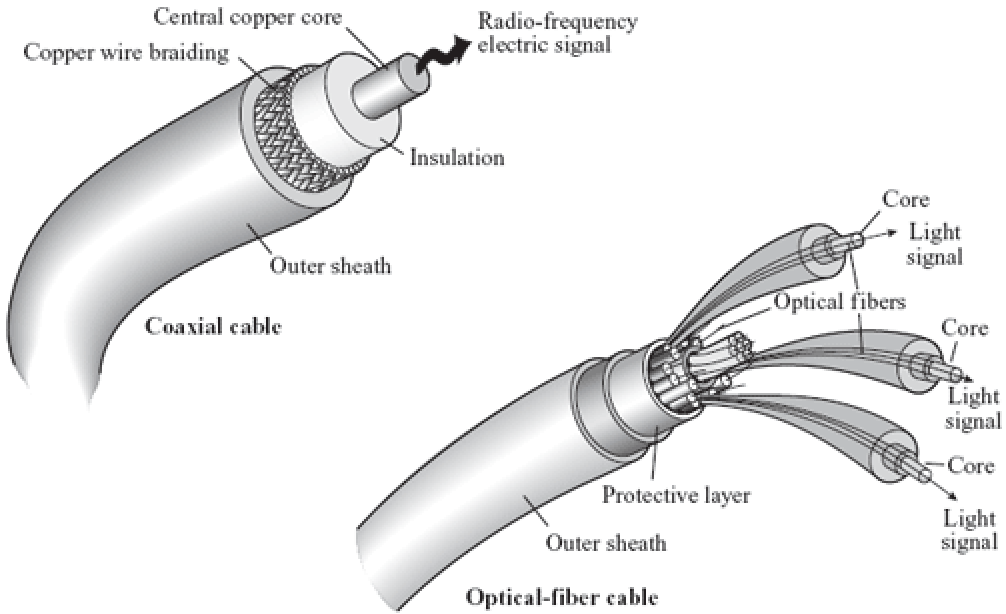
- n is the refractive index
- c is the velocity of light in a vacuum (3×10^8 m/s)
- v is the velocity of light in a substance

How the light is transmitted



Light is propagated by Total internal reflection

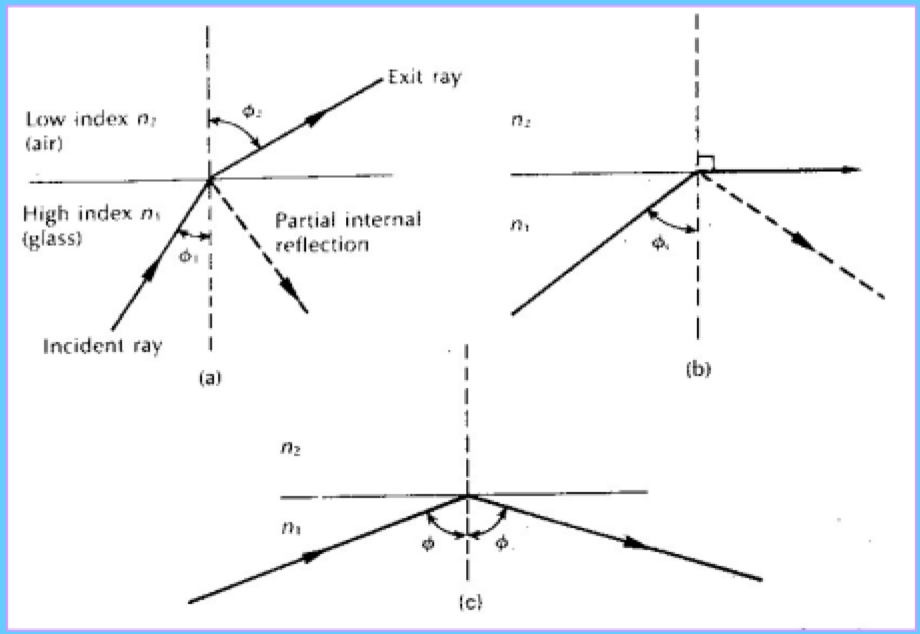
Fibre



Central copper core
Copper wire braiding
Radio-frequency electric signal
Insulation
Outer sheath
Coaxial cable
Core
Light signal
Optical fibers
Core
Light signal
Core
Light signal
Protective layer
Outer sheath
Optical-fiber cable

Total Internal Reflection

- Light entering from glass-air interface ($n_1 > n_2$) - **Refraction**



Snell's Law:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

or $$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

$$\Rightarrow \phi_2 > \phi_1$$

Limiting Case : At $\phi_2 = 90^o$, refracted ray moves parallel to interface between dielectrics and $\phi_1 < 90^o$

Angle of incidence, $\phi_1 \to \phi_C$; **critical angle**

Total Internal Reflection

e.g. Under what condition will light be trapped inside the fiber core?

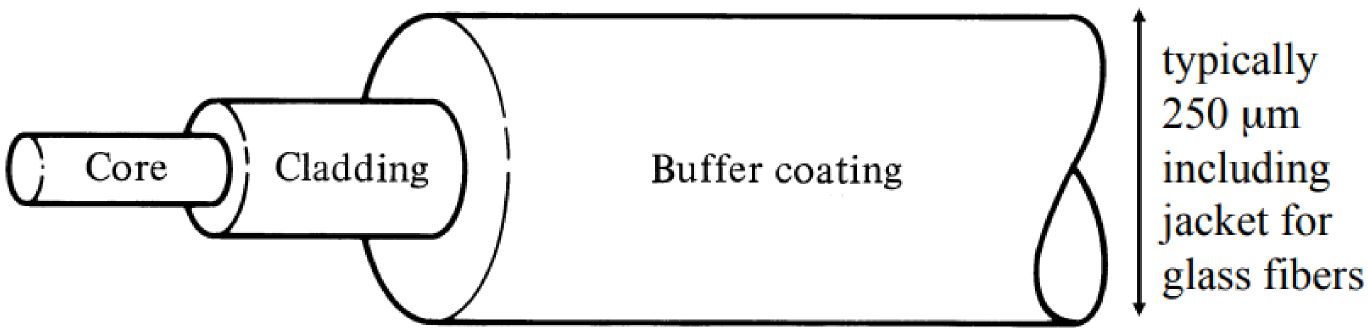
$n_1 = 1.46$; $n_2 = 1.44$

$$\theta > \theta_c$$

$$\theta_c = \sin^{-1}(n_2/n_1) = \sin^{-1}(1.44/1.46) = 80.5^o$$

Optical Fiber Structure

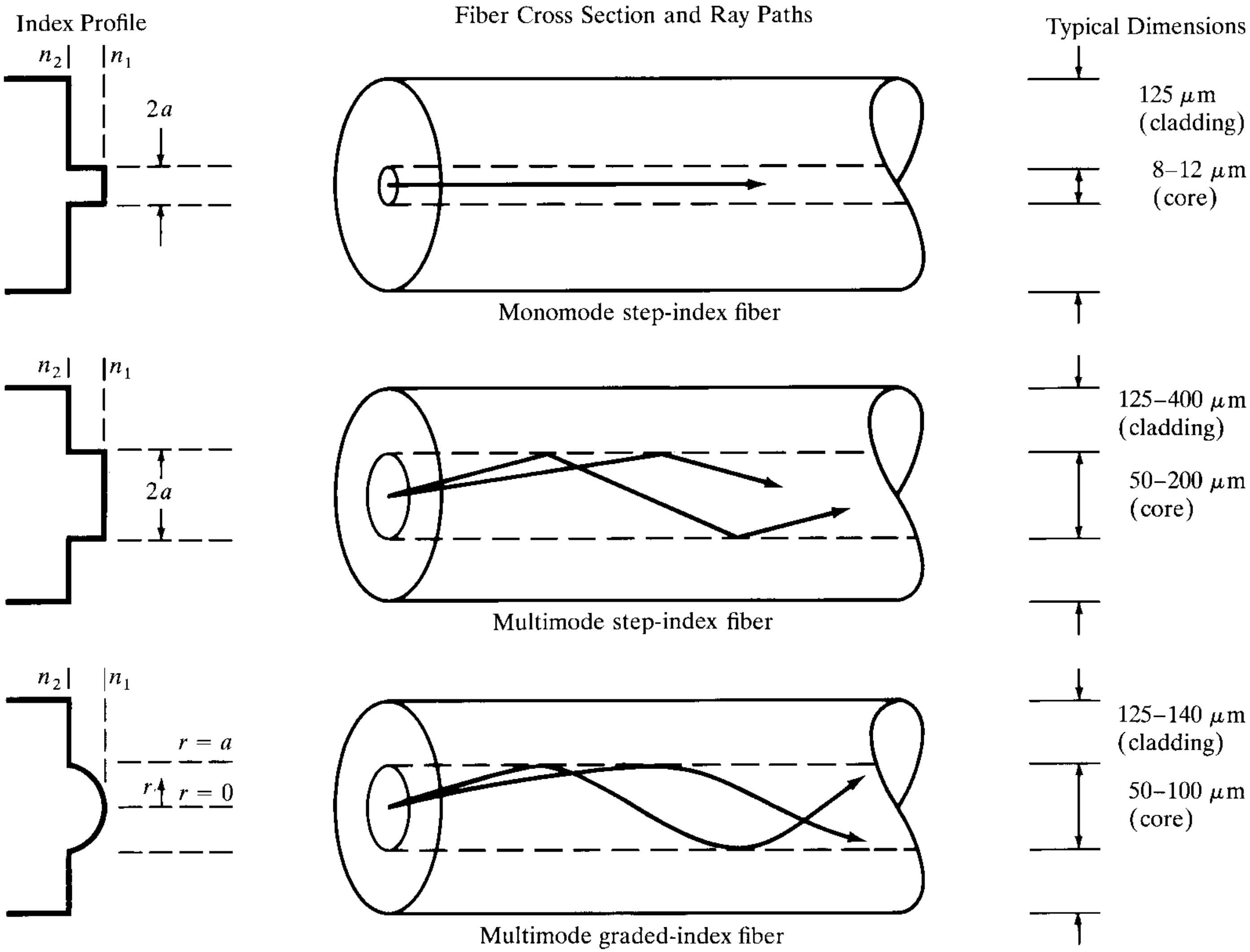
- A typical bare fiber consists of a core, a cladding, and a polymer jacket (buffer coating).



- The polymer coating is the first line of mechanical protection.

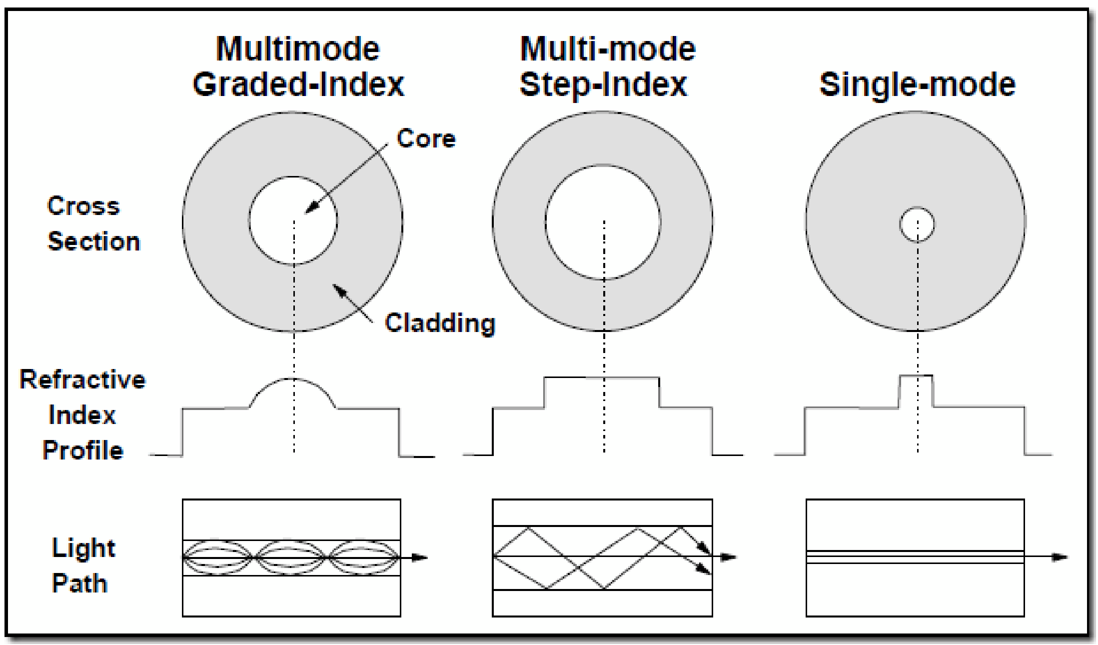
- The coating also reduces the internal reflection at the cladding, so light is only guided by the core.

Different Structures of Optical Fiber

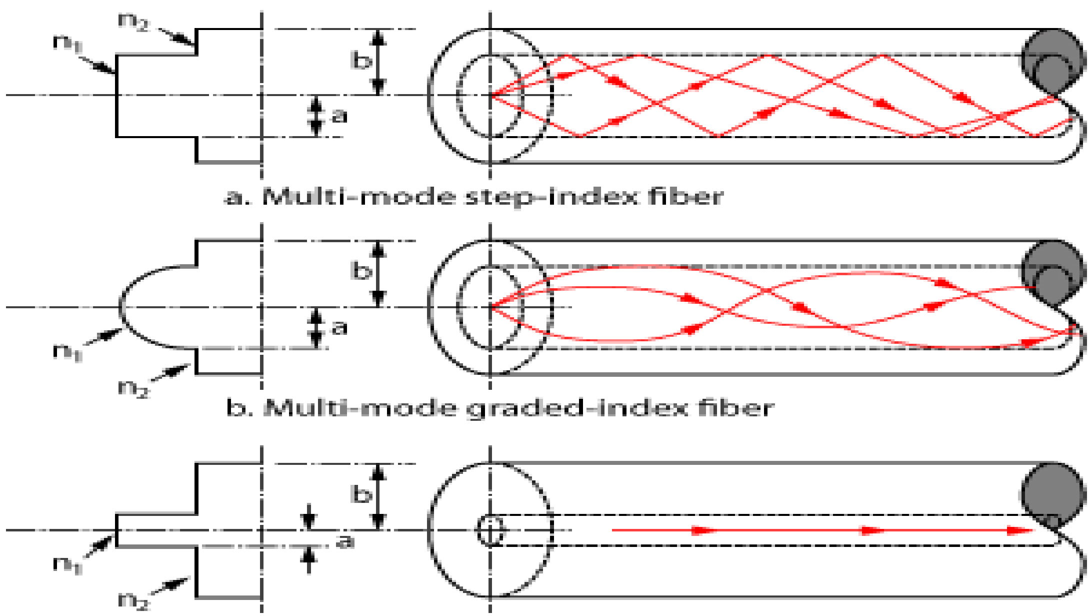


Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Cross section of step index and graded index fiber



Fiber Types



a. Multi-mode step-index fiber

b. Multi-mode graded-index fiber

c. Single-mode step-index fiber

Graded-Index Fibre structure

- Power law for refractive-index variation

$$n(r) = \begin{cases} n_1 \left[1 - 2\Delta \left(\frac{r}{a} \right)^{\alpha} \right]^{1/2} & 0 \le r \le a \\ n_1 (1 - 2\Delta)^{1/2} \approx n_1 (1 - \Delta) = n_2 & r \ge a \end{cases}$$

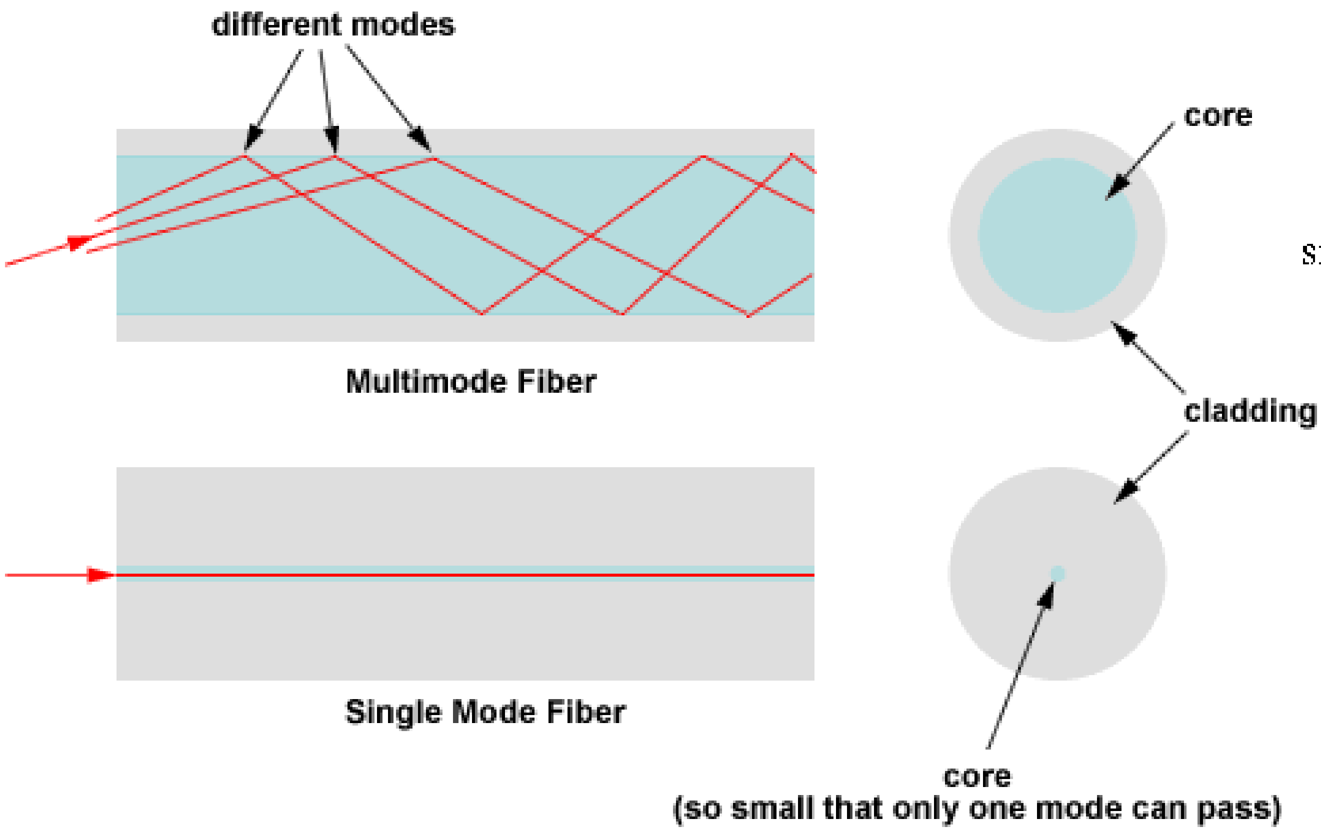
where

•*a* is the core radius

•n_1 is the refractive index of the core

•n_2 is the refractive index of the cladding

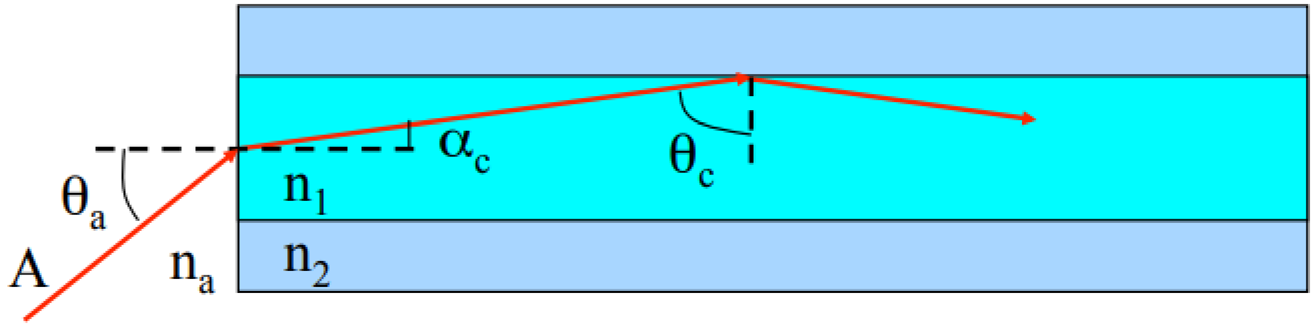
•α defines the shape of the index profile



$$\sin \phi_c = \frac{n_2}{n_1}$$

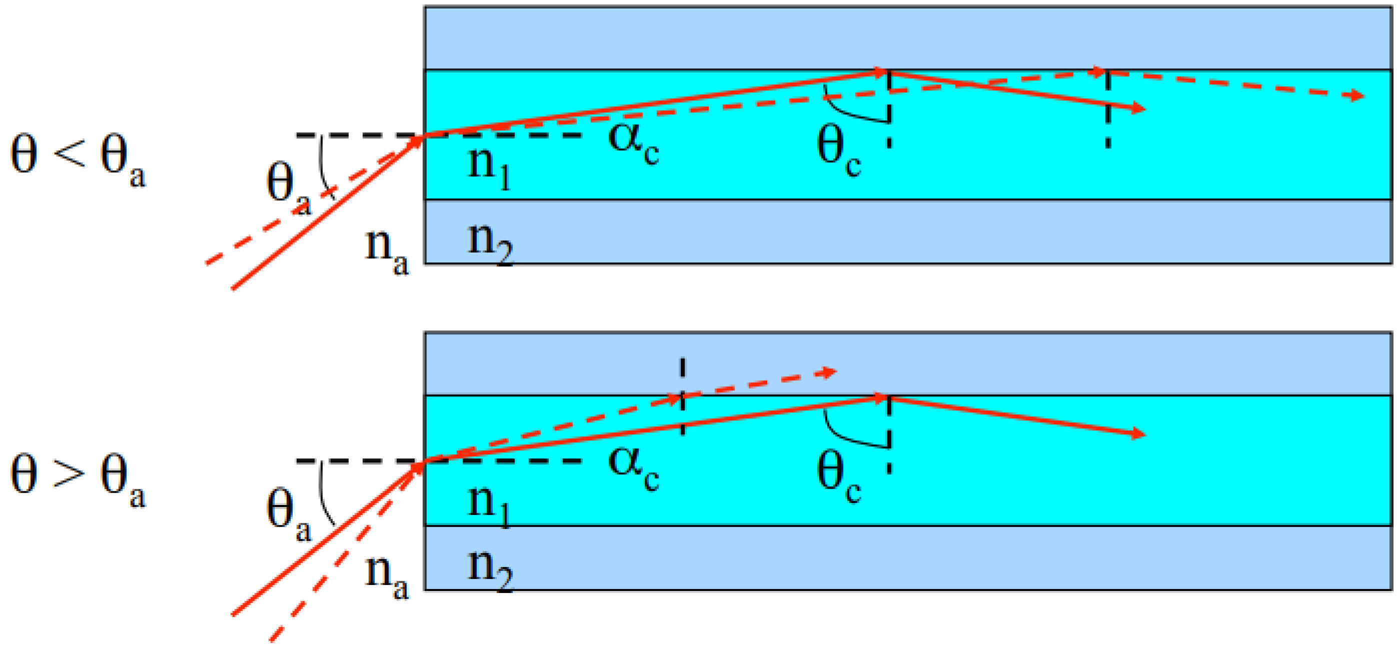
Acceptance angle

- Only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than θ_c) at the core-cladding interface are transmitted by total internal reflection.



- Ray A incident at the critical angle θ_c at the core-cladding interface enters the fiber core at an angle θ_a to the fiber axis, and is refracted at the air-core interface.

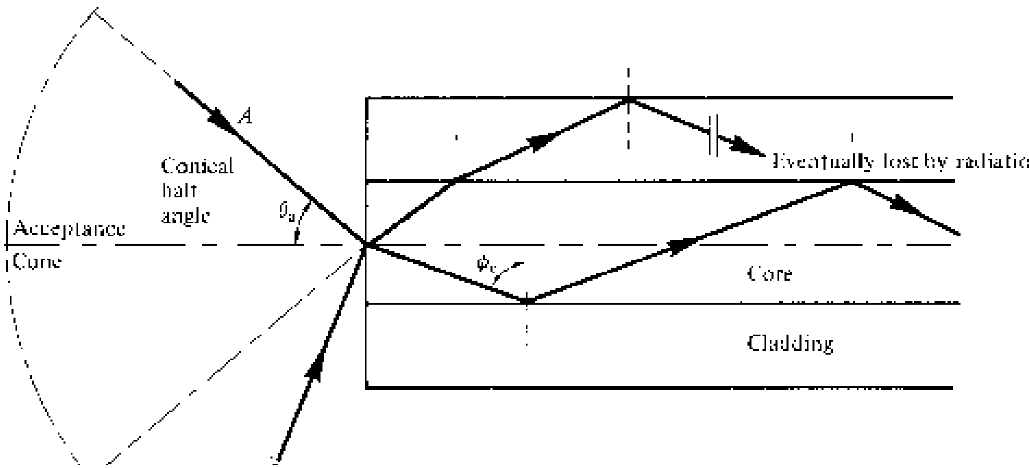
Acceptance angle

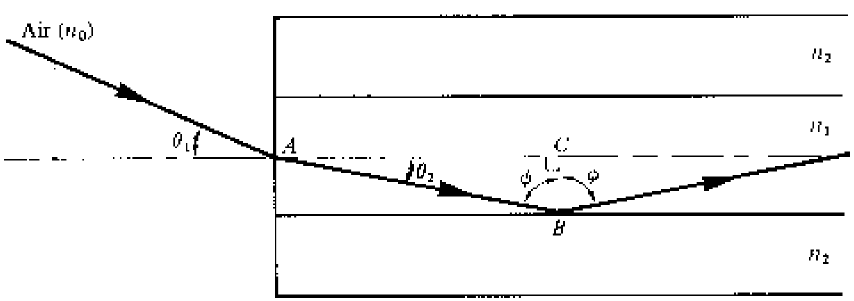


- Any rays which are incident into the fiber core at an angle > θ_a have an incident angle less than θ_c at the core-cladding interface.

These rays will NOT be totally internal reflected, thus eventually loss to radiation (at the cladding-jacket interface).

Acceptance angle





$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$

$$\phi = \frac{\pi}{2} - \theta_2$$

$$n_0 \sin \theta_1 = n_1 \cos \phi$$

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{\frac{1}{2}}$$

$$\sin \phi_c = \frac{n_2}{n_1}$$

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$\mathrm{NA} = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

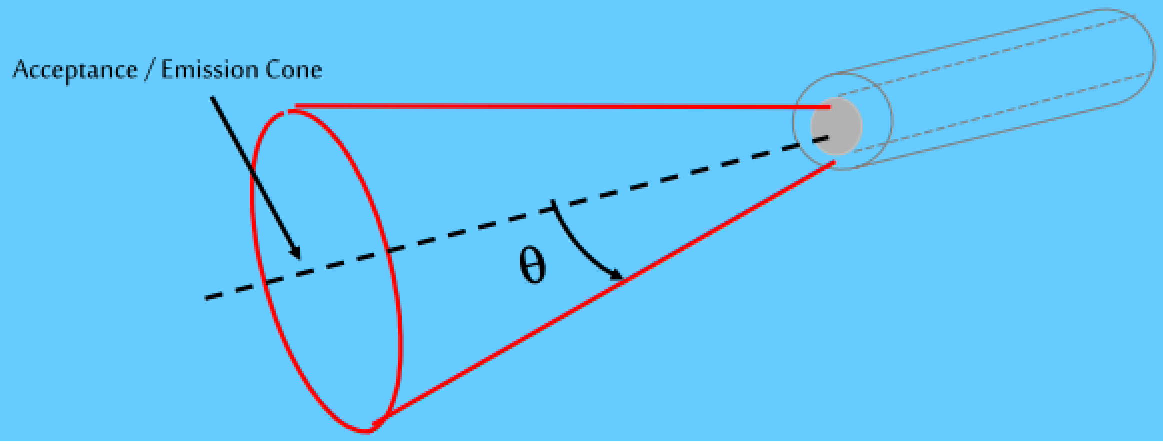
$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \quad \text{index difference } \Delta$$

$$\simeq \frac{n_1 - n_2}{n_1} \qquad \text{for } \Delta \ll 1$$

$$\mathrm{NA} \simeq n_1 (2\Delta)^{\frac{1}{2}}$$

Numerical Apreture

- **A Very useful parameter :** ***measure of light collecting ability of the fiber.***
  - Larger the magnitude of NA, greater the amount of light accepted by the fiber from the external source



$$\mathrm{NA} = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

- If the refractive index of the air is one then

$$\mathrm{NA} = \sin \theta_a$$

NA and Δ (Relative R.I Difference)

- In terms of relative R.I. difference 'Δ' between core and cladding,

$$\Delta = \frac{n_1^2 - n_2^2}{n_1^2 + n_2^2} \cong \frac{n_1^{\,2} - n_2^{\,2}}{2n_1^{\,2}} \cong \frac{n_1 - n_2}{n_1} \quad (\text{for } \Delta << 1)$$

$$NA = n_1(2\Delta)^{1/2}$$

- NA ; independent of core and cladding diameters
- Holds for fiber diameters as small as 8 μm

☛ **NA varies from:** **0.12 - 0.20 for SMFs**
0.20 - 0.50 for MMFs

Graded-Index Fibre structure

- Determining the NA for graded-index fibres is more complex than for step index fibres, since it is a function of position across the core end face. Geometrical optics considerations show that light incident on the fibre core at position r will propagate as a guided mode only if it is within the local numerical aperture NA(r) at that point

Graded-Index Fibre structure

- Local numerical aperture

$$NA(r) = \begin{cases} \left[n^2(r) - n_2^2\right]^{1/2} \approx NA(0)\sqrt{1-(r/a)^\alpha} & r \le a \\ 0 & r > a \end{cases}$$

where the Axial numerical aperture is defined as

$$NA(0) = \left[n^2(0) - n_2^2\right]^{1/2} = \left[n_1^2 - n_2^2\right]^{1/2} \approx n_1\sqrt{2\Delta}$$

the NA of a graded-index fibre decrease from NA(0) to zero as r moves from the fibre axis to the core-cladding boundary

Problems

A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47.

Determine: (a) the critical angle at the core–cladding interface; (b) the NA for the fiber; (c) the acceptance angle in air for the fiber.

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50}$$

$$= 78.5^\circ$$

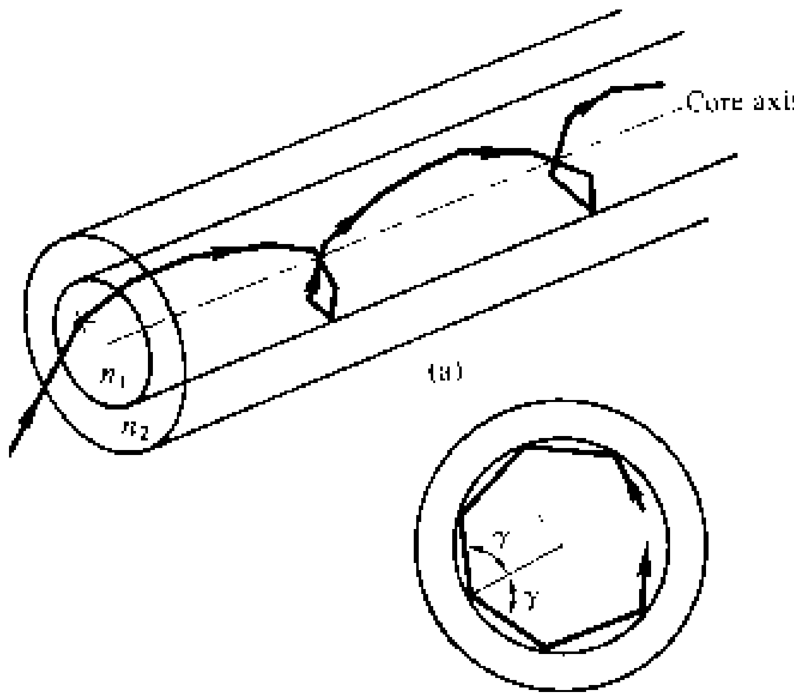
$$\mathrm{NA} = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.50^2 - 1.47^2)^{\frac{1}{2}}$$

$$= (2.25 - 2.16)^{\frac{1}{2}}$$

$$= 0.30$$

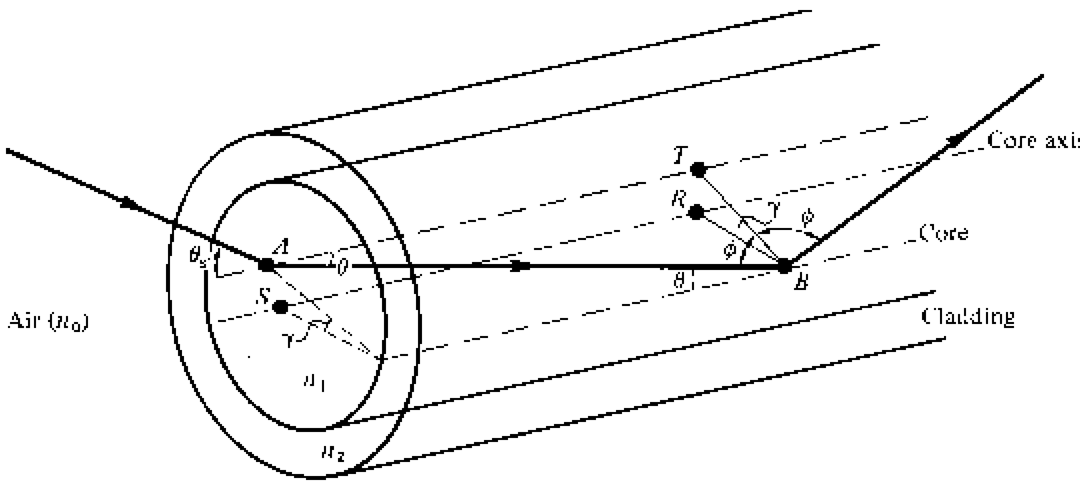
$$\theta_a = \sin^{-1}\mathrm{NA} = \sin^{-1} 0.30$$

$$= 17.4^\circ$$



(a)

(b)



$$n_0 \sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{\frac{1}{2}} = \mathrm{NA}$$

$$\cos \gamma \sin \theta = \cos \phi$$

$$\sin \theta_{as} = \frac{n_1}{n_0} \frac{\cos \phi_c}{\cos \gamma} = \frac{n_1}{n_0 \cos \gamma} \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}}$$

An optical fiber in air has an NA of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

The acceptance angle for meridional rays

$$\theta_a \quad \sin^{-1} NA = \sin^{-1} 0.4$$

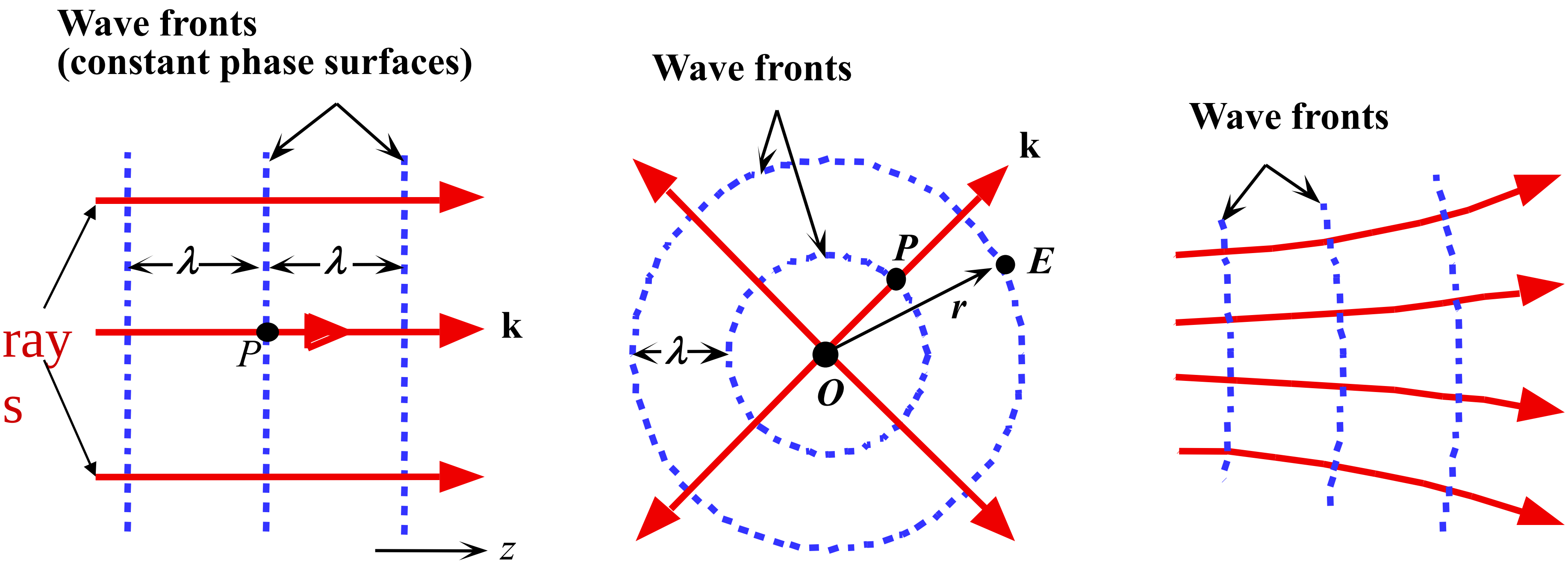
$$= 23.6°$$

$$\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right) = \sin^{-1}\left(\frac{0.4}{\cos 50°}\right)$$

$$= 38.5°$$

Theory of light

- Quantum theory ray optics
- Wave theory
- Electromagnetic wave
- In engineering discipline, we should choose the appropriate & easiest physical theory that can handle our problems



A perfect plane wave

(a)

A perfect spherical wave

(b)

A divergent beam

(c)

Examples of possible EM waves

Electromagnetic Optics

- Electromagnetic radiation propagates in the form of two mutually coupled **vector** waves, an **electric field wave** & a **magnetic field wave**. Both are vector functions of position & time.
- In a <u>source-free, linear, homogeneous, isotropic & non-dispersive media, such as free space,</u> these electric & magnetic fields satisfy the following partial differential equations, known as **Maxwell' equations:**

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

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

$$\nabla \cdot \vec{E} = 0$$

$$\nabla \cdot \vec{H} = 0$$

Linearly Polarized Electromagnetic Plane wave

$$\vec{E} = \mathrm{e}_x E_{0x} \cos(\omega t - kz)$$

$$\vec{H} = \mathrm{e}_y H_{0y} \cos(\omega t - kz)$$

where :

$\omega = 2\pi f$: Angular frequency [rad/m] [2-7]

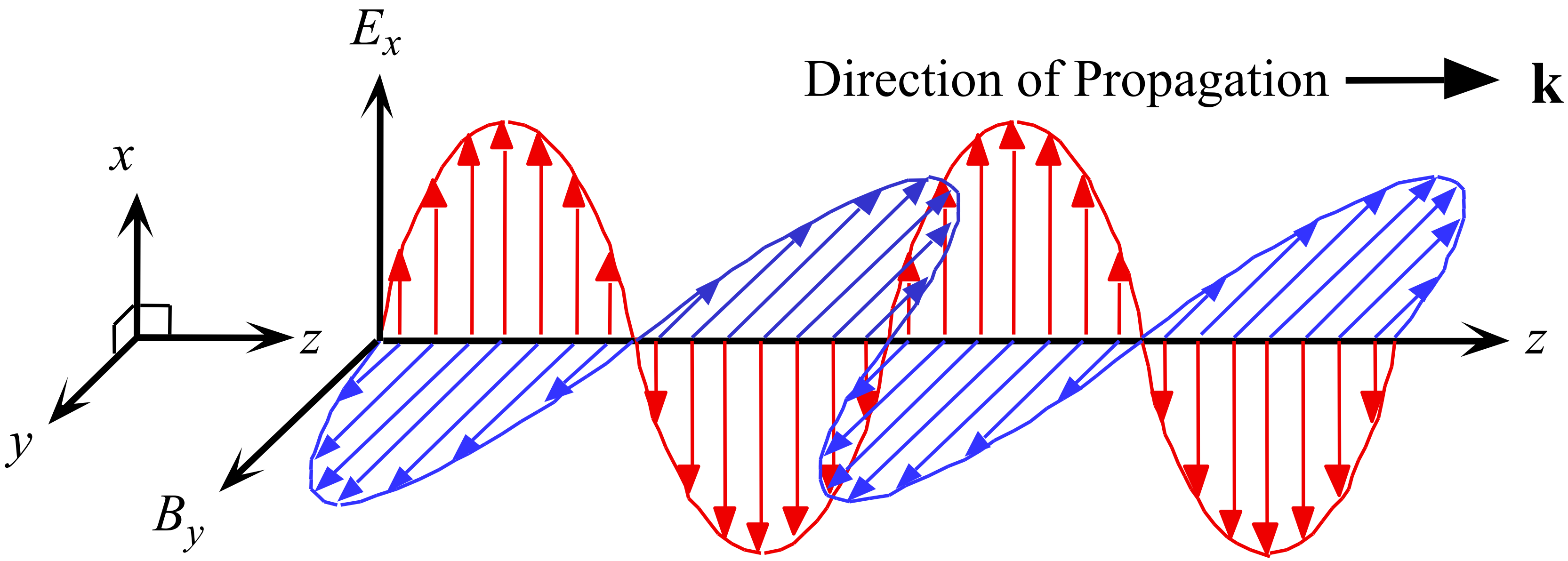
k : Wavenumber or wave propagation constant [1/m]

$\lambda = \dfrac{2\pi}{k}$: Wavelength [m]

$\eta = \dfrac{E_{0x}}{H_{0y}} = \sqrt{\dfrac{\mu}{\varepsilon}}\ [\Omega]$: intrinsic (wave) impedance [2-8]

$v = \dfrac{1}{\sqrt{\mu\varepsilon}}\ [\mathrm{m/s}]$: velocity of wave propagation [2-9]

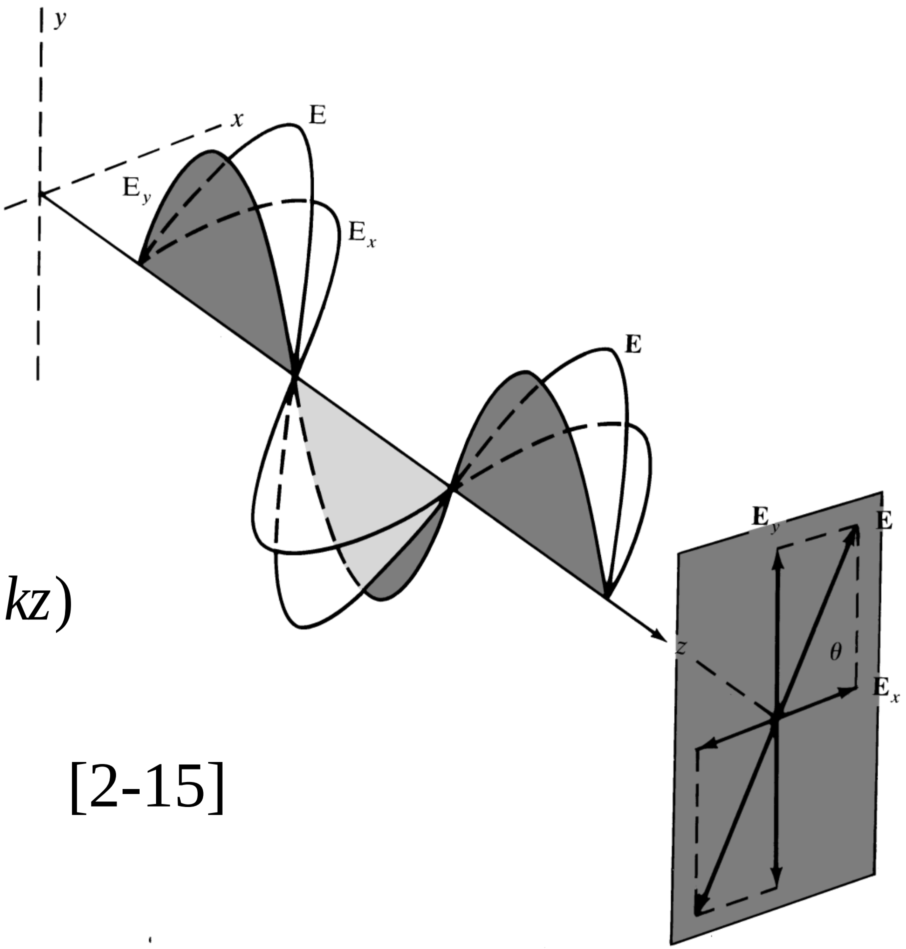
EM wave



An electromagnetic wave is a travelling wave which has time varying electric and magnetic fields which are perpendicular to each other and the direction of propagation, z.

General form of linearly polarized plane waves

Any two orthogonal plane waves Can be combined into a linearly Polarized wave. Conversely, any arbitrary linearly polarized wave can be resolved into two independent Orthogonal plane waves that are in phase.



$$\vec{E} = \mathrm{e}_x E_{0x} \cos(\omega t - kz) + \mathrm{e}_y E_{0y} \cos(\omega t - kz)$$

$$E = \left|\vec{E}\right| = \sqrt{{E_{0x}}^2 + {E_{0y}}^2}$$

$$\theta = \tan^{-1}\left(\frac{E_{0y}}{E_{0x}}\right)$$

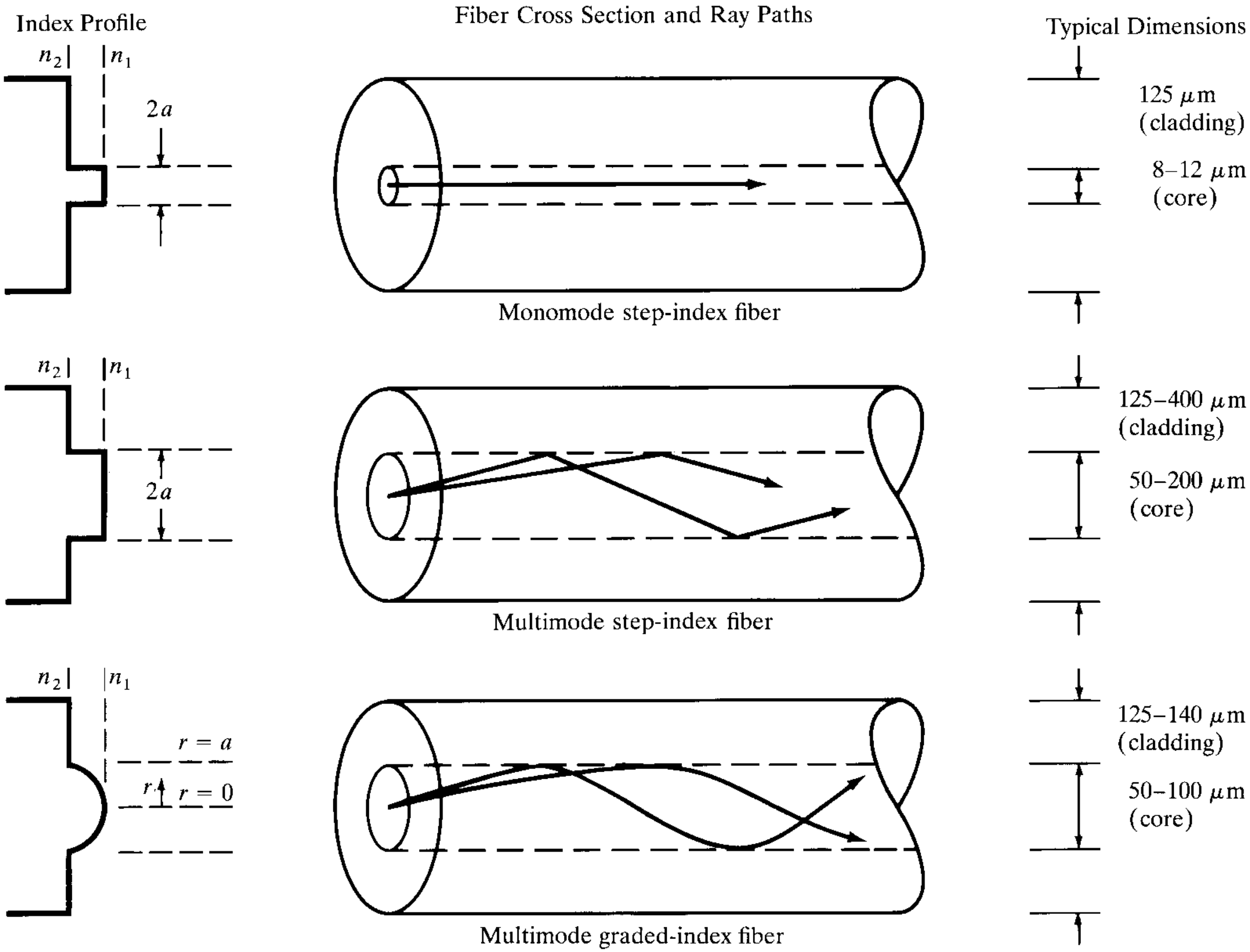
[2-15]

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Rays and Modes

- EM wave guided along an optical fiber can be represented by superposition of bound or trapped mode
- Modes describes distribution of light energy across the fiber
- The precise pattern depends wavelength
- Single mode
- Multimode fiber

Different Structures of Optical Fiber



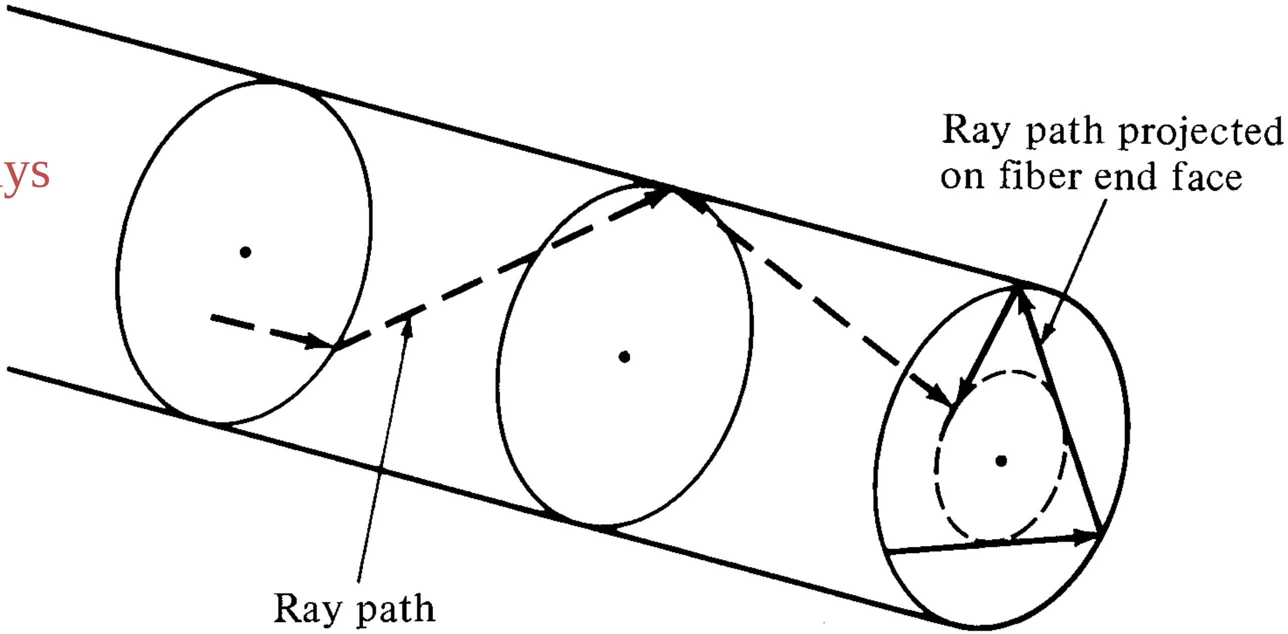
Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Rays

- Meridional ray
- Skew rays

Ray Optics Theory (Step-Index Fiber)

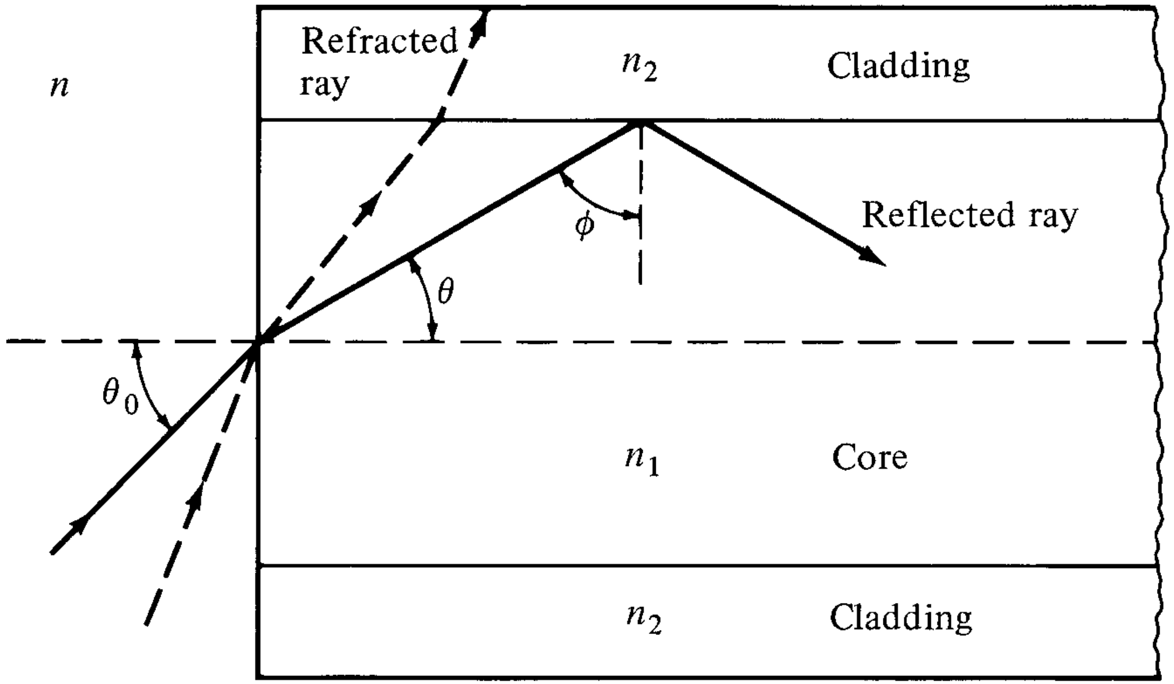
Skew rays



Each particular guided mode in a fiber can be represented by a group of rays which Make the same angle with the axis of the fiber.

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Optical Waveguide Acceptance angle

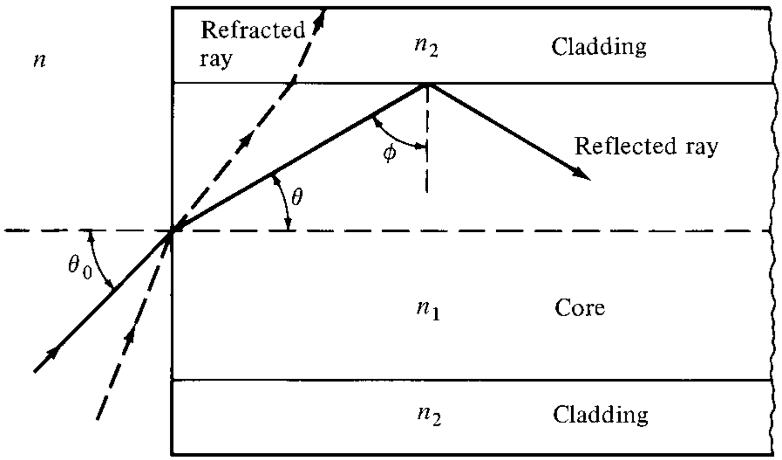


Propagation mechanism in an ideal step-index optical waveguide.

Launching optical rays to slab waveguide

$$\sin\phi_{\min} = \frac{n_2}{n_1}$$; minimum angle that supports TIR

[2-21]



Maximum entrance angle, $\theta_{0\max}$ is found from the Snell's relation written at the fiber end face.

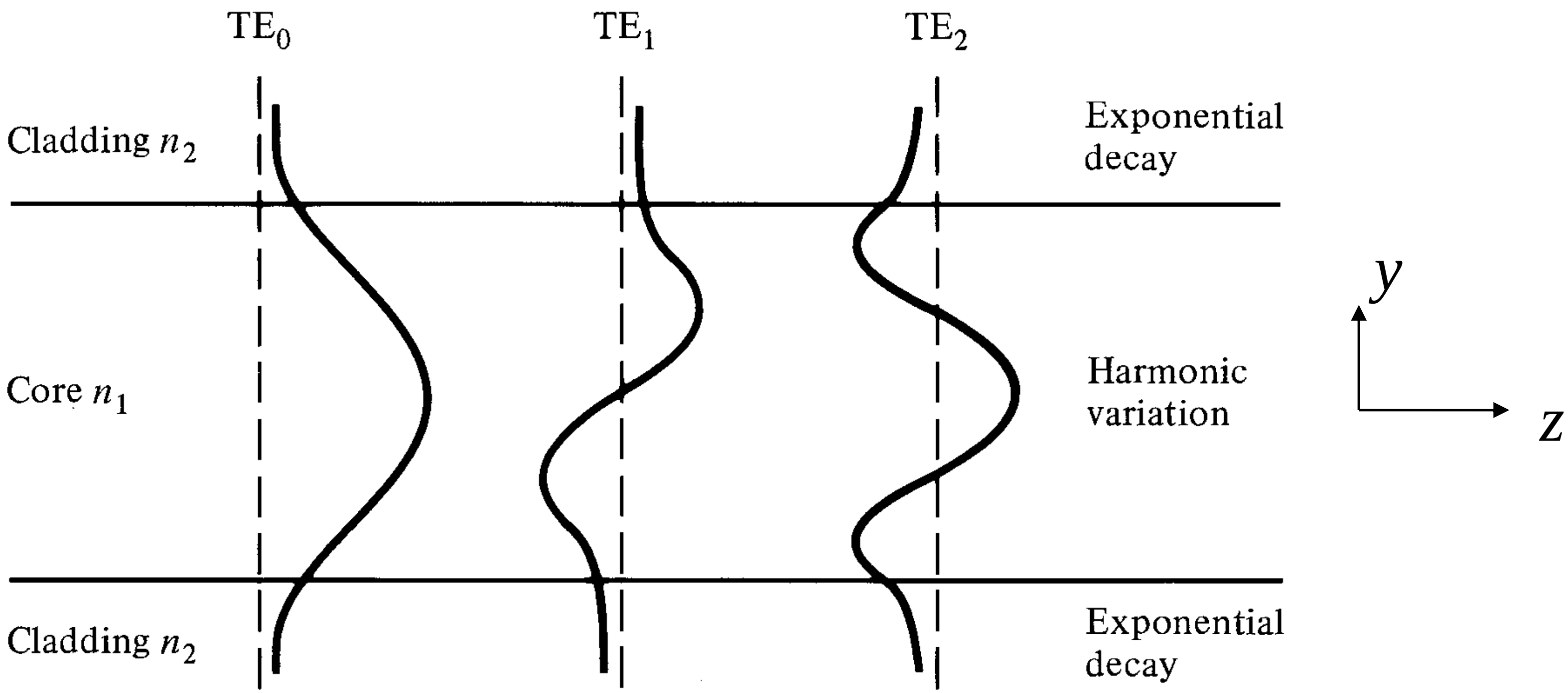
$$n\sin\theta_{0\max} = n_1 \sin\theta_c = \sqrt{n_1^{\,2} - n_2^{\,2}} \quad [2\text{-}22]$$

Numerical aperture:

$$\mathrm{NA} = n\sin\theta_{0\max} = \sqrt{n_1^{\,2} - n_2^{\,2}} \approx n_1\sqrt{2\Delta} \qquad [2\text{-}23]$$

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad [2\text{-}24]$$

TE modes in slab waveguide



$$\vec{E}_m(x,y,z,t) = \mathrm{e}_x f_m(y)\cos(\omega t - \beta_m z) \qquad \text{(TE)}$$

$$m = 0,1,2,3 \;(\text{mode number}) \qquad \text{(TM)}$$

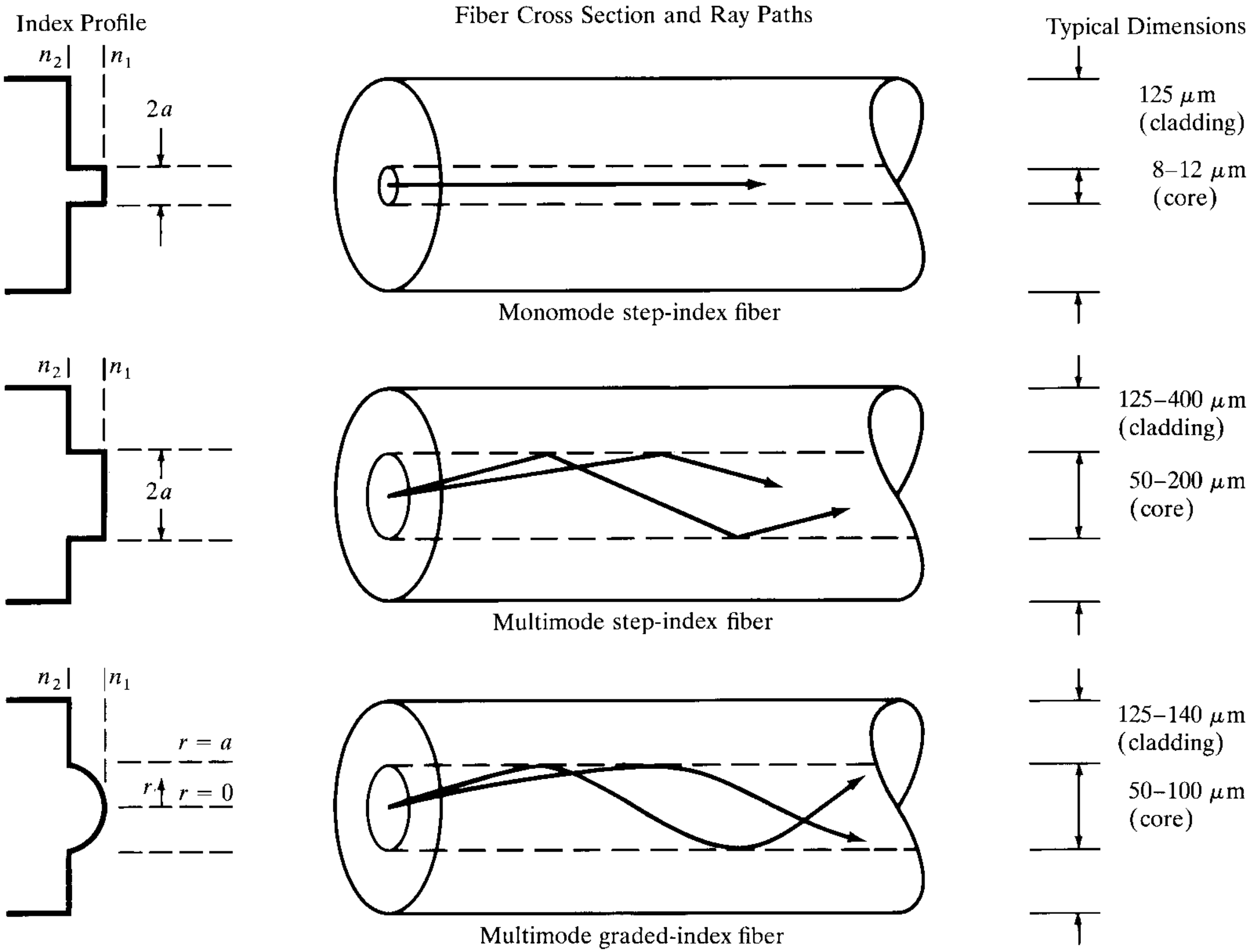
Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Modes in slab waveguide

- The order of the mode is equal to the # of field zeros across the guide. The order of the mode is also related to the angle in which the ray congruence corresponding to this mode makes with the plane of the waveguide (or axis of the fiber). **The steeper the angle, the higher the order of the mode**.
- For higher order modes the fields are distributed more toward the edges of the guide and penetrate further into the cladding region.
- **Radiation modes** in fibers are not trapped in the core & guided by the fiber but they are still solutions of the Maxwell' eqs. with the same boundary conditions. These infinite continuum of the modes results from the optical power that is outside the fiber acceptance angle being refracted out of the core.
- In addition to bound & refracted (radiation) modes, there are **leaky modes** in optical fiber. They are partially confined to the core & attenuated by continuously radiating this power out of the core as they traverse along the fiber (results from Tunneling effect which is quantum mechanical phenomenon.) A mode remains guided as long as

$$n_2 k < \beta < n_1 k$$

Different Structures of Optical Fiber



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Mode designation in circular cylindrical waveguide (Optical Fiber)

TE_{lm} modes : The electric field vector lies in transverse plane.

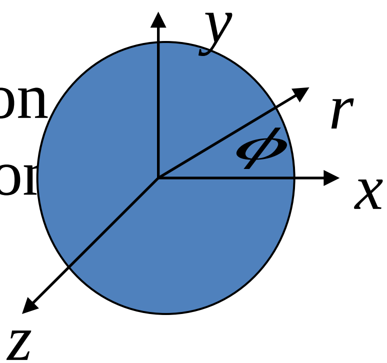
TM_{lm} modes : The magnetic field vector lies in transverse plane.

Hybrid HE_{lm} modes : TE component is larger than TM component.

Hybrid EH_{lm} modes : TM component is larger than TE component.

l= # of variation cycles or zeros in ϕ direction

m= # of variation cycles or zeros in r direction



Linearly Polarized (LP) modes in weakly-guided fibers ($n_1 - n_2 << 1$)

$\mathrm{LP}_{0m}(\mathrm{HE}_{1m}), \mathrm{LP}_{1m}(\mathrm{TE}_{0m} + \mathrm{TM}_{0m} + \mathrm{HE}_{0m})$

Fundamental Mode: $\mathrm{LP}_{01}(\mathrm{HE}_{11})$

V Number

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} = \frac{2\pi a}{\lambda}\,\mathrm{NA}$$

No of modes

$$M \approx \frac{V^2}{2}$$

For Graded-Index Fibre structure

- The number of bound modes in a graded-index fibre is

$$M = \frac{\alpha}{\alpha + 2} a^2 k^2 n^2 \Delta$$

Mode-Field Diameter (MFD)

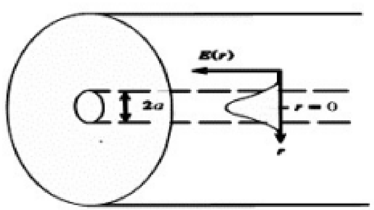
- Important parameter determined from mode-field distribution of fundamental LP_{01} mode.
- Characterized by various models
- Main consideration: how to approximate the electric field distribution
- Gaussian distribution

$$E(r) = E_0 e^{-\frac{r^2}{W^2}}$$

Mode-Field Diameter (MFD)

- MDF width $2W_0$ of the LP_{01} mode can be defined as:

$$2W_0 = 2\left[\frac{\int_0^\infty r^3 E^2(r)\,dr}{\int_0^\infty r E^2(r)\,dr}\right]^{1/2}$$

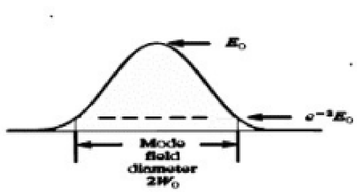


where

•*E(r)* denotes the field distribution of the LP_{01} mode

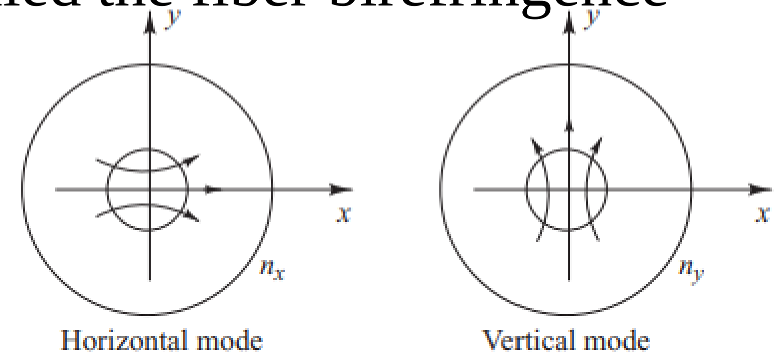
•*r* is the radius

•W_0 is the width of the electric field distribution



Fiber birefringence
Propagation Modes in Single-Mode Fiber

The modes propagate with different phase velocities, and the difference between their effective refractive indices is called the fiber birefringence



Two polarizations of the fundamental HE_{11} mode in a single-mode fiber

$$B_f = n_y - n_x$$

Equivalently, we may define the birefringence as

$$\beta = k_0(n_y - n_x)$$

fiber beat length, $L_p = 2\pi/\beta$