Fiber-Optic Communications Technology

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Course website:
http://opt.zju.edu.cn/octech/

Overview of the course (I)

Order	Time	Teacher	Content
1	Feb 16	Shiming Gao	Introduction and Physics of Light
2	Feb 23	Shiming Gao	Optical Fibers: Basics
3	Mar 1	Sailing He	Overview & Introduction (1)
4	Mar 8	Sailing He	Overview & Introduction (2)
5	Mar 15	Shiming Gao	Optical Fibers: A Deeper Look
6	Mar 22	Shiming Gao	Single-Mode Fibers: Basics
7	Mar 29	Shiming Gao	Single-Mode Fibers: A Deeper Look
8	Apr 5	Shiming Gao	Fabrication, Cabling, Installation, and Testing
9	Apr 19	Shiming Gao	Optical Transmitters (1)
10	Apr 26	Shiming Gao	Optical Transmitters (2)
11	May 3	Shiming Gao	Receivers (1)
12	May 10	Shiming Gao	Receivers (2)
13	May 17	Shiming Gao	Amplifiers
14	May 24	Sailing He	Passive Components (1)
15	May 31	Sailing He	Passive Components (2) & Prospects
16	Jun 7	Shiming Gao	Review & Questions

Overview (II)

- Experiments:
  - Testing of Optical Fibers
    - NA, coupling, loss
  - Optic-Fiber Sensing Systems
    - Dual-beam interference, temperature sensing, stress sensing
  - Testing of Fiber Components
    - Optical switching, isolator, attenuator
  - Optical Fiber Communication
    - Data transmission, voice transmission
- Score:
  - Examination 60%,
  - Experiment 20%,
  - Homework & Class-Interactive 20%
- Teaching Assistant:
  - Kai Hu (88206514-227, hukai@coer.zju.edu.cn)
- Website： http://opt.zju.edu.cn/octech

Overview (III)

- Textbook:
  - Djafar K. Mynbaev and Lowell L. Scheiner, Fiber-Optic Communications Technology, 1st Edition, 科学出版社(英文影印版)，2002.
- References:
  - 徐公权等，光纤通信技术，机械工业出版社, 2002.
  - G. P. Agrawal, Fiber-Optic Communications Systems, John Wiley & Sons, 2002.
  - 廖延彪，光纤光学，清华大学出版社，2000.
  - 杨祥林，光纤通信系统，国防工业出版社，2003.

Chapter 1

Introduction to Telecommunications and Fiber Optics

- **Why Fiber-optic communications?**
- **What is the basic blocks of fiber-optic communications systems?**
- **What we will learn in this course?**

1.1 Why Fiber-Optic Communications?

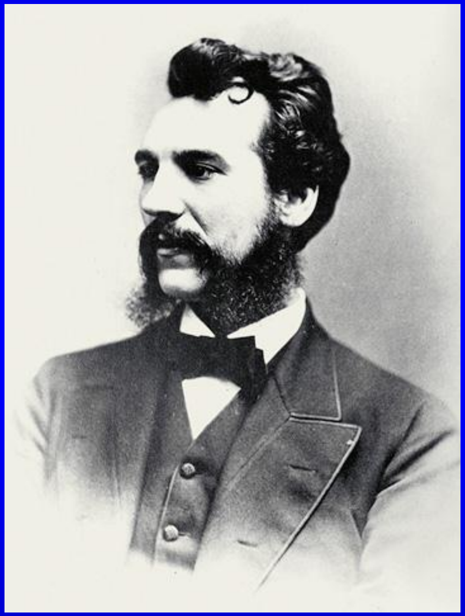
- **What is telecommunications?**
  - Tele: over a distance
  - Communications: exchange of information----voice, video, and data
  - Telecommunications is the exchange of information over a certain distance using some type of equipments.
- **Original light communications**
  - “Light” → “Fire”
  - Beacon(烽火台): ~780 BC, King You of Zhou;
  - Early Middle Ages (500-1000 AD), Russian

1.1 Why Fiber-Optic Communications?

- Telegraph(电报1837):
  - Carriers: current, **EM waves**
  - Coding: Morse Code
- Telephony(电话1876):
  - Voice → Electric pulses
  - Analog signals
- Information:
  - Voice
  - Video
  - Data

Morse

Bell



- Media: Cooper wire, coaxial cable, air, optical fiber
- Modern Communications: Conversion—Modulation—Transmission----Demodulation

1.1 Why Fiber-Optic Communications?

- What we want from modern telecommunications?
  - Capacity, capacity, and more capacity!
  - Information-carrying capacity is the ability of a communication link to transmit a certain amount of information per unit of time.
- More information is produced
  - Postindustrial era → Information era
  - Internet, telephone, mobile, credit card, online bank, online TV, movie, ………
- Analog → Digital
  - Analog: amplitude, frequency, phase
  - Digital: bits “0” and “1”
  - ☺More reliable!
  - ☹Require more channel capacity!

1.1 Why Fiber-Optic Communications?

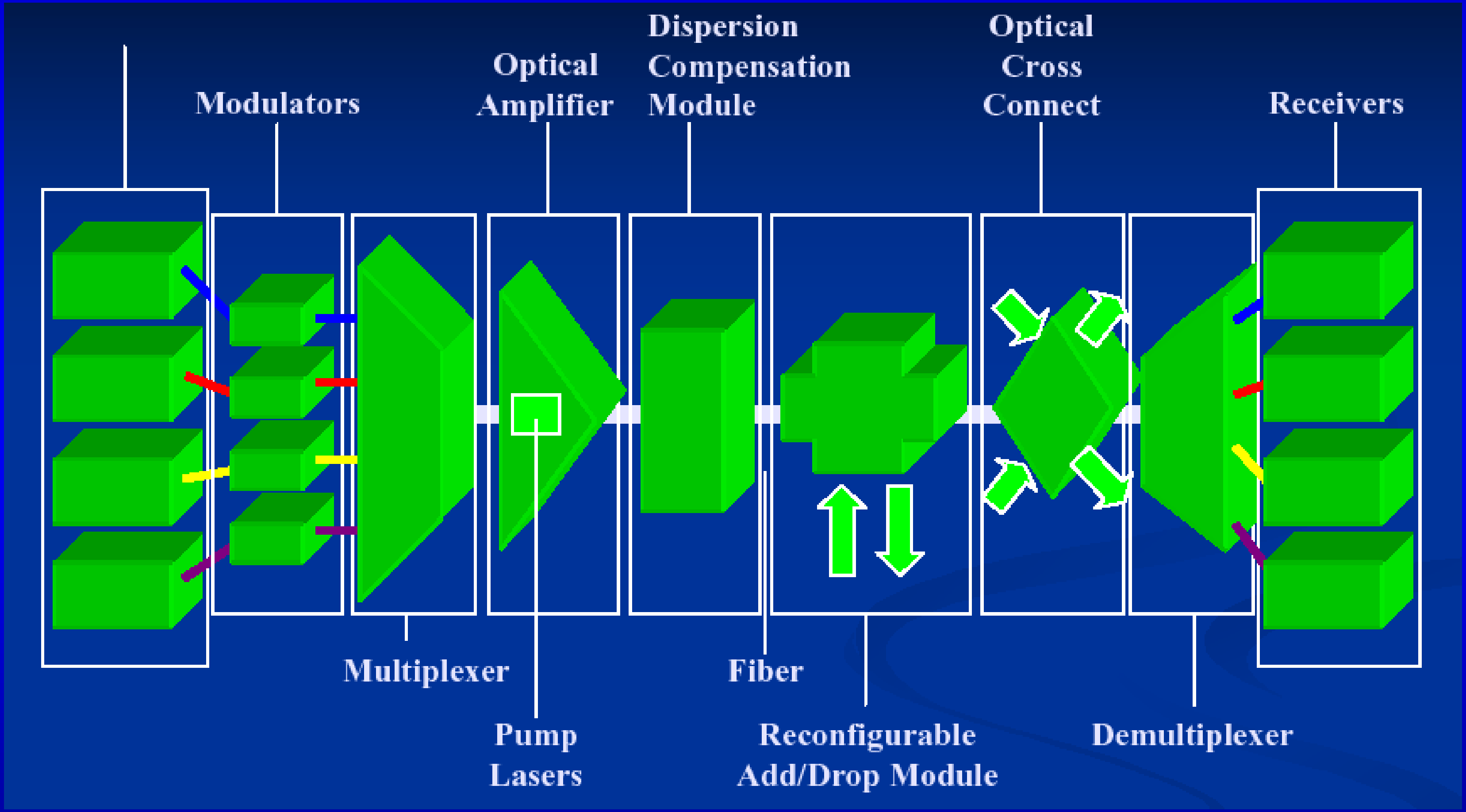
- The capacity limit
  - Shannon-Hartley theorem:

$$C = BW \times \log_2(1 + SNR)$$

  - Bndwidth: the range of frequencies within which the signals can be tranmitted without substantial attenuation
  - The higher the carrier's frequency, the greater the channel bandwidth and the higher the information-carrier capacity.
- Cooper wire: 1MHz
- Coaxial cable: 100MHz
- Radio frequency: 500 KHz~100MHz
- Microwave: 100GHz (Satellites, Radio over fiber)
- Optical fiber: 50THz!

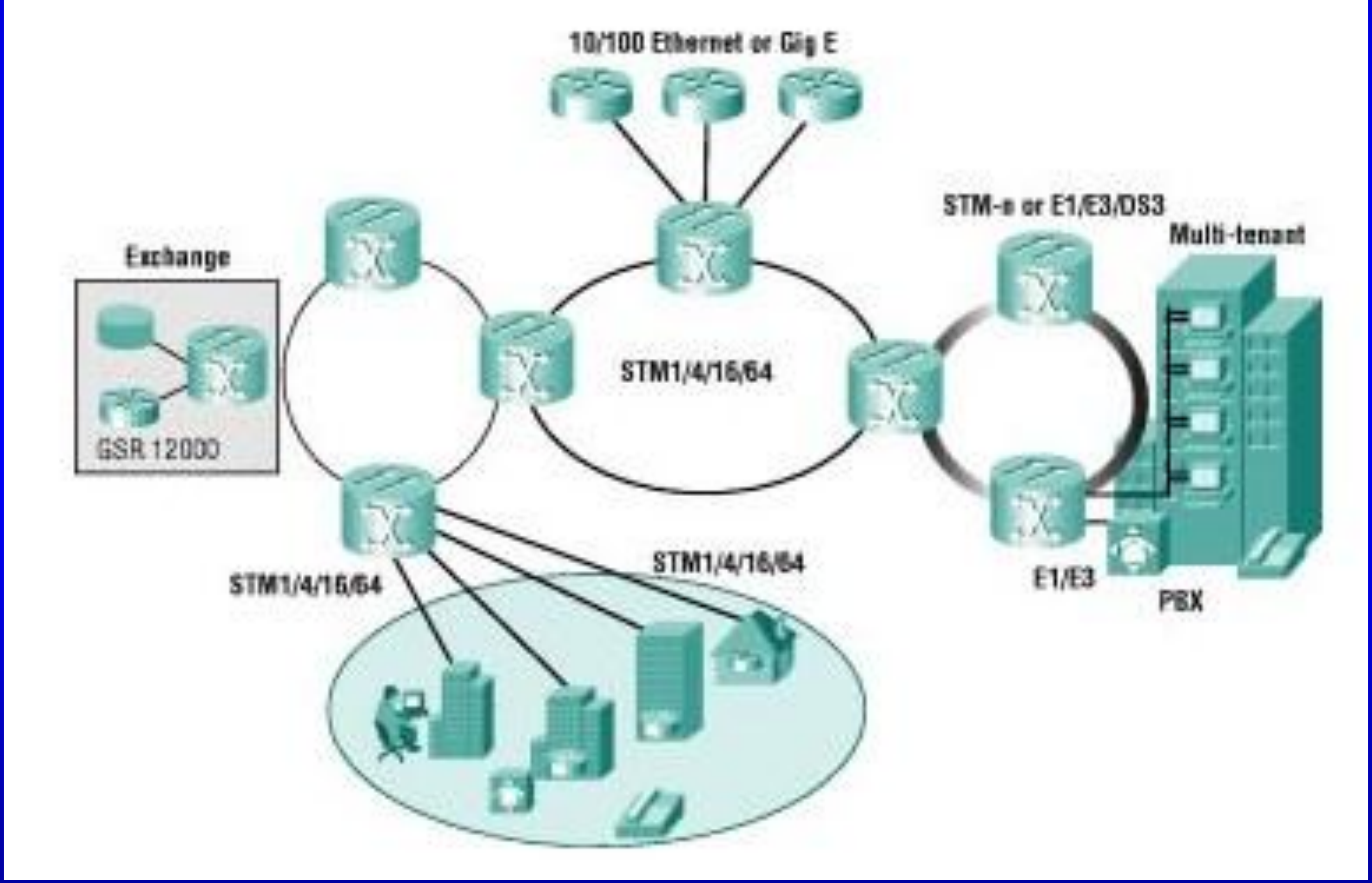
1.2 Basic blocks of fiber communications systems

- Fiber-optic communications link



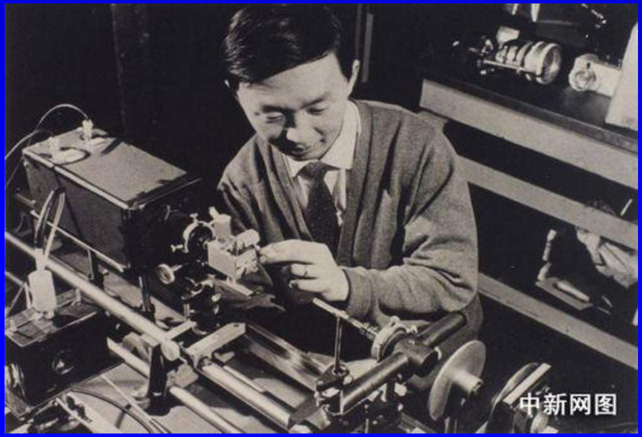
1.2 Basic blocks of fiber communications systems

- Fiber-optic communications network



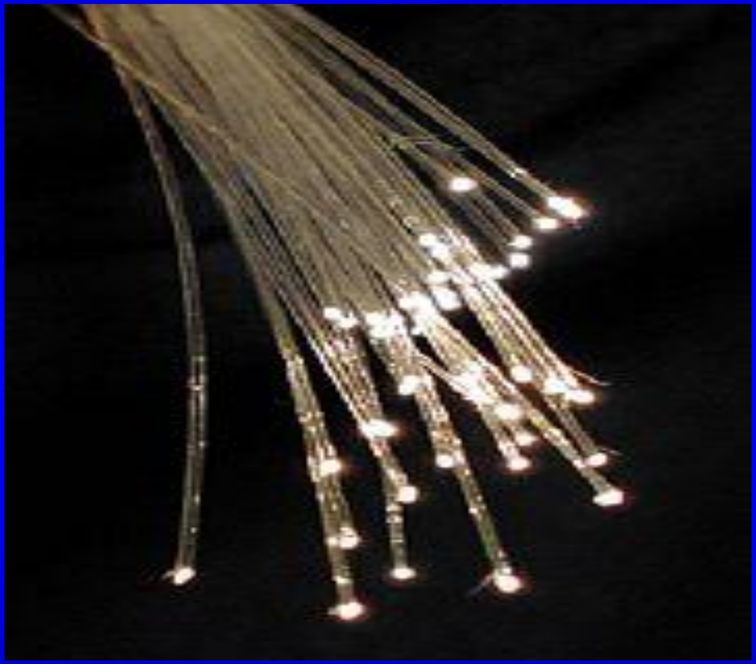
1.2 Basic blocks of fiber communications systems

- Optical fiber
  - How to guide light?
    Total internal reflection
  - Where to go?
  - In 1965, Charles K. Kao with Hockham concluded that the fundamental limitation for glass light attenuation is below **20 *dB/km*** (*decibels per kilometer*), which is a key threshold value for optical communications. (Nobel Prize 2009)



Optical Fibers

- Attenuation: 1970 Corning <20 dB/km
  - Macrobending loss
  - Microbending loss
  - Scattering
  - Absoprtion
- Dispersion
  - Intermodal dispersion
  - Chromatic dispersion
- Mode
  - Multi-mode fiber
  - Single-mode fiber
- Special fibers
  - Erbium-doped fiber, polymer fiber, photonic crystal fiber, …



Optical devices in fiber-optic communications system

- Transmitter
  - Light source
  - Convert an information signal from electric to light
- Receiver
  - Photondetector
  - Convert an optical information signal back into an electrical signal.
- Amplifier
  - Erbium-doped fiber amplifier (EDFA)
  - Fiber Raman amplifier (FRA)
- Optical signal processing components
  - Ensure the system running

Common passive and active components

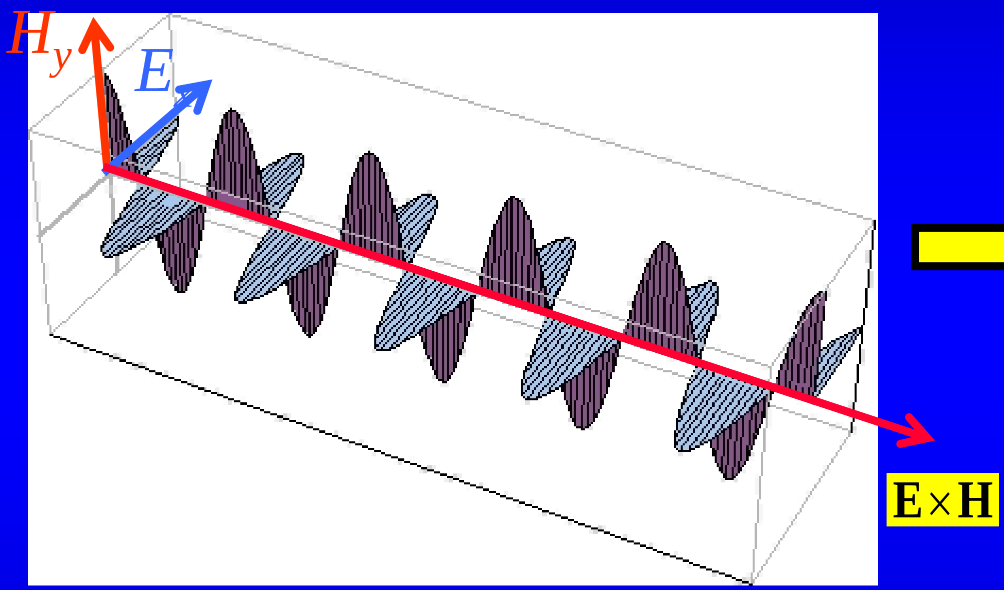
- Optical connectors
- Optical attenuators
- Couplers/splitters
- Isolators
- Circulators
- Filters
- Optical add/drop multiplexer
- Wavelength multiplexer and demultiplexer
- Modulators
- Switches
- Wavelength converters
- Optical cross-connects

Chapter 2

Physics of Light : A Brief Overview

- EM waves (电磁波) ?
- Ray （光射线）?
- Photons （光子）?

2.1 Electromagnetic Waves *(the wave view)*

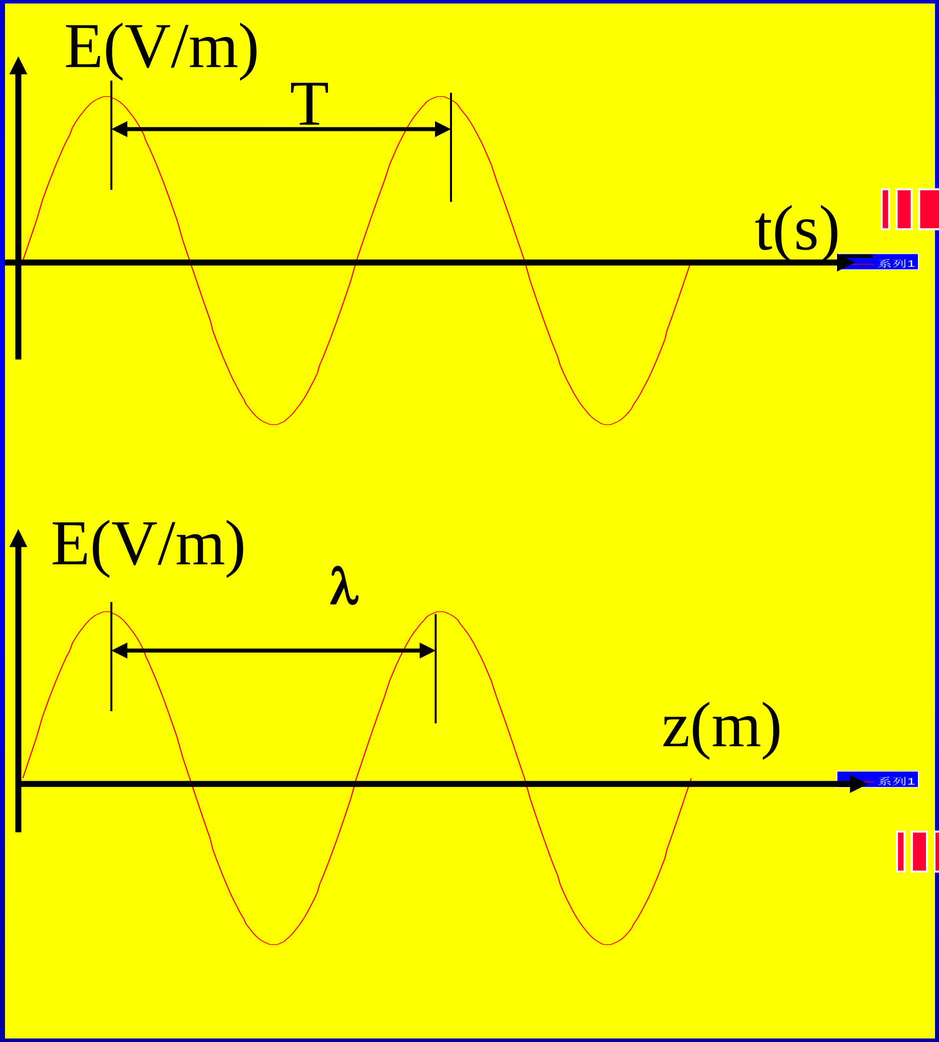


Transverse electromagnetic (TEM) waves

(*in free space*)

Right-hand rule

◆ Two Important Concepts



Time dependence at a spatial point

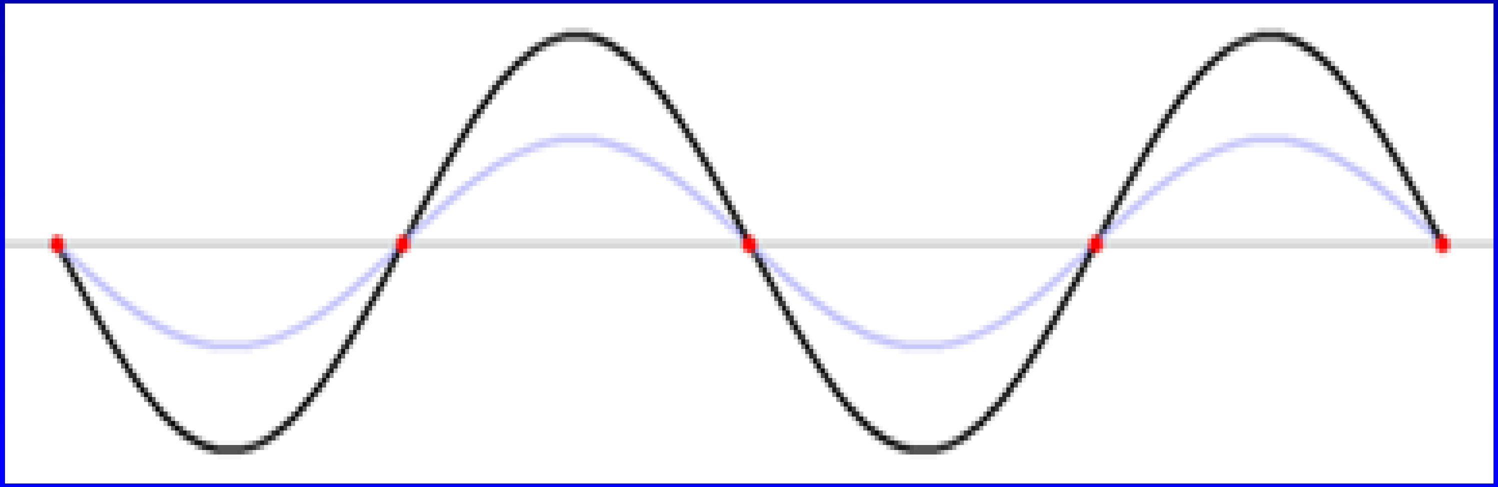
T — **Period**（s）

f =1/T—**Frequency**

(cycle/s=Hz)

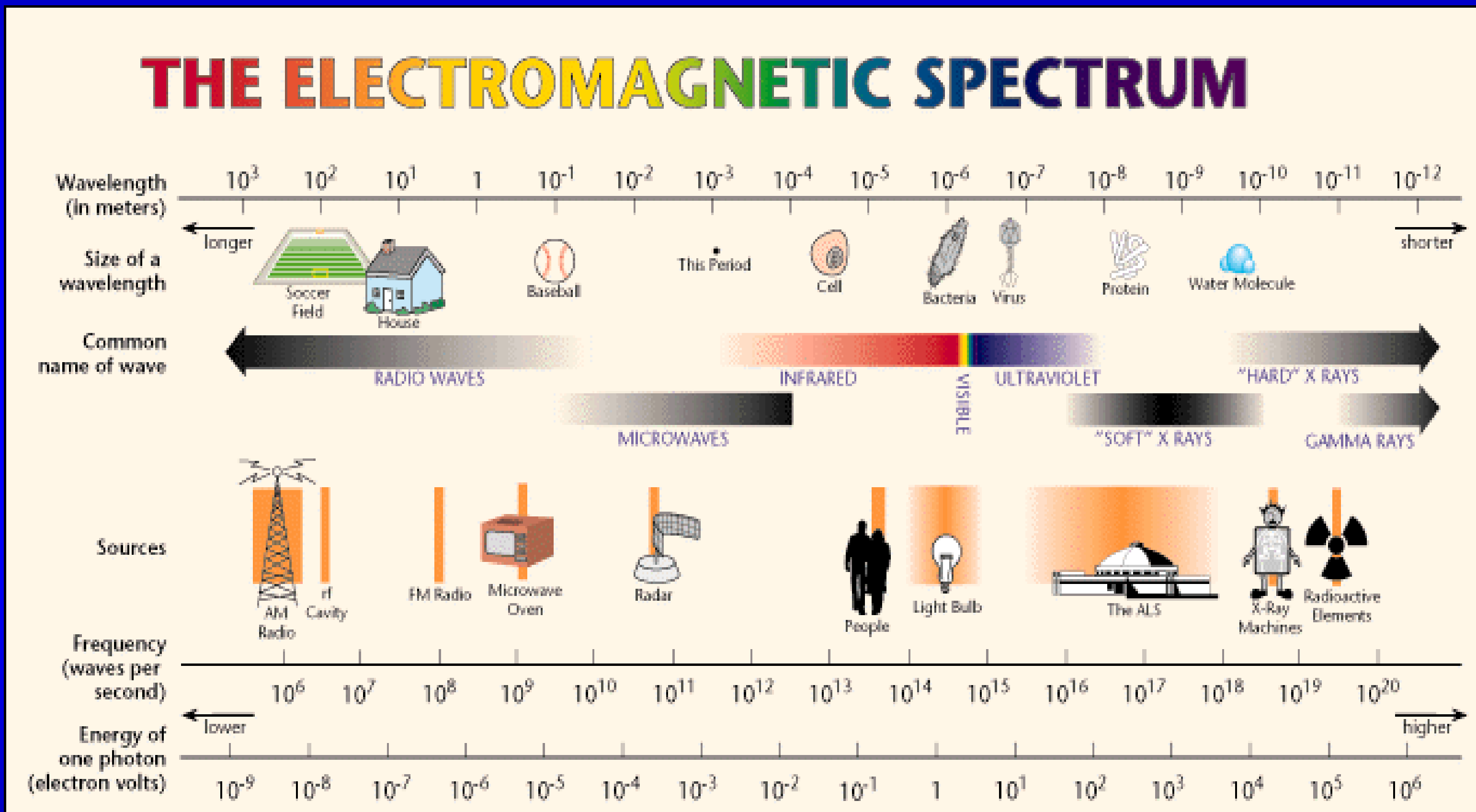
Spatial dependence at a fixed time

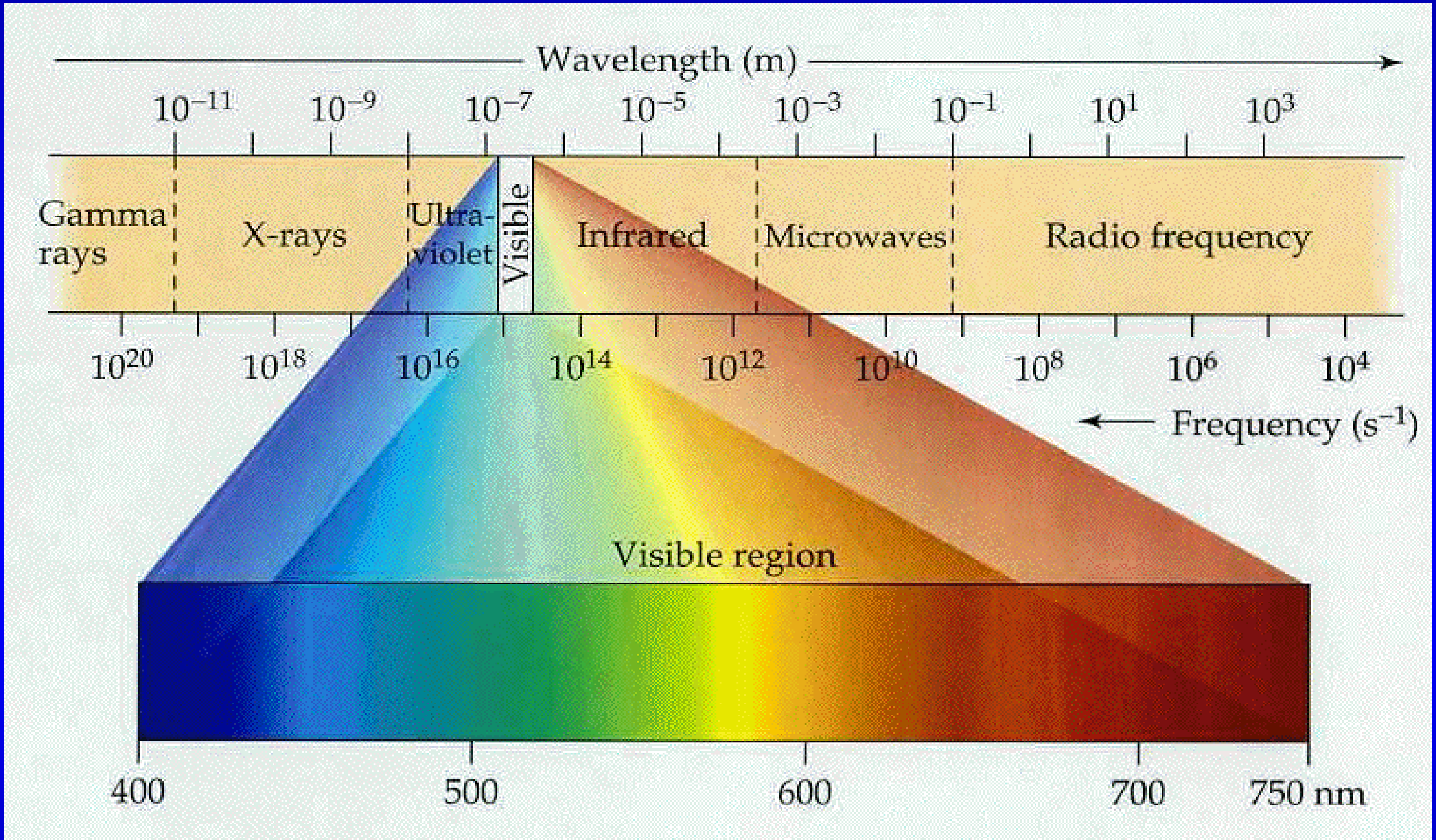
λ — **Wavelength** (m)



A standing wave (black) depicted as the sum of two propagating waves traveling in opposite directions (red and blue).

◆ EM waves come in all sizes




Wavelength (m)
10−11
10−9
10−7
10−5
10−3
10−1
10¹
10³
Gamma rays
X-rays
Ultra-violet
Visible
Infrared
Microwaves
Radio frequency
10²⁰
10¹⁸
10¹⁶
10¹⁴
10¹²
10¹⁰
10⁸
10⁶
10⁴
Frequency (s−1)
Visible region
400
500
600
700
750 nm

2.2 Beams or Rays *(the geometric-optics view)*

◆ **Refractive index** (折射率) **for nonmagnetic materials**

-> a measure of how much a ray of light is bent when propagating from one medium into another

–> v=c/n : the speed of light in a material of refractive index n

$$v = \frac{1}{\sqrt{\mu_o \varepsilon_o \varepsilon_r}} = \frac{c}{n}$$

$$n = \sqrt{\varepsilon_r}$$

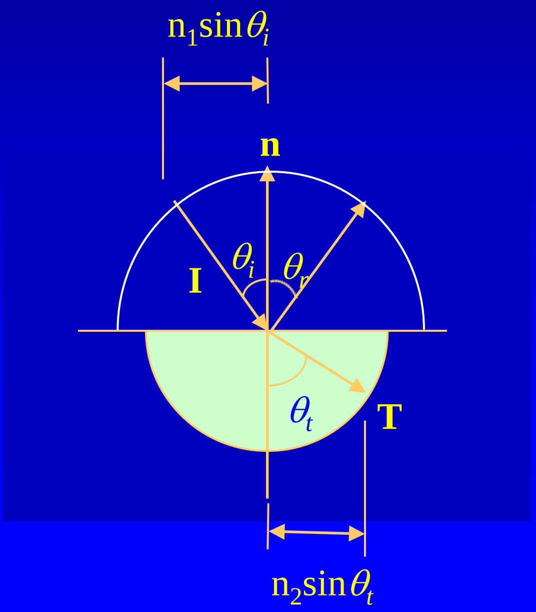
Example： ***light propagates in glass and many plastics***

n ~ 1.5, and ε_r ~ 2.25

$$v = c/n = 3\times10^8 (m/s)/1.5 = 2.0\times10^8 (m/s)$$

$\lambda = \lambda_0/n$ (wavelength shortening)

◆ Snell's Law of Refraction
(斯涅尔 折射定律)



- Governs the geometry of refraction.

$$n_1 \sin\theta_i = n_2(\lambda) \sin\theta_t(\lambda)$$

n_1 = RI of incident medium

n_2 = RI of medium into which the light is transmitted

- If the light is transmitted into a denser medium (光密介质), it is refracted toward the normal of the interface.

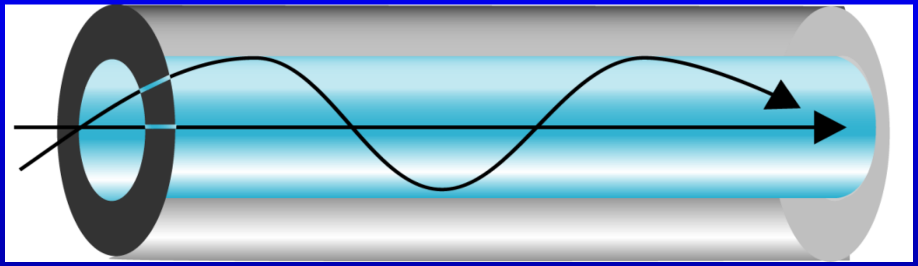
- If the light is transmitted into a rarer medium (光疏介质), it is refracted away from the normal of the interface.

◆ Total Internal Reflection （全内反射）

- At some angle, called the ***critical angle***, light is bent to lie exactly in the plane of the interface.
- At all angles greater than this, the light is reflected back into the incident medium: ***total internal reflection*** (TIR).
- Snell's law gives critical angle θ_c

$$n_1 \sin\theta_c = n_2(\lambda)\sin(\pi/2)$$

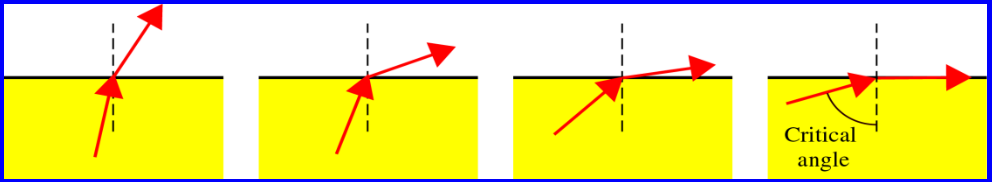
$$\sin\theta_c = n_2(\lambda)/n_1$$



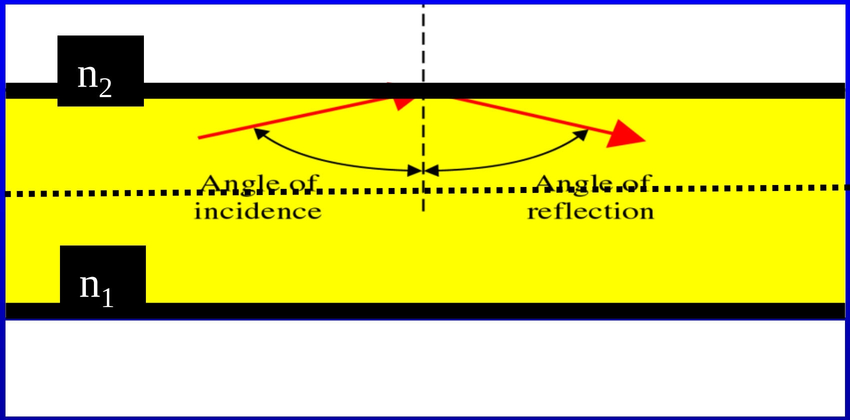
*** Waveguide or**
*** Optical Fiber**

◆ Critical Angle (临界角)

- When a beam propagates from a dense material into a less dense medium, the refraction angle increase with the increment of the incident angle.
- Critical angle: The incident angle at which the refracted angle is 90 degree.



Example:



$$n_1 \sin\Theta_1 = n_2 \sin\Theta_2 \Rightarrow$$

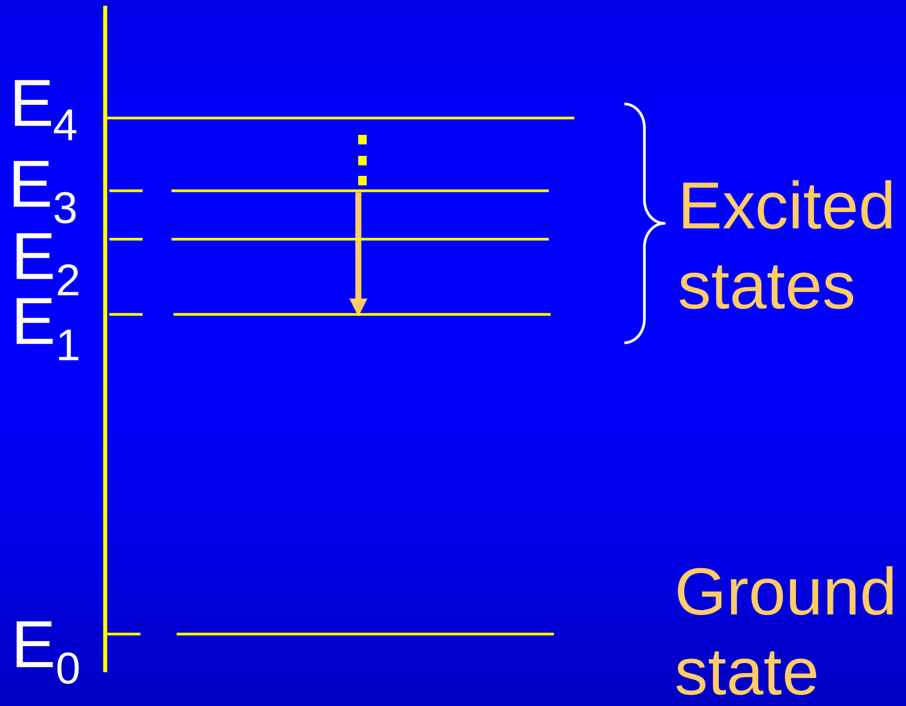
$$\because n_1 = 1.6, n_2 = 1.0, \Theta_2 = 90^\circ$$

$$\therefore \Theta_{1c} = \sin^{-1}\frac{1}{1.6} = 38.68^\circ$$

2.3 A Stream of Photons（光子） *(the quantum view)*

◆ **The Bohr theory： the line spectrum of hydrogen.**

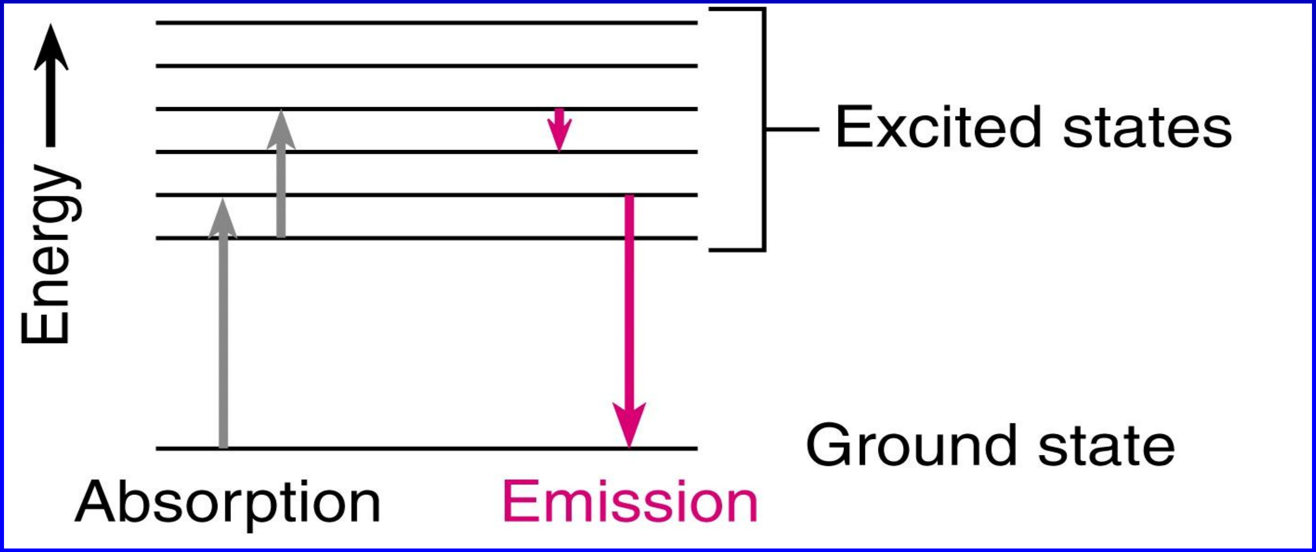
Energy-level Diagram:
(能级图)



absorption or emission:

$$E_{photon} = \Delta E_{atom}$$

◆ Radiation (辐射) and Absorption（吸收）



$$E_p = \Delta E = hf = hc/\lambda$$

$$\therefore \lambda = c \cdot h / \Delta E$$

（$1eV = 1.602 \times 10^{-19}$ J)

$= 1248/E_p$ (eV) (in terms of nm)

CLASS	FREQUENCY	WAVELENGTH	ENERGY
Y	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
SX	3 EHz	100 pm	12.4 keV
	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 µm	1.24 eV
MIR	30 THz	10 µm	124 meV
FIR	3 THz	100 µm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 µeV
UHF	3 GHz	1 dm	12.4 µeV
VHF	300 MHz	1 m	1.24 µeV
HF	30 MHz	10 m	124 neV
MF	3 MHz	100 m	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF/ULF	3 kHz	100 km	12.4 peV
SLF	300 Hz	1 Mm	1.24 peV
ELF	30 Hz	10 Mm	124 feV
	3 Hz	100 Mm	12.4 feV

Legend:

Y = Gamma rays

HX = Hard X-rays

SX = Soft X-Rays

EUV = Extreme ultraviolet

NUV = Near ultraviolet

Visible light

NIR = Near infrared

MIR = Moderate infrared

FIR = Far infrared

Radio waves:

EHF = Extremely high frequency (Microwaves)

SHF = Super high frequency (Microwaves)

UHF = Ultrahigh frequency

VHF = Very high frequency

HF = High frequency

MF = Medium frequency

LF = Low frequency

VLF = Very low frequency

VF = Voice frequency

ULF = Ultra low frequency

SLF = Super low frequency

ELF = Extremely low frequency

◆ Example

1) Suppose an LD radiates red light at λ=650 nm. What is the energy of a single photon?

$$E_p = hf = hc/\lambda = (6.6\times10^{-34}\,J\cdot S)\times(3\times10^{8}\,m/s)/(650\times10^{-9}\,m)$$
$$= 3.04\times10^{-19}\,J$$

2) Suppose the energy gap of an LD is 2.5 eV. What color will it radiate?

$$E_p = 2.5eV\times(1.602\times10^{-19}\,J/eV)\approx 4\times10^{-19}\,J$$

$$\lambda = c\cdot h/\Delta E = (6.6\times10^{-34}\,J\cdot S)\times(3\times10^{8}\,m/s)/(4\times10^{-19}\,m)$$
$$= 500\,nm$$

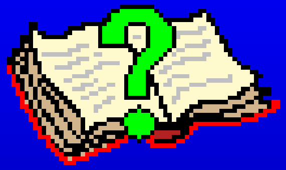
Summary

- **EM waves :** waveguide analysis,
  functional device,
  mode coupling
- **Ray :** qualitative or phenomena explanation
- **Photons :** active device,
  interaction with materials,
  semiconductor laser,

Question :

What's the difference between the three models ?

And the relations ?



References:

1. Gerd Keiser, Optical fiber communications, Publisher Boston, Mass. : McGraw-Hill, c2000.
2. G. P. Agrawal, Fiber-optic communication systems, Publisher New York : John Wiley, c2002
3. Hermann A. Haus, Waves and fields in optoelectronics, Publisher Englewood Cliffs, NJ : Prentice-Hall, c1984.

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