EEE6217: MSc EEE
Optical Communications and Optoelectronic Devices

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The ongoing update

- Credit: 15 (previously:10)
- Increase the contents for concepts and theories for optical communication part
- More information on optoelectronics for optical communication, in particular, III-nitride based optoelectronics
- Latest information on emerging applications and discussion of different types of optoelectronics

Policy on Hand-outs

- **I will print out enough hand-outs for everyone before the class**
- **I will throw away any copies not picked up at the end of the class**
- **I will not keep copies for you to pick up later**
- **I will put the lecture-notes in the web**

Objectives

- **Understand optical communication systems:**
  History, basic theory, structure, design

- **Understand basic theory of optical waveguide**

- **Understand each component and its operation mechanism**
  Optical fibre and accessories; Optical sources; Receivers; Optical amplifiers; etc

- **Understand the future development in optical communication**

Course Books

Systems/general:

“Optical Communication Systems” By G Gowar, Publisher - Prentice Hall

“Optical Fibre Communications” By JM Senior, Publisher – Prentice Hall

Opto-electronic Devices

“Semiconductor Opto-electronic Devices” By P Battacharya, Publisher – Prentice Hall

“Semiconductor Opto-electronics” By J Singh, Publisher – McGraw Hill

Better still – have a look around this class-mark in library - 621.3827

Course Organization – First Half

Topic 1	Introduction
Topic 2	Optical Fibre – Waveguide
Topic 3	Optical Fibre – Dispersion
Topic 4	Optical Fibre – Attenuation and Manufacture
Topic 5	Loss and Dispersion limit
Topic 6	Bit error
Topic 7	Optical amplifiers
Topic 8	WDM
Topic 9	System design
Topic 10	Optical fibre sensor technology
Topic 11	Visible light communication systems
Topic 12	Non line-of-sight communication

Course Organization – Second Half

Topic 13	Revision of Semiconductor Physics
Topic 14	LEDs- introduction
Topic 15	LEDs- Advanced LEDs
Topic 16	Introduction of III-nitride semiconductors & devices
Topic 17	III-nitride semiconductor based solid state lighting
Topic 18	White LEDs for visible light communication systems
Topic 19	UV-LEDs for non line-of-sight communication
Topic 20	LDs- introduction
Topic 21	Characteristics of LDs
Topic 22	Advanced LDs
Topic 23	Some issues on LDs
Topic 24	Low-dimensional LDs
Topic 25	Photodetector-1
Topic 26	Photodetector-2

What You Need to Know

- I will try to give background explanations as we go - I am aware there is a difference in experiences of the cohort
- Take a look at

  EEE207 “Semiconductor Electronics and Devices”;

  EEE118 “Electronic Devices”

- **Optics, refractive index, reflection, refraction, photons**
- **Interference, interferometers,**
- **Noise**
- **Basic semiconductor physics: energy bands**
- **Band-gaps, electrons, holes, dopants, optical transitions….**
- **So on….**

Topic 1

1. Introduction

1.1 Brief review of modern optoelectronics
1.2 History and current status of optical communication systems
1.3 Structure of optical communication systems
1.4 Advantages of optical communication systems
1.5 Requirements for optical communication systems

2. Review of the theory of electro-magnetic wave

Opto-Electronics

Opto-electronics play a revolutionary role in almost every aspect of the modern society

- **Information Technology and Telecommunications**

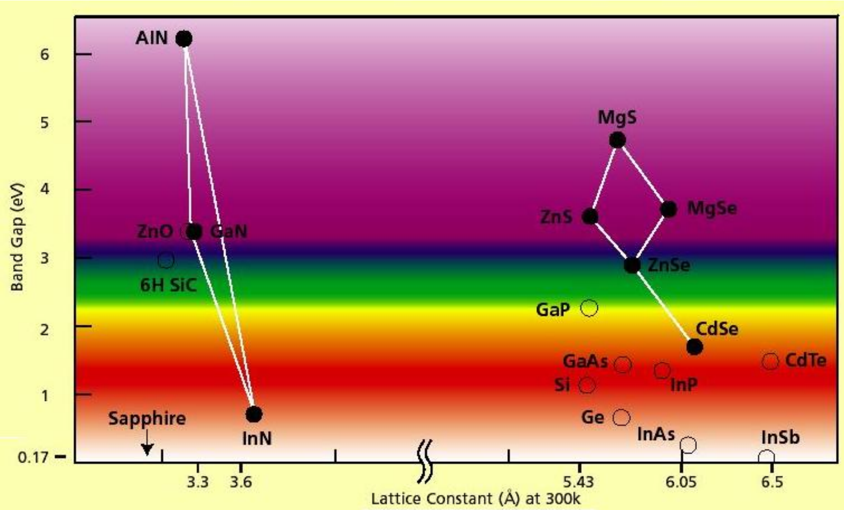
  Information storage, Display, **Information Transport/ Processing**
- **Health Care and Life Sciences**

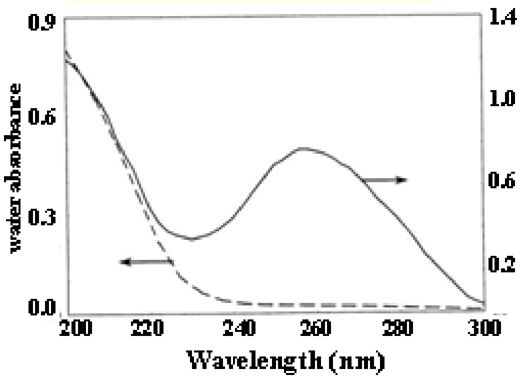
  Bio-image, Bio-detection, Surgery, etc
- **Sustainable & clean Energy and its Storage, Energy-saving**

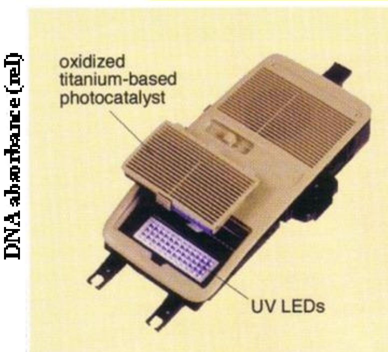
  Solid state Lighting, Solar-cell, Hydrogen-generation
- **Environmental Protection**

  Optical sensors, water-purifier, and air purifier
- **Security and Entertainment**

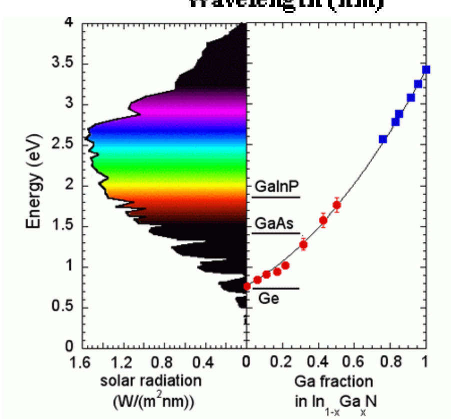
Opto-Electronics in Practical Applications

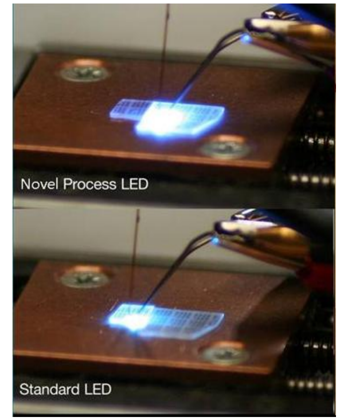






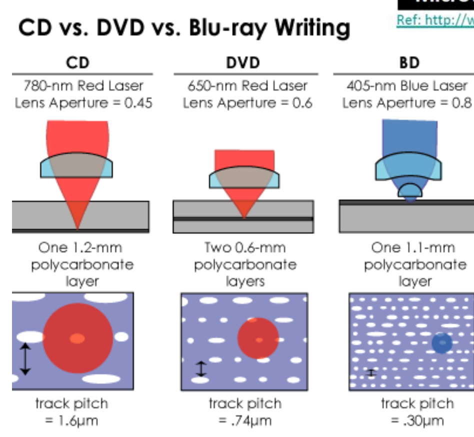
An photocatalyst purifier using Toyoda Gosei LEDs has been used in air conditioning systems in Toyota cars.

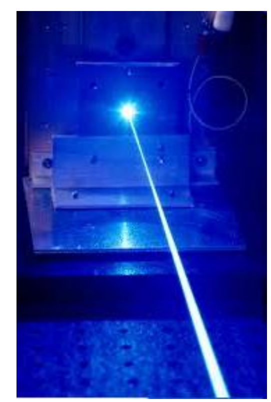




Ref: http://www.mitsubishi-tv.com/product/L65A90/

Ref: http://www.engadget.com/tag/microvision/

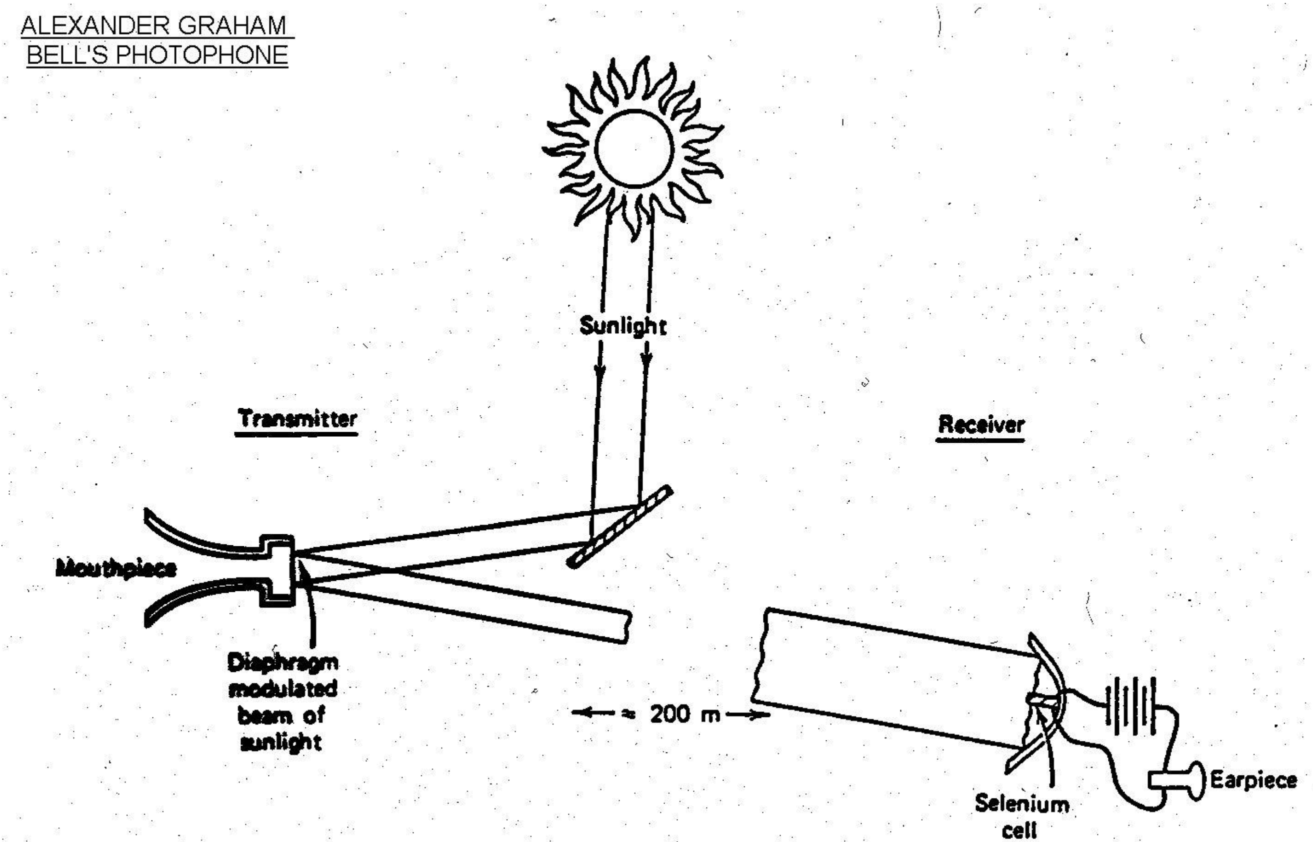




Optical communication (ancient time)

Using fire work to transmit information in China (3000 years ago)

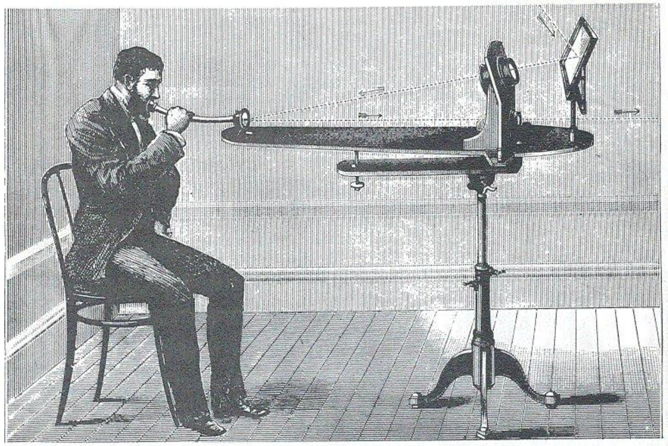
1880 - Bell's Photophone-precursor to optic communications



Selenium (at the focal point of its parabolic receiver): electrical resistance is higher when it is in the dark, and lower when it is exposed to light.

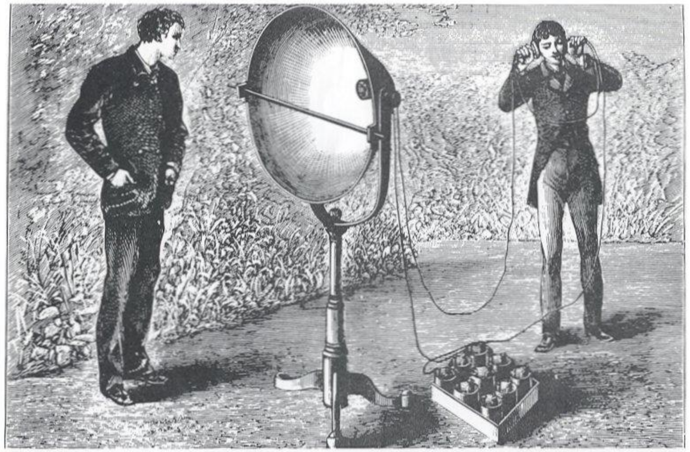
Modulation: transmitted light beam can be modulated using a mirror, where either concave or convex form can occur based on vibration by a person's voice, thus focusing or dispersing the light from the light source

Transmission System



The photophone of Bell and Tainter: the transmitter [1881]

200m of air

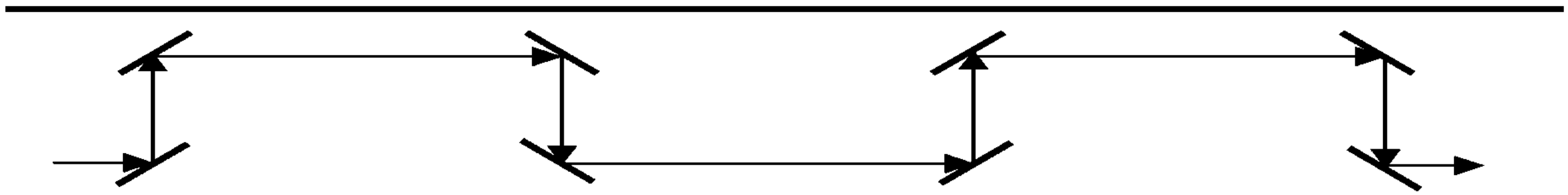


The photophone of Bell and Tainter: the receiver [1881]

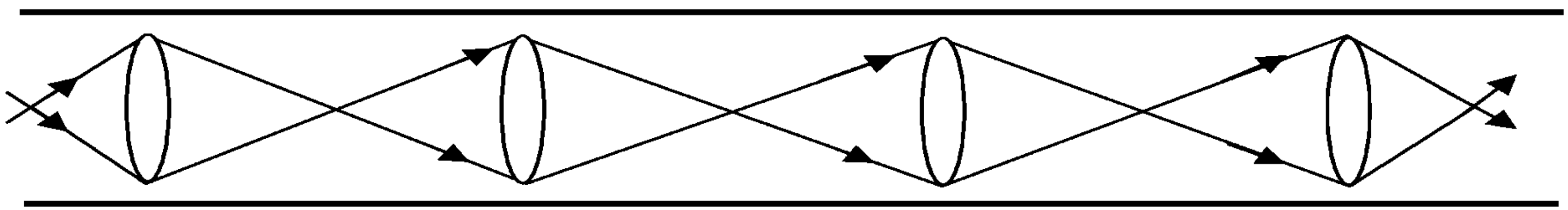
Transmitter, Receiver, transmission medium – air

- **For Fibre Optics: transmission medium is glass (SiO_2)**
- **2 major technological breakthroughs: laser diodes (semiconductor) and optical fibre**

Other Kinds of Optical Communication

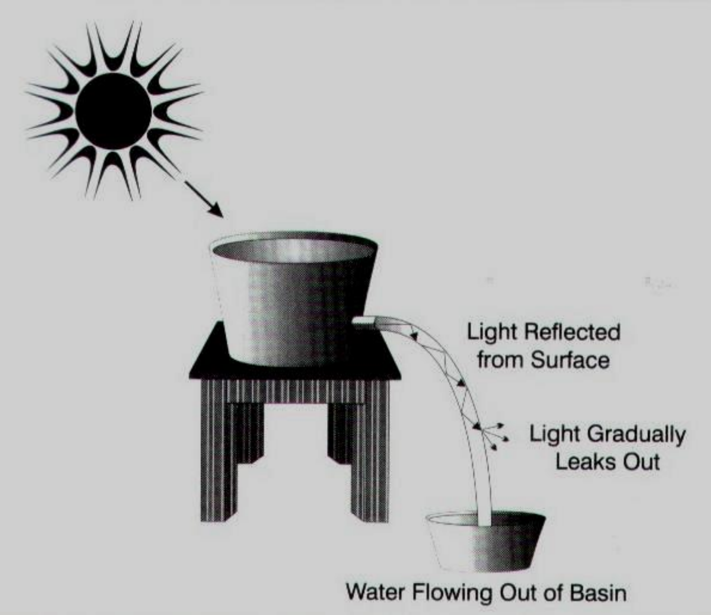


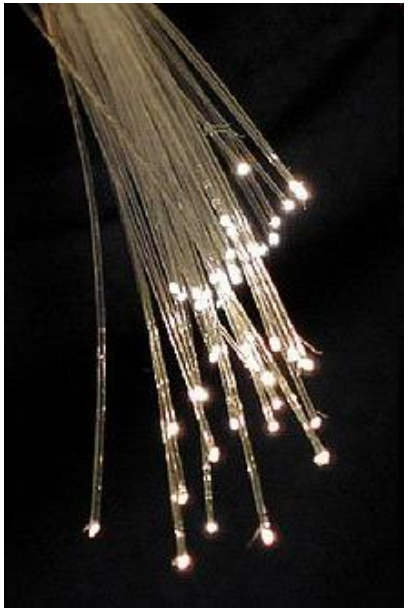
Reflection waveguide



Optical lens waveguide

Very expensive, difficult maintenance, and thus not practical





1953- Dr Kapany (Imperial College) invented a very basic optical fibre, consisting of two materials with different refractive indice, where light can be transmitted inside

However, the loss is around **1000 dB/km** (**$dB=10\log_{10}(P_{in}/P_{out})$**) with then best sample, and thus can not be used for optical communication (only used for Endoscopy)

The Nobel Prize winner in Physics 2009

“for groundbreaking achievements concerning the transmission of light in fibers for optical communication”

Charles K. Kao, Born in 1933 (Shanghai, China)
Ph.D in 1965, UCL

Kao, K. C.; Hockham, G. A. (1966). "Dielectric-fibre surface waveguides for optical frequencies". *Proc. IEE* **113** (7): 1151–1158.

Two major breakthroughs:

- Calculated how to transmit light over long distances via optical glass fibres.
- Purifying the existing optical glass fibres would be possible to transmit light signals over **100 km**, compared to only **20 m** for the fibres available in the 1960s.

History in developing modern optical fibre

Based on Kao's theory, Corning company in USA used MOCVD to fabricate 1st low-loss optical fibre

Before 1970:	**1000 dB/km**	
1970:	20 dB/km	(1/100)
1972:	4 dB/km	(1/2.512)
1973: (Bell)	2.5 dB/km	(1/1.778)
1974: (Bell)	1.1 dB/km	(1/1.288)
1976: (NTT)	0.47 dB/km	(1/1.114)
1979:	0.2 dB/km	(1/1.047)
1990:	0.14 dB/km	(1/1.033)

Current: **0.1 dB/km (1/1.023)**, close to the theoretical limit

Another major breakthrough in 1970s

Optical source: laser diodes

1970: Bell (US), NEC (Japan)

DH GaAlAs Based Laser Diodes with a life time of a few hrs

1973: Lifetime of 7000 hours

1976: NEC (Japan) reporting 1.3 μm InGaAsP laser diodes

1977: Bell (US) reporting a laser diode with a lifetime of 10,000 hrs

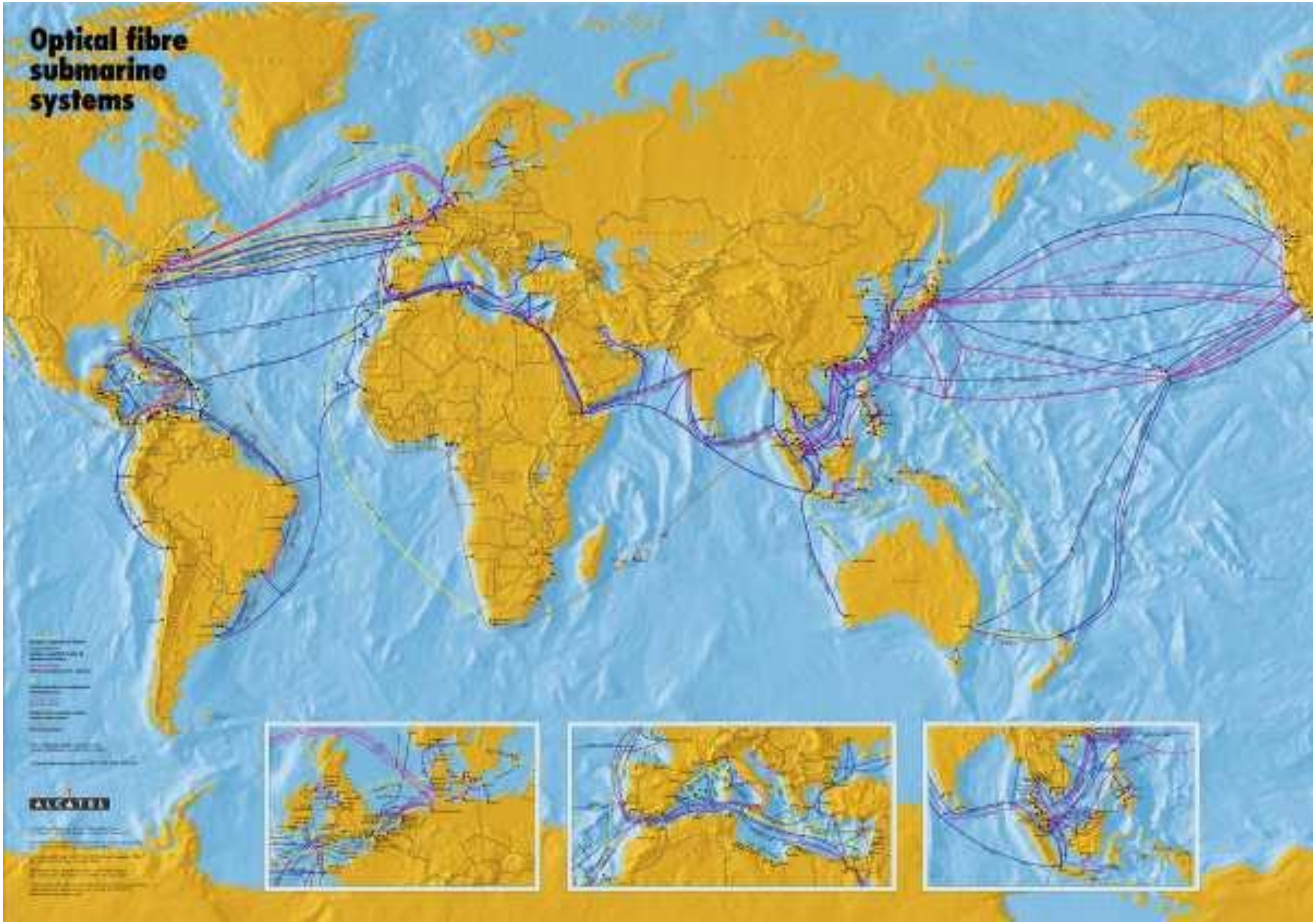
1979: AT&T (US) and NEC (Japan) reporting 1.55 μm laser diodes

Why are laser diodes with a wavelength of either 1.3 μm or 1.5 μm so important for optical communication ?

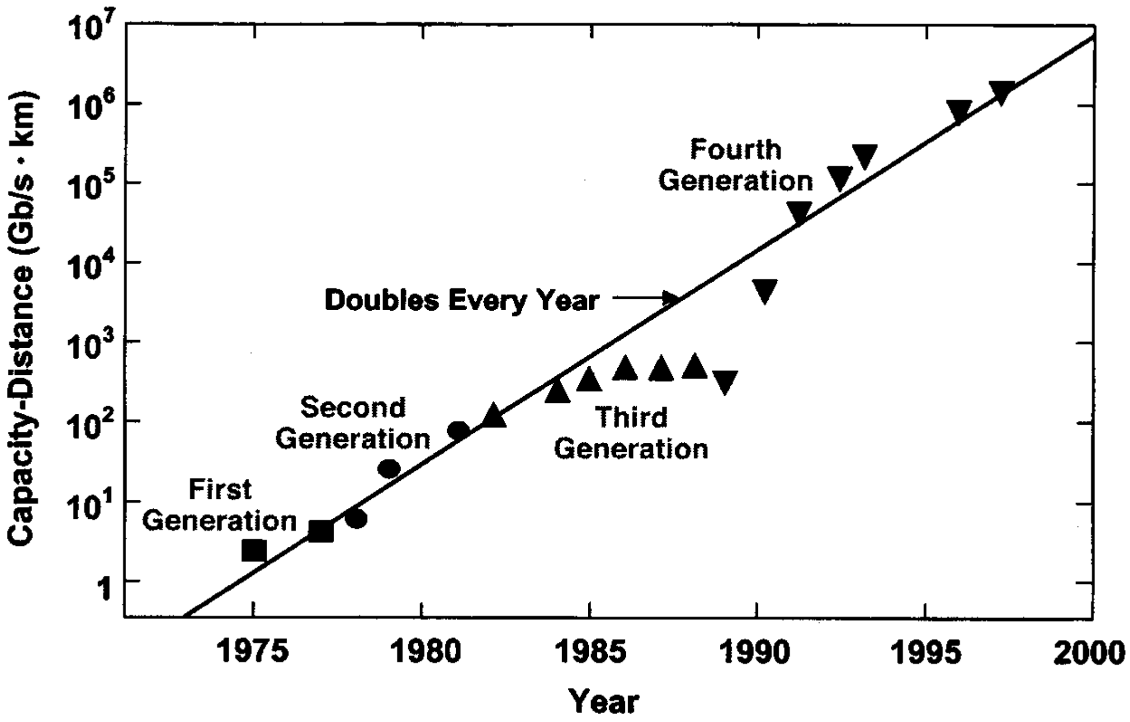
History of developing optical communication system

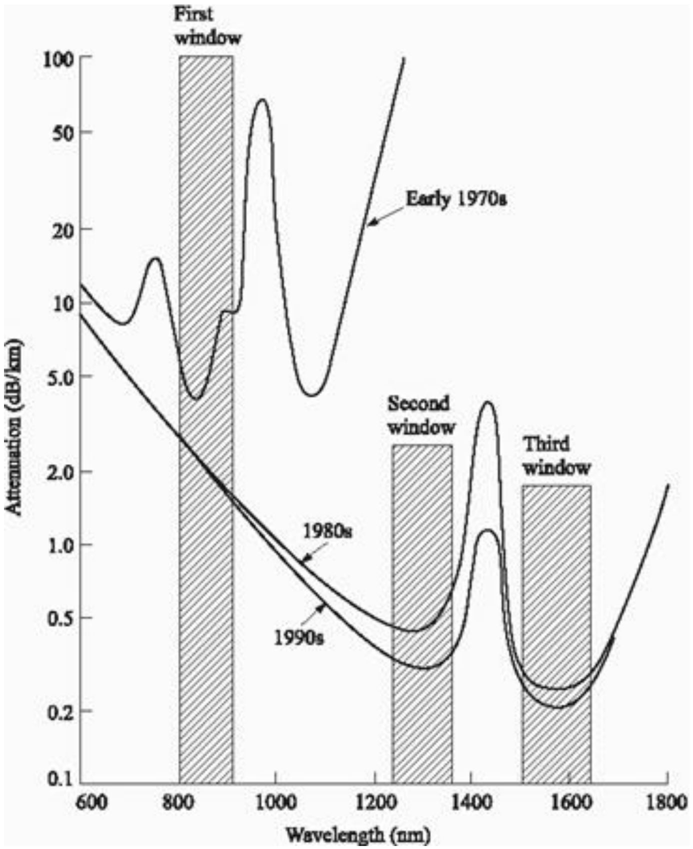
1976:	Test of 1st optical communication system in Atlanta, US
1980:	Commercialization of FT – 3 system, US
1976-1978:	Test of multiple-mode system with a Bit rate of 34Mb/s (step index) and 100Mb/s (graded index)
1983:	1st optical cable in Japan
1988:	1st TAT -8 submarine system across Atlantic Ocean
1989:	1st TPC-3/HAW-4 submarine system across Pacific *Ocean*

Submarine Systems



History of Modern Optical Communications





1966-1979: GaAs-LD (0.8 μm), multiple-mode, Bit-rate 10~100 Mb/s, 10 km

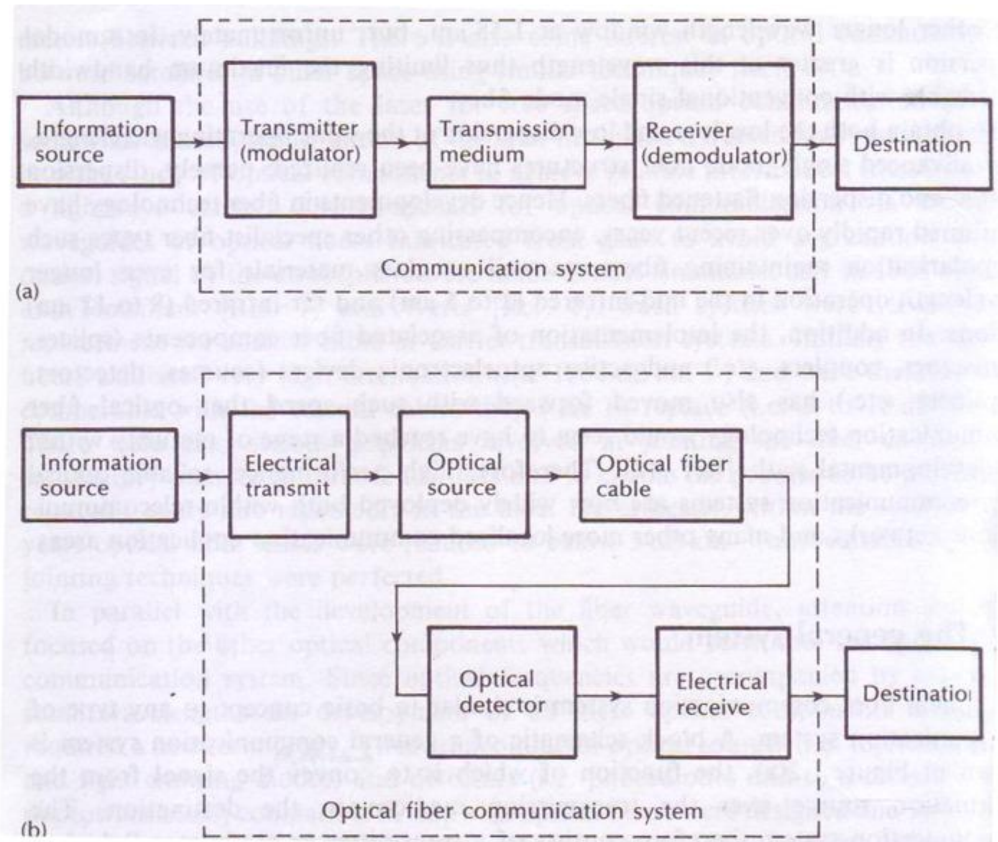
1980-1985: InGaAs-LDs (1.3 μm), single-mode, Bit-rate 2.0Gb/s, 50km

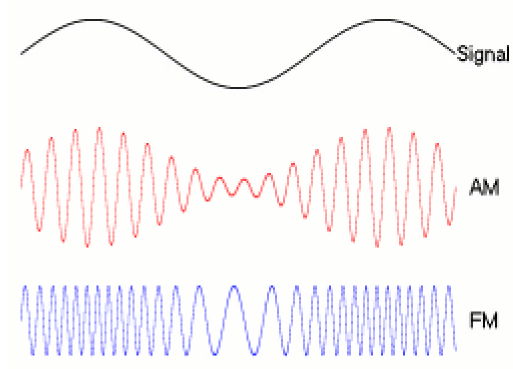
1985-1990: InGaAsP (1.55 μm), single-mode, Bit-rate 2.5~10 Gb/s, 100 km

After 1990: InGaAsP (1.55 μm), single-mode, Bit-rate 2.5~10 Gb/s, **14000 km**

Communication system

Communication: signal transmitted from one to another place





Modulation: process of varying one or more properties of a high-frequency periodic waveform (*carrier)*, with a *signal* containing information to be transmitted
For example: radio and TV

Ideally: **1 More information (bandwidth, high frequency)**
2 Long distance and fast
3 High security and safety
4 Signal remaining high quality

Advantages of Optical Fibres

- **Enormous potential bandwidth**
- **Small size and light weight**

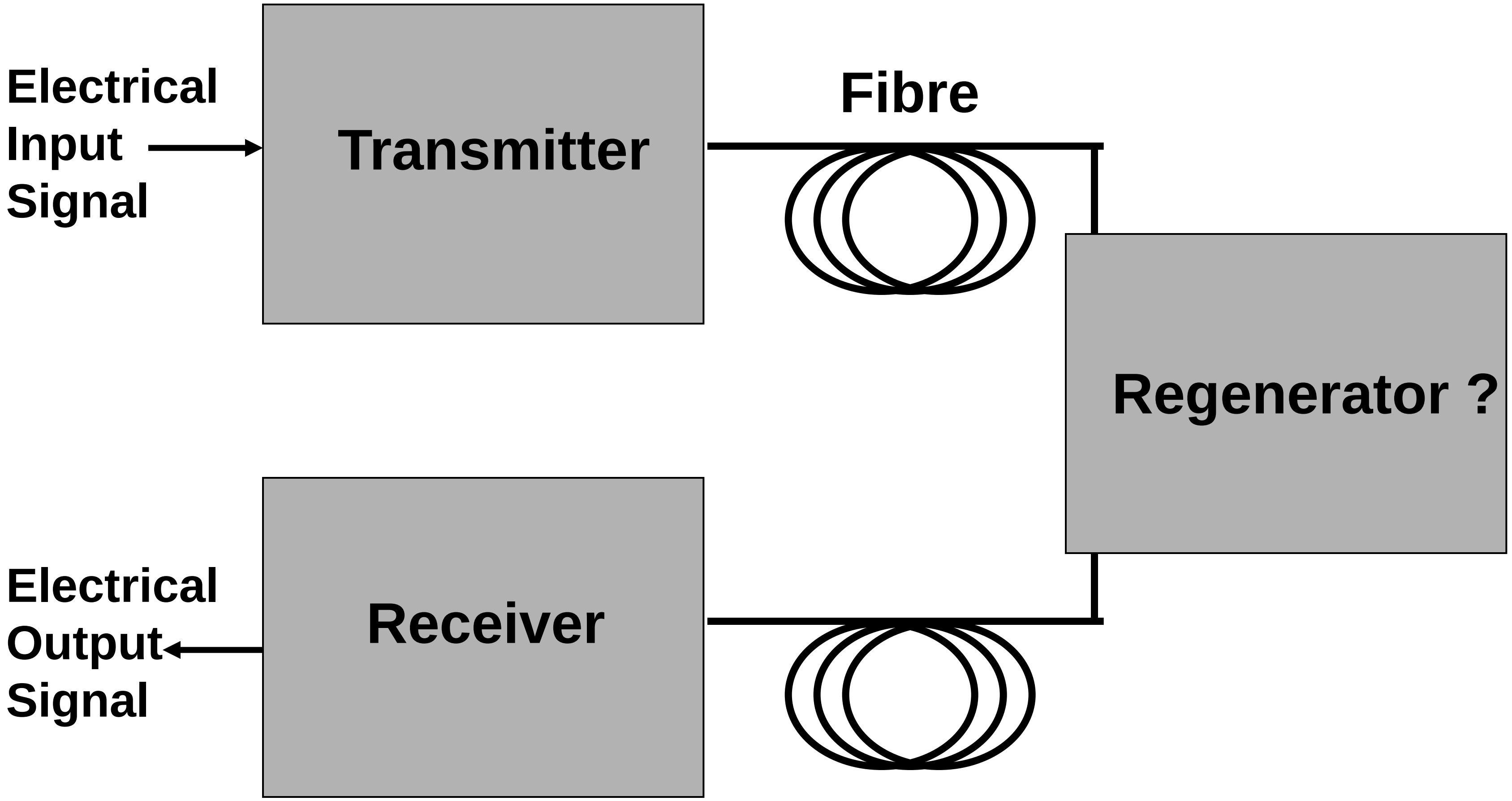
  similar performance: metal cable 11 kg/m, while 90g/m for optical fibre
- **Electrical isolation:**

  Glass**:** insulating material
- **Signal Attenuation**
  – Silica glass fibres have attenuation less than 0.2 dB/km
    - Only need signal repeaters every 30 km or so.
    - This is 5-15 times better than copper cables!
- **Electromagnetic Interference**
  – Optical Fibres immune to electro-magnatic interference (EMI).
    - Can be used in electrically noisy environments
    - Good for secure info transmission as no EM radiation leakage**.**

Disadvantages of Optical Fibre

Mechanical properties:	**fragile**
Connection:	**difficult, leading to loss in signal**
Moisture:	**leading to optical loss due to OH-**
Bending:	**leading to optical loss**

Optical Fibre System



Fibre Optic System Design

Design Variables;

System - configuration, signal coding, data rate, BER, multiplexed?, switching requirements,

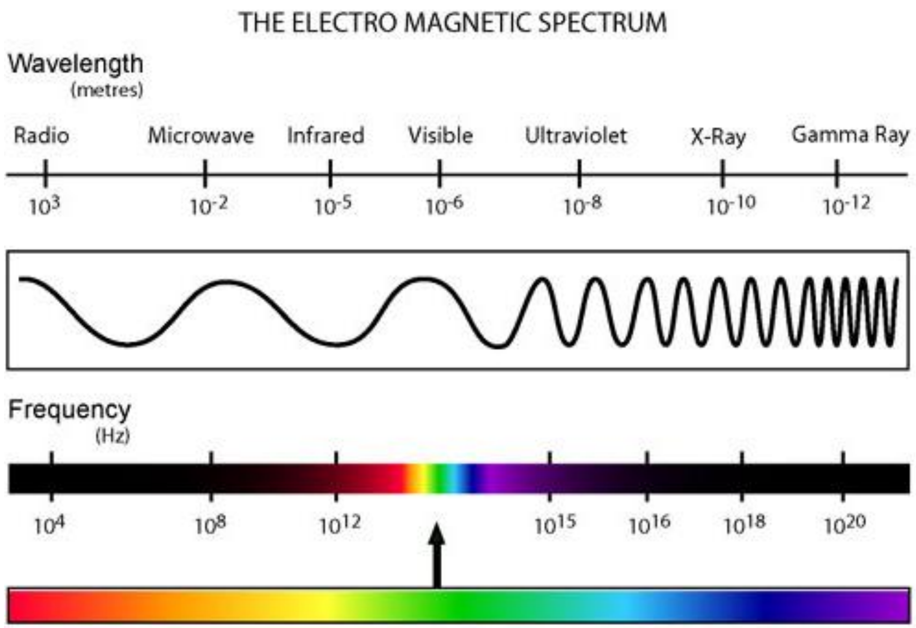
Transmitter – output power, divergence, spectral linewidth, response time, wavelength, direct/indirect modulation?

Fibre – type (single/multimode), core diameter, NA, coupling losses between Tx and fibre, attenuation, dispersion, number of splices & couplers, etc.,

Receiver – response time, bandwidth, sensitivity

Regenerators Required – what type?

Light



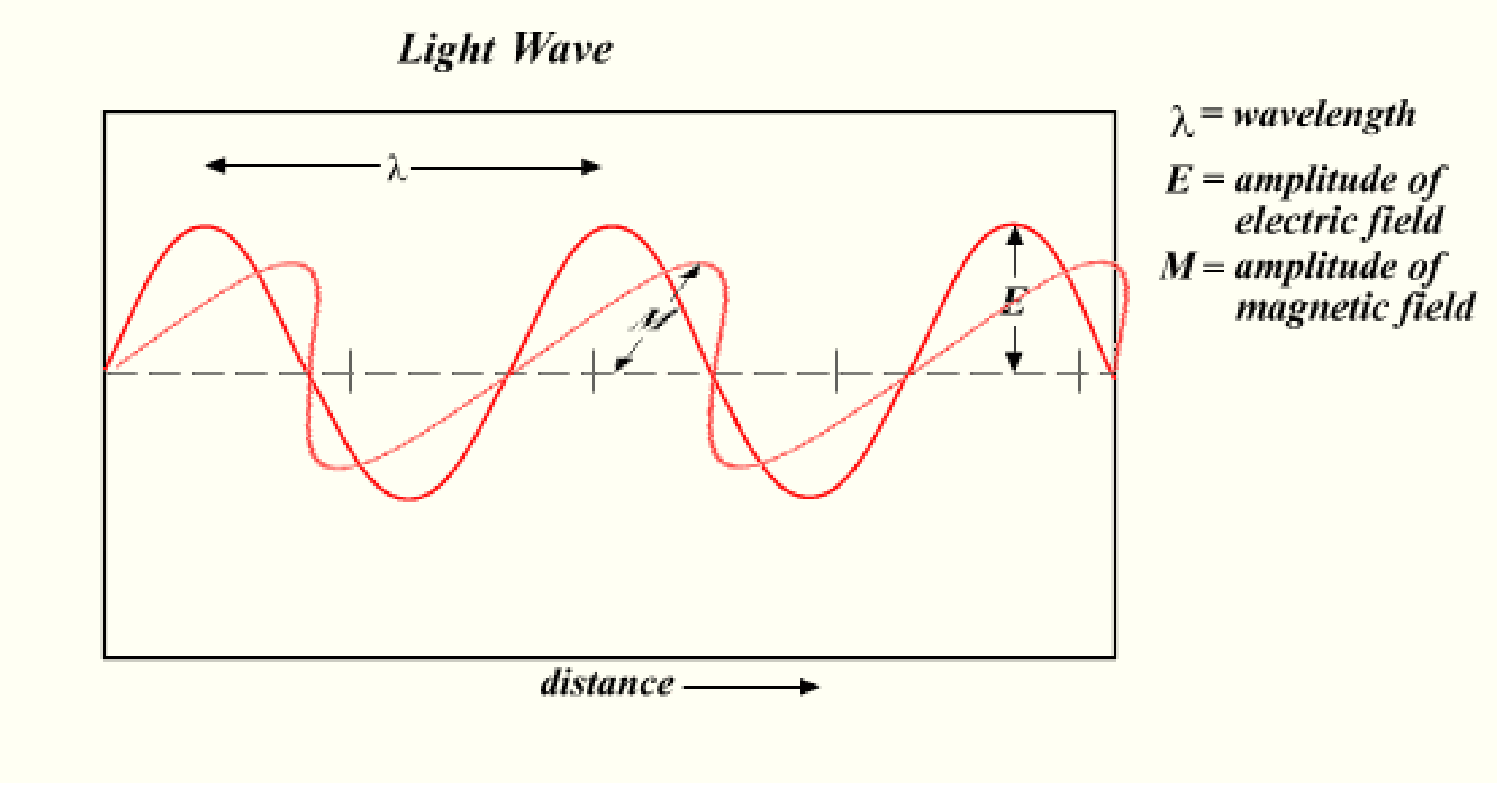
- Light can be described both as a particle and a wave
- Light: electro-magnetic wave
- Energy (E) and Momentum (p):

  Special relativity gives $E^2 = c^2p^2 + m^2c^4$

  Photon has no mass (m): $E=cp$

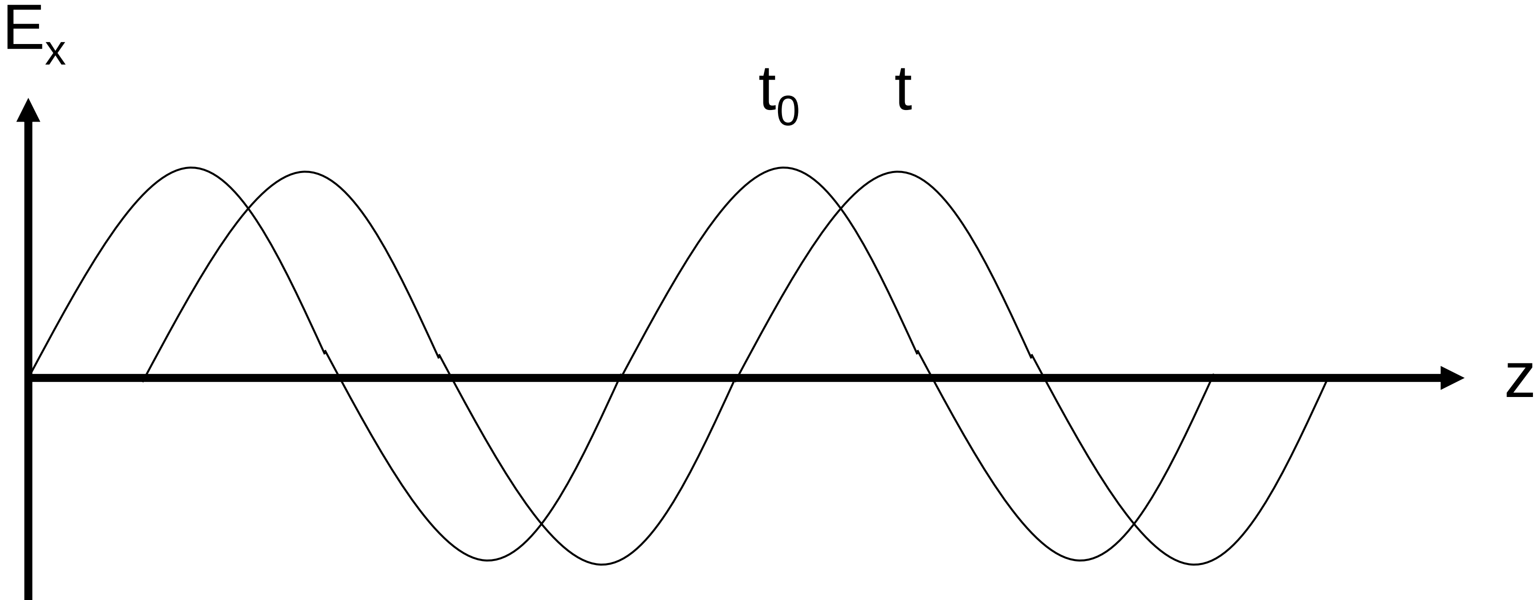
  $E=hf$; $c=\lambda f$, where c: speed of light; λ: wavelength; f: frequency

Light as an 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

Electromagnetic Waves - Monochromatic



$$E_x = E_0\, e^{\,i(\omega t - kz)}; \text{ or } E_x = E_0 \sin(\omega t - kz)$$

E_0:	**Electric field amplitude**
f:	**frequency**
$\omega=2\pi f$:	**angular frequency**
$K=2\pi/\lambda$:	**propagation constant or wave number**

Maxwell's Equations

The behavior of electro-magnetic waves obey a set of four equations, which are called Maxwell's Equations.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

E: electric field
B: magnetic field
ε_0: vacuum permittivity
μ_0: vacuum permeability

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

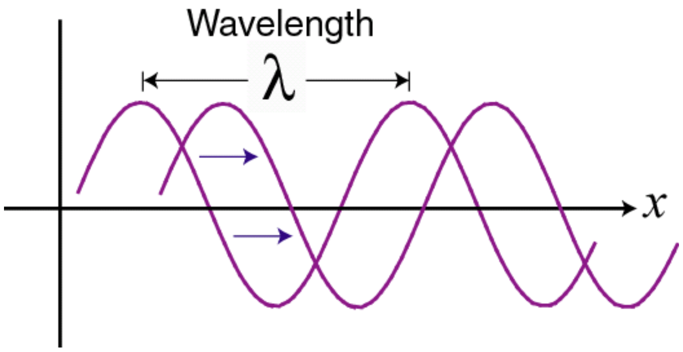
Phase Velocity

Phase velocity:

the rate at which the phase of the wave propagates in space

Phase velocity:

wavelength(λ) / period(T)



- $\mathbf{v} = \lambda / T; f = 1/T$:

  $$\boxed{v = \lambda f}$$

- $k = 2\pi / \lambda, \ \omega = 2\pi f = 2\pi / T$

  $$\boxed{v = \omega / k}$$

EM propagation in a medium (refractive index)

In a non-vacuum, EM wave must still satisfy Maxwell's Equations, where the propagation of the EM wave will become slow as a result of the interaction between the EM wave and the medium.

The interaction between the EM wave and the medium can be described by relative permittivity and relative permeability of the medium

$$v = \frac{1}{\sqrt{\mu_0 \mu \varepsilon_0 \varepsilon}}$$

Refractive index: is defined as the ratio of the velocity in free space to the velocity in the medium:

$$n = \frac{c}{v} = \sqrt{\varepsilon \mu}$$

n: **a fundamental parameter of a medium and also a function of ω**

EM propagation in a medium (refractive index)

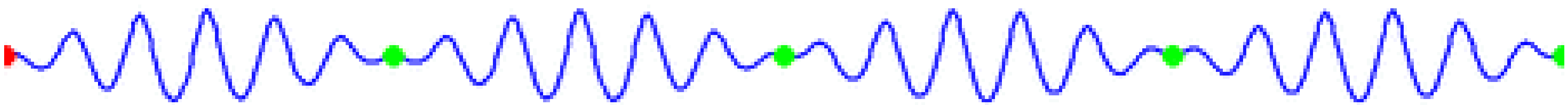
In a dielectric medium:

$$K_{medium} = nK_{vacuum}$$
$$\lambda_{medium} = \lambda_{vacuum} / n$$
$$f_{medium} = f_{vacuum}$$
$$v = c / n$$

Frequency remains unchanged in different mediums,
c: velocity in the vacuum

Refractive index:
(1) Crystal: anisotropic, as it depends on the direction where the interaction between EM wave and crystal depends on crystalline orientation
(2) Non-crystalline material: material properties and structures are isotropic, and therefore, the interaction between EM wave and the non-crystalline material does not depends on direction

Group Velocity-I



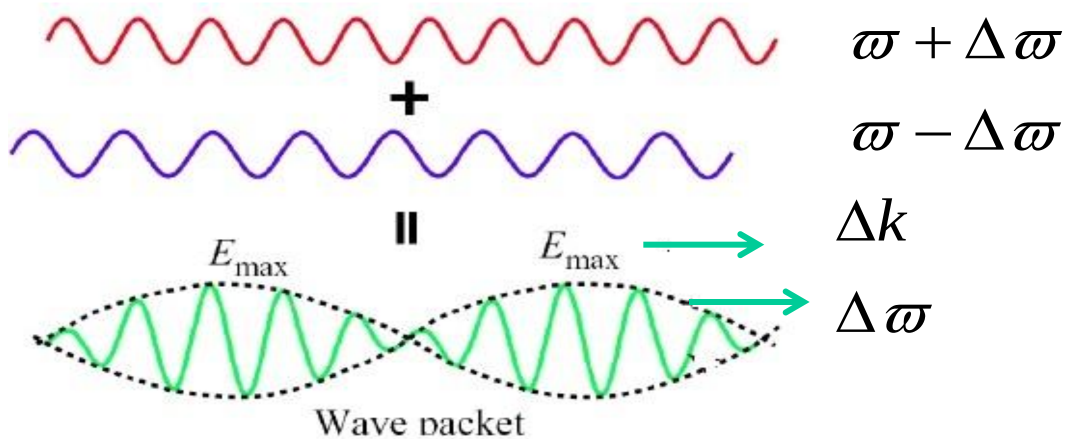
- **There is no perfect monochromatic wave (pure single frequency), and thus group velocity needs to be introduced.**
- **Group velocity describes the speed of propagation of a light pulse or packets of light.**
- **For example**: two waves with frequencies **ω-Δω and ω+Δω**, wave-numbers **k -Δk and k +Δk**, assuming having a same electric field amplitude simply for mathematical process

$$E_{x1} = E_0 \cos[(\varpi - \Delta\varpi)t - (k - \Delta k)z]$$

$$E_{x2} = E_0 \cos[(\varpi + \Delta\varpi)t - (k + \Delta k)z]$$

Group Velocity-II

$$E_{x1}+E_{x2}=E_0\cos[(\Delta\varpi)t-(\Delta k)z]\cos(\varpi t-kz)$$

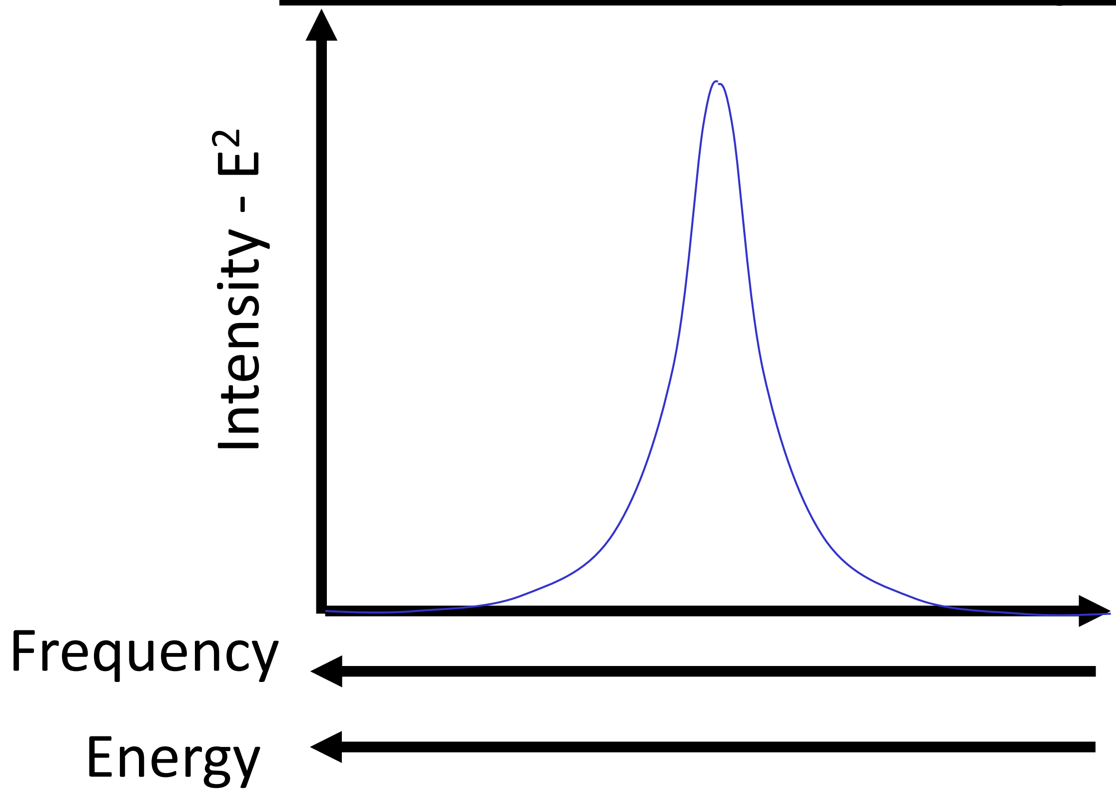


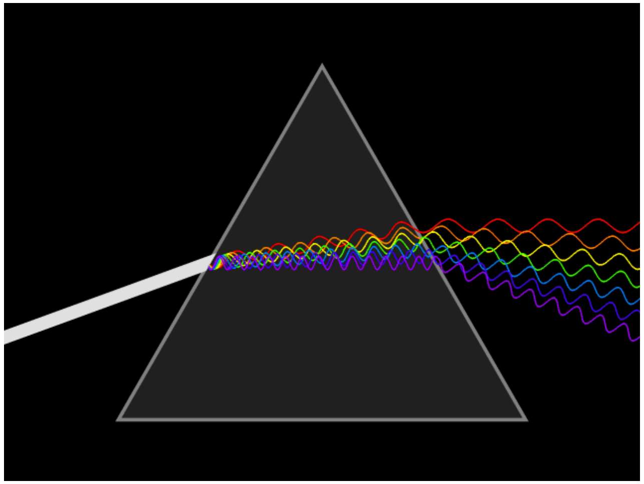
- Generate a wave packet :
- Two parts from the above expression:

  (1) The maximum amplitude propagates with a wave-number of Δk and a frequency $\Delta\omega$ (Ref: a single frequency wave: constant amplitude)

  (2) The group velocity: **speed of the envelope of** the amplitude variation; namely, speed with which energy is propagated $\boxed{v_g=\dfrac{d\varpi}{dk}}$
- For comparison: phase velocity $\boxed{v_g=\dfrac{\varpi}{k}}$
- In the vacuum: group velocity = phase velocity

Modulation or Envelope of Wave





- We have a speed for an EM wave.....
- At what speed does the information travel?
- In dispersive media (all except vacuum) different wavelengths may travel at different velocities

T1 Summary - Light Propagation

- Light can be considered as a wave
- Governed by Maxwell's equations
- For monochromatic wave in media can define a phase velocity = c / n_{phase}
- For non-monochromatic light, the wave packet travels with the phase velocity only if n_{phase} is not a function of wavelength.
- This is not the case for silica (glass) so introduce n_{group}
- Group velocity = c / n_{group}

T1 - Tutorial Questions

- Define phase velocity
- Define group velocity
- When are they equal and not equal ?
- What is the consequence of the later case?

- A 1 hour lecture script is stored on a computer hard disk in ASCII format (i.e. 1 character = 8 bits). Estimate the total number of bits assuming 200 words per minute and an average of 5 letters per word. How long will it take to transmit the data ata bit rate of 1GBit/s?