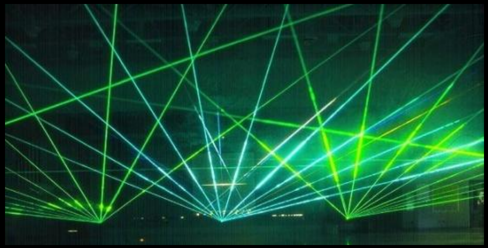
OPTOELECTRONICS AND PHOTONICS

WHAT IS OPTOELECTRONICS?

The Optics Revolution

1960 The beginning of the 20th century optics renaissance…



1998 Dawn of the optics revolution…

National Report Predicts Optics Revolution

May 15, 1998

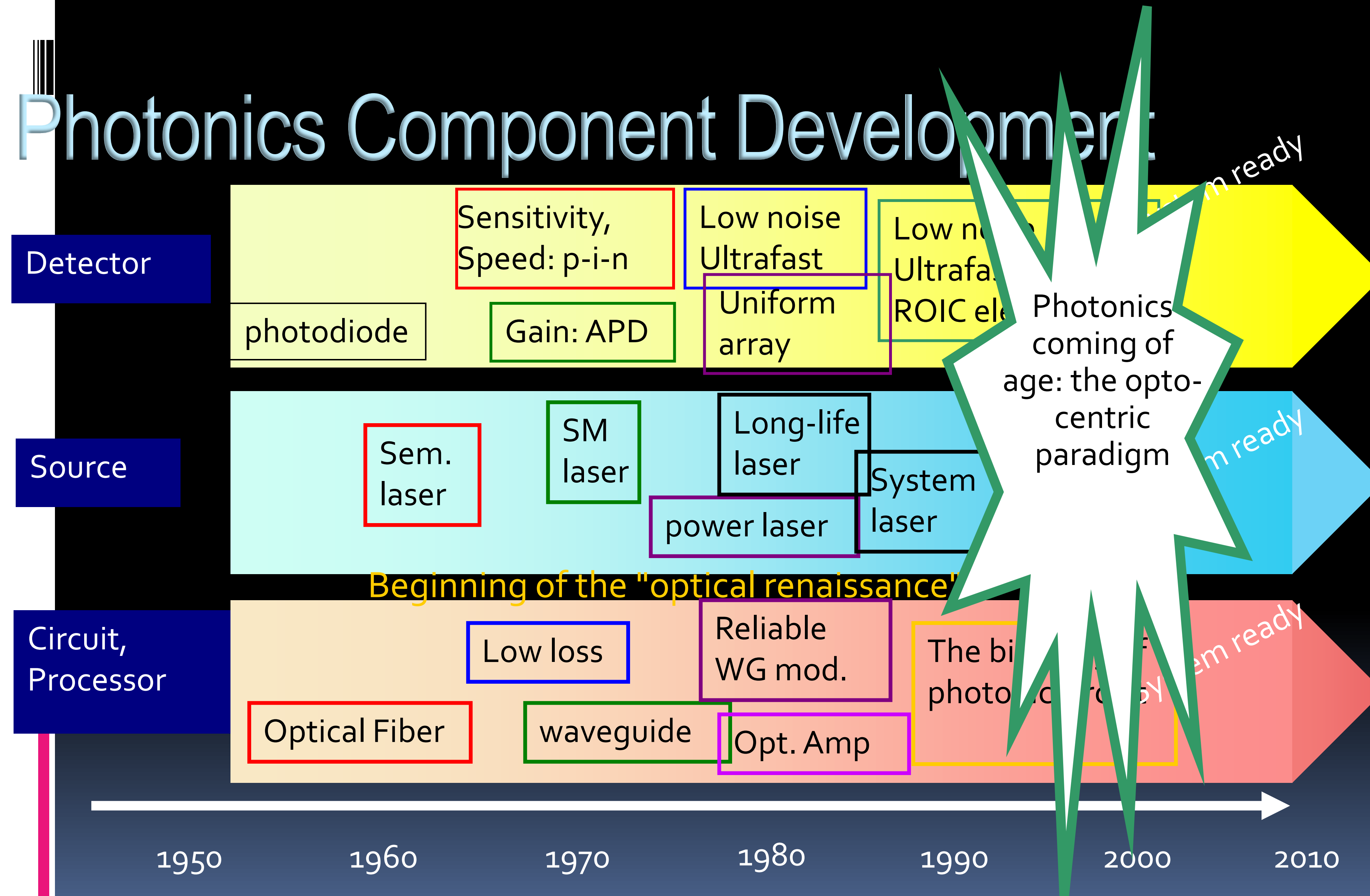
National Research Council

HARNESSING LIGHT

Optical Science and Engineering for the 21st Century

Source: Han Le & Assoc

Photonics Component Development



INFORMATION TECHNOLOGY

Charge of the Light Brigade

1/31/00

Next-generation optical gear is entering the local market

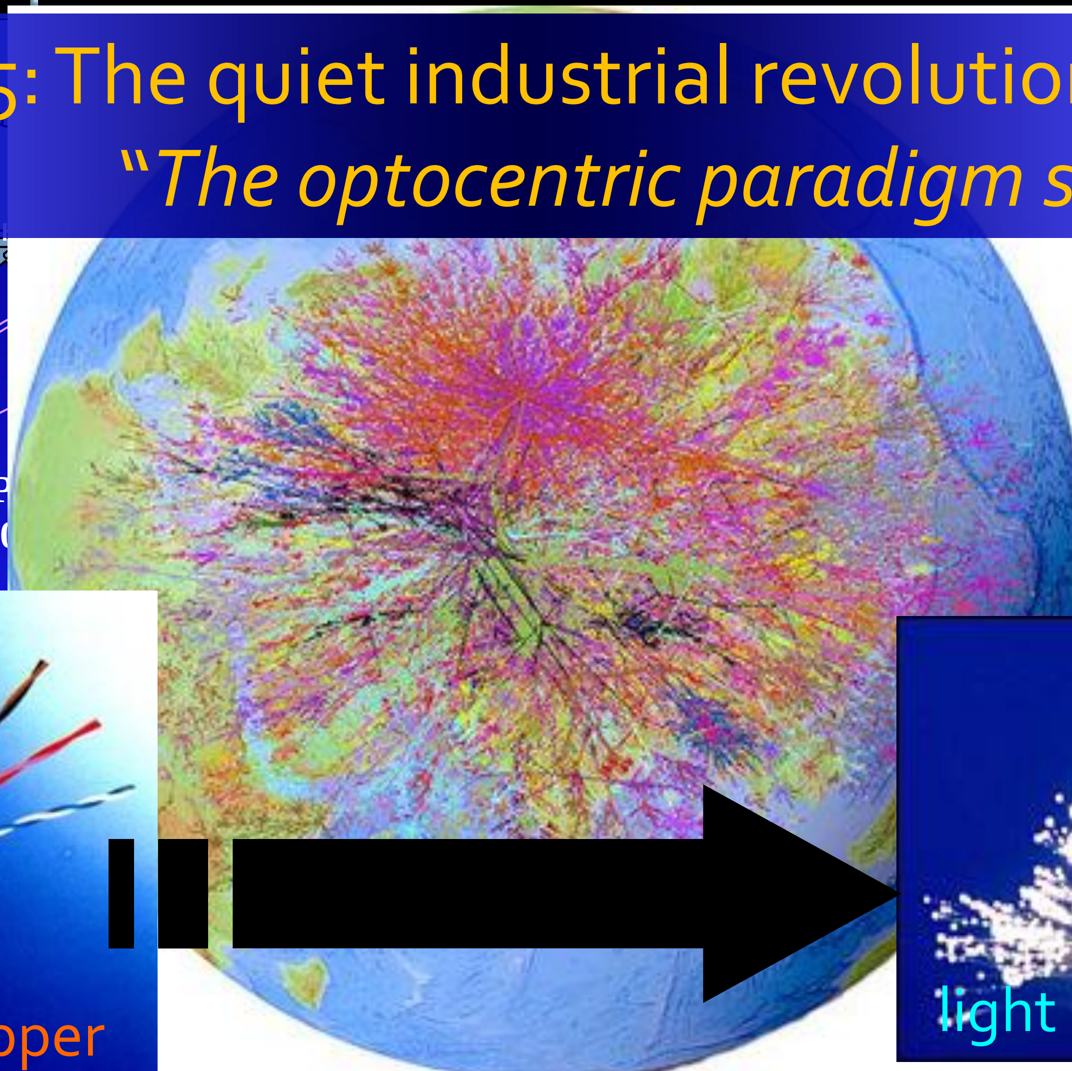
"… Over the past year, optical-networking companies have become the darlings of the technology world…"

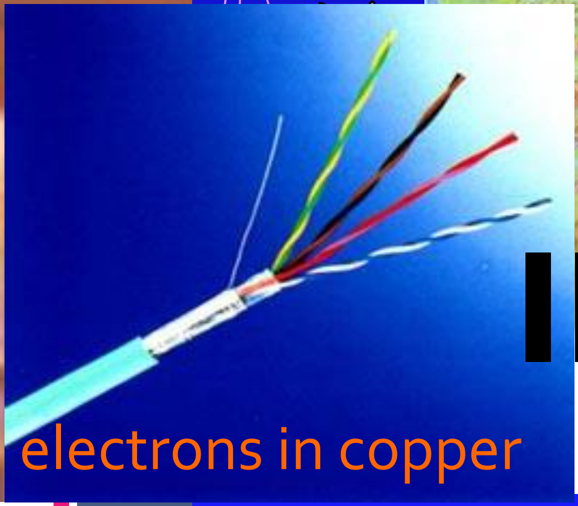
The technology could be crucial in realizing the promise of the Internet. Optical technology has the potential to boost the capacity of telephone companies' networks a millionfold. "'You're not going to be a player in the next generation without optics,"' says Michael O'Dell, chief scientist at MCI WorldCom Inc.'s UUNet Internet unit. "It's life and death." – 1/2000

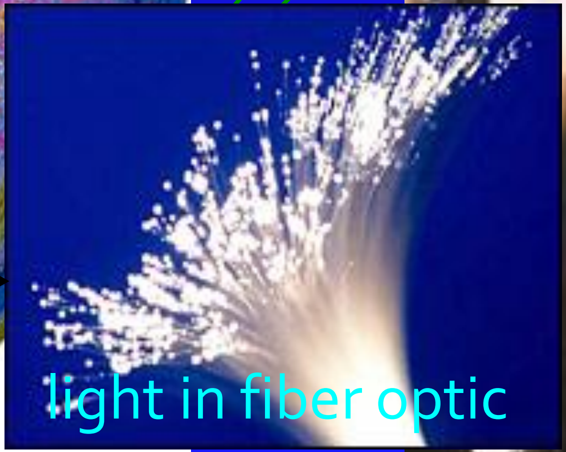
The Optical Internet and Telecom World

1999-2005: The quiet industrial revolution:

"*The optocentric paradigm shift*"

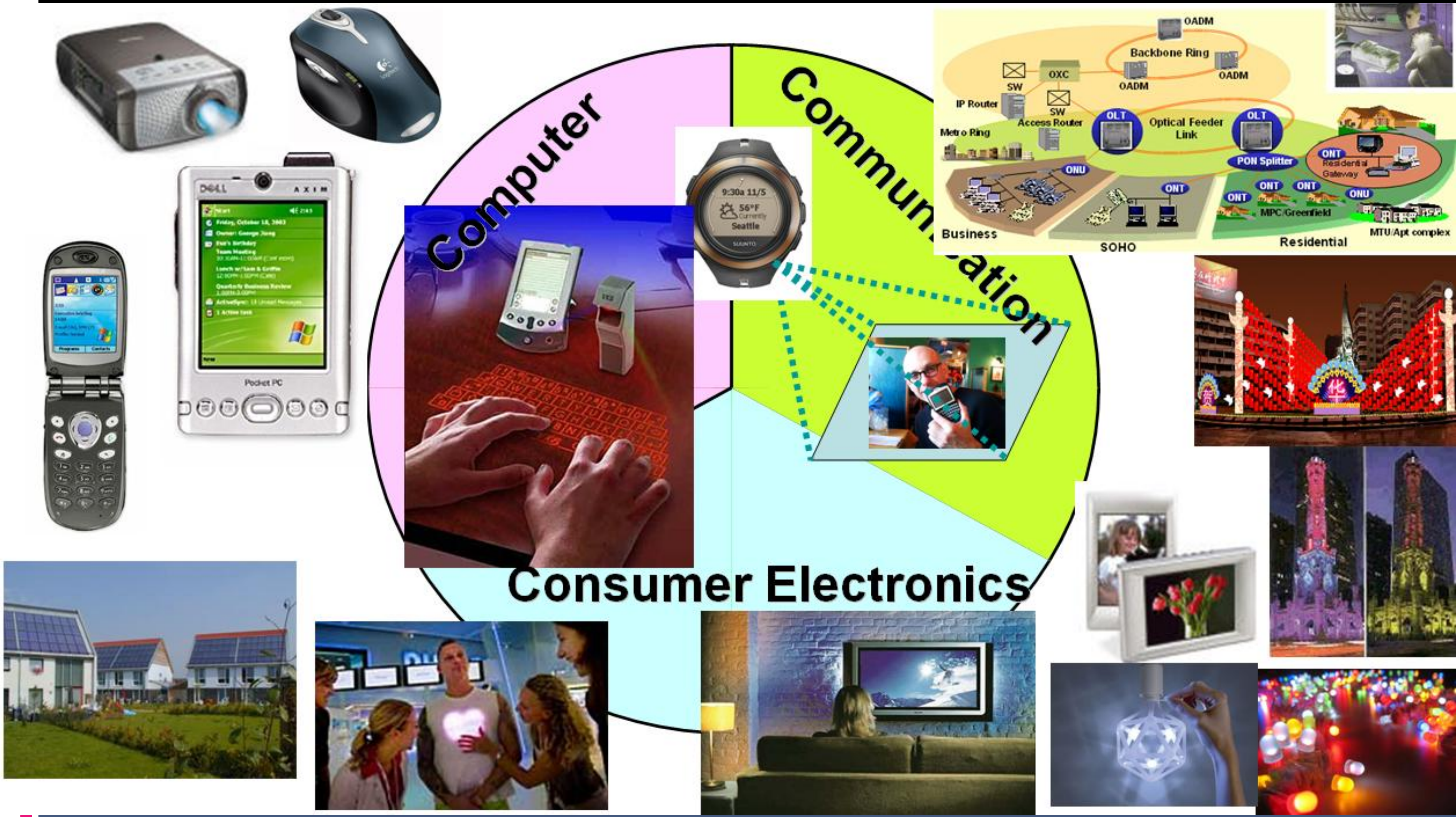






Source: Han Le & Assoc

The Second Optics Revolution...



ource: Michael Lebby – US-OIDA
Han Le & Assoc

Link: From Japan OITDA

Optoelectronic Devices

- Light-to-current conversion:

  Photodiodes, photodetectors

  - p-i-n, (*why need i*?) dark current, I-V curves, photovoltaic current sources
  - APD, avalanche region, gain, multiplication factors

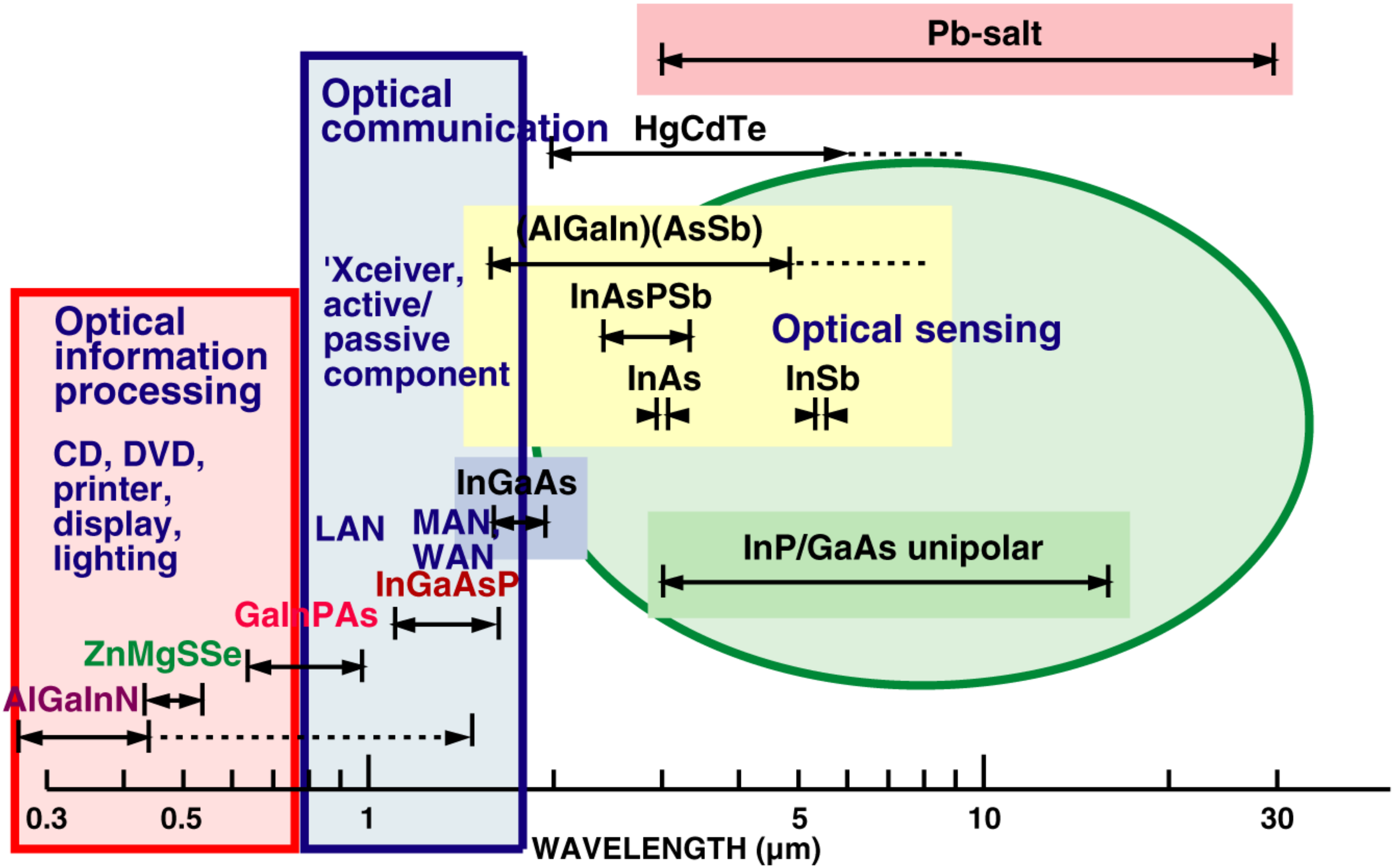
  Power devices: solar cells

- Current-to-light conversion: LEDs, lasers, optical amplifiers*: Fluorescence, optical gain, stimulated emission, coherent radiation, threshold, efficiency*

- Electric field/light interaction effects: Electro-optic modulator, electroabsorption modulator (LCD for example)

- Photonic circuits: light conditioning, manipulation structure

Wavelength of semiconductor photonic devices
(emitters, detectors, amplifiers/modulators, energy converters,...)



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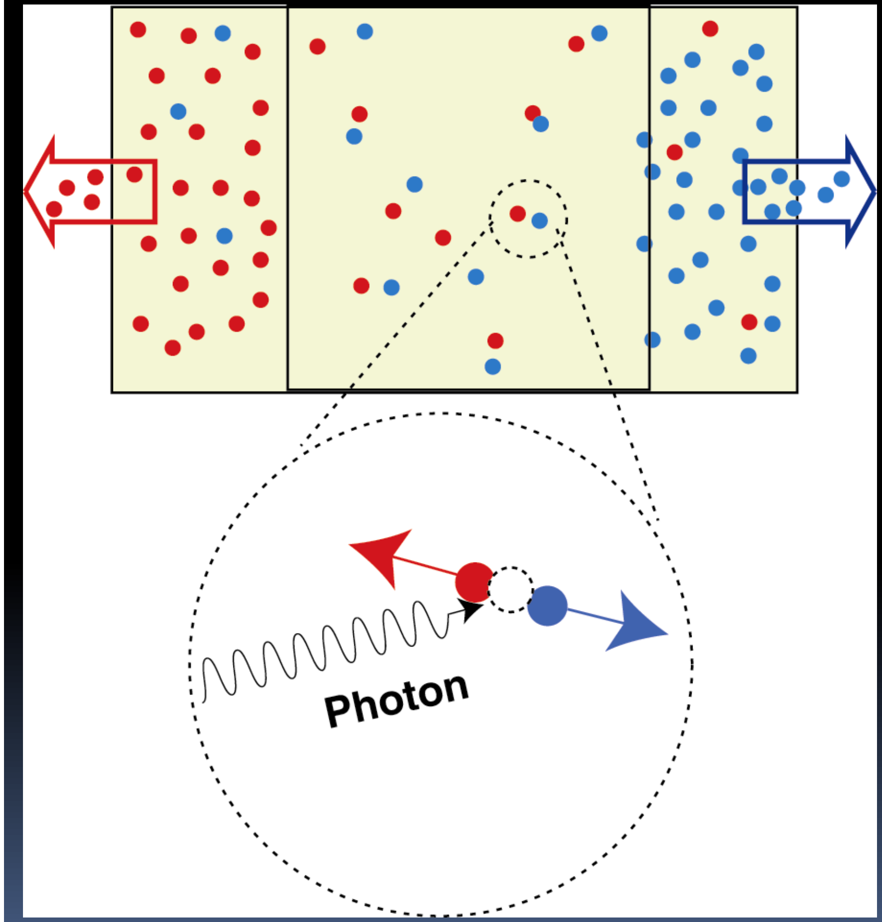
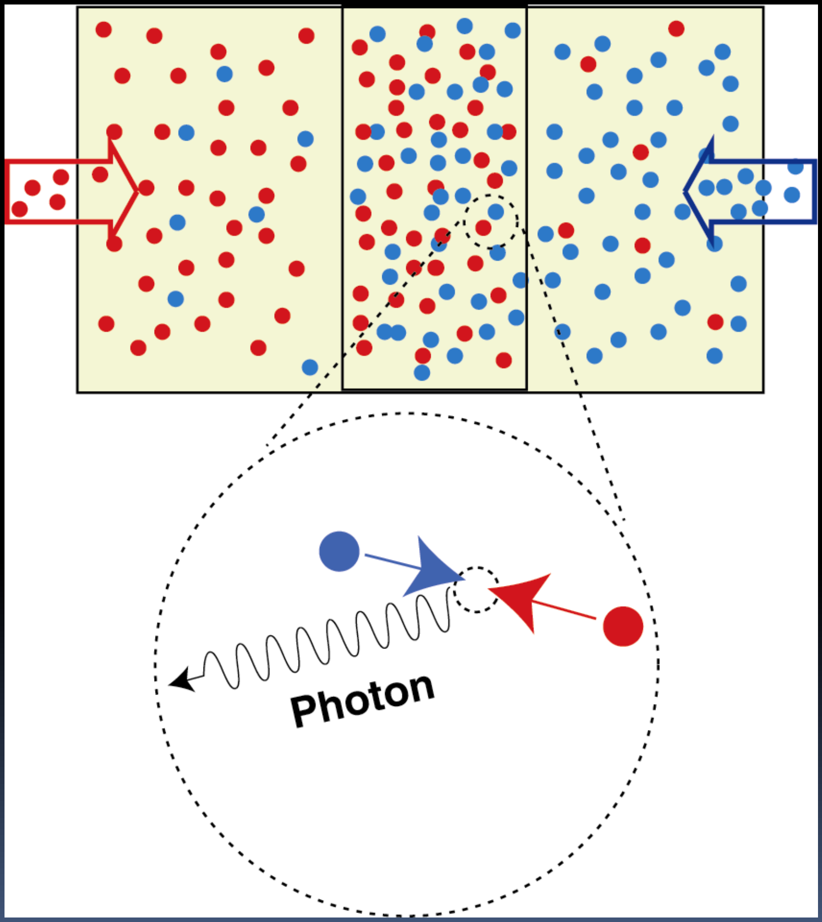
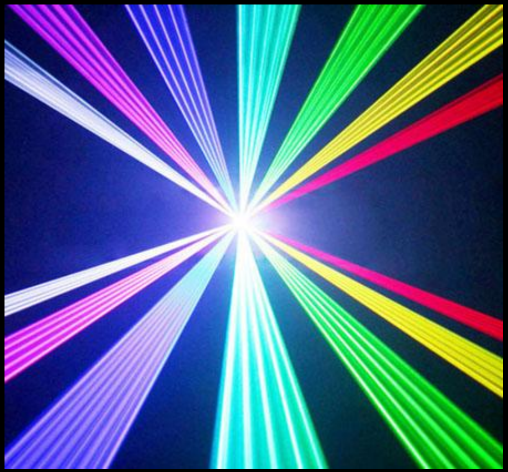
Comparison of Photodiodes and Light Emitters



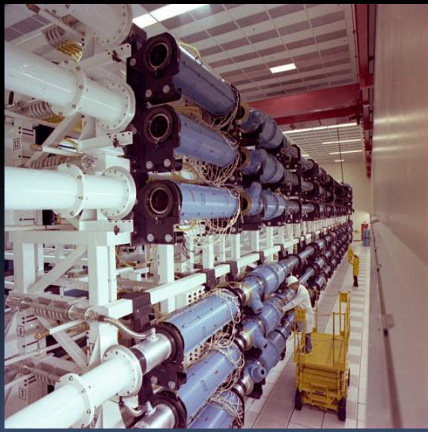


Where is the depletion width?



ECE 6323

LIGHT SOURCE: THE LASER P.1



Laser Primer

- Introduction
- Fundamentals of laser
- Types of lasers
- Semiconductor lasers

What is laser?

- Is it… Light Amplification and Stimulated Emission Radiation?

No…. So what if I know an acronym?

What exactly is "*Light Amplification and Stimulated Emission Radiation*"?

Laser is a device that emits a special type of light source…

What is laser? (*continued…*)

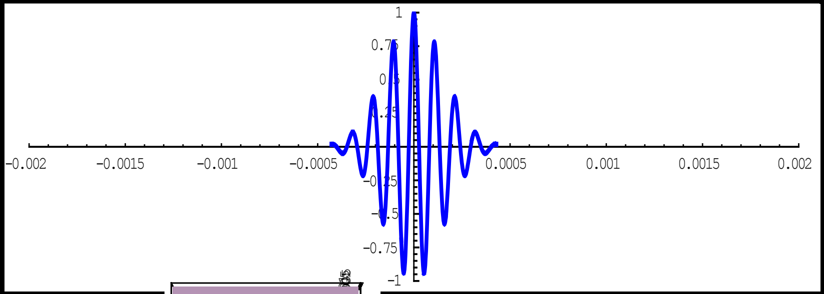
- Laser is a device that emits a “special type” of light..
- What is so special this type of light?
  - Is it because it is collimated (goes as a straight and narrow beam?
  - Is it because it is bright?
  - Is it because it has a single color?
  - Is it because it is “pretty”? Well… that depends what “pretty” is?
  - Is it …?
- NONE OF THE ABOVE! It emits COHERENT light!

Uh… what is "coherent" light, by the way?

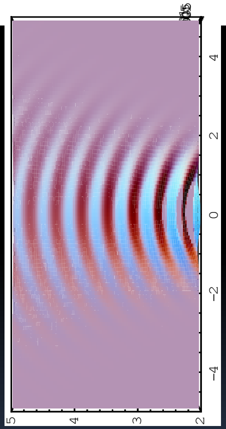
- Is it light that can speak in clear sentence and not drunk?
- Coherent light: the photons have the same phase, temporally, spatially.
  - Temporal coherence
  - Spatial coherence

Implications of coherent light on optical communication application

- Temporal coherence: can be made into short pulse with minimum bandwidth: transform-limited pulse



- Spatial coherence: can be focused into small spot (and still high power): diffraction-limited beam



Laser is essential for efficient optical communication: short pulse in small space

Fundamentals of laser

- Fundamental physics: stimulated emission and amplification of light: optical gain
  - Materials and energy input: pump
  - Device: optical amplifier
- Fundamental optics: optical cavity and optical modes
  - Device: optical resonator
- Fundamental of laser physics:
  - Lasing process
  - Behavior, properties
  - Laser engineering

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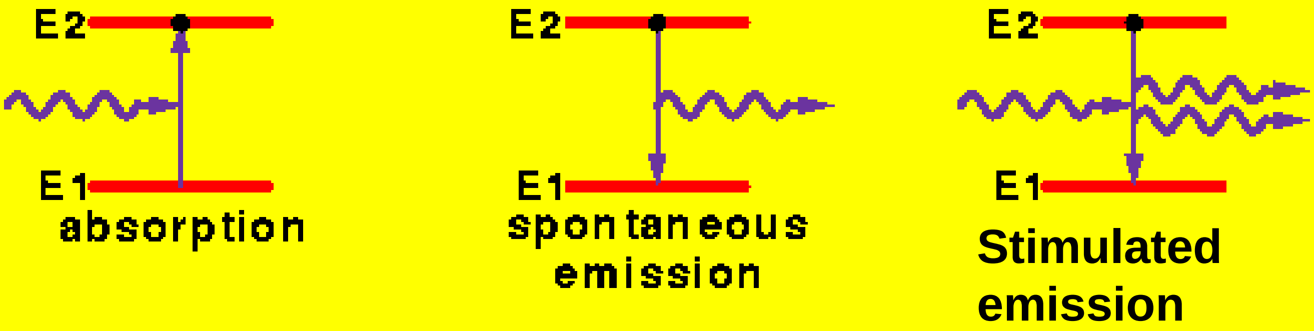
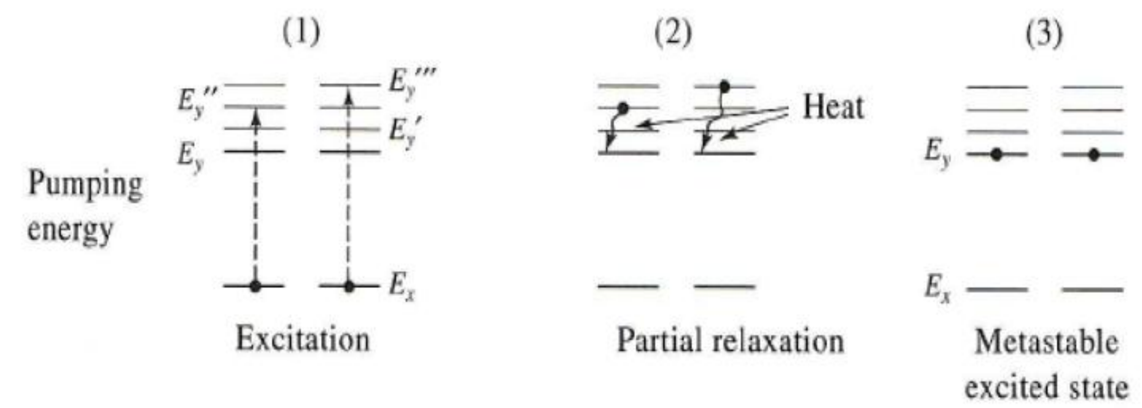
Review of modern physics

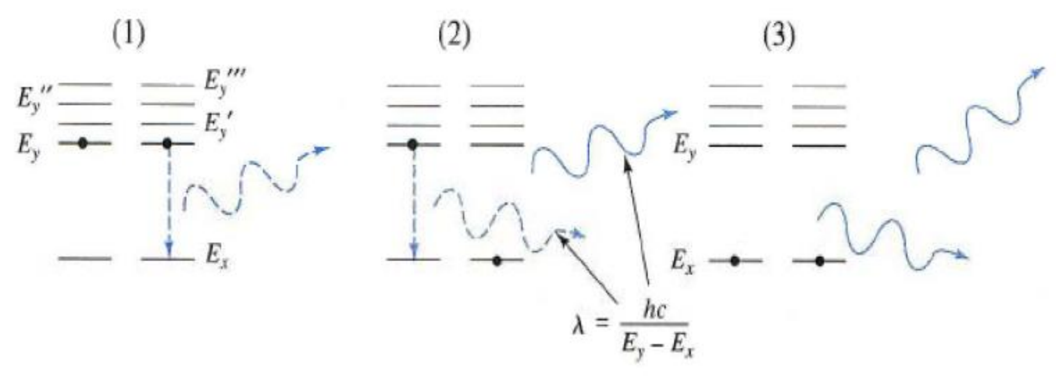
Fundamental processes:



Pumping and Spontaneous emission

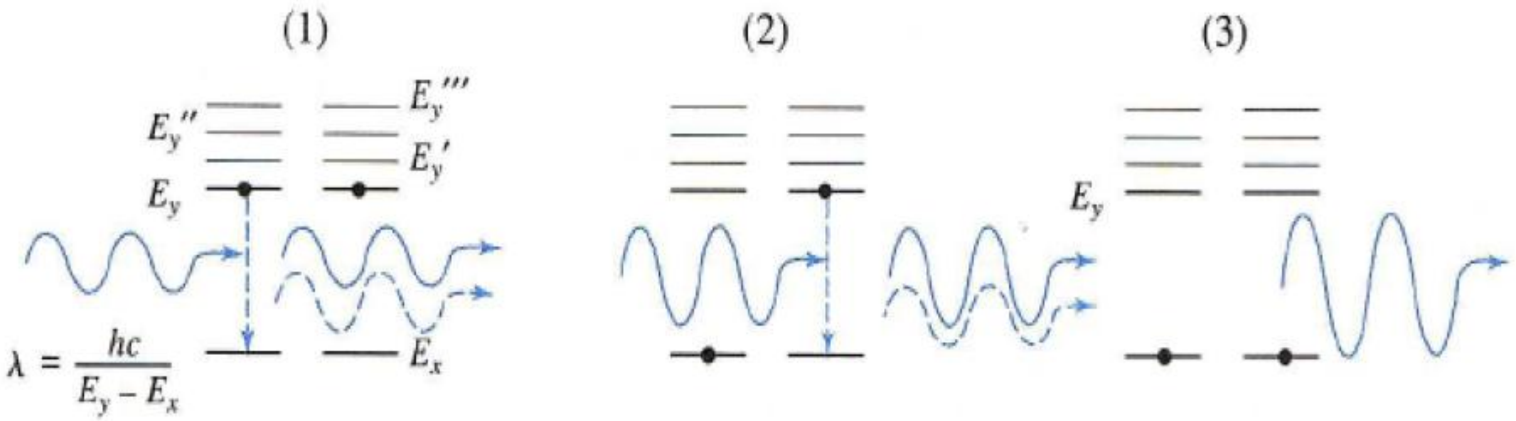


(a) Pumping (excitation by electrical, radiant, or chemical energy)



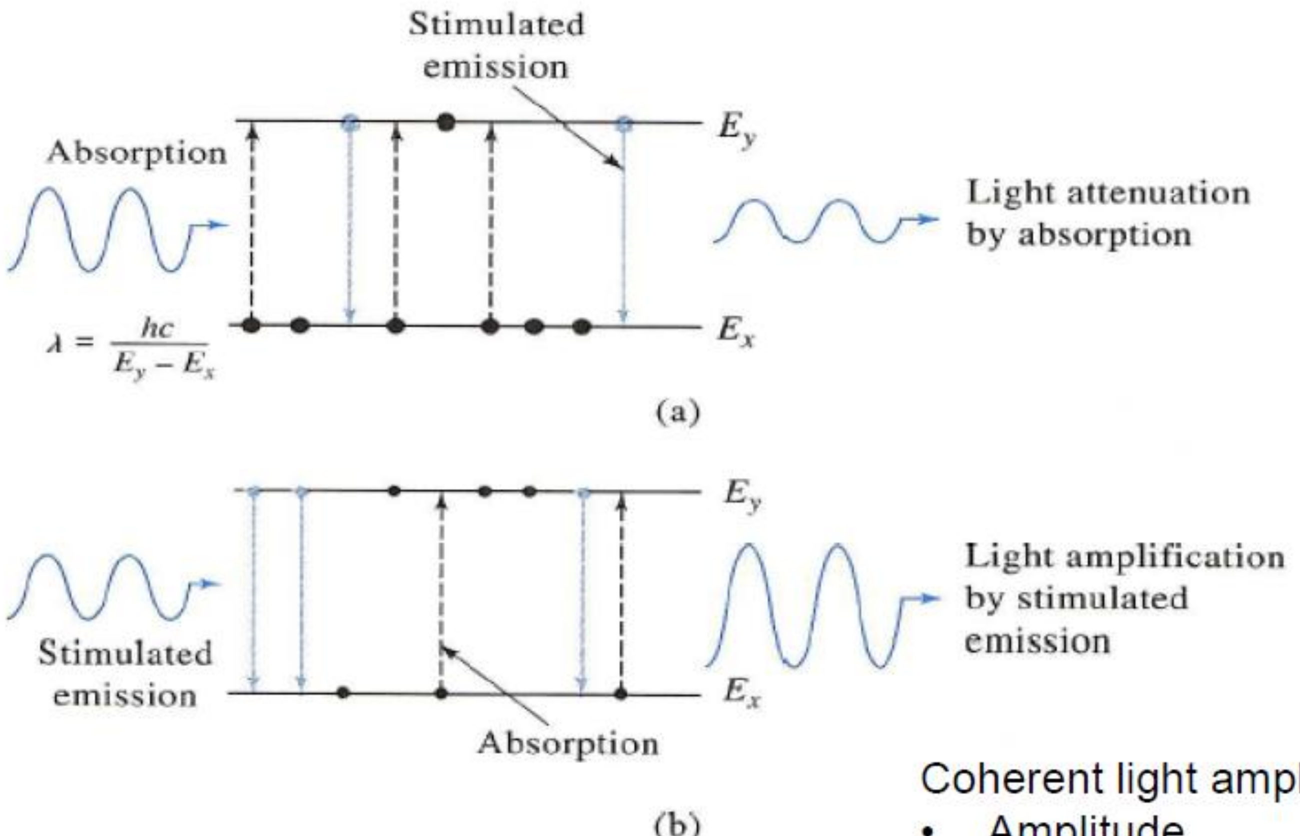
(b) Spontaneous emission

Stimulated emission



(c) Stimulated emission

Stimulated emission through a population



Coherent light amplification:

- Amplitude
- Phase
- Polarization

$$R_{12} = B_{12} N_1 \rho(hf)$$

B_{12} = proportionality constants termed the Einstein coefficients

N_1 = atoms per unit volume with energy $hf\,(= E_2 - E_1)$.

$\rho(hf)$ = photon density per unity frequency which represents the number of photons per unit volume with an energy

The rate of downward transition (involves spontaneous and stimulated emission) is given by:

$$R_{21} = A_{21}N_2 + B_{21}N_2\rho(hf)$$

where, the first term is due to spontaneous emission (does not depend on the photon density $\rho(hv)$ to drive it) and the second term is due to stimulated emission which requires photons to drive it.

A_{21} and B_{21} = proportionality constants termed the Einstein coefficients for spontaneous and stimulated emissions respectively

$N_2 =$ atoms per unit volume with energy E_2

$\rho(hf) =$ photon density per unity frequency which represents the number of photons per unit volume with an energy $hf\,(= E_2 - E_1)$.

Now, *in thermal equilibrium*, in the collection of atoms we are considering, radiation from the atoms must give rise to an equilibrium photon energy density, $\rho_{eq}(hf)$, that is given by *Planck's black body radiation distribution law*,

$$\rho_{eq}(hf) = \frac{8\pi hf^3}{c^3\left[\exp\left(\frac{hf}{k_B T}\right) - 1\right]}$$

Principle of detailed balancing

To find the coefficients A_{21}, B_{12}, B_{21}, we consider the events in equilibrium, that is the medium in thermal equilibrium (no external excitation). There is no net change with time in the populations at E_1 and E_2 which means

$$R_{12} = R_{21}$$

and furthermore in thermal equilibrium Boltzmann statistics demands that

$$\frac{N_2}{N_1} = \exp\left[-\frac{(E_2 - E_1)}{k_B T}\right]$$

where k_B is the Boltzmann constant and T is the absolute temperature.

From the above equations, we can show that

$$B_{12} = B_{21}$$

And

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}$$

the ratio of stimulated to spontaneous emission:

$$\frac{R_{21}(stim)}{R_{21}(spon)} = \frac{B_{21} N_2 \rho(hf)}{A_{21} N_2} = \frac{B_{21}\rho(hf)}{A_{21}}$$

Substituting

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}$$

To above equation

$$\frac{R_{21}(stim)}{R_{21}(spon)} = \frac{c^3 \rho(hf)}{8\pi h f^3}$$

The higher photon density (the more light) the higher the stimulated emission rate is compared with spontaneous emission: when $P_{stim} \gg P_{spont}$: lasing occurs

Population inversion concept

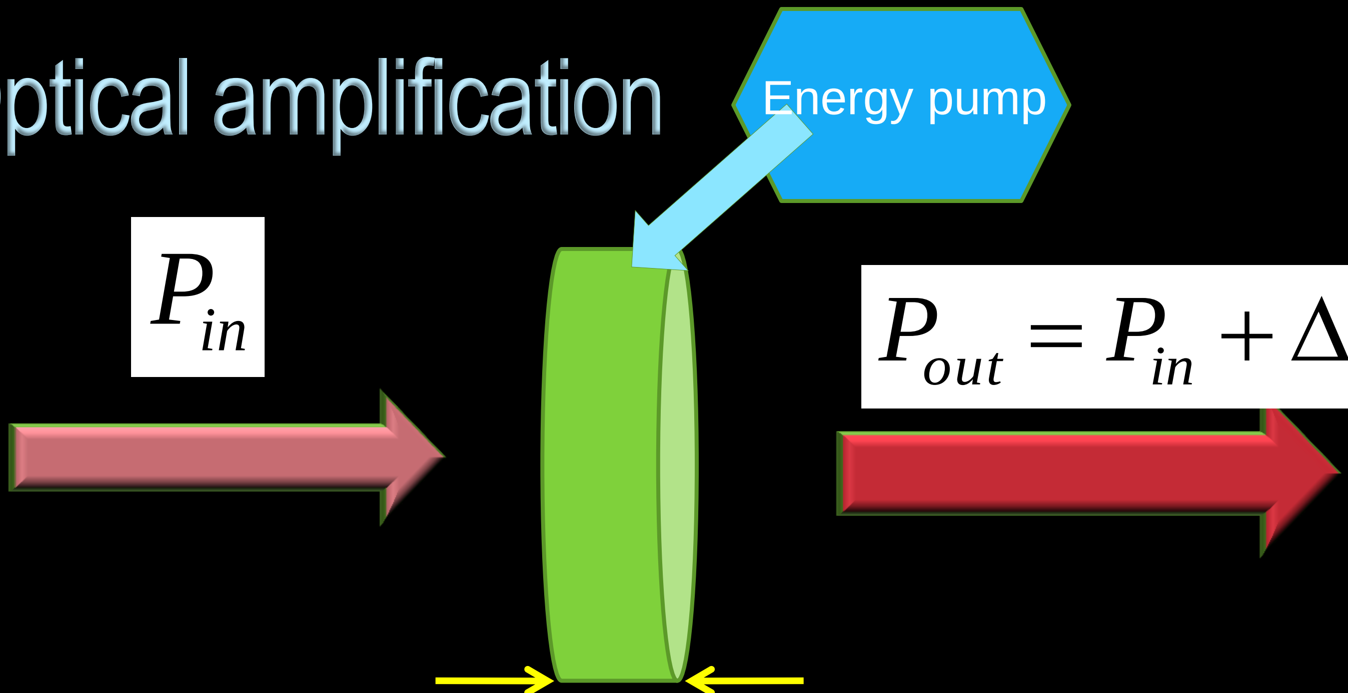
The ration of stimulated emission to absorption is

$$\frac{R_{21}(stim)}{R_{12}(absorp)} = \frac{N_2}{N_1}$$

There are two important conclusions. For stimulated photon emission to exceed photon absorption, we need to achieve population inversion, that is $N_2 > N_1$. For stimulated emission to far exceed spontaneous emission, we must have a large photon concentration which is achieved by building an optical cavity to contain the photons.

Population inversion requirement $N_2 > N_1$ means that we depart from thermal equilibrium. According to Boltzmann statistics $N_2 > N_1$ implies a negative absolute temperature. The laser principle is based on non-thermal equilibrium.

Optical amplification



$$P_{in}$$

$$P_{out} = P_{in} + \Delta P$$

$$\Delta z$$

$$\Delta P = P_{in}\, \gamma (N_2 - N_1)\, \Delta z$$

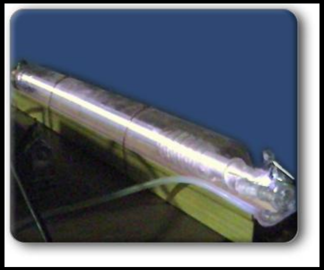
$$\frac{dP}{dz} = gP$$

If g>0: Optical gain (else, loss)

Optically amplified signal: coherent with input: temporally, spatially, and with polarization

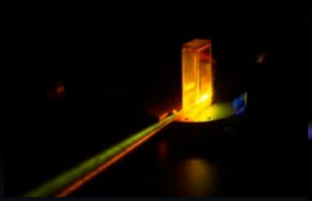
Media for optical amplification (and lasers)

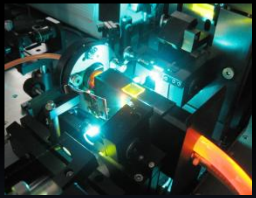
- Gas: atomic, molecular



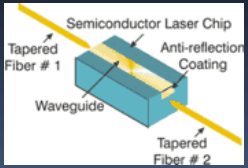


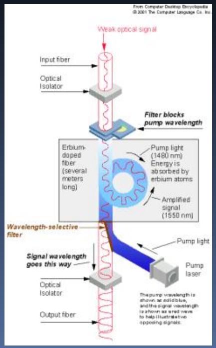
- Liquid: molecules, micro particles in a solution





- Solid: semiconductor, doped materials (EDFA)



Fundamentals of laser

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- Fundamental of laser physics:
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  - Behavior, properties
  - Laser engineering

Optical cavity

Why optical cavity is essential to the laser?

- Has only certain modes (and frequencies)
- Allows the structure to be a resonator when the input coincides with the modes
- Allows a self-oscillation solution without any input

Fundamentals of laser

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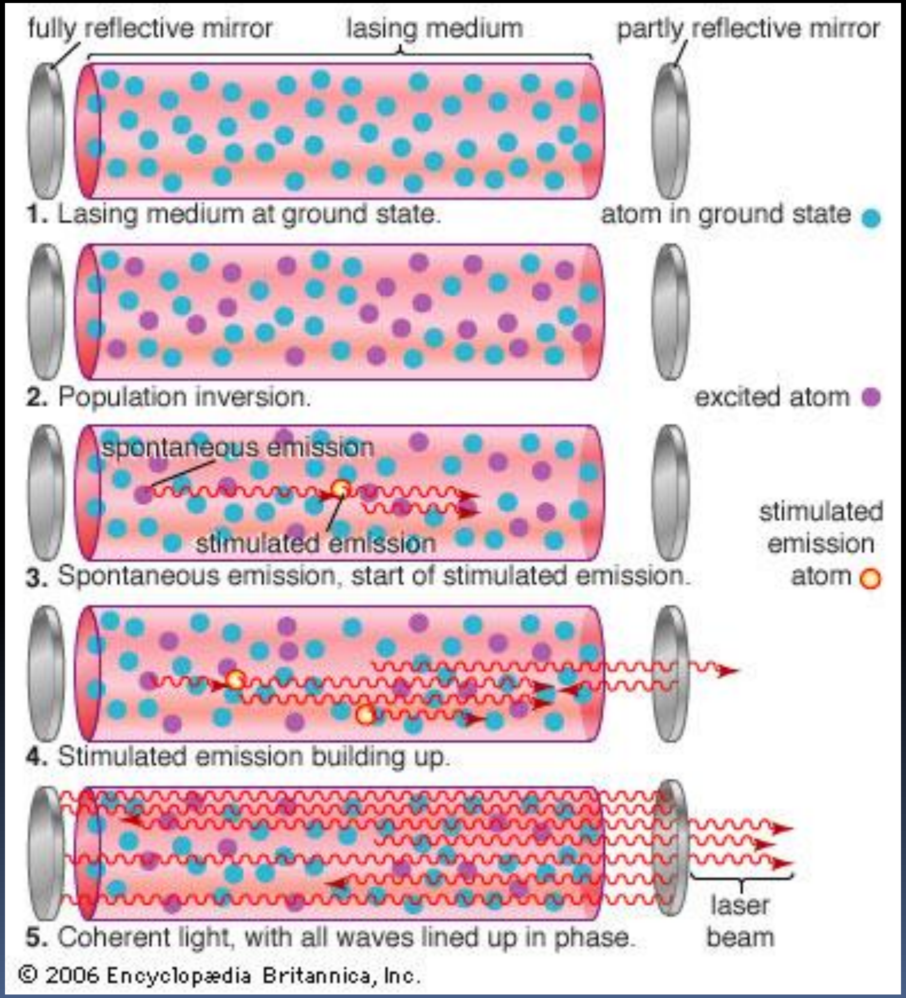
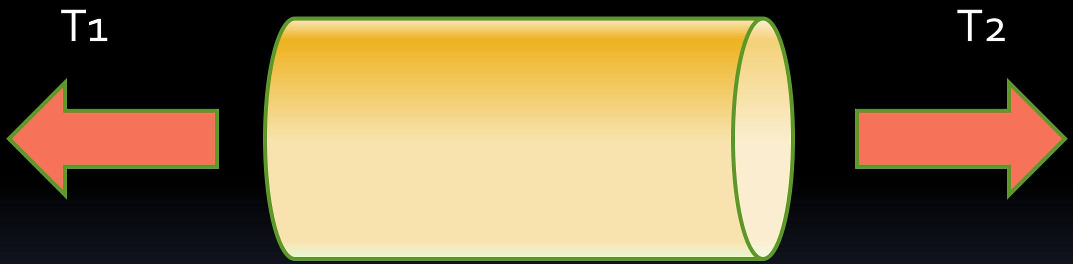
Illustrative concept



Basic laser equation



$$\begin{pmatrix} T2 \\ 0 \end{pmatrix} \; : \; : \; \left(\begin{matrix} \dfrac{\cdot \; l \; T1 \; rp2 \cdot \; {}^{2} \; l \; rp1 \; rm2 \; rp2 \cdot \; tm2 \; tp2}{tm1 \; tm2} \\ \dfrac{\cdot \; l \; \cdot \; l \; rm2 \; rp1 \; T1}{tm1 \; tm2} \end{matrix} \right)$$

Basic Laser Properties

- **A threshold**: the pump power where the net gain after one round trip is equal to the total cavity loss. Above this, the laser emits laser radiation (not spontaneous emission)
- The output light has frequencies and spatial profiles that are the **optical modes** of the laser cavity
- There are two types of spatial modes: **longitudinal modes** determined by the cavity length, and **transverse modes** determined by the cavity lateral geometry. Each spatial mode is a combination of a longitudinal and a transverse mode.
- Likewise, there are **polarization modes**, and the combination of spatial and polarization modes determines unique modes.
- There is a **unique frequency** with each mode
- A laser may emit a single dominant mode (under certain pump power), which is called **single-mode operation** or **single-mode laser**. The ratio of the dominant mode power to that of all other modes is called side-mode suppression ratio. Otherwise, it is called **multi-mode operation** or **multi-mode laser**

Optoelectronic Devices

- **Light-to-current conversion:**
  Photodiodes, photodetectors
  - p-i-n, (*why need i*?) dark current, I-V curves, photovoltaic current sources
  - APD, avalanche region, gain, multiplication factors

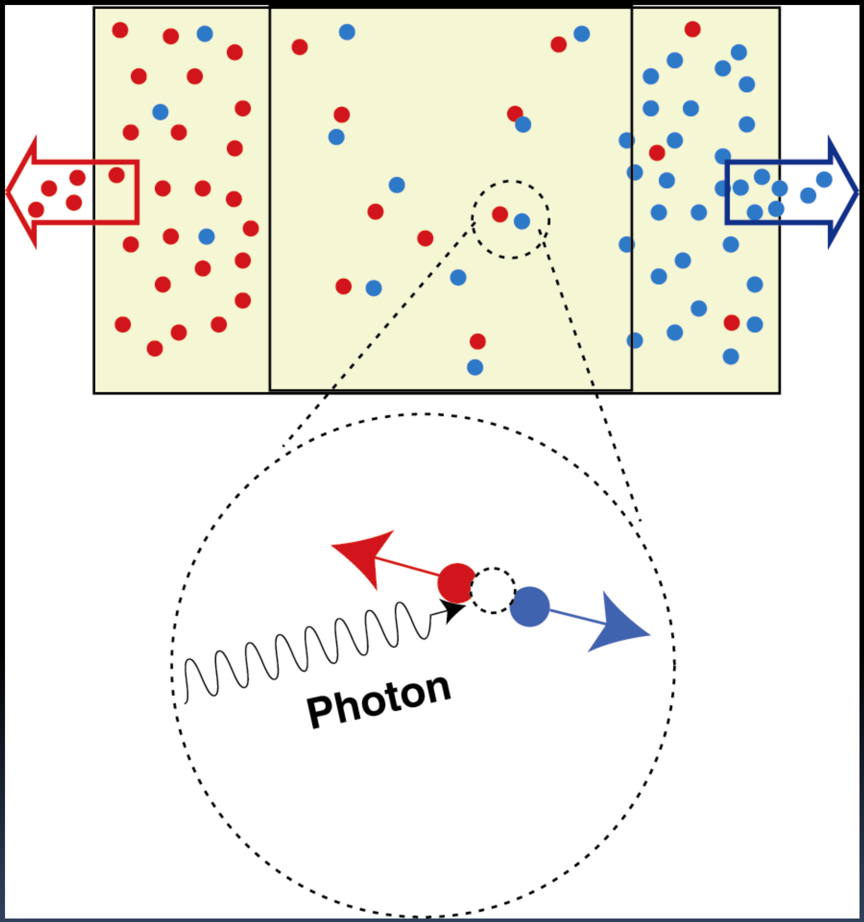
  Power devices: solar cells

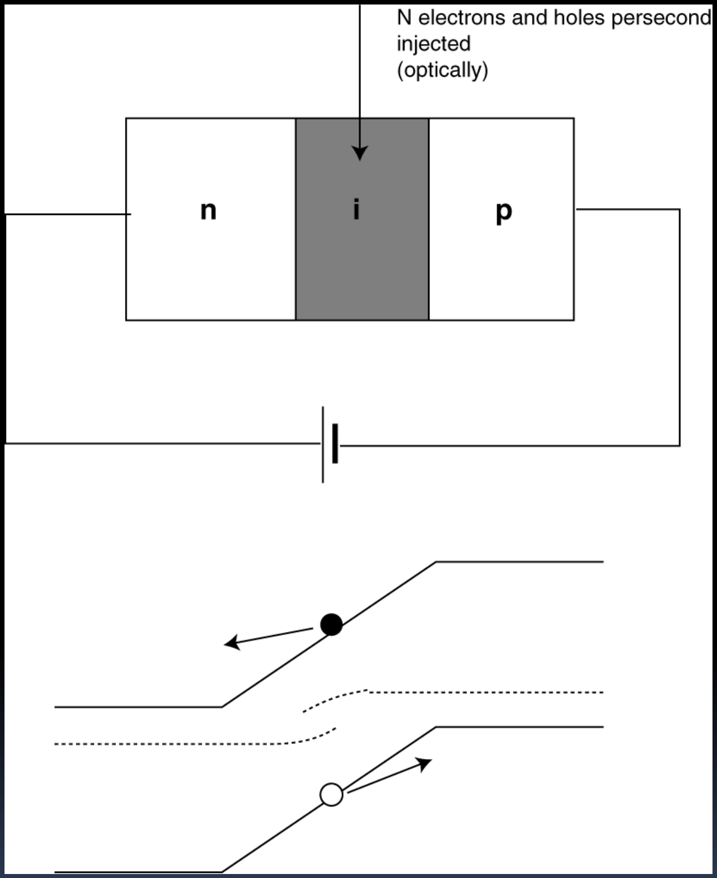
- **Current-to-light conversion:** LEDs, lasers, optical amplifiers*: Fluorescence*, *optical gain*, *stimulated emission*, *coherent radiation*, *threshold*, *efficiency*

- **Electric field/light interaction effects**: Electro-optic modulator, electroabsorption modulator, (LCD for example)

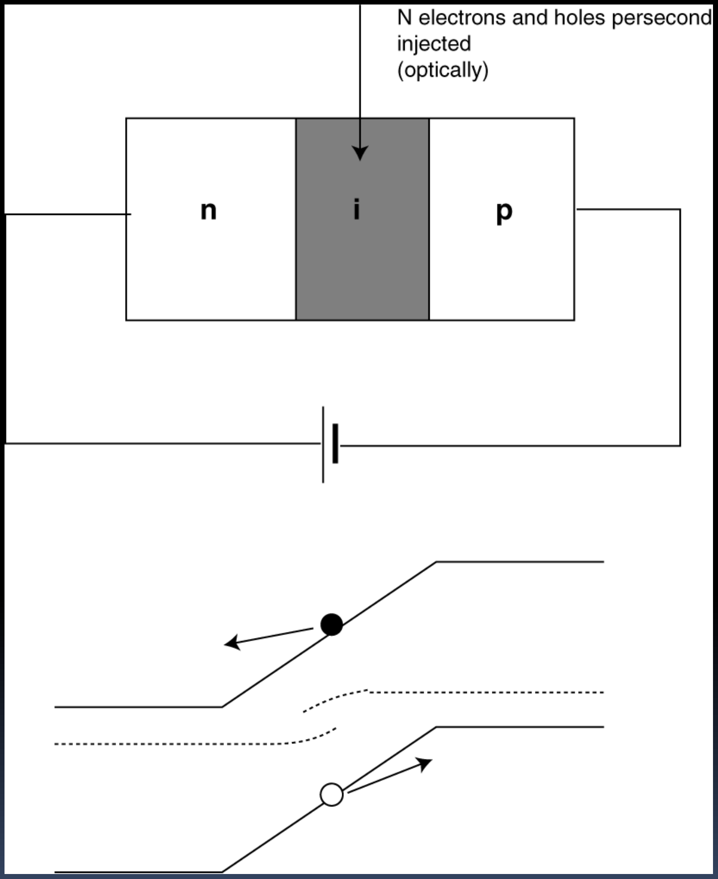
- **Photonic circuits: light conditioning, manipulation structure**

p-i-n Photodiode

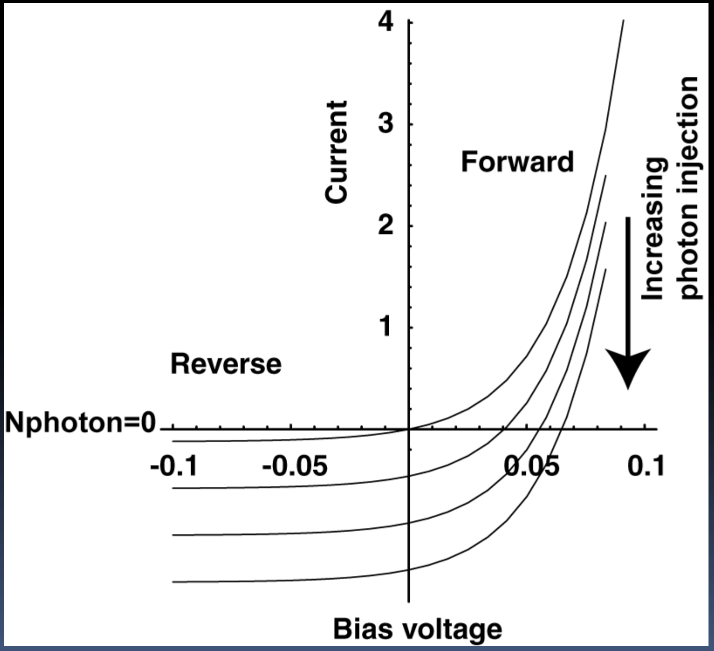




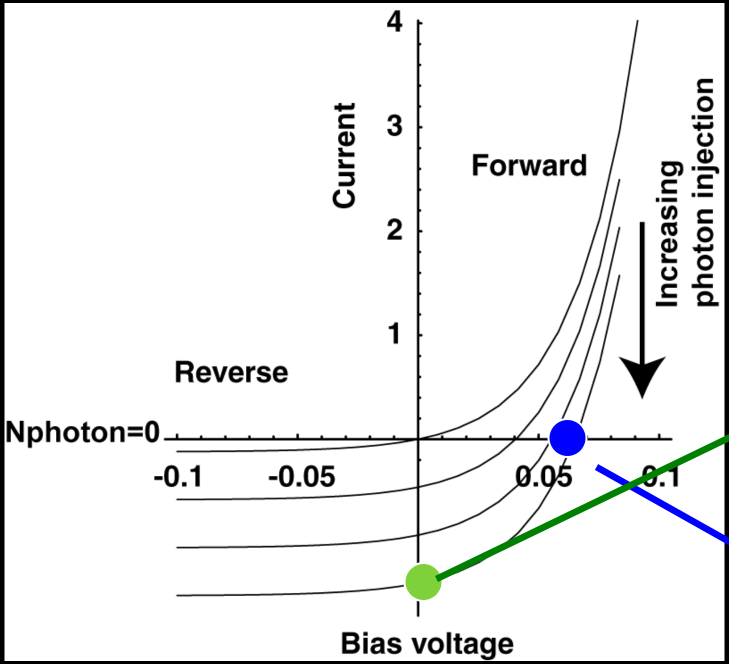
Photocurrent

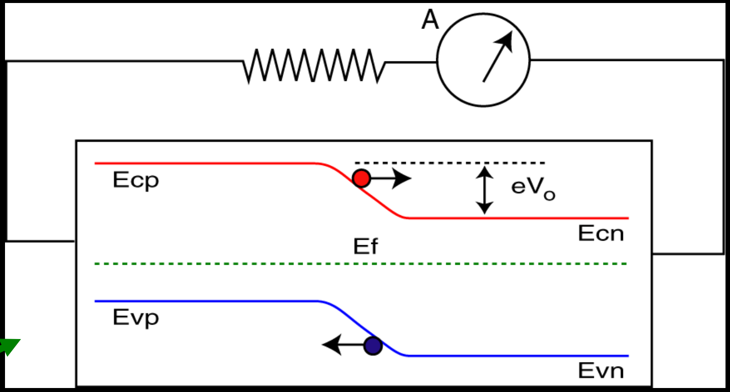


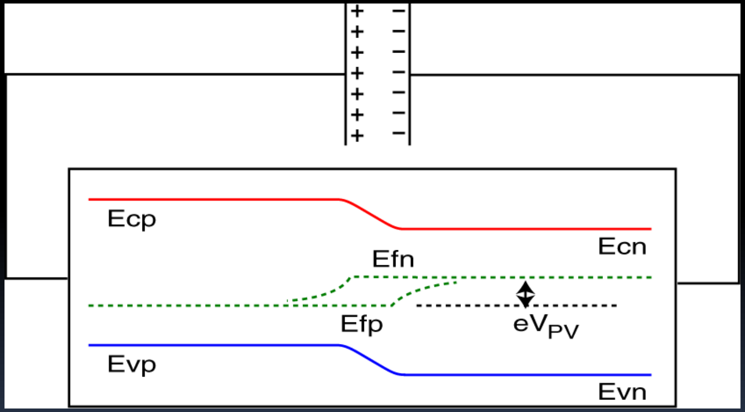
What is g_{op}?



Photovoltaic effects





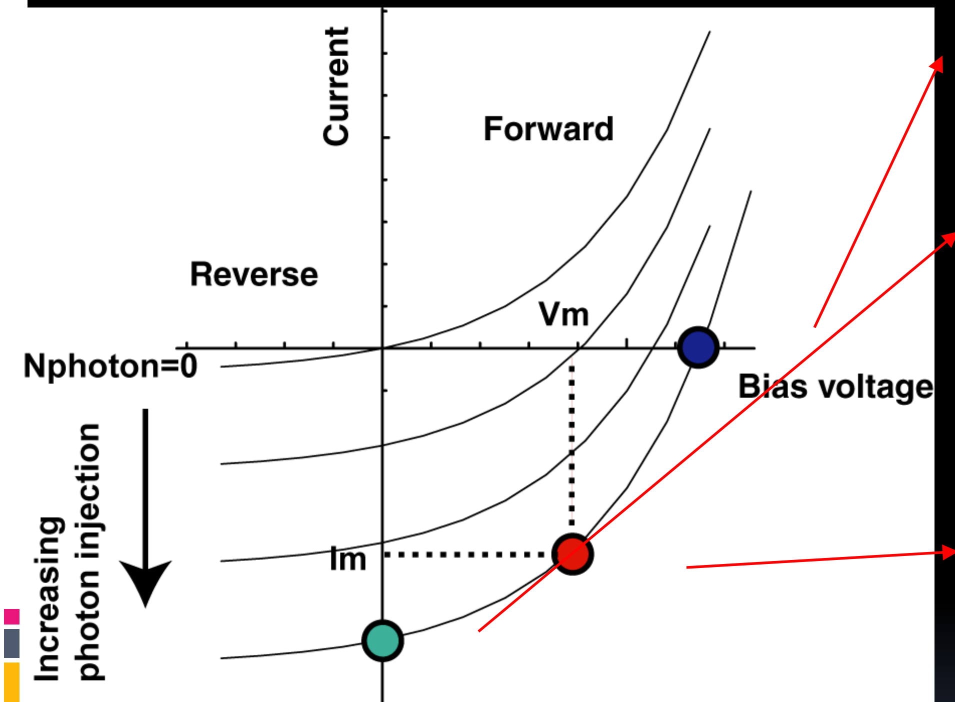


$$I_{total} = I_s\left(e^{qV_{PV}/k_BT} - 1\right) - I_{op} = 0$$

$$e^{qV_{PV}/k_BT} = 1 + I_{op}/I_s$$

$$V_{PV} = \frac{k_BT}{q}\ln\left(1 + I_{op}/I_s\right)$$

Photovoltaic power devices: solar cells

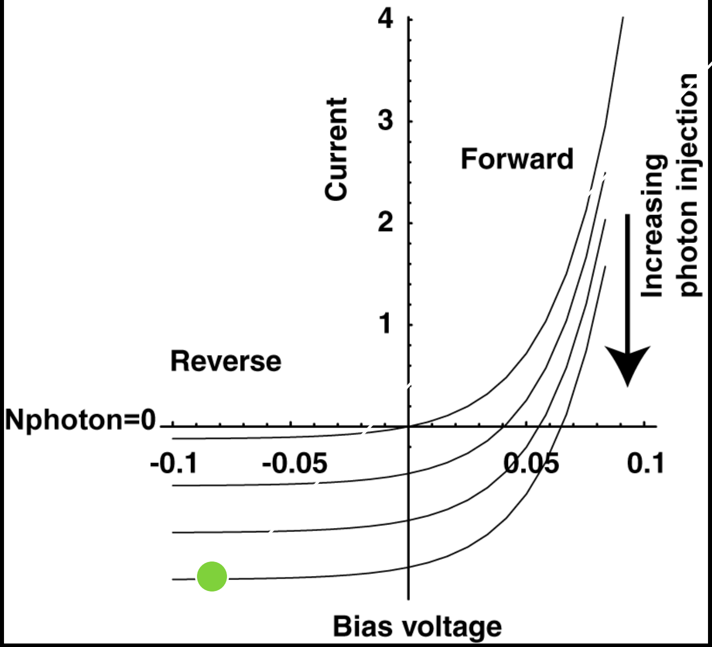


Power = 0

Power = 0

Maximum power < 0

Photodetectors



Current linearly proportional to light intensity:

$$I_{total} = I_s\left(e^{qV/k_BT} - 1\right) - I_{op} \approx -\left(I_{dark} + I_{op}\right)$$

$$I_{op} = RP$$

P is optical power, R is defined as responsivity

Key figure-of-merit: minimum detectable power (noise equivalent power); bandwidth

Detector link

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LCD

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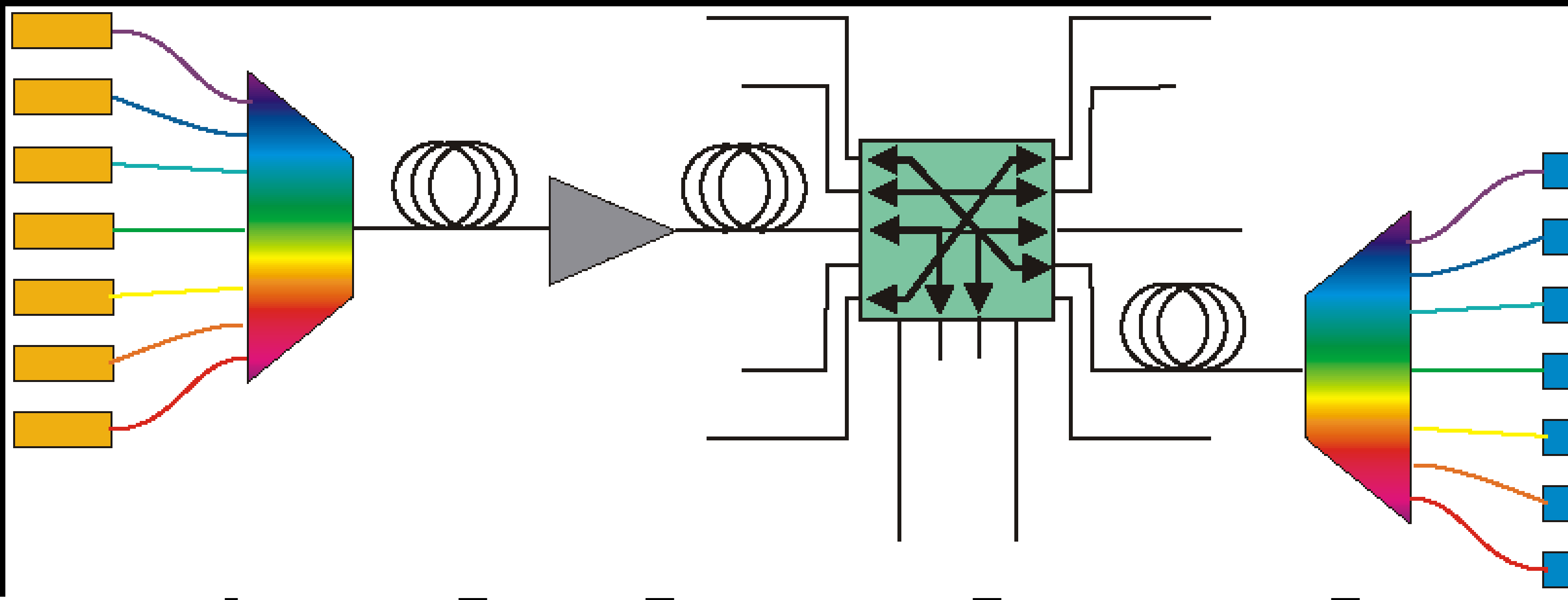
Optical/DWDM networking technology



Transmitter
- Laser
  - -DFB, DBR, VCSEL
  - -Tunable, fiber
- Modulator
  - -Electro-optic
  - -Electroab-sorption

WDMux
- TF filters
- Fiber Bragg G
- Array wave-guide grating
- Diffraction G
- Other gratings

Fiber
- Convent. fiber
- DSF, NZDSF
- Improved fiber

Optical amplifier
- Erbium-doped Fib. Amp (EDFA)
- Semicond. (SOA)
- Others (Raman)

Optical switch
- Path switch
- Add/Drop mux
- λ-router
- Cross connect
- Couplers
- circulators

Receiver
- Ultrafast PD