LASER: basic principles and applications

Dr. Alessia Polemi
MATE351
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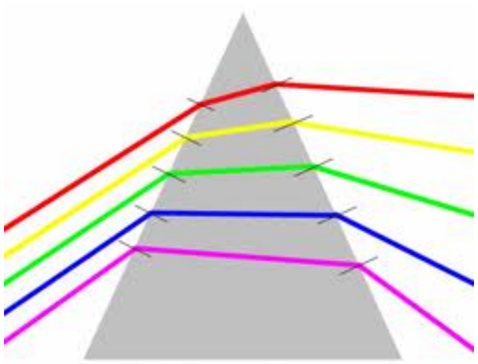
Sources:
Electrical Properties of Materials, Solymar and Walsh
Principles of Electronic Materials and Devices, Kasap
Basic Lasers Principles, Melles Griot
The internet

INTRODUCTION

Lasers = devices that produce intense beams of light

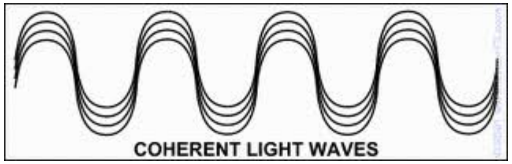
monochromatic

Wavelength (color) is extremely pure



coherent

Photons (energy) have a fixed phase relationship with respect to one another.



highly collimated

Beam has very low divergence, it can travel over great distances or can be focused to a very small spot with high brightness

HISTORY

- basic operating principles of the laser by Charles Townes and Arthur Schalow from the Bell Telephone Laboratories in 1958,
- first actual laser, based on a pink ruby crystal, demonstrated in 1960 by Theodor Maiman at Hughes Research Laboratories

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- since that time, thousands of lasers have been invented but only a much smaller number have found practical applications in scientific, industrial, commercial, and military applications

helium neon laser

solid-state laser

semiconductor diode laser

…..

WHAT?

LASER

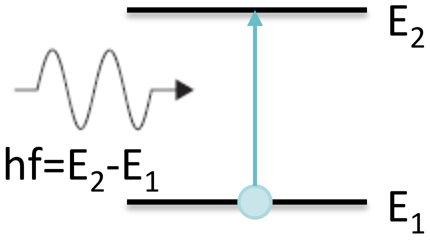
Light Amplification by Stimulated Emission of Radiation

Light: electromagnetic radiation ranging from 1 nm to 1000 mm in wavelength

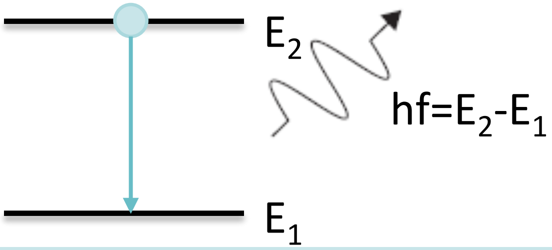
- visible spectrum: 400 to 700 nm
- near infrared (NIR): 700 nm to 10 mm
- far infrared (FIR): anything beyond that
- ultraviolet (UV): 200 to 400 nm
- deep ultraviolet (DUV): below 200 nm

Stimulated emission?

SPONTANEOUS AND STIMULATED EMISSION

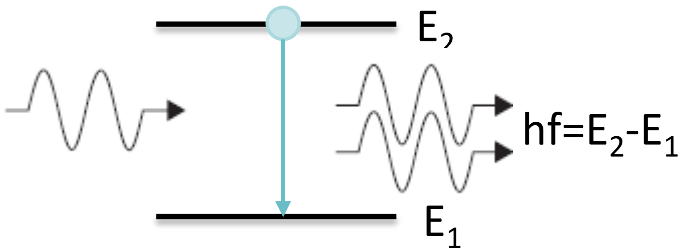


1) ABSORPTION



2) EMISSION: **SPONTANEOUS EMISSION**

- Photon emitted in a random direction and a random phase
- Time to decay τ=time constant for spontaneous emission



3) EMISSION: **STIMULATED EMISSION**

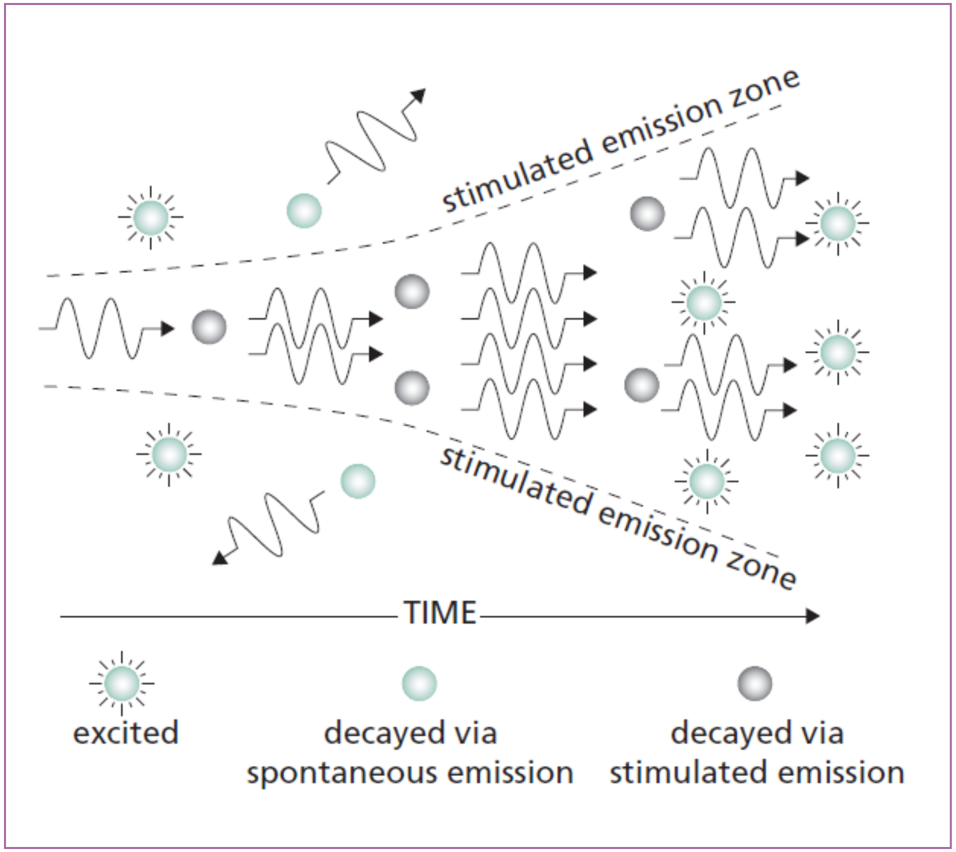
- A photon w/ energy $hf=E_2-E_1$ passes by
- Probability that photons will cause the electron to decay in such a way that photon is emitted
  - same frequency
  - same direction
  - same phase

of the passing photon

SPONTANEOUS AND STIMULATED EMISSION

Assumption: group of atoms

- all begin in the same excited state
- most are effectively within the stimulation range of a passing photon
- τ is very long (τ =time to decay)
- probability for stimulated emission is 100%



Initial incoming photon is amplified. All in the same direction

SPONTANEOUS AND STIMULATED EMISSION

- Who gives the energy for atoms in excited state? Need of a PUMP source
- Probability of stimulated emission is quite small
- Not all the atoms are in the excited state (the opposite is true)

$$\frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{kT}}$$

$$N_{2,1} = population\ \ of\ state\, E_{2,1}$$

Boltzmann's
principle of
thermodynamics

$$\Delta N = N_1 - N_2 = \left(1 - e^{-\frac{hf}{kT}}\right) N_1$$

- There will always be more atoms in the lower energy levels than in the upper ones

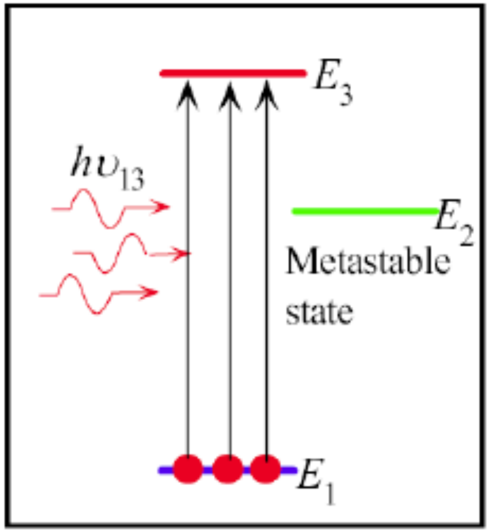
- Probability for an individual atom to absorb a photon is the same as the probability for an excited atom to emit a photon via stimulated emission → 2 levels not enough

to make a laser we need a ***population inversion***

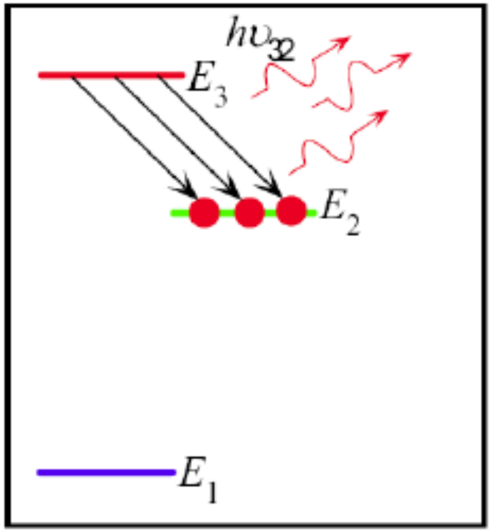
POPULATION INVERSION AND LASING

1) Imagine 3-levels system (at least)
2) External excitation moves atoms to E_3 (collision w/ another atom, absorption of high energy radiation, …)→ **E_3 =pump energy level**
3) Suppose that a state E_2 exists where atoms from E_3 decay by spontaneous emission→ **E_2 =metastable level,** τ to decay to E_1 is long
4) Now a photon entering the population at E_2 will generate stimulated emission = coherent amplification

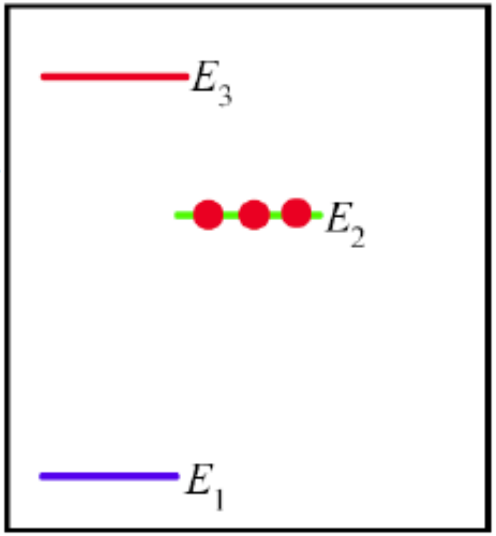
→ **LASING EMISSION**



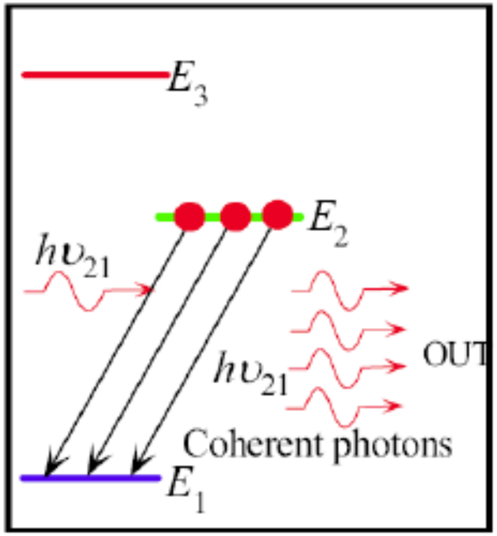
pumping



Metastable level



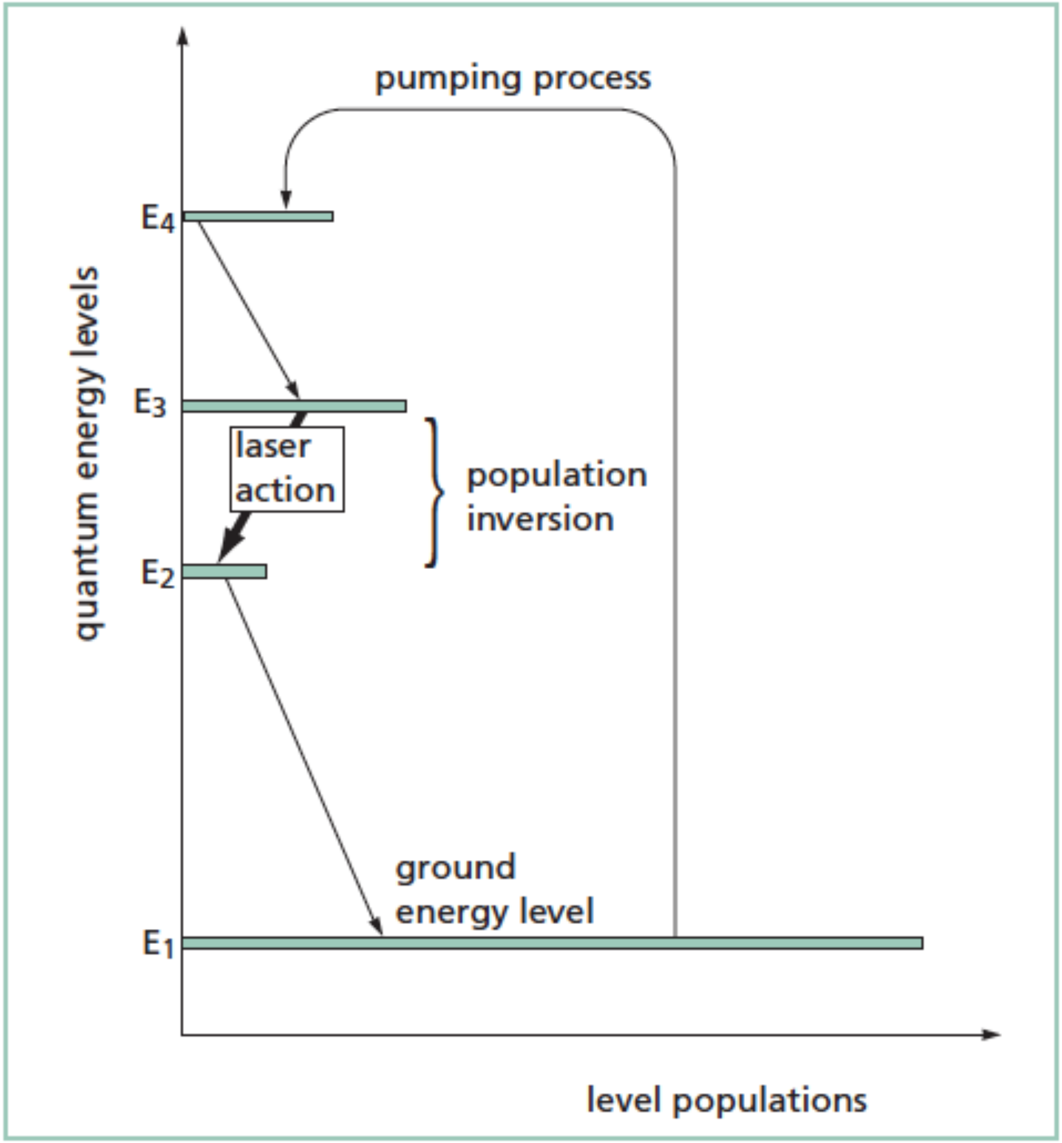
Population inversion



Lasing

POPULATION INVERSION AND LASING

4-LEVELS SYSTEM



THE RESONATOR

☹ Overall gain is quite small: most of the excited atoms in the population emit spontaneously

? make the majority of the atoms in the population to contribute to the coherent output

↓

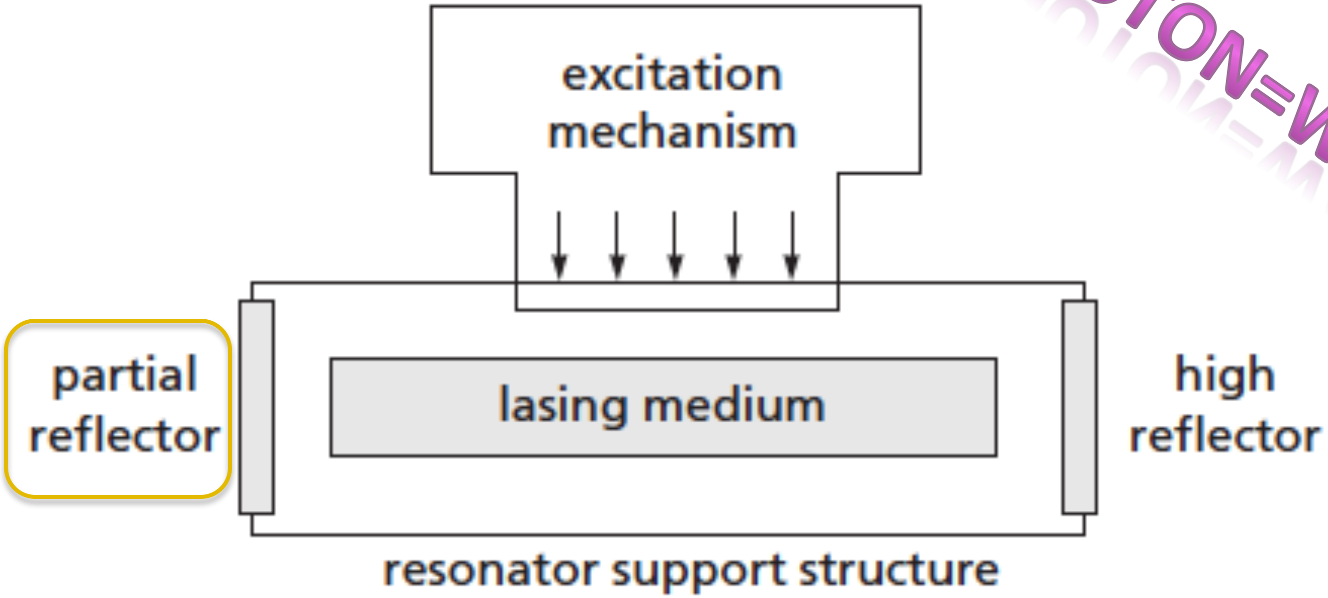
RESONATOR

a system of mirrors that reflects undesirable (**off-axis**) photons out of the system and reflects the desirable (**on-axis**) photons back into the excited population where they can continue to be amplified

THE RESONATOR

PHOTON=WAVE!

Lets the light out



Atoms radiating outside the lasing medium get reflected back and forth and they have the opportunity to stimulate more excited atoms

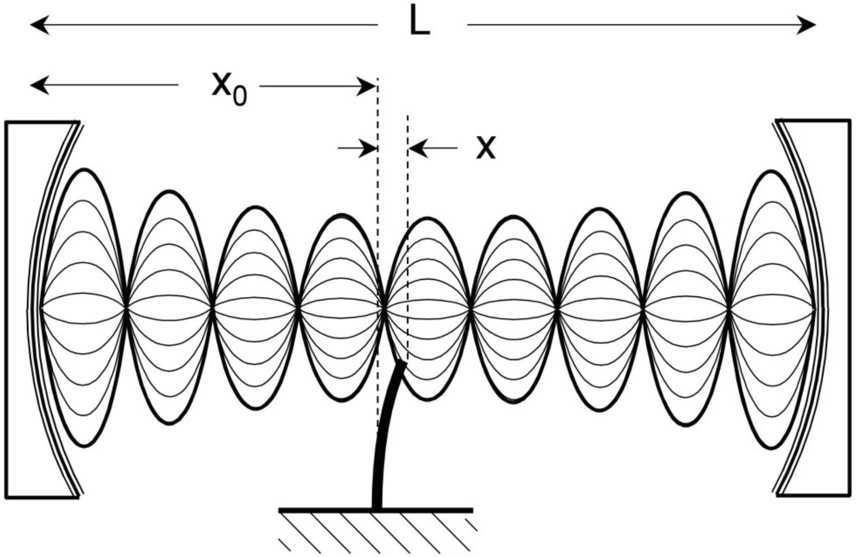
→ spontaneous emission decreases, stimulated emission along the axis predominates

→ **LASER**

THE RESONATOR

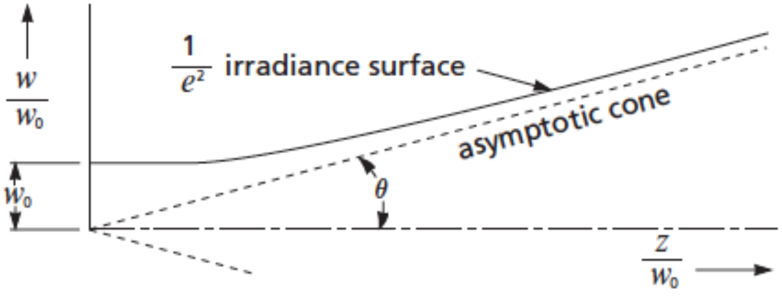
1) Modeling the cavity→ resonant cavity (Fabry-Perot)

$$L = n\,\lambda/2$$



THE RESONATOR

2) Optimizing reflection

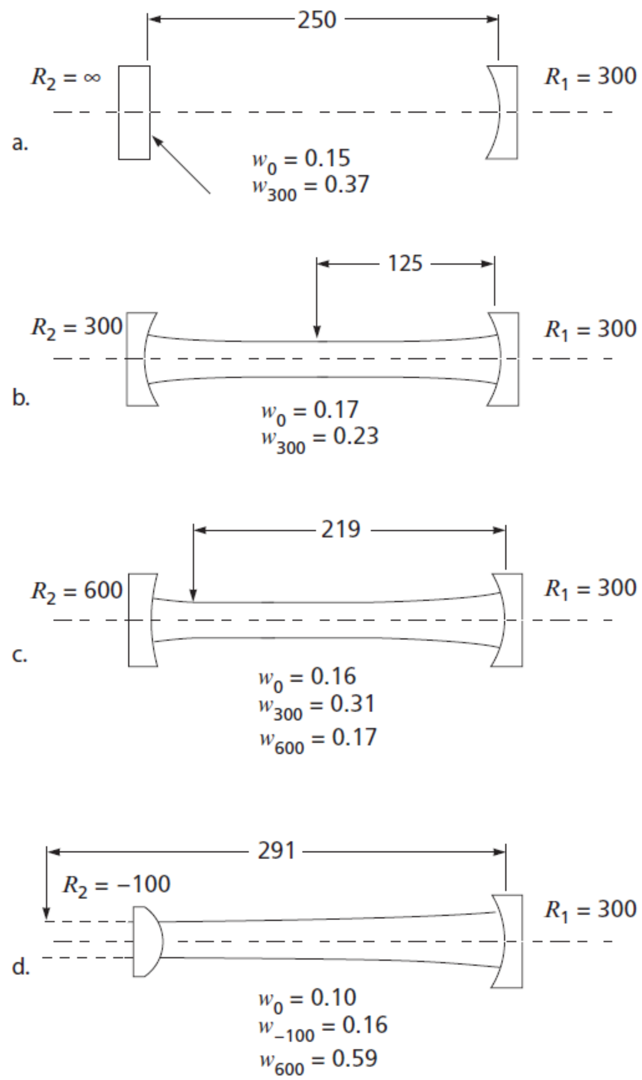


Growth in beam diameter as a function of distance from the beam waist

$$I(r) = I_0 e^{-2r^2/w^2} = \frac{2P}{\pi w^2} e^{-2r^2/w^2}$$

$$\left[w(z) = \frac{\lambda z}{\pi w_0} \right]$$

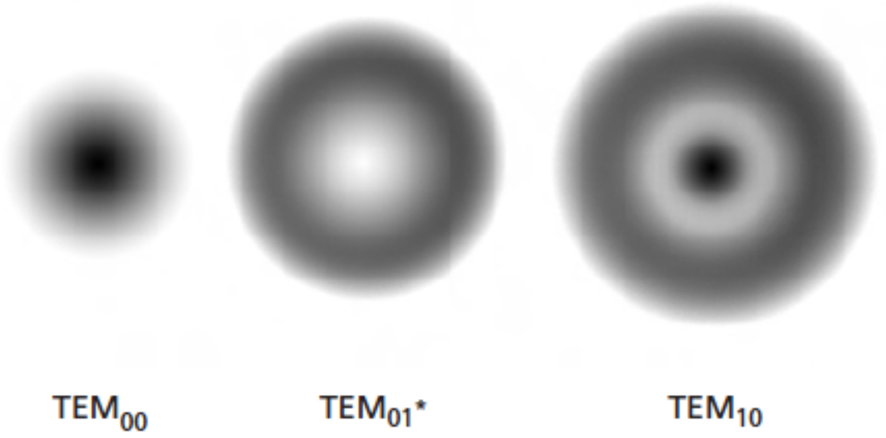
(irradiance distribution of the Gaussian fundamental beam)

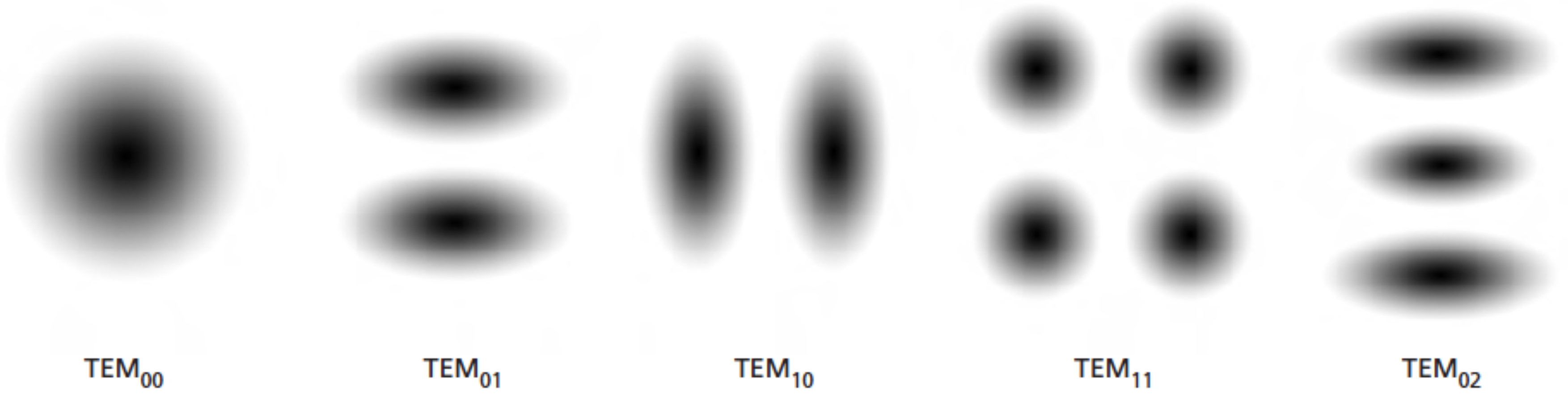


dimensions in mm

THE MODES

Depending on the shape of the cavity





REDUCING THE ORDER OF THE LASING MODE: add sufficient loss to the higher-order modes so that they cannot oscillate → by placing a fixed or variable aperture inside the laser cavity

PRACTICAL LASERS

- Organic/inorganic
- Crystalline/non crystalline
- Insulator/semiconductor
- Gas/liquid
- Fixed frequency/tunable
- High power/low power
- CW/pulsed
- Pumped by
    - Another laser
    - Fluorescent lamps
    - Electric arcs
    - Electron radiation
    - Injected electrons
    - Chemical means

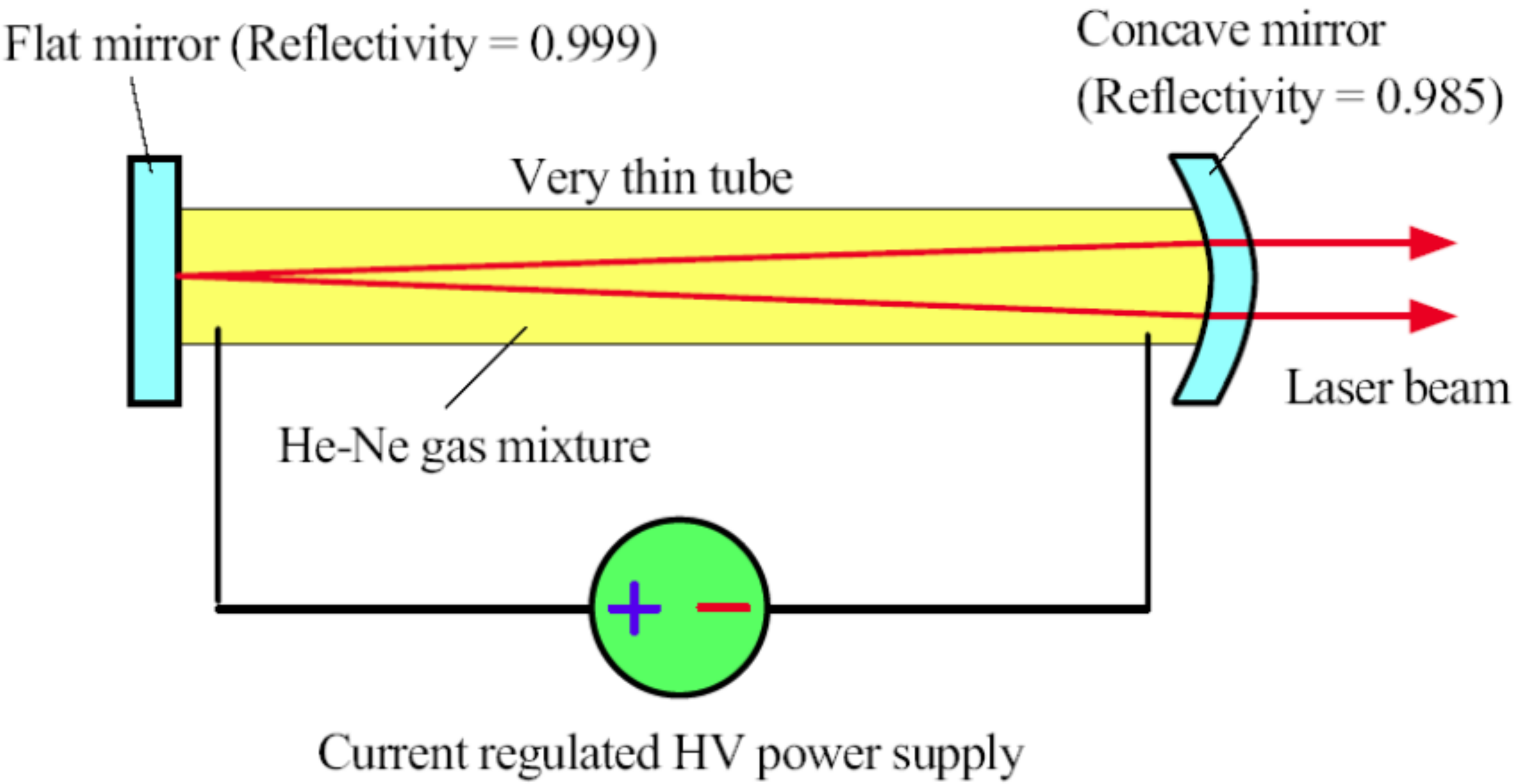
He-Ne LASER

General features

- Gas discharge laser
- Sold in great quantity (second only to semiconductor lasers)
- Operates in a high-voltage (kV), low-current (mA) glow discharge
- Most familiar output wavelength is 633 nm (red), but also available with output at 543 nm (green), 594 nm (yellow), 612 nm (orange), and 1523 nm (near infrared)
- Output power is low, ranging from a few tenths to tens of mW, depending on the wavelength and size of the laser tube

He-Ne LASER

Configuration



He-Ne LASER

- Helium → major constituent (85%) of the gas mixture
- Neon → the actual lasing medium

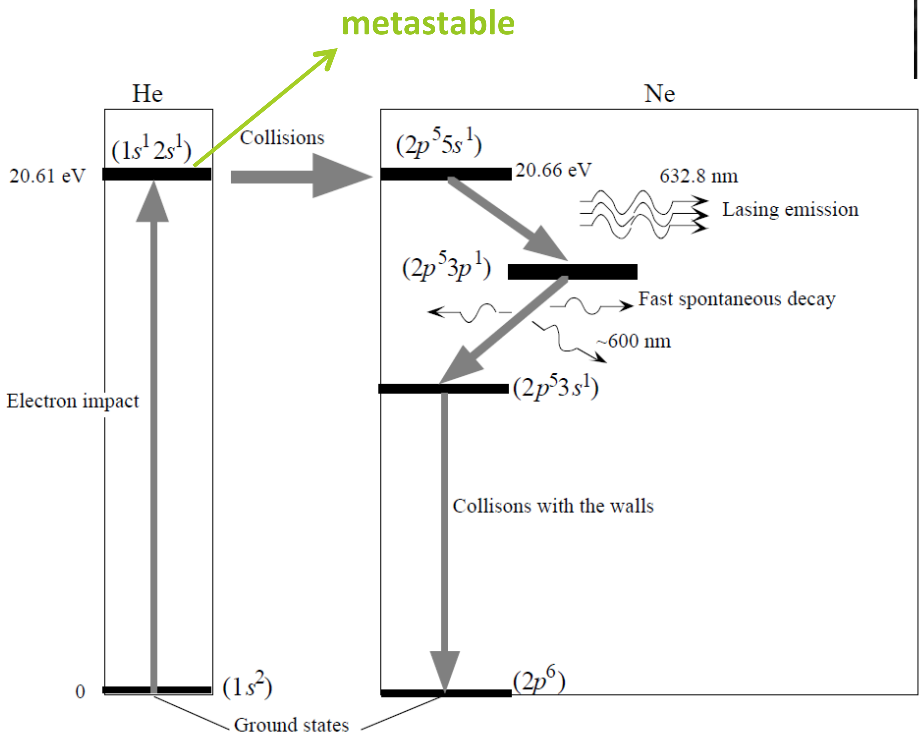
1) Electrical discharge pumps the helium atoms to an excited state that closely matches the upper energy levels of the neon atoms

$$He + e^{-1} \longrightarrow He^{*} + e^{-1}$$

2) This energy is then transferred to the neon atoms via collisions of the second kind = exciting the neon to a higher energy level as opposed to transferring the energy as kinetic motion

$$He^{*} + Ne \longrightarrow Ne^{*} + He$$

3) Emission of a photon from one Ne* from 5s to 3p→ avalanche of stimulated emission



The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).

He-Ne LASER

Popularity

- small and compact
- best inherent beam quality of any laser (virtually pure beam)
- extremely long lived (operating life of 50,000 hours or more)
- they generate relatively little heat
- relatively low acquisition and operating cost

He-Ne LASER

Efficiency

Exercise.

A typical low-power 2.5mW HeNe laser tube operates at dc voltage of 2KV and carries a current of 5mA. What is the efficiency of the laser?

$$\text{Efficiency}=Output\ power/Input\ power=2.5\ 10\uparrow-3\ W/(5\ 10\uparrow-3\ A)(2000V)$$
$$=0.00025\ or\ 0.025\%$$

A modern stabilized HeNe laser.
| SOURCE: Courtesy of Melles Griot.

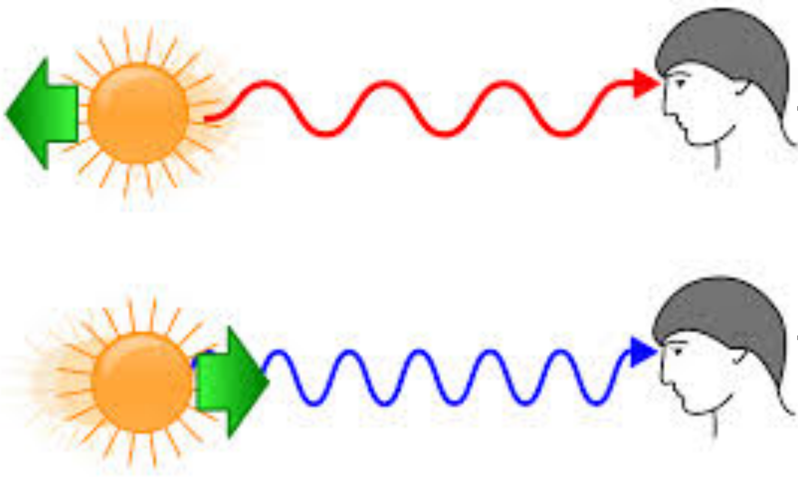
LASER OUTPUT SPECTRUM

Output radiation is not at one single well defined wavelength → it covers a spectrum of wavelength with a central peak.

Doppler effect

- Gas atoms are in random motion → $KE = 1/2\, mv^2 = 3/2\, kT$
- If radiation frequency is f_0

<u>Detected frequency:</u>



→ $f_1 = f_0\,(1 - v/c)$

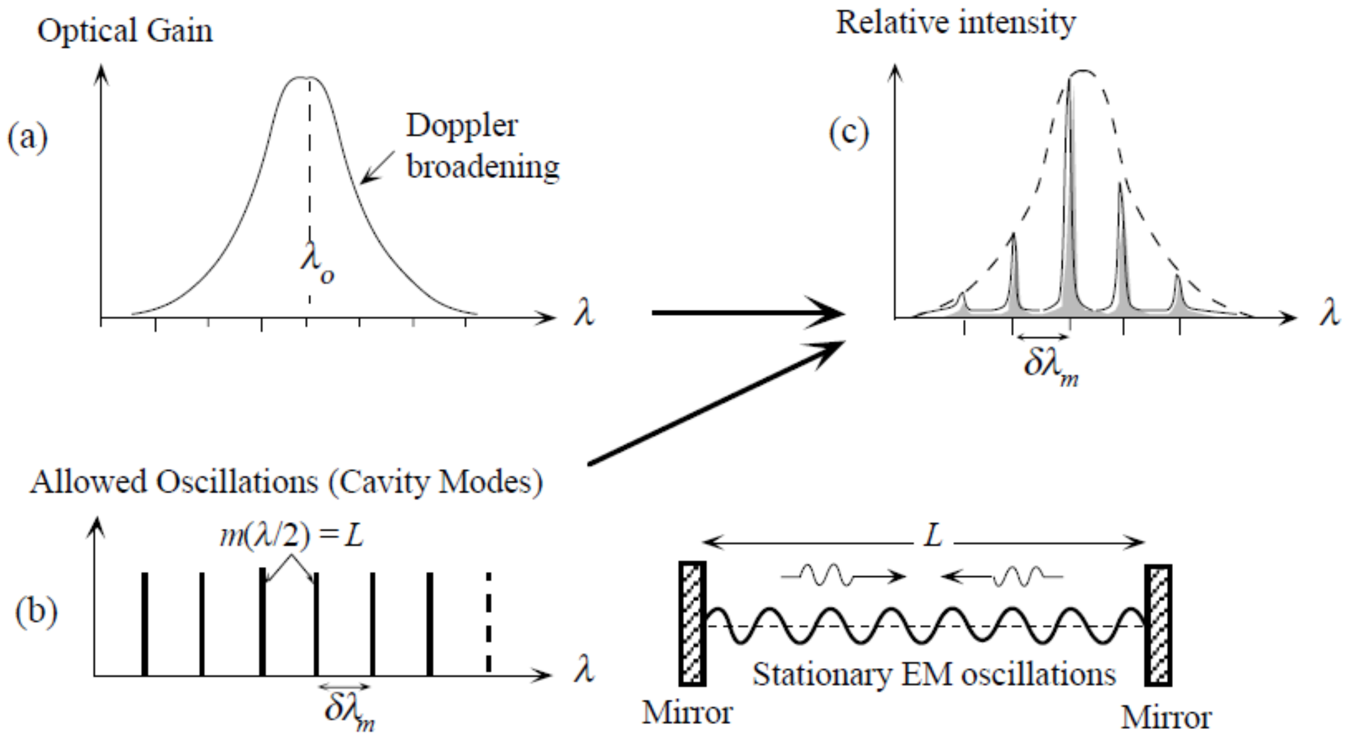
→ $f_2 = f_0\,(1 + v/c)$

The observer detects a range of frequencies
$\Delta f = f_2 - f_1$

Doppler-broadened linewidth

v = relative velocity of the atom wrt the observer

LASER OUTPUT SPECTRUM



(a) Optical gain vs. wavelength characteristics (called the optical gain curve) of the lasing medium. (b) Allowed modes and their wavelengths due to stationary EM waves within the optical cavity. (c) The output spectrum (relative intensity vs. wavelength) is determined by satisfying (a) and (b) simultaneously, assuming no cavity losses.

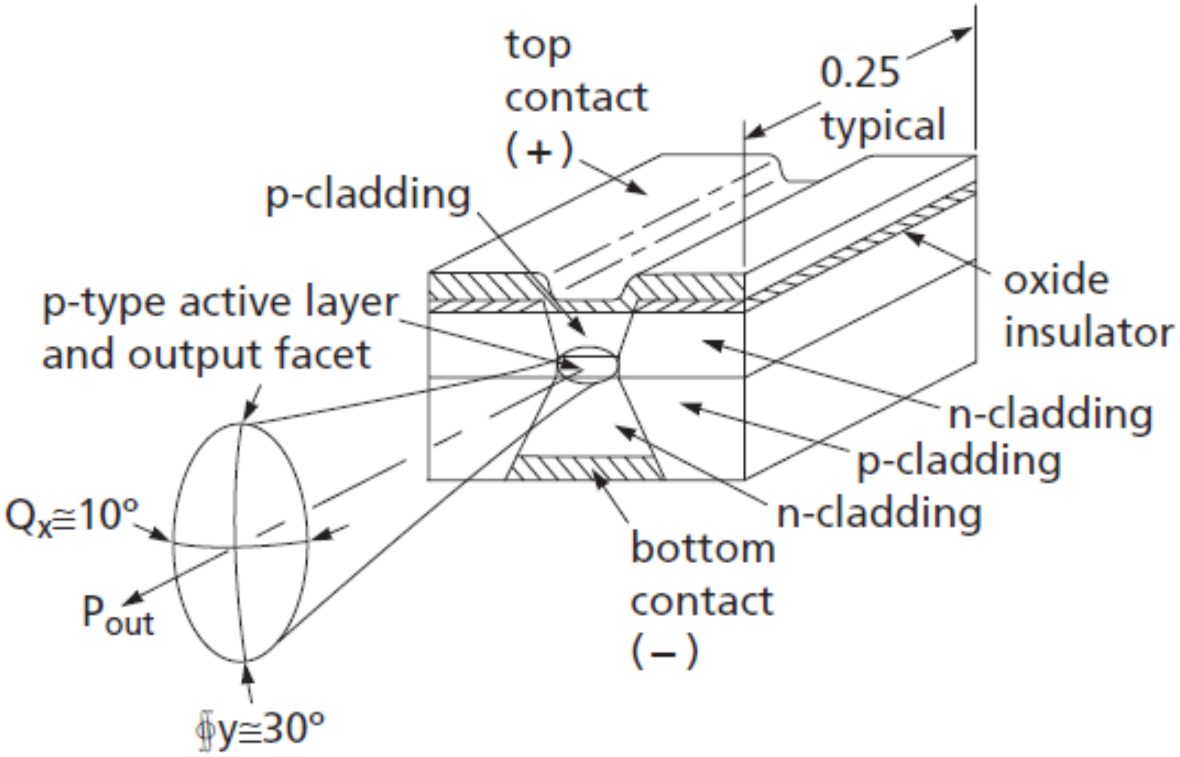
SEMICONDUCTOR LASERS

General features

- High efficiency (50% electrical-to-power conversion rate)
- Low voltage
- Small and compact
- Robust and have long life
- Inexpensive because production is suitable for mass production
- Low power consumption

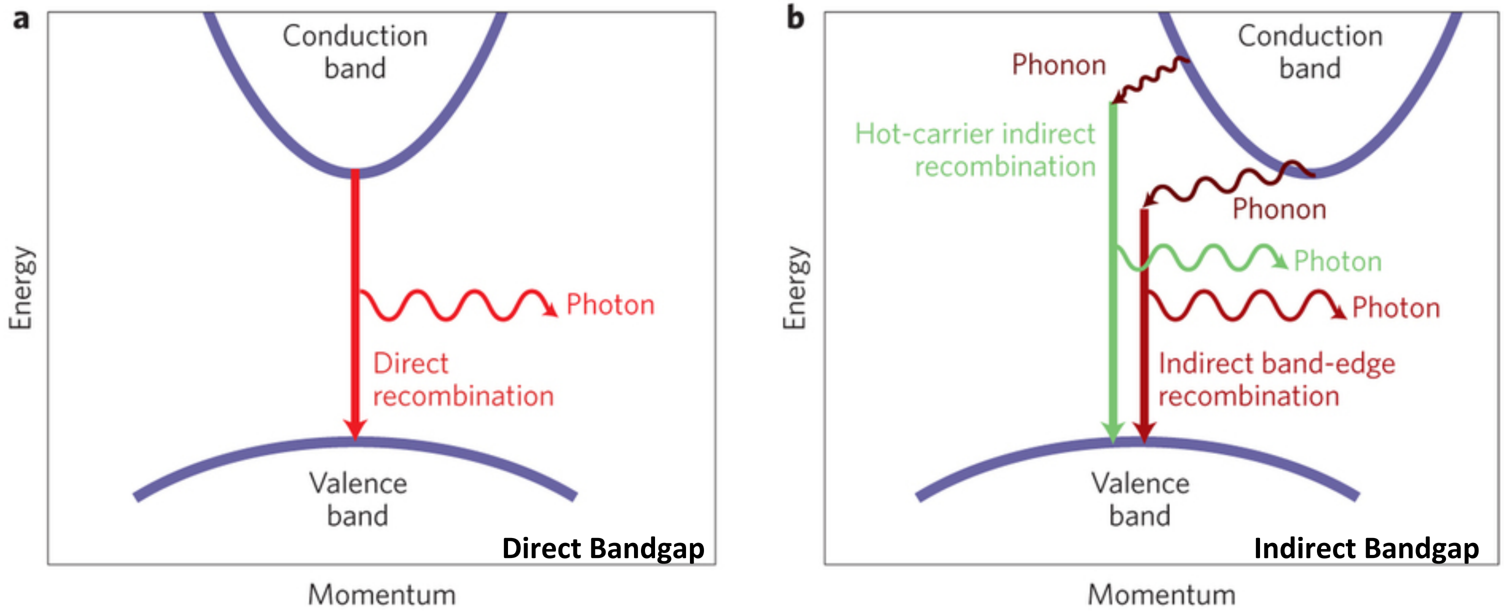
SEMICONDUCTOR LASERS

Configuration



SEMICONDUCTOR LASERS

- III-V compounds, E_g determines the lasing wavelength
- Three main families
  - GaN-based → UV-blue output
  - GaAs-based → red-NIR output
  - InP-based → IR output
- DIRECT BANDGAP SEMICONDUCTORS



Direct band-gap semiconductors with efficient recombination of injected holes and electrons because no phonons (lattice vibrations) are required to conserve momentum in the recombination interaction.

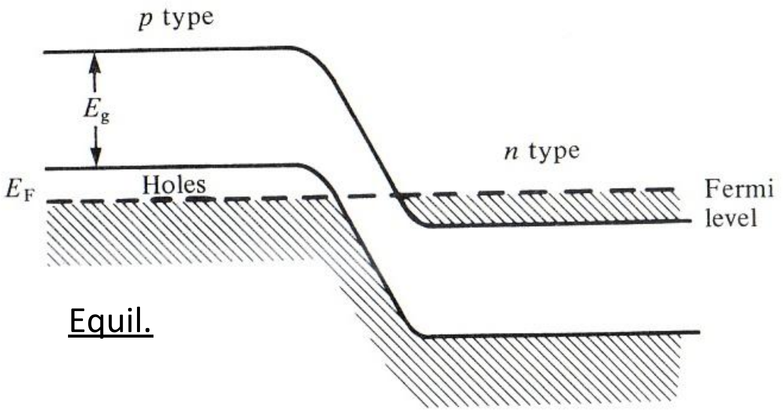
SEMICONDUCTOR LASERS

Lots of electrons in CB eager to descend to VB where there are lots of empty states eager to receive them

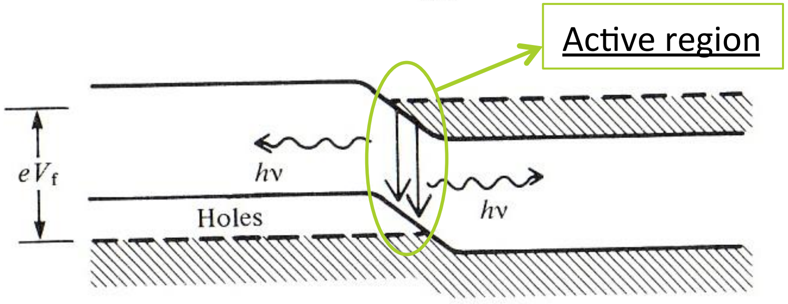
Degenerate pn junction

Very high impurity level → Fermi level moves up into CB (and down into VB)

Built-in energy ≈ E_g



(a)



(b)

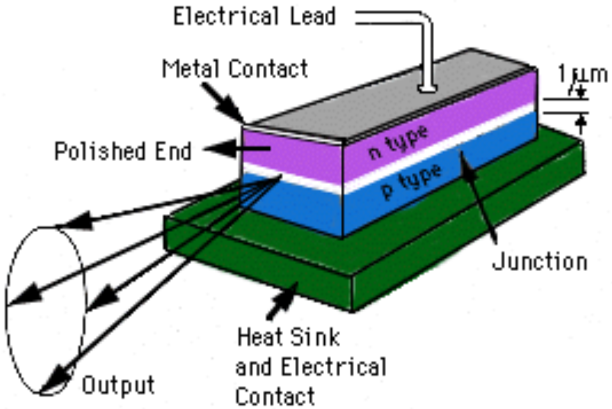
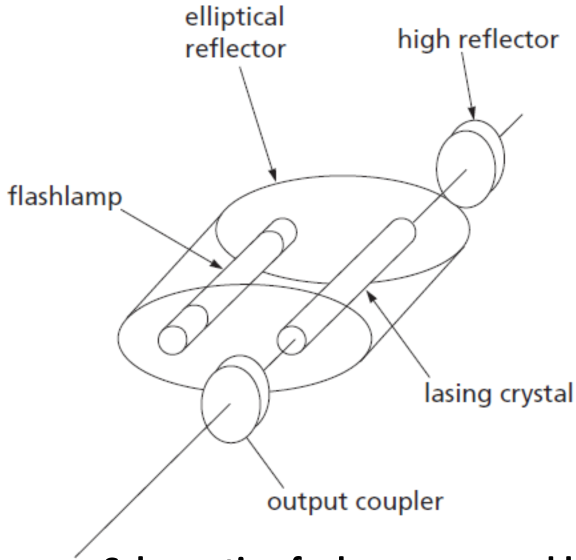


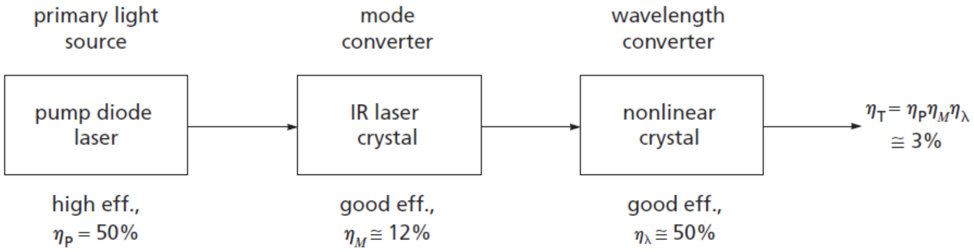
Diagram of Semiconductor Laser

MANY MORE…

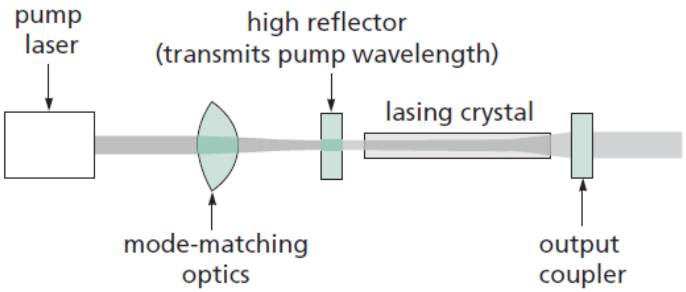
- Solid state lasers (Ruby laser)
- Optically pumped laser
  - Lamp-pumped
  - Laser-pumped
- Diode pumped solid state lasers (DPSS)
- Quantum cascade lasers
- Masers (microwave amplification)
- ...



Schematic of a lamp-pumped laser



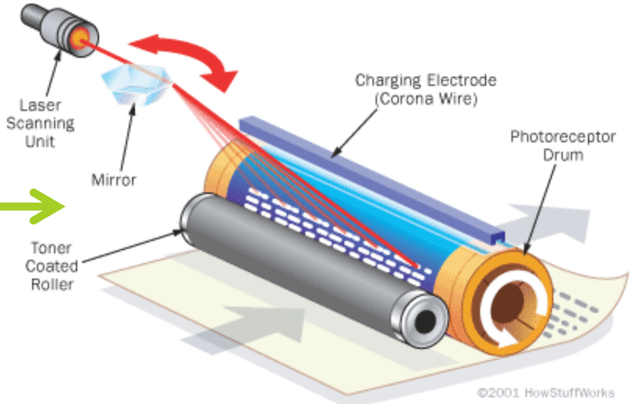
The logic for DPSS lasers



Schematic of a laser-pumped laser

APPLICATIONS

Lasers: a part of daily life



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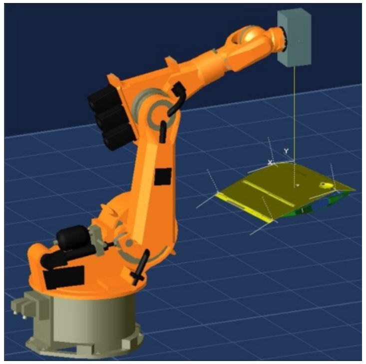
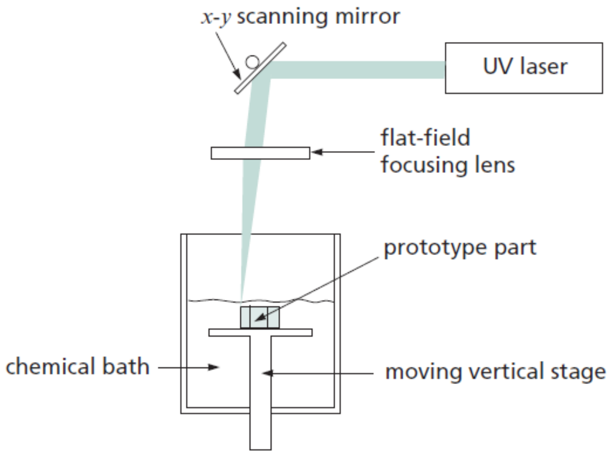
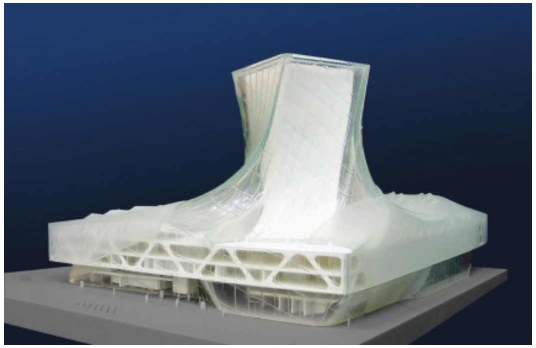
APPLICATIONS

Industrial applications



- *Laser welding robots in automotive*
- *Laser-cut dies for complex cardboard boxes and engraving*
- *Stereolitography (rapid prototyping)*

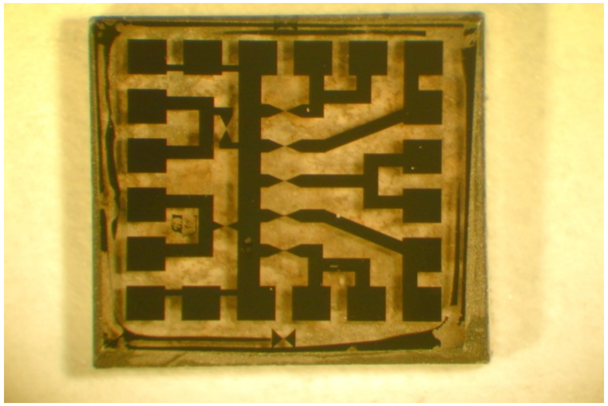


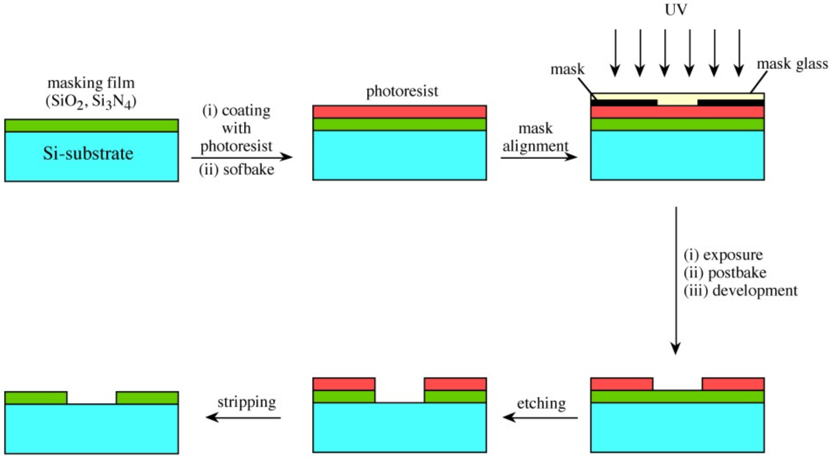


APPLICATIONS

Industrial applications

- *Photolitography* for electronic circuits

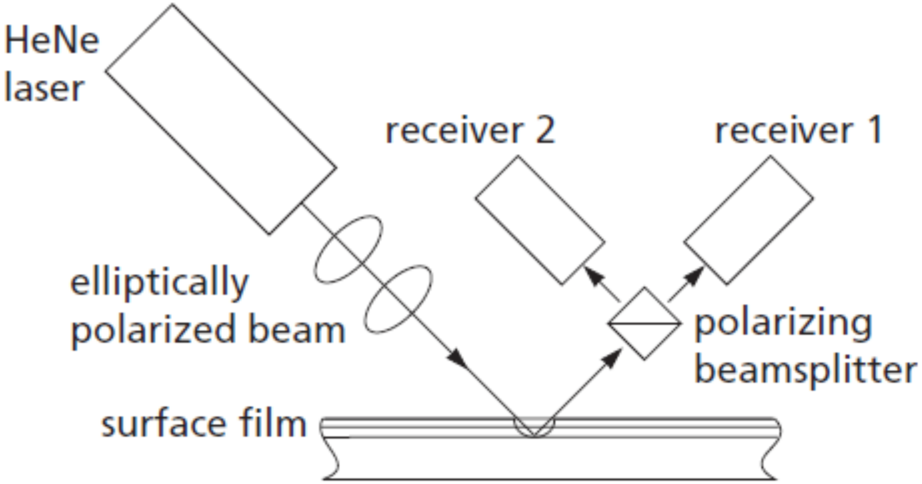




APPLICATIONS

Industrial applications

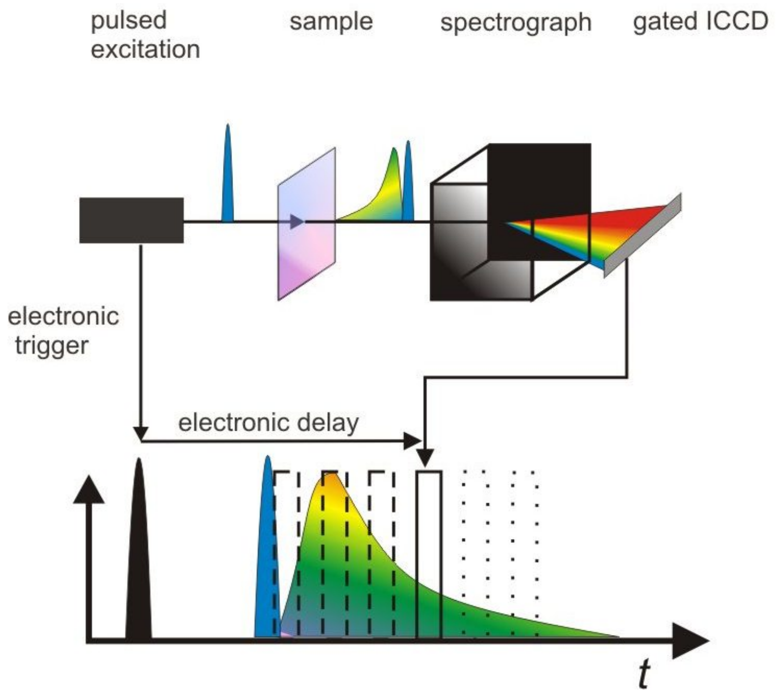
- *Non contact measurements*: scatter, polarimetry, ellipsometry
    - *Scatter measurements*: to detect defects in semiconductor wafers. Lasers have excellent pointing stability, constant wavelength, and power stability to calculate the correct size of defects
    - *Polarimetry and ellipsometry*: to measure film thickness if refractive index is known, and viceversa



APPLICATIONS

Scientific applications

- *Time-Resolved Spectroscopy*: used to used to observe phenomena that occur on a very short time scale (understand biological processes such a photosynthesis, which occur in picoseconds or less)



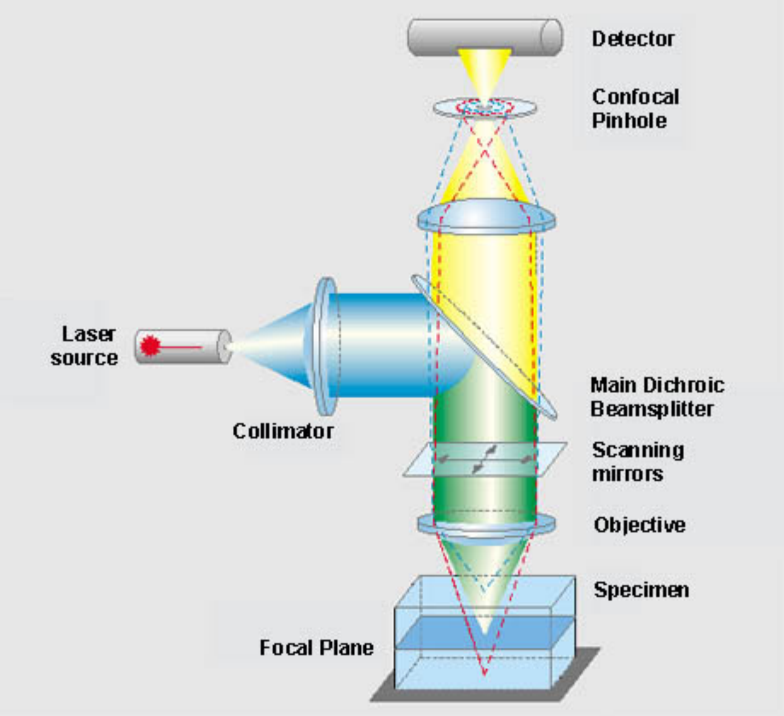
- Fluorescing sample excited by a laser with pulse length much shorter than the time duration of the effect being observed

- Using conventional fluorescence spectroscopy measurement techniques, the time domain of the fluorescence decay process can be analyzed

APPLICATIONS

Scientific applications

- *Confocal Scanning Microscopy*: to build up a three-dimensional image of a biological sample



Visible laser used as light source

Light is focused on the sample

A pinhole is placed in front of the detector at an optical distance that is exactly the same as the optical distance between the focus point and the illuminating source point - confocal condition → only light generated at the illuminating point will pass through the pinhole; out-of-focus light will be blocked

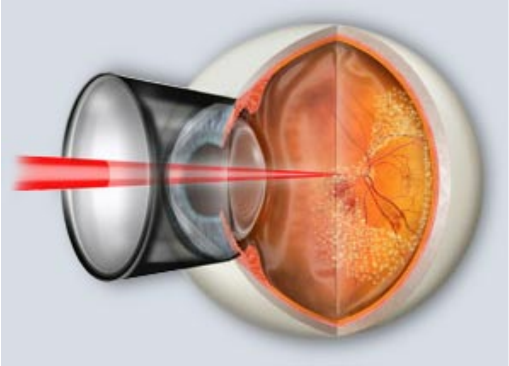
APPLICATIONS

Scientific applications

- *TIR (Total Internal Reflection)*
- *Fluorescence Correlation Spectroscopy*
- *Microarray scanning*
- *Holography*
- …

APPLICATIONS

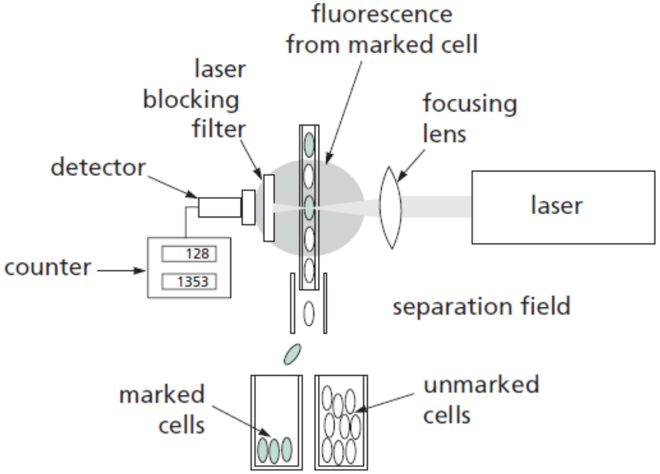
Medical applications



- *Photocoagulation*: argon-ion laser to seal off ruptured blood vessels on the retina of the eye

- *Surgical applications*: cutting tissues, correcting vision, removing tatoos, …

- *Flow cytometry*: measuring single cells. Not only key research tool for cancer and immunoassay disease research, but also used in food industry for monitoring natural beverage drinks for bacterial content or other disease-causing microbes. 488nm (blue) argon-ion laser and the 632nm (red) and 594nm (yellow) HeNe lasers



END OF LECTURE

LASER: basic principles and applications

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