Semiconductor Lasers
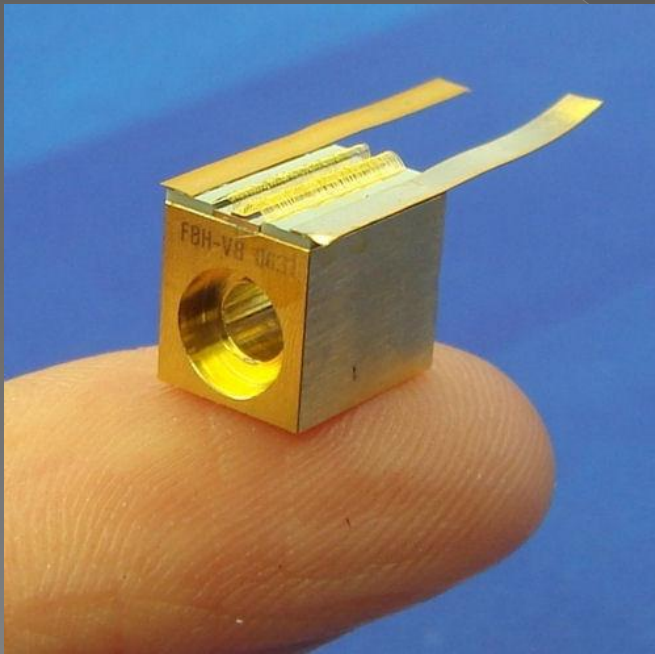
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Outline

- Intro to Semiconductor Devices
- Fabry-Perot Resonators
- Interaction of Photons with Atoms
- General LASER Theory
- The Laser Diode
- Waveguiding and other Parameters of interest
- Applications

Intro to Semiconductor Devices

- Semiconductor has conductivity between conductor and insulator.
- The comprehensive theory of semiconductors relies on the principles of quantum physics to explain the motions of electrons through a lattice of atoms.
- Doping a semiconductor with a small amount of impurity atoms greatly increases the number of charge carriers within it.
- When a doped semiconductor contains excess holes it is called "p-type", and when it contains excess free electrons it is known as "n-type"
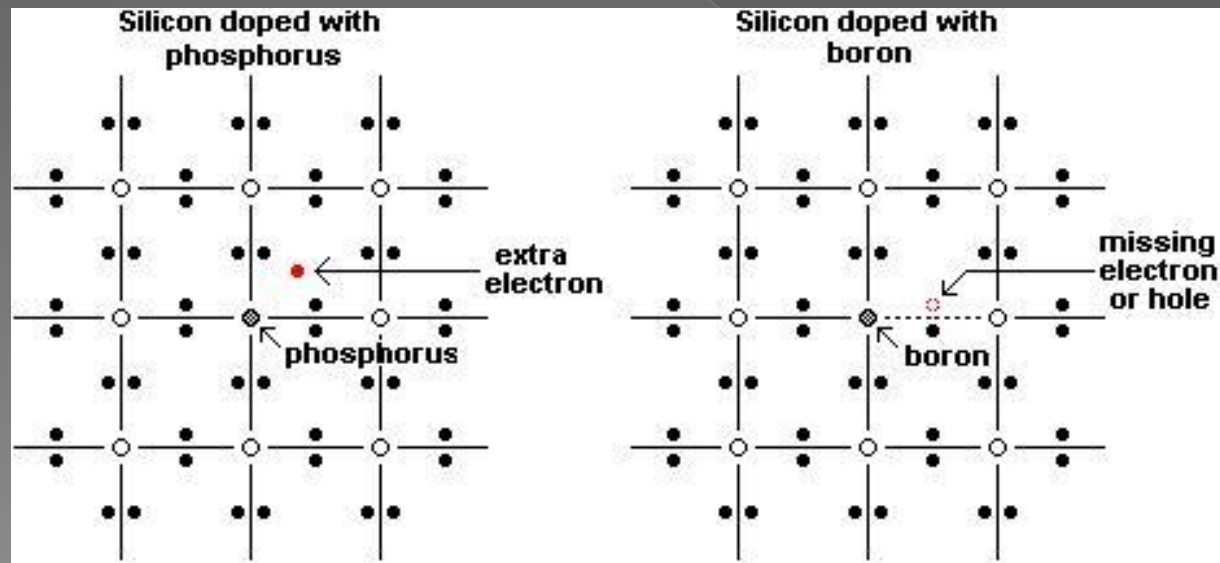
PN Junction

- elementary "building blocks" of most semiconductor electronic devices.
- Only permit current under forward bias due to minority carrier concentration profile.
- Not limited to Silicon, can be done with a number of materials and configurations
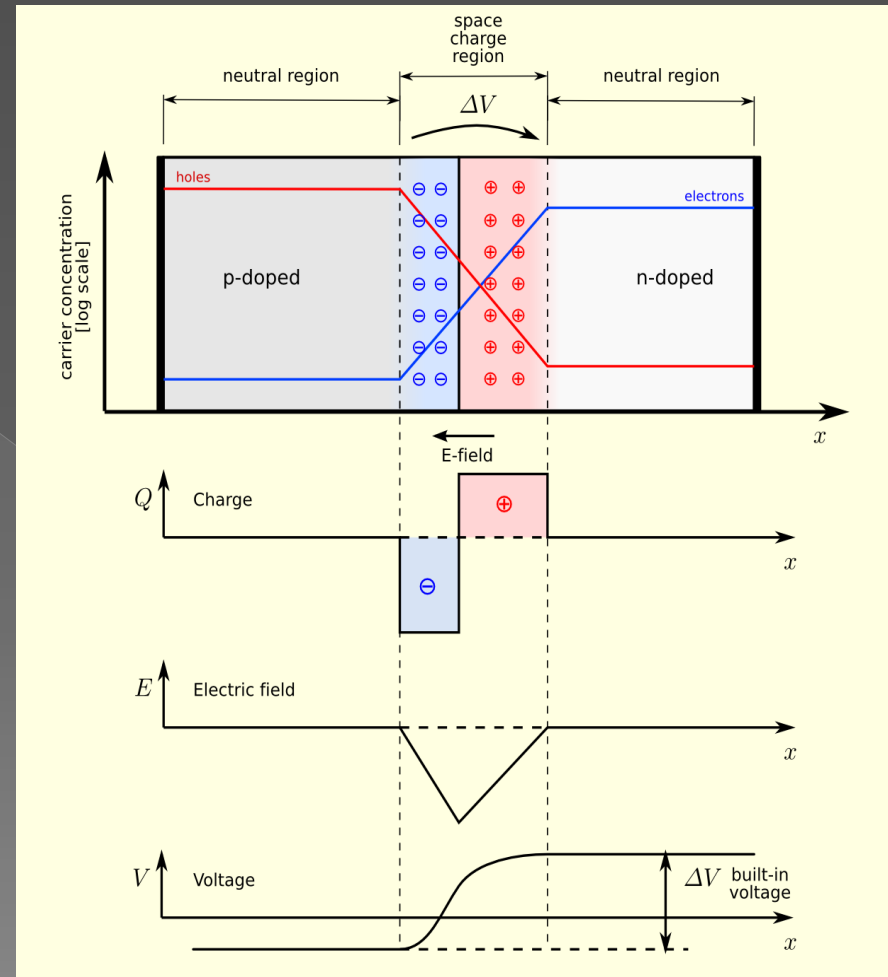
Carrier Generation/Recombination

- Carrier *generation* describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers.

- *Recombination* describes processes by which a conduction band electron loses energy and re-occupies the energy state of an electron hole in the valence band.

- During *radiative recombination*, a form of spontaneous emission, a photon is emitted with the wavelength corresponding to the energy released.*

free-electron energy

unfilled bands

conduction band

band gap

valence band

filled bands

E
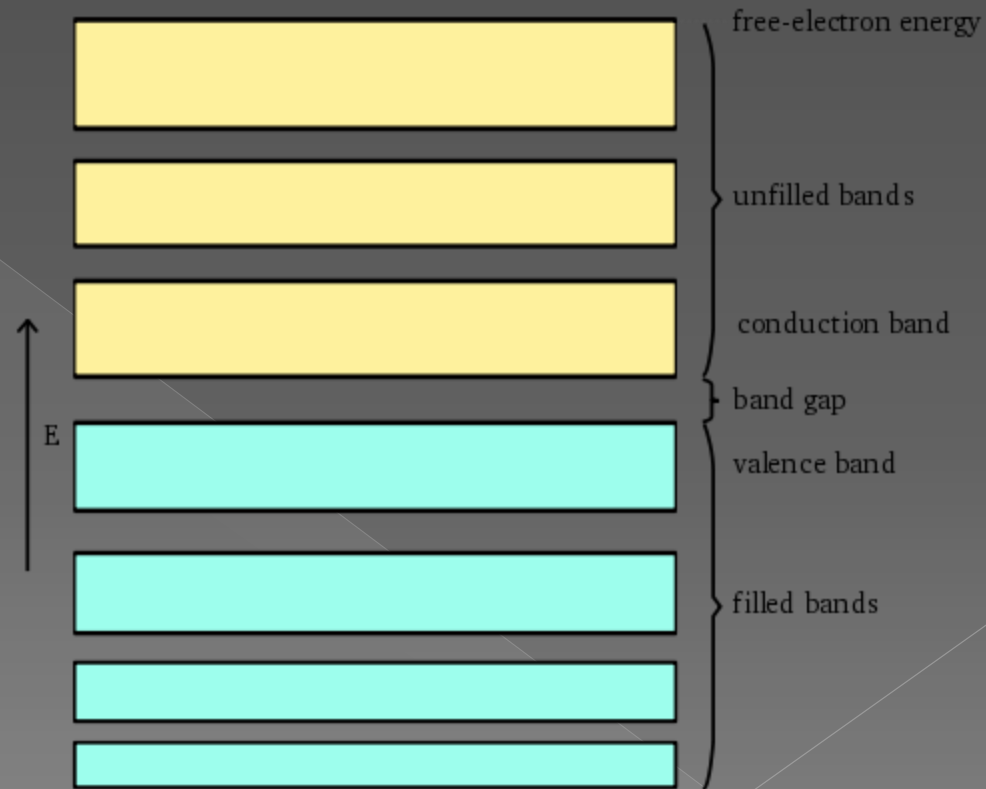
*mostly limited to "direct bangap" Semiconductors.

Occupation of Energy Levels

- Given by Maxwell Boltzmann distribution, if KT>>E_f where the later is the Fermi Energy. (Other wise we need to use QM and Fermi-Dirac statistics.)
- Allows us to derive the condition of population inversion. More about why later.
- The Law of the Junction—rigorously derived by integrating density of states and Fermi-Dirac distribution over the energy in the conduction band to infinity.
- Leads to threshold current where more charge carriers in conduction and are being injected into depletion region.
- Intrinisic n_i for silicon = 10^{10} GaAs = 10^6

$$N_i = \frac{g_i}{e^{(\varepsilon_i - \mu)/kT}} = \frac{N}{Z} g_i e^{-\varepsilon_i/kT}$$

$$N = \sum_i N_i$$

$$Z = \sum_i g_i e^{-\varepsilon_i/kT}$$

The Maxwell Boltzmann Distribution
Population inversion for 2-level system:

$$N_1 + N_2 = N$$
$$\Delta E_{12} = E_2 - E_1,$$

$$\frac{N_2}{N_1} = \exp \frac{-(E_2 - E_1)}{kT},$$
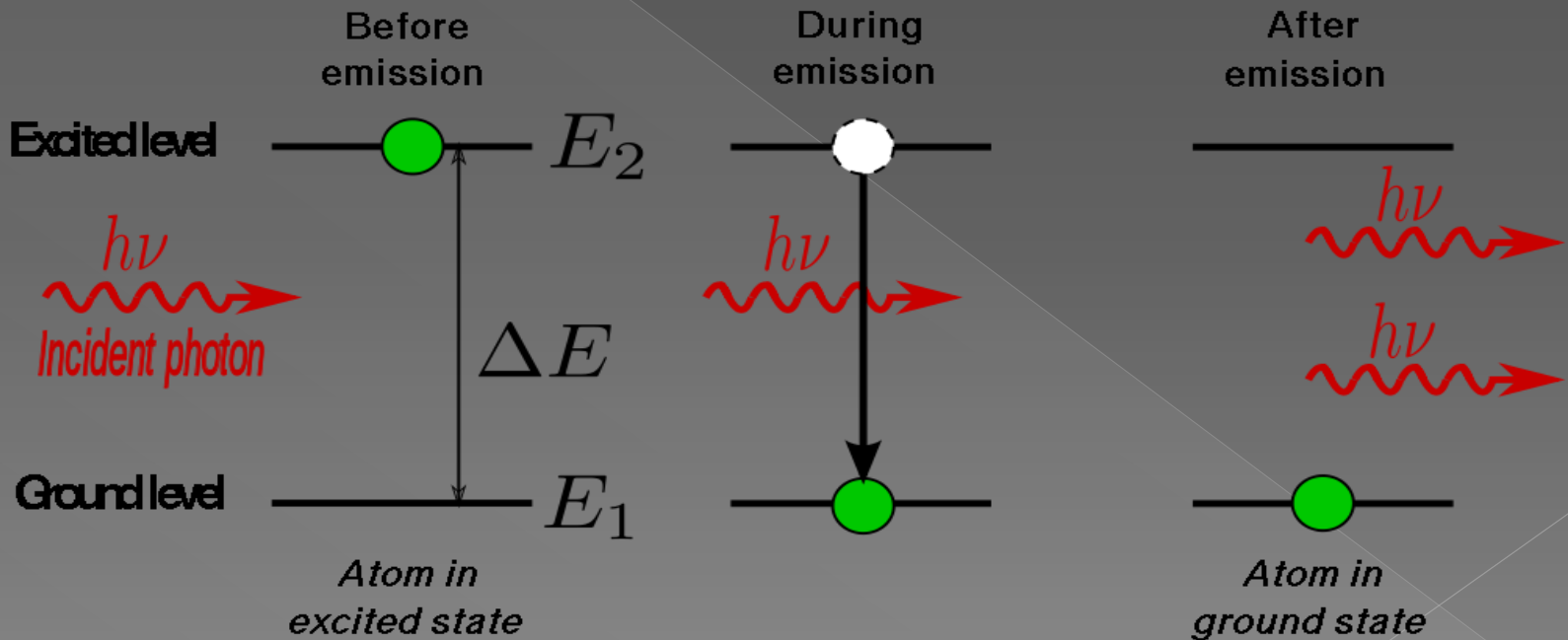
Want $N_2 > N_1$

$$n = \int_{E_C}^{\infty} N(E)f(E)dE \qquad (1)$$

and

$$p = \int_{-\infty}^{E_V} N(E)(1 - f(E))\, dE \qquad (2)$$

Shifting gears…Fabry-Perot Resonators

- Fabry–Pérot interferometer or etalon is typically made of a transparent plate with two reflecting surfaces, or two parallel highly reflecting mirrors. Allows for certain resonance frequencies (related to geometry of cavity).
- $V_f = c/2d$
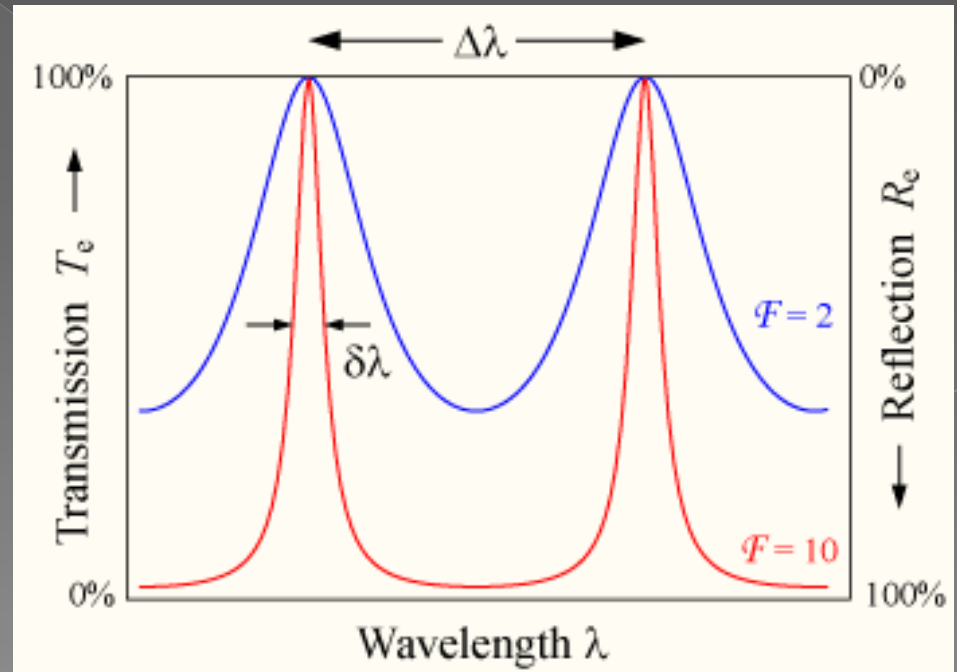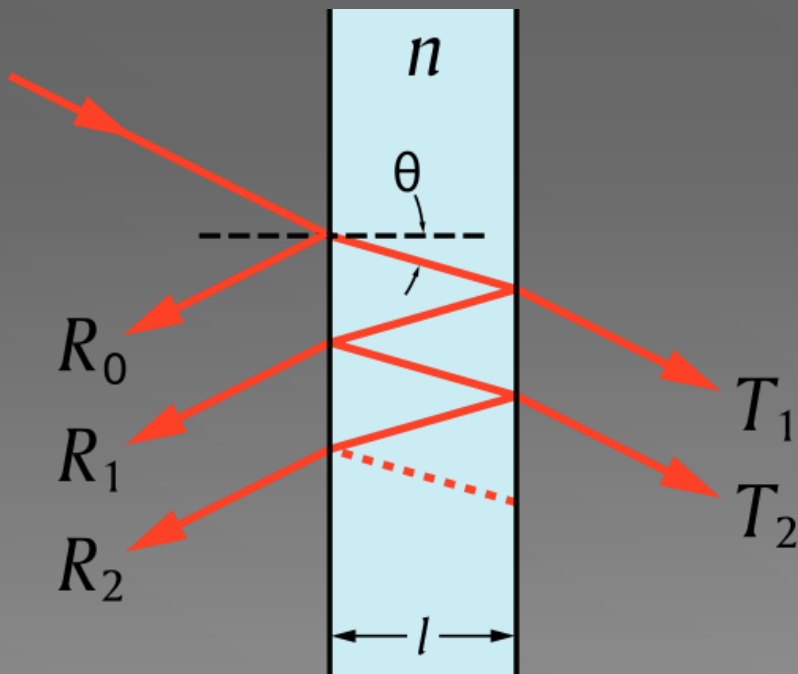
Interactions of Photons with Atoms

- Formally studied with QED
- Process of Stimulated Emission in a 2-level system can be modeled with time dependent perturbation where time varying perturbation is an oscillating electric field (monochromatic plane wave – i.e. light).

Before emission	During emission	After emission
Excited level — ● — E_2	○	
$h\nu$	$h\nu$	$h\nu$
Incident photon		$h\nu$
ΔE		
Ground level — E_1	●	●
Atom in excited state		Atom in ground state

$$E_2 - E_1 = \Delta E = h\nu$$

General LASER Theory

- Need a gain medium with population inversion and incident photons.
- Consider a quantized radiation field in a cavity of volume V, containing atoms. Probability density (per unit time) for absorption or emission of a photon from a given unoccupied mode can be modeled with the following equations for probability density.
- **σ(v)** is the a function of frequency (Energy. QED treats EM field as QHO's).
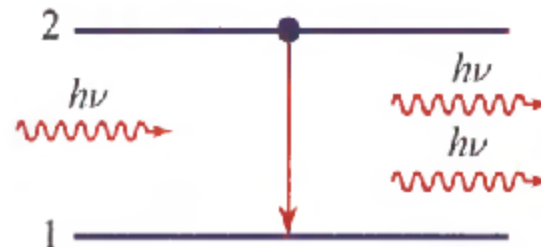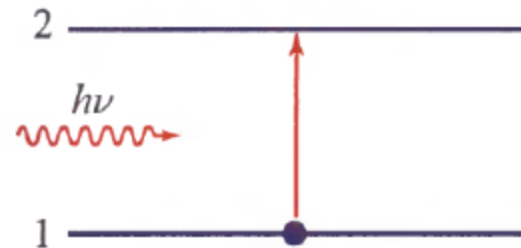
$$p_{ab} = \frac{c}{V}\sigma(v)$$

units of area

$\sigma(v)$ = transition cross section; obtain from W.F. or experiment

$$P_{ab} = n\frac{c}{V}\sigma(v)\ [= n\ p_{ab}(v)]$$

If mode has n photons, prob. density of going to n+1 photons:

$$P_{st} = n\frac{c}{V}\sigma(v)$$

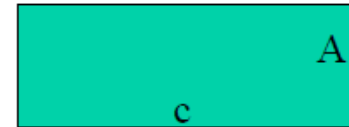$$p_{sp} + P_{st} = (n+1)\frac{c}{V}\sigma(v)$$

LASER Amplification

- The gain in photon density is related to the population difference of states. Hence gain requires population inversion

Consider a cylinder along direction of propagation (k) of base area A

Volume swept out (per unit time)

$$V = cA$$

Number of photons in cylinder is then

$$n = \phi A = \phi \frac{V}{c} \qquad \phi = \frac{nc}{V} \quad \text{: photon flux}$$

$$W_i = P_{ab} = P_{st} = n \frac{c}{V} \sigma(\nu) = \phi \sigma(\nu)$$

$$\boxed{W_i = \phi \sigma(\nu)}$$
Induced transition rate

Can Also write photon flux as intensity/energy per photon:

$$\phi(z) = I(z) / h\nu$$

Density of Absorbed and Emitted Photons (ignoring spontaneous emission.)

$$\rho_{ab} = N_1 W_i \qquad \rho_{st} = N_2 W_i$$

$$\rho_{gained} = \rho_{st} - \rho_{ab} = (N_2 - N_1)W_i = NW_i$$

LASER Gain

- Gain coefficient comes from density of modes, live time of state without spontaneous emission and normalized transition cross section.

- Flux is related to intensity/energy per photon.

- Laser gain $\quad d\phi = \rho_{gained}\,dz = NW_i\,dz$

$$W_i = \phi\sigma(\nu)$$

$$\frac{d\phi}{dz} = NW_i = N\sigma(\nu)\phi(z) = \gamma(\nu)\phi(z)$$

$$\gamma(\nu) = N\sigma(\nu) = NSg(\nu) \qquad S = \frac{\lambda_0^2}{8\pi\tau_{sp}}$$

$$\frac{d\phi}{dz} = \gamma(\nu)\phi(z)$$

integrate..

$$\gamma(\nu) = N\frac{\lambda_0^2}{8\pi\tau_{sp}}g(\nu)$$

Gain coefficient

$$\phi(z) = \phi(0)e^{\gamma(\nu)z}$$

$$I(z) = I(0)e^{\gamma(\nu)z}$$

Empirical Peak Amplification Coefficient:

$$\gamma = \alpha(J/J_T - 1) \qquad J_T = \frac{el\,\Delta n_T}{\eta_i\,\tau}$$
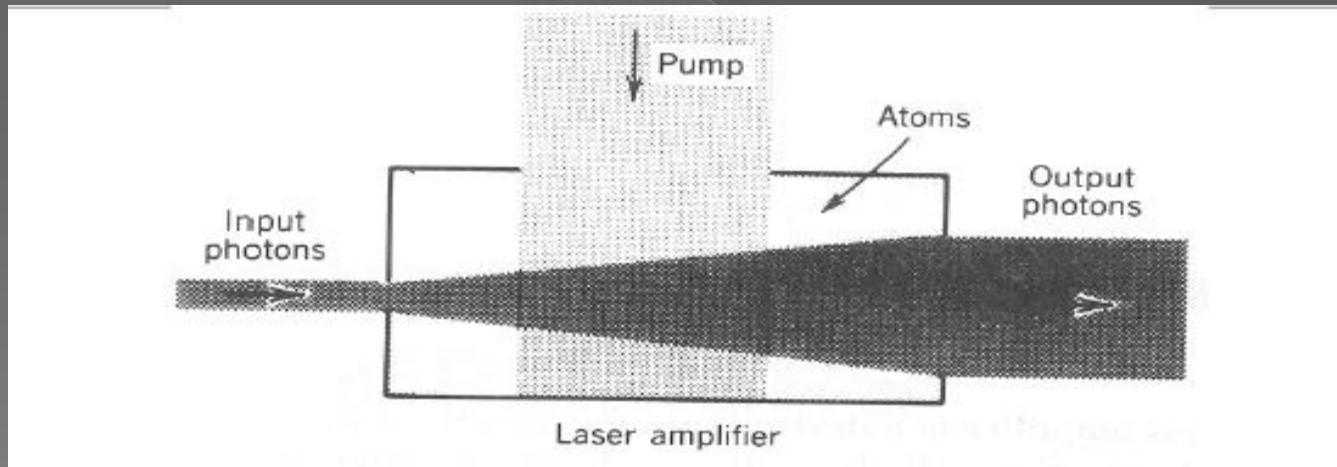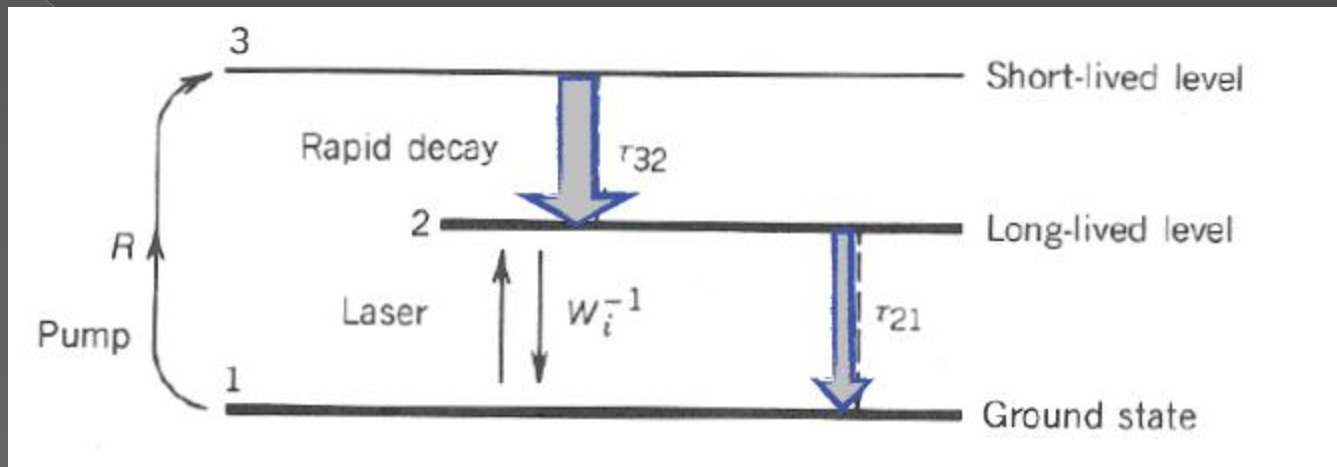
Single pass gain in a laser amplifier of length d
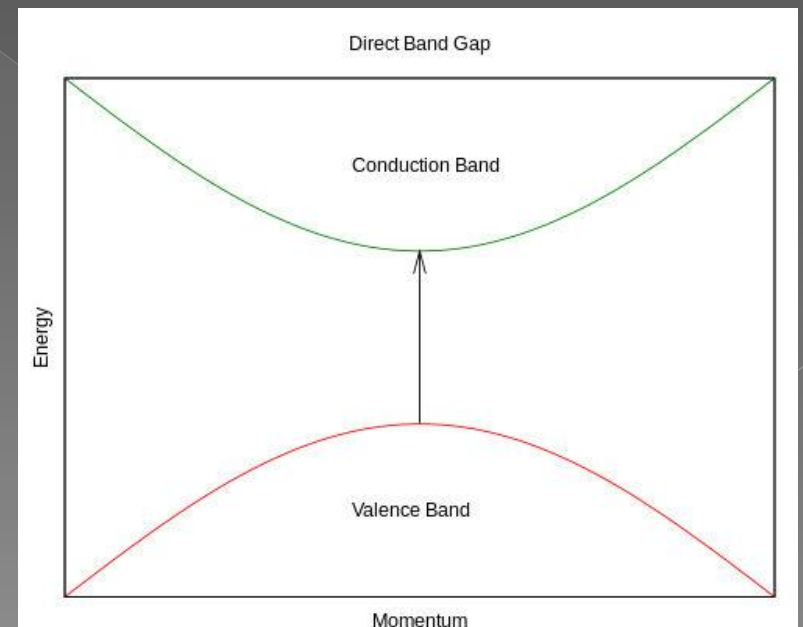
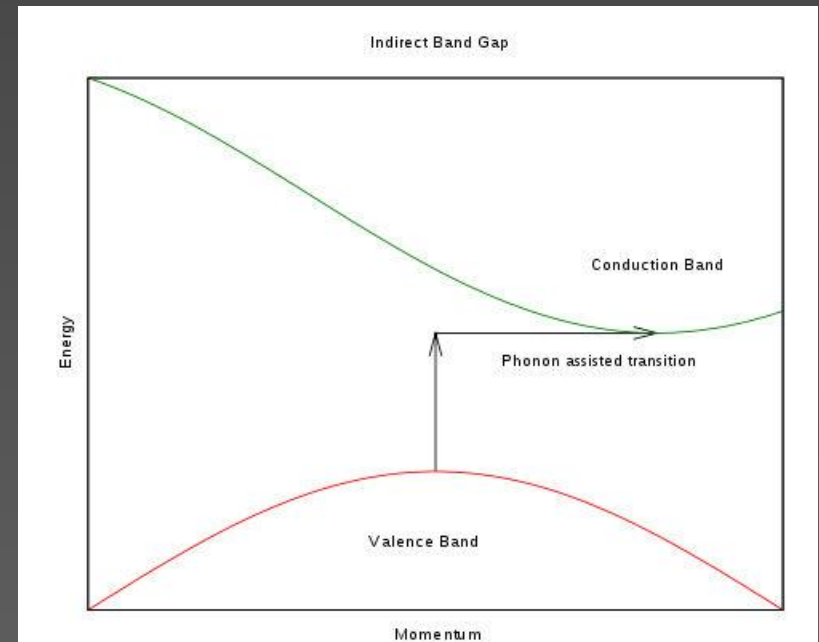$$G(\nu) = \exp[\gamma(\nu)d]$$

Visualization of Laser System

- Example of a 3-level LASER system (still 2 level system where the actual Lasing happens.)

LASER Diode

- Forward electrical bias across the laser diode causes holes and electrons to be "injected" from opposite sides of the *p-n* junction into the depletion region.

- When an electron and a hole are present in the same region, they may recombine or "annihilate" with the result being spontaneous emission

- The difference between the photon-emitting semiconductor laser and conventional phonon-emitting (non-light-emitting) semiconductor junction diodes lies in the use of a different type of semiconductor, one whose physical and atomic structure confers the possibility for photon emission. These are the "direct bandgap" semiconductors.

- Eg: Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride

Indirect Band Gap

Conduction Band

Phonon assisted transition

Valence Band

Energy

Momentum

Direct Band Gap

Conduction Band

Valence Band

Energy

Momentum

More About the Laser Diode

- A nearby photon with energy equal to the recombination energy can also cause recombination by stimulated emission.

- Stimulated emission causes gain in an optical wave (of the correct wavelength) in the injection region, and the gain increases as the number of electrons and holes injected across the junction increases.

- An optical waveguide is made on the crystal surface. The two ends of the crystal are cleaved to forma Fabry–Perot resonator. Due to difference in the index of refraction of GaAs and the air a mirror is not necessary, light will be reflected. Photons emitted into a mode of the waveguide will travel along the waveguide and be reflected several times from each end face before they are emitted.

- As a light wave passes through the cavity, it is amplified by stimulated emission, but light is also lost due to absorption and by incomplete reflection from the end facets. If there is more amplification than loss, the diode begins to "lase". Happens at a threshold current.

- Index of refraction for GaAs, n=3.6

H=200 um

L= 2000-4000 um

B=60-200 um

Waveguiding Layer
Active Region
Waveguiding Layer
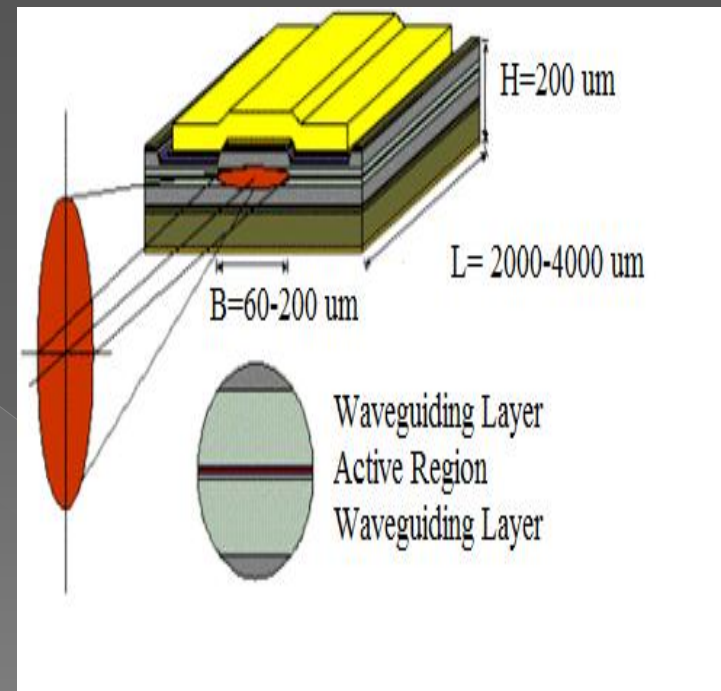
$$R = \left(\frac{n-1}{n+1}\right)^2$$

Waveguiding

- By Solving Maxwell's equations in a waveguide we can find the allowed modes. For a Rectangular geometry we can support Hermite Gaussian (Transverse) modes

- The Following intensity pattern:

- Due to the geometry there is more spatial confinement in the vertical than the lateral direction, so only the latter supports higher order modes (which we would actually like to avoid since we want a purely Gaussian beam for many applications.)
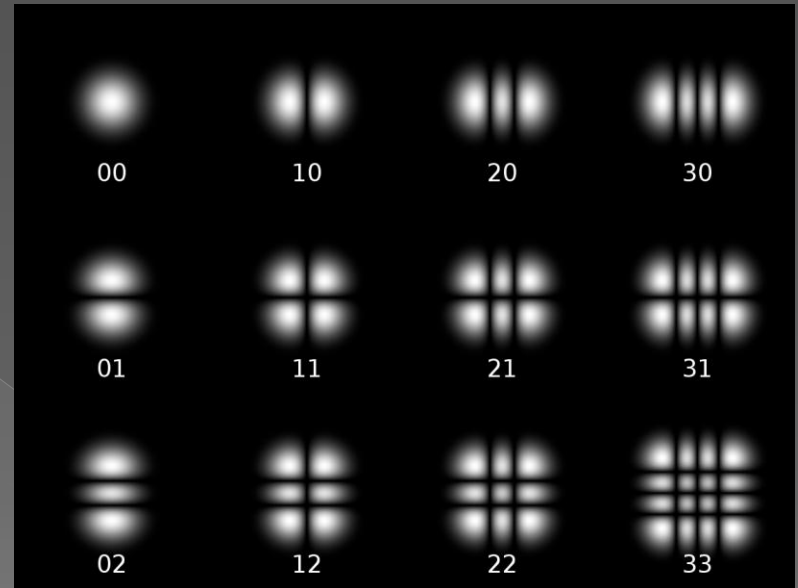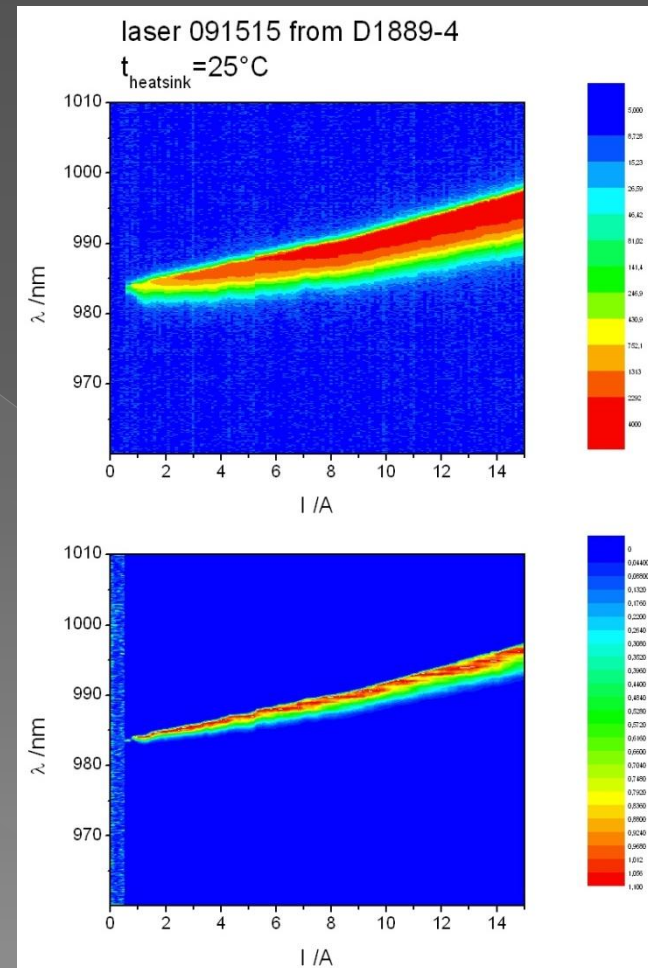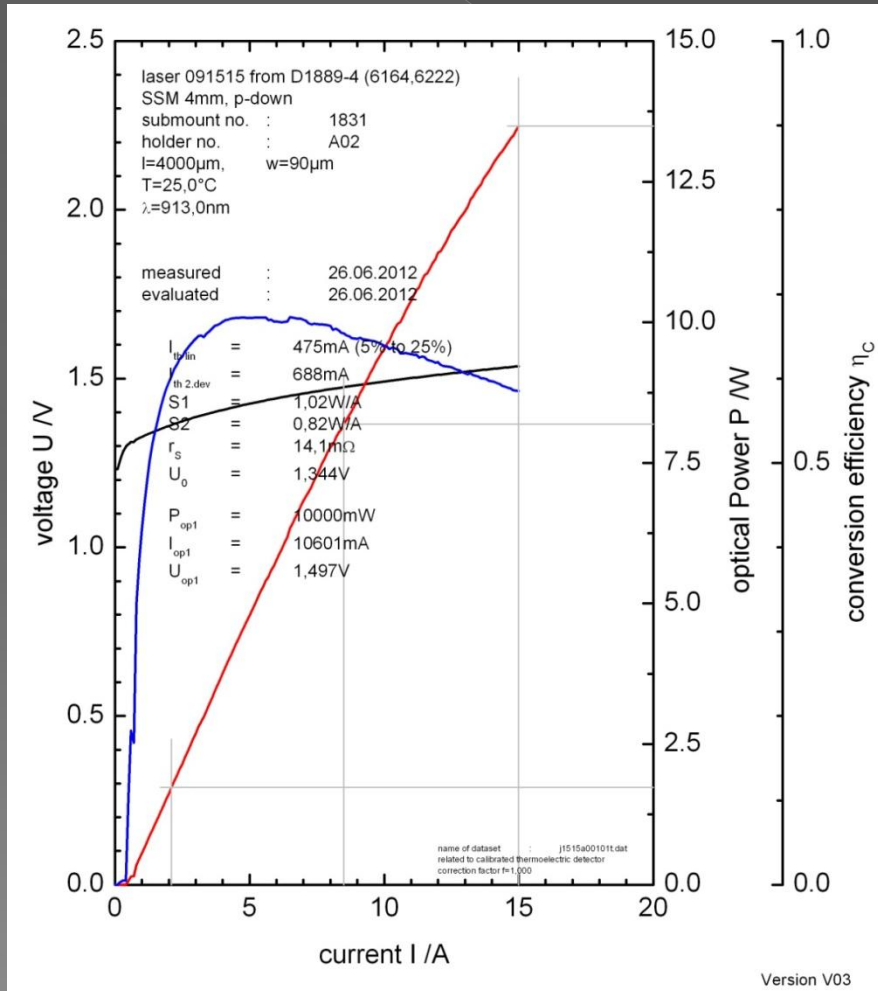
$$I_{mn}(x, y, z) = I_0 \left[H_m \left(\frac{\sqrt{2}x}{w} \right) \exp \left(\frac{-x^2}{w^2} \right) \right]^2 \left[H_n \left(\frac{\sqrt{2}y}{w} \right) \exp \left(\frac{-y^2}{w^2} \right) \right]^2$$

Actual Measurements of Beam Profile Taken with Photodiode

- Goniophotometers measure the spatial distribution of light
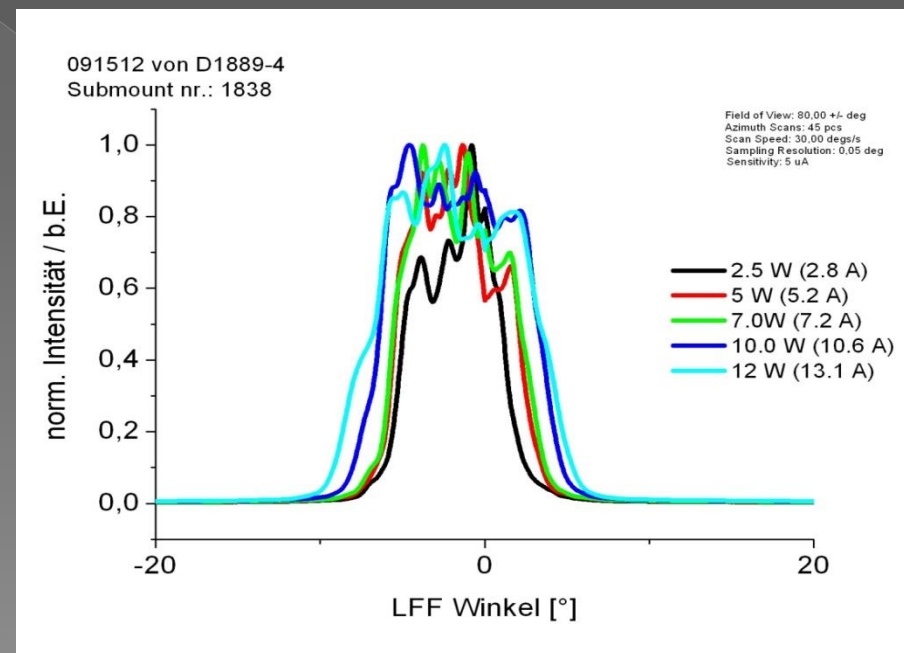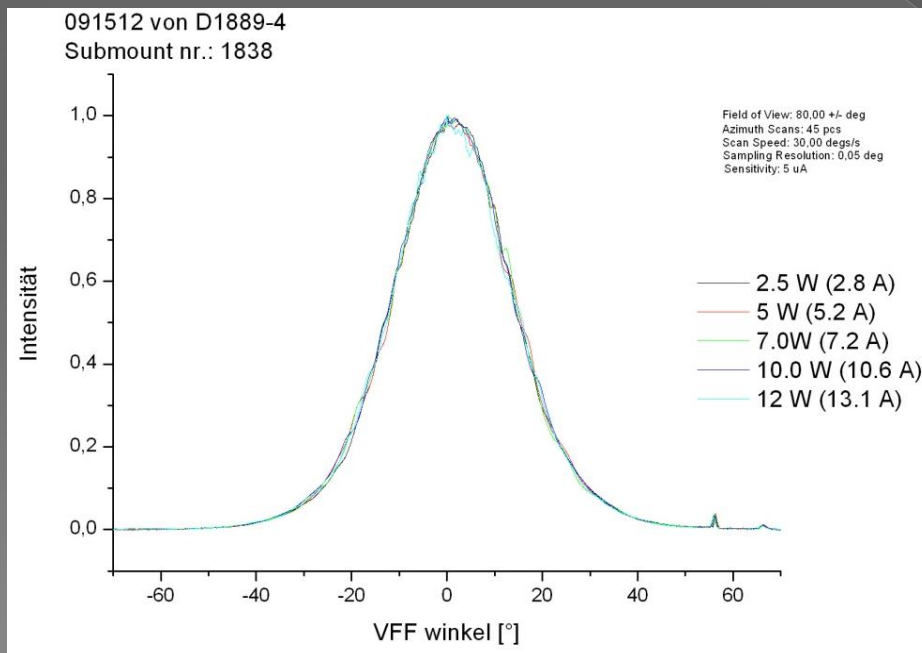
Other Parameters: Current/Voltage/Optical Power profile and Emission Wavelength

Applications

- Laser diodes find wide use in telecommunication as easily modulated and easily coupled light sources for fiber optics communication.

- pumping other lasers, such as diode-pumped solid-state lasers.

- Infrared and red laser diodes are common in CD players, CD-ROMs and DVD technology. Violet lasers are used in HD DVD and Blu-ray technology.

- medicine and especially dentistry have found many new uses for diode lasers. The 800 nm – 980 nm units have a high absorption rate for hemoglobin and thus make them ideal for soft tissue applications

- Theoretical use in Photonic IC's

Summary

- Laser requires population inversion in order for photon flux to increase as photons move through gain medium.

- In a Laser diode this is achieved by injection charge carriers into the active region.

- Any questions?

Sources

- http://en.wikipedia.org
  - › /Laser_Diode
  - › /PN_Junction
  - › /Fabry-Perot
  - › /Direct_and_Indirect_Bandgap
  - › /Transverse_Mode
- *Fundamentals of Photonics* by Saleh and Teich
- http://www.seit.adfa.edu.au/staff/sites/hrp/papers/pota04-j.pdf