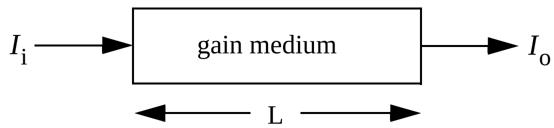
Chapter 5
LASERS

[reading assignment: Hecht, 13.1]

Light **A**mplification by **S**timulated **E**mission of **R**adiation

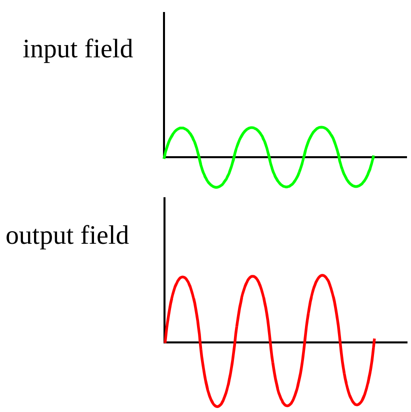
Basic laser architecture:

- The key element in any laser is the *gain medium* (light amplification)

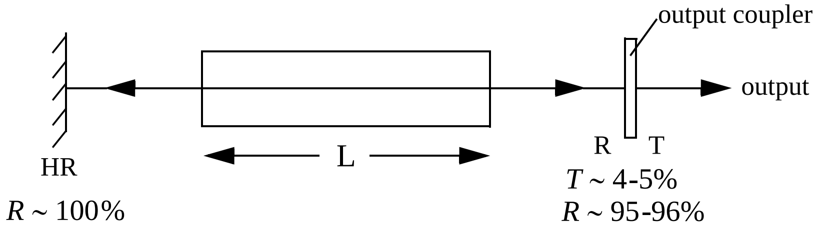


$I_o = e^{gL} I_i$ g : gain coefficient

The light intensity is increased as it passes through the gain medium. We can examine what happens in each of our 3 viewpoints of light:



- The next element is feedback by an "optical resonator"



Light bounces back and forth between the mirrors. On each *round trip*, ~ 4-5% of circulating power leaks out.

This is restored by the round trip gain e^{2gL}.

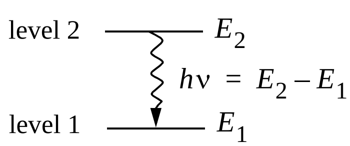
<u>Laser Threshold Condition</u>

If the loss is, for example, 4%, and if , then the gain exceeds the loss, and the system oscillates. Power grows inside the resonator.

Steady state? High power level *saturates* the gain. At a certain power level gain = loss.

<u>Mechanism for gain</u>

Atomic energy levels



N_2 : number of atoms in level 2
N_1 : level 1

Spontaneous emission: Atoms in level 2 randomly "decay," emitting a photon with energy $h\nu$. On average, the atom is in level 2 for time τ_2 before emitting the photon. Then

Under most conditions .

Absorption: Consider an atom in level 1. Now, a photon comes along with energy $h\nu$. The photon is absorbed, and the atom moves to level 2.

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Stimulated emission: Consider an atom in level 2. Now, a photon comes along with energy $h\nu$. In this case, the atom emits another photon, with the same ν, the same direction, and moves to level 1. There are now two photons travelling together.

Stimulated emission and absorption both occur. The net effect is expressed by the equation:

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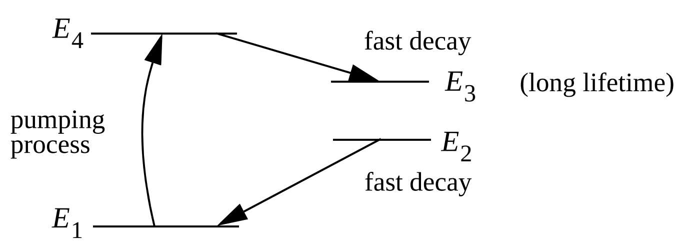
<u>Population inversion</u>

If $N_2 < N_1$, $\frac{dN_2}{dt}$ is positive. Photons are being absorbed, and the excited state population is *increasing*.

But if somehow (i.e., inverted population), $\frac{dN_2}{dt}$ is negative! The excited state population is decreasing. On net, photons are being produced.

This is the origin of *gain*. To achieve population inversion is not easy. First, energy must be pumped into the system. But this is not enough. We also need favorable energy levels.

<u>4-Level laser</u>

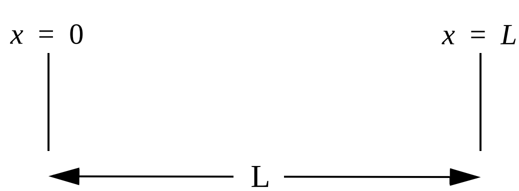


Due to long lifetime in level 3, population stacks up. Any atoms in level 2 rapidly drop back to level 1.

Inversion is reached on $3 \rightarrow 2$ transition.

Saturation: As the circulating laser field builds up, $3 \rightarrow 2$ transitions occur more rapidly. This builds up population in level 2. Now the gain is proportional to $(N_3 - N_2)$. When $N_2 = N_3$, $G \rightarrow 0$. Steady state is reached when $N_3 - N_2$ is just positive enough for gain to be exactly equal to the loss.

<u>Optical resonator</u>

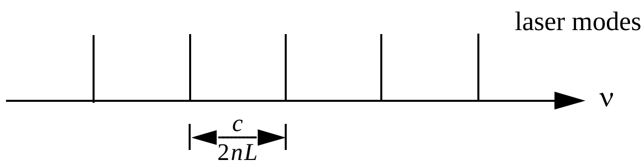


The mirrors impose a boundary condition on electric field, $E = 0$ at the mirror surface. Recall plane wave electric field is $E = \sin(kx - \omega t)$, where $k = \frac{2\pi}{\lambda}$. So, the boundary condition is satisfied if

We can visualize this condition as saying that an integer number of half wavelengths fit in the resonator.

Recall $\nu = \frac{c}{\lambda n}$. So,

This gives the allowed frequencies of oscillation:



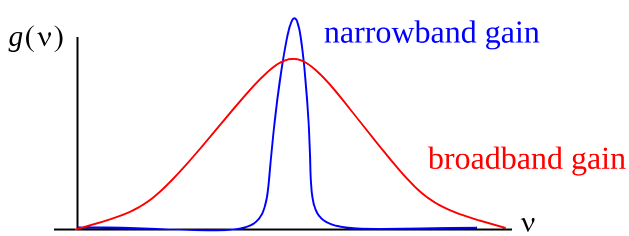
is mode spacing.

Longitudinal modes – Typical values:

HeNe laser: $L = 50 \text{ cm} \rightarrow \frac{c}{2L} = 300 \text{ MHz}$

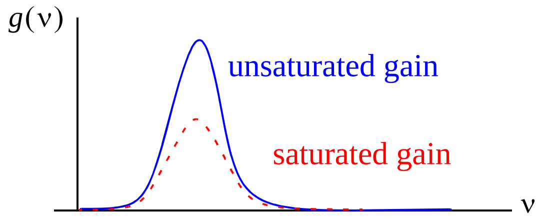
Diode laser:

Laser *gain* spectrum

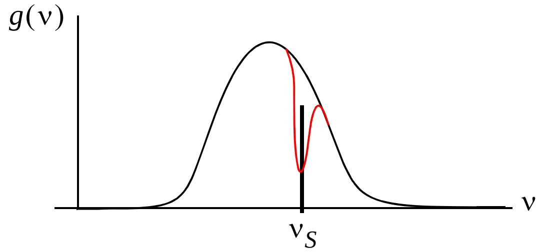


<u>Homogeneous vs. inhomogeneous broadening</u>

Saturation behavior can be of two types.



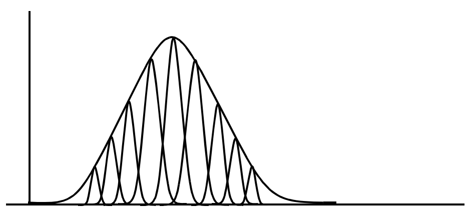
homogeneous broadening: Under saturation, entire gain curve is reduced. Shape is unchanged



inhomogeneous broadening:

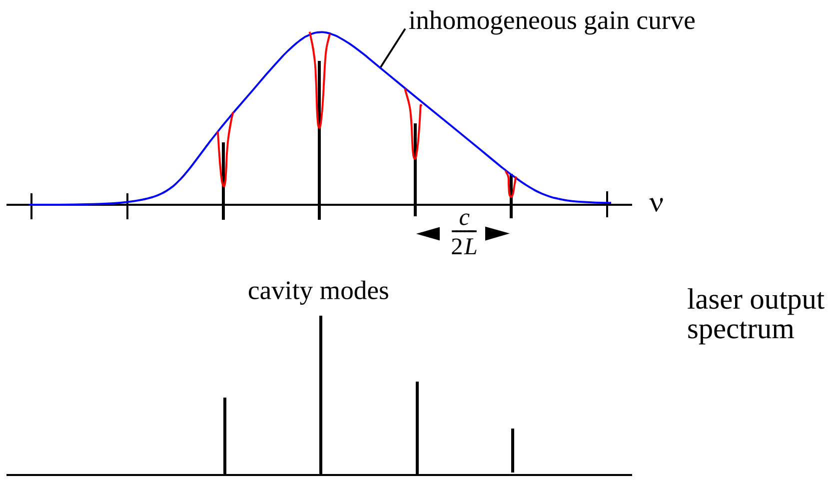
- saturating signal is at ν_S
- gain only saturates in narrow band around ν_S

The inhomogeneous case is usually due to broadening that results from a collection of atoms with varying resonant center frequencies.

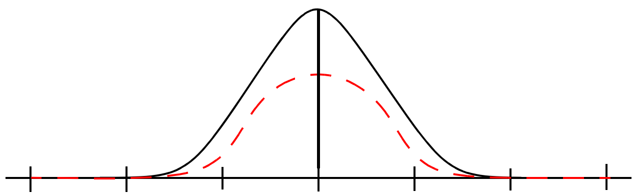


<u>Laser oscillation</u>

Inhomogeneous case: *All* modes above threshold will oscillate



Homogeneous case: Only the highest gain mode oscillates. Entire gain curve saturates until gain = loss for oscillating mode. Then gain < loss for all other modes.



<u>Gaussian beams</u>

Plane waves: $E(x, y, z) = E_0 e^{-i(kz - \omega t)}$.

Another solution to Maxwell's equations:

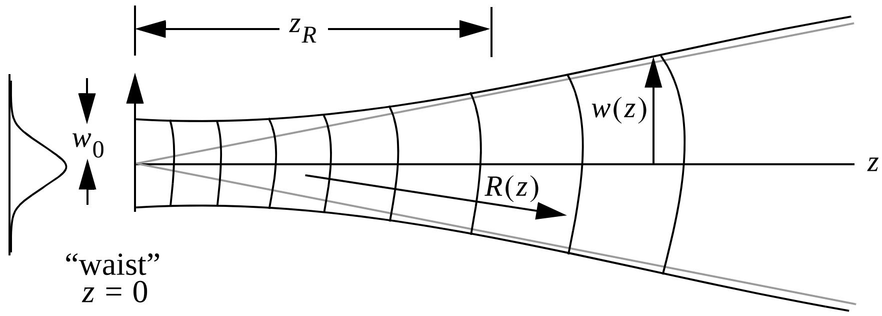
- Paraxial approximation: Ψ variation with z is slow compared to x, y variation.
- Plug this form into Maxwell's equations. Use paraxial approximation. The resulting solution is:

$$E = E_0 \frac{w_0 \exp[-ikz + i\eta(z)]}{w(z)} \exp\left[-\frac{x^2 + y^2}{w^2(z)} - ik\frac{x^2 + y^2}{2R(z)}\right]$$

The transverse amplitude profile of the beam is Gaussian:

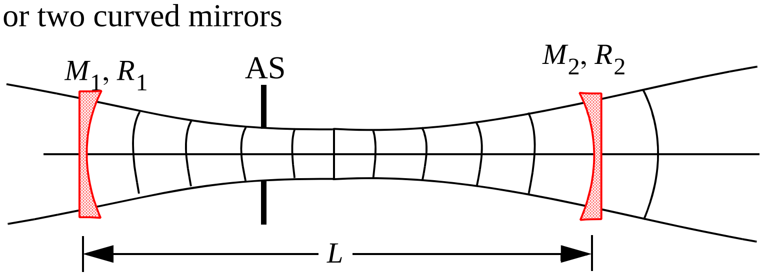
$\eta(z)$: phase shift of plane wave phase

$\eta(z) = \tan^{-1}(z/z_R)$



Lasers can be made to generate this Gaussian beam (in most cases)

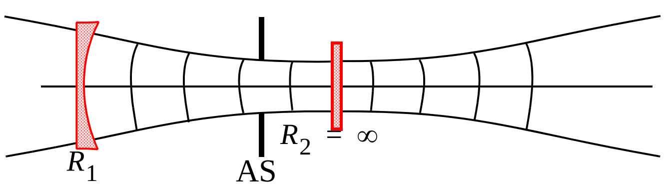
- Use one or two curved mirrors



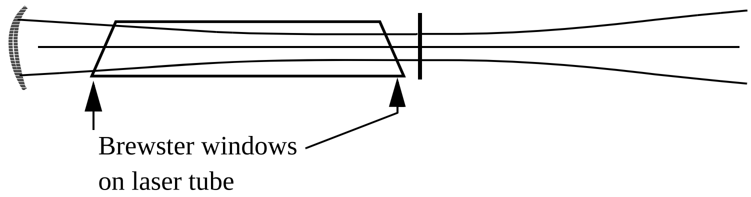
Given R_1, R_2, L, there is one unique Gaussian beam (transverse mode) that fits into the laser resonator. Gaussian beam curvature must *match* mirror curvatures R_1, R_2. Beam waist occurs accordingly.

The output beam is simply the continuation of this Gaussian beam.

To get the beam waist to occur right at the laser output mirror, we use a flat output mirror:



We have to limit the transverse aperture in the laser resonator in order to select the Gaussian mode. We could use a special aperture sized to ~ 3w. Or, the laser gain medium itself could be the aperture:



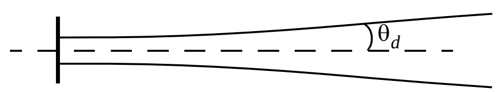
Properties of Gaussian beam

- Long collimation length:

Take $w_0 = 0.5$ mm, $\lambda = 632$ nm (HeNe laser). So, $Z_R = 1.2$ meters.

- Low divergence: for $z \gg z_R$

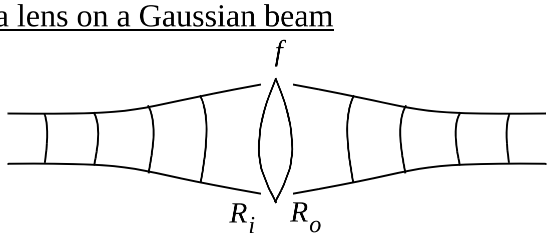
θ_d : divergence half angle



In the paraxial approximation, .

Continuing with our example, $w_0 = 0.5$ mm, $\lambda = 632$ nm, $\theta_d = 0.4$ mrad. So, after 10 m, $w(10\text{ m}) \cong 4$ mm.

Effect of a lens on a Gaussian beam



- The beam size is unaffected by the lens.
- The beam radius of curvature obeys lens law

After the lens, the beam has a radius of curvature R_o. The beam reaches a focus at distance $\approx R_o$ (if $f \gg z_R$).

Suppose the lens has a 4cm diameter, the beam radius at the lens is $w(\mathrm{lens}) = 1\ \mathrm{cm}$, and that $R_o = 10\ \mathrm{cm}$.

It is easy to show that . Then for our case, $w_o = 2\mu\mathrm{m}$.

Note, $w(\mathrm{lens})/R_0 \cong \mathrm{NA}$. So, $w_o = \frac{\lambda}{\pi\mathrm{NA}} \cong 0.32\frac{\lambda}{\mathrm{NA}}$. This is reminiscent of our finding for imaging systems that resolution = $0.6\frac{\lambda}{\mathrm{NA}}$. The spot size for a focused Gaussian beam is very closely related to imaging resolution.

<u>Various laser types</u>

Laser pumping processes:

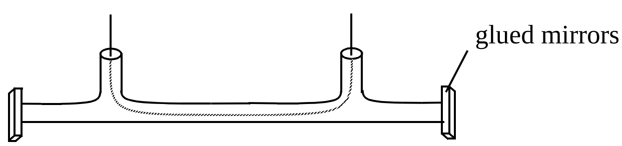
Electrons: Gas discharge or electron beam

Optical: a) incoherent – flashlamp, arc lamp, solar

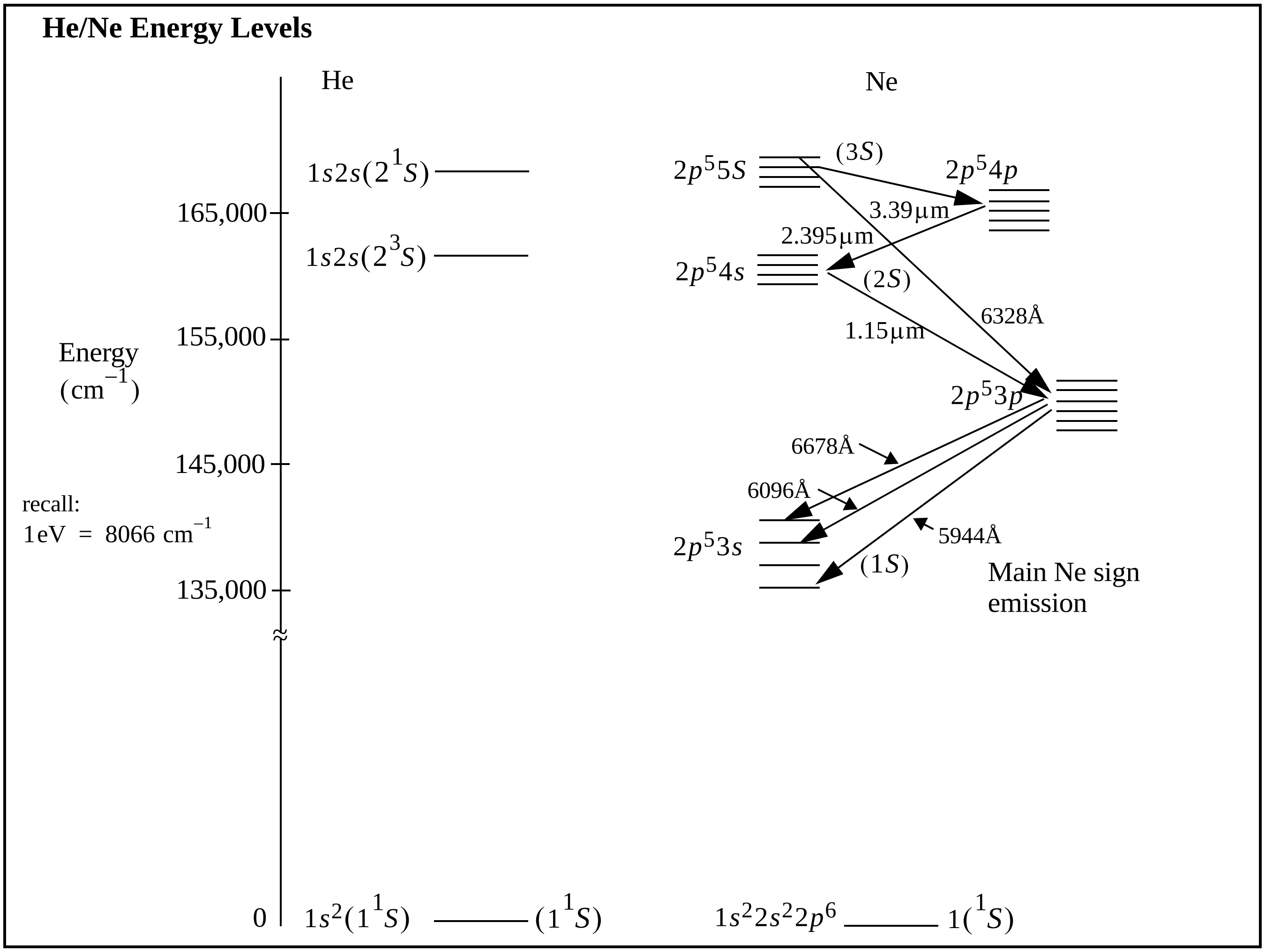
b) coherent – another laser

Electrical current: Semiconductor diode laser

<u>Gas discharge laser construction</u>

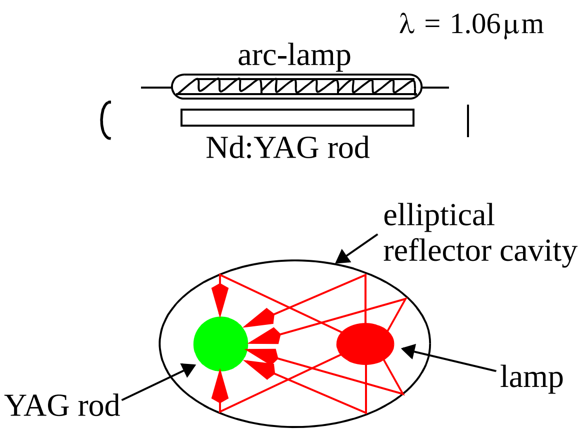


– Ne excited states $1s^2 2s^2 2p^5 3s$, $1s^2 2s^2 2p^5 3p$, $1s^2 2s^2 2p$

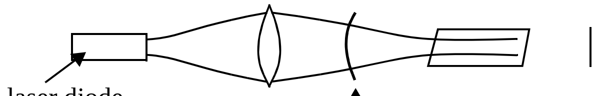


Optically pumped lasers

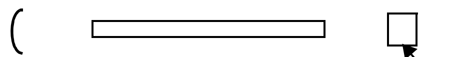
Nd:YAG laser



Diode pumping



Q-switching



Upper-level lifetime in Nd:YAG is ~ 100 μsec

1. Modulator has low transmission

2. Population builds up in upper state

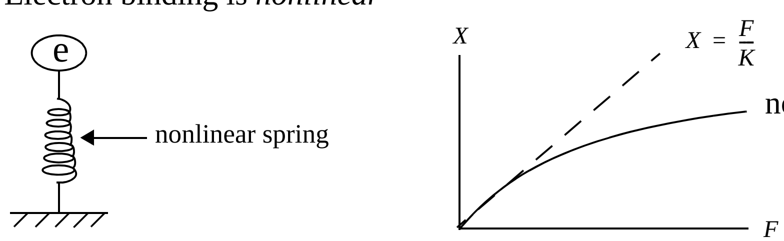
3. Inversion density >> threshold, but no lasing

4. Modulator switches to high transmission

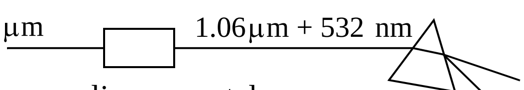
5. Laser action builds up rapidly, energy stored is released in a giant pulse

<u>Second harmonic generation SHG</u>

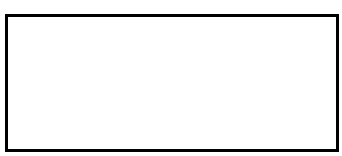
"Nonlinear" crystal – Electron binding is *nonlinear*



When such a system is driven by a sinusoidal signal $\sin(\omega t)$, the response contains harmonics: $\sin(2\omega t), \ldots$. These can radiate under suitable conditions

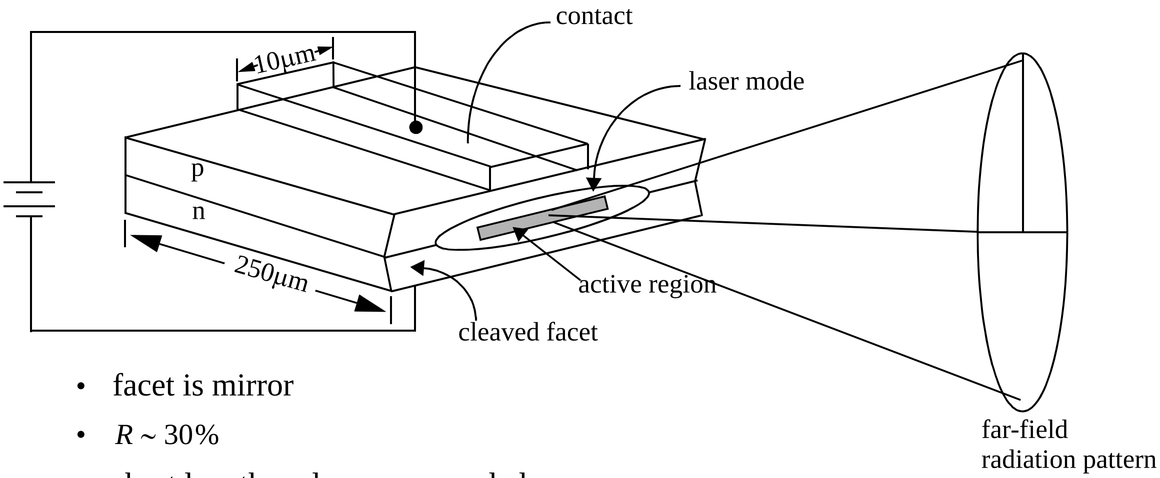


Conversion efficiency:



$\eta > 70\%$ can be obtained.

Diode Lasers

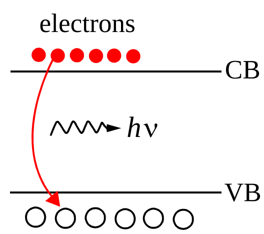


- facet is mirror
- $R \sim 30\%$
- short length $\rightarrow$ large α_m needed

- Forward-biased pn diode
  - Active area $\sim 40\mu m \times 250\mu m \times \sim 1\ \mu m$
  - Typical current drive: 15 mA $\rightarrow$ Current density across junction ~ 1 KA/cm^2 !
  - Typical voltage ~ 2 V $\rightarrow$ 30mW input power
  - Typical overall efficiency ~ 50%, 15mW output!
  - Because of the small size, the electrical capacitance is small and the device can be modulated at frequencies > 10 GHz

<u>Atoms?</u> – Electrons and holes

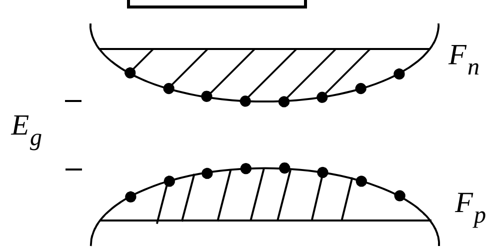
This is the big difference with all other lasers. Electrons and holes are spread out over the whole crystal:



$$e + h \rightarrow h\nu$$

<u>Optical transitions in semiconductors</u>

Conservation of momentum $\boxed{\qquad}$ – not possible in indirect gap semiconductor



Pauli exclusion principle: Only 2 electrons can occupy each k– state. This gives rise to "band-filling."

"Pump" high density of electrons and holes into same region.

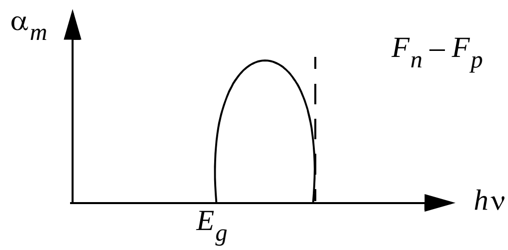
F_n, F_p :quasi-Fermi levels

F_n :energy of highest occupied electron state

F_p :energy of lowest hole state

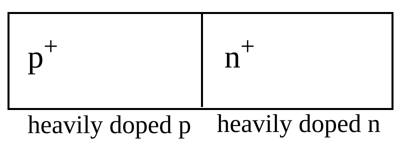
Inversion condition: $\boxed{F_n - F_p > E_g}$

Equilibrium: $F_n = F_p \cong E_g / 2$

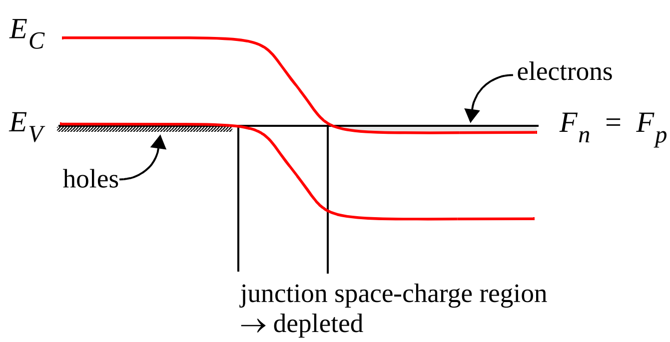


How to achieve inversion:

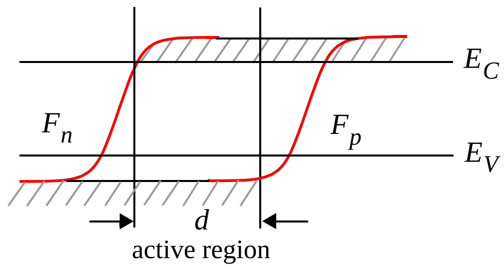
p-n Junction



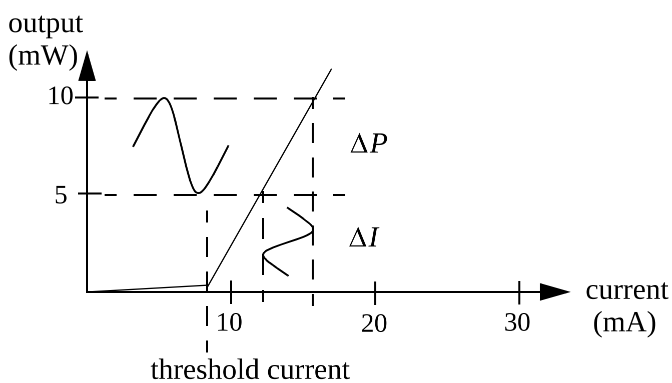
Equilibrium:



Forward bias:

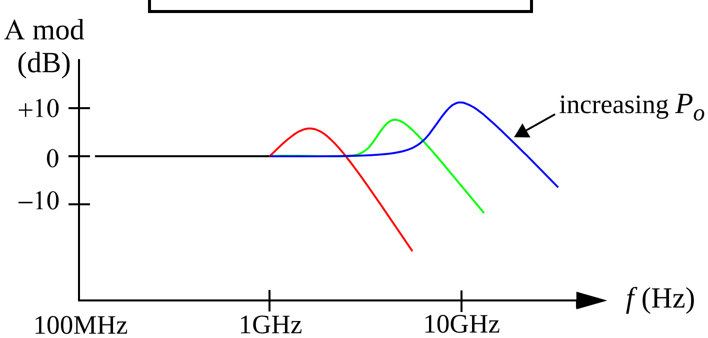


d ~ 1μm controlled by carrier diffusion



Modulate current $\rightarrow$ modulate output

Frequency response



Increasing P_o $\rightarrow$ increasing stimulus emission rate $\rightarrow$ faster discharge of jn capacitance