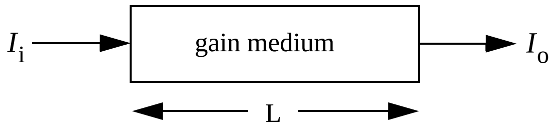
Lecture 16

[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)



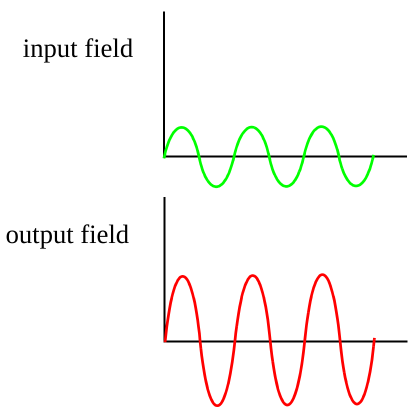
$I_o = e^{gL} I_i$ g : gain coefficient

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:

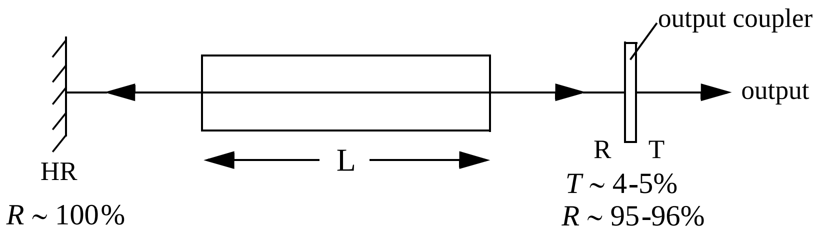
– ray direction is preserved

– photons are added with same λ, direction

– wave is reinforced *coherently*



- 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}.

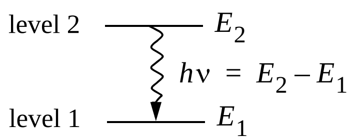
<u>Laser Threshold Condition</u>

If the loss is, for example, 4%, and if $\boxed{e^{2gL} > 1.04}$, 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

$$\boxed{\frac{dN_2}{dt} = -\frac{N_2}{\tau_2}}$$

Under most conditions $\boxed{N_2 \ll N_1}$.

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.

$$\boxed{\frac{dN_1}{dt} = -BIN_1 = -\frac{dN_2}{dt}}.$$

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.

$$\boxed{\frac{dN_2}{dt} = -BIN_2 = -\frac{dN_1}{dt}}$$

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

$$\boxed{\frac{dN_2}{dt} = -BI(N_2 - N_1)}.$$

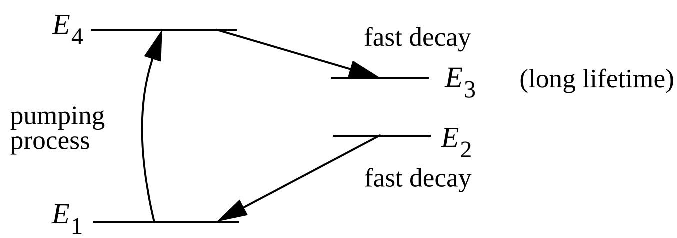
Population inversion

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 $\boxed{N_2 > N_1}$ (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.

4-Level laser

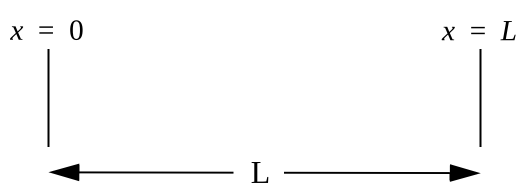


Due to long lifetime in level 3, population stacks up. Any atoms in level 2 rapidly drop back to level 1.

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.

Optical resonator



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

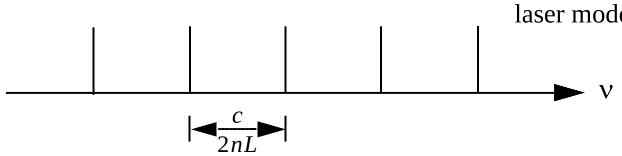
$$\boxed{kL = m\pi}.$$

$$\boxed{\frac{2\pi}{\lambda}L = m\pi \quad \rightarrow \quad L = \frac{m\lambda}{2} \quad \lambda = \frac{2L}{m}}$$

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, $\boxed{\nu = \frac{mc}{2nL}}$.

This gives the allowed frequencies of oscillation:



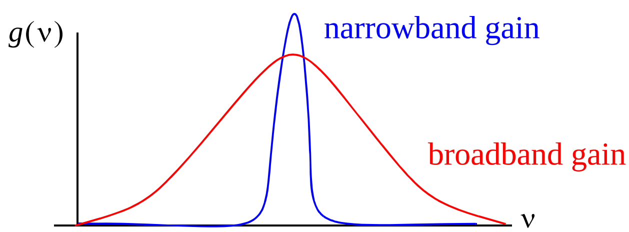
$\boxed{\frac{c}{2nL}}$ is mode spacing.

Longitudinal modes – Typical values:

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

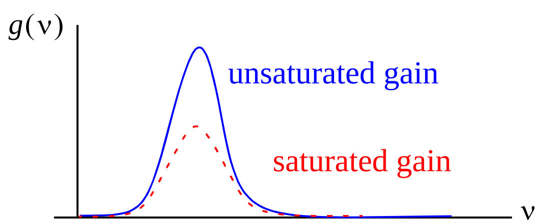
Diode laser: $\boxed{L = 0.25\text{ mm} \rightarrow \frac{c}{2nL}(n \sim 3.5) = 170\text{ GHz}}$

Laser *gain* spectrum

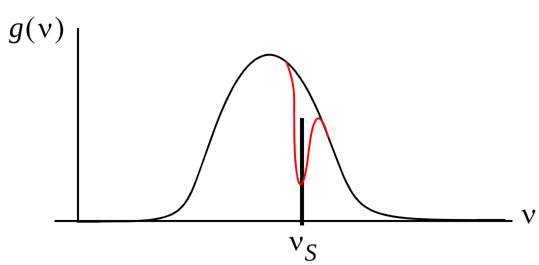


Homogeneous vs. inhomogeneous broadening

Saturation behavior can be of two types.



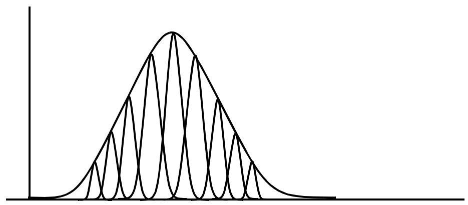
homogeneous broadening: Under saturation, entire gain curve is reduced. Shape is unchanged



inhomogeneous broadening:

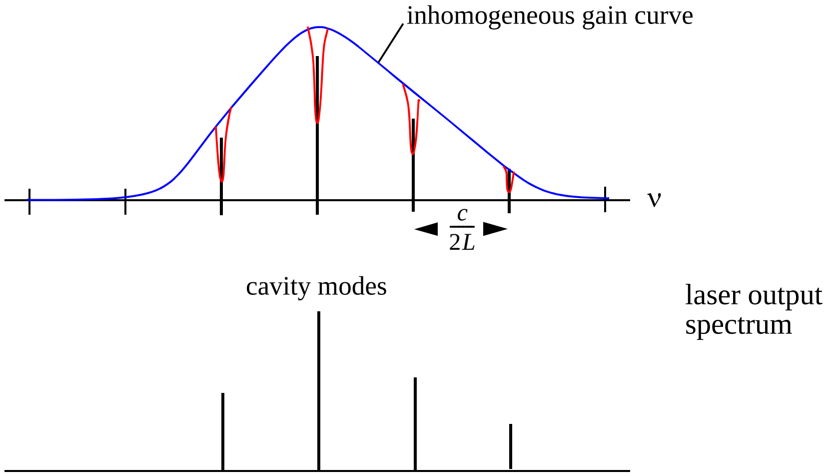
- saturating signal is at ν_S
- gain only saturates in narrow band around ν_S

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.