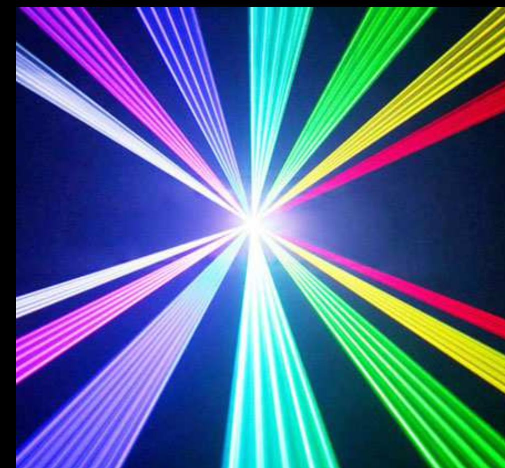


ECE 6323

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…*)

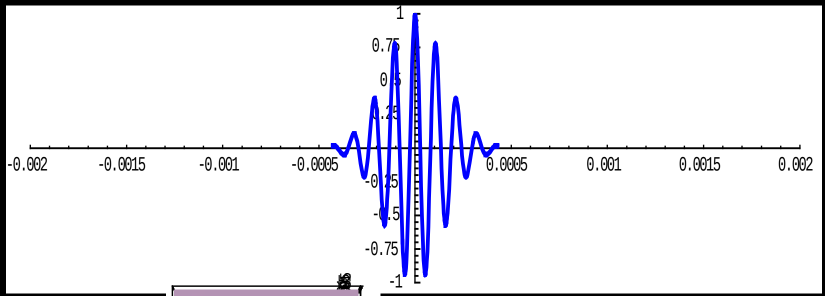
- Laser is a device that emits a “special type” of light..
- What is so special this type of light?
  - Is it because it is collimated (goes as a straight and narrow beam?
  - Is it because it is bright?
  - Is it because it has a single color?
  - Is it because it is “pretty”? Well… that depends what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

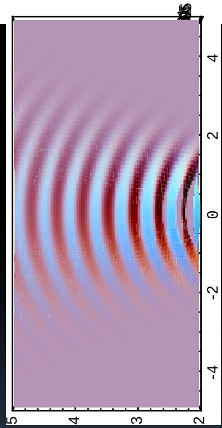
Uh… what is “coherent” light, by the way?

- 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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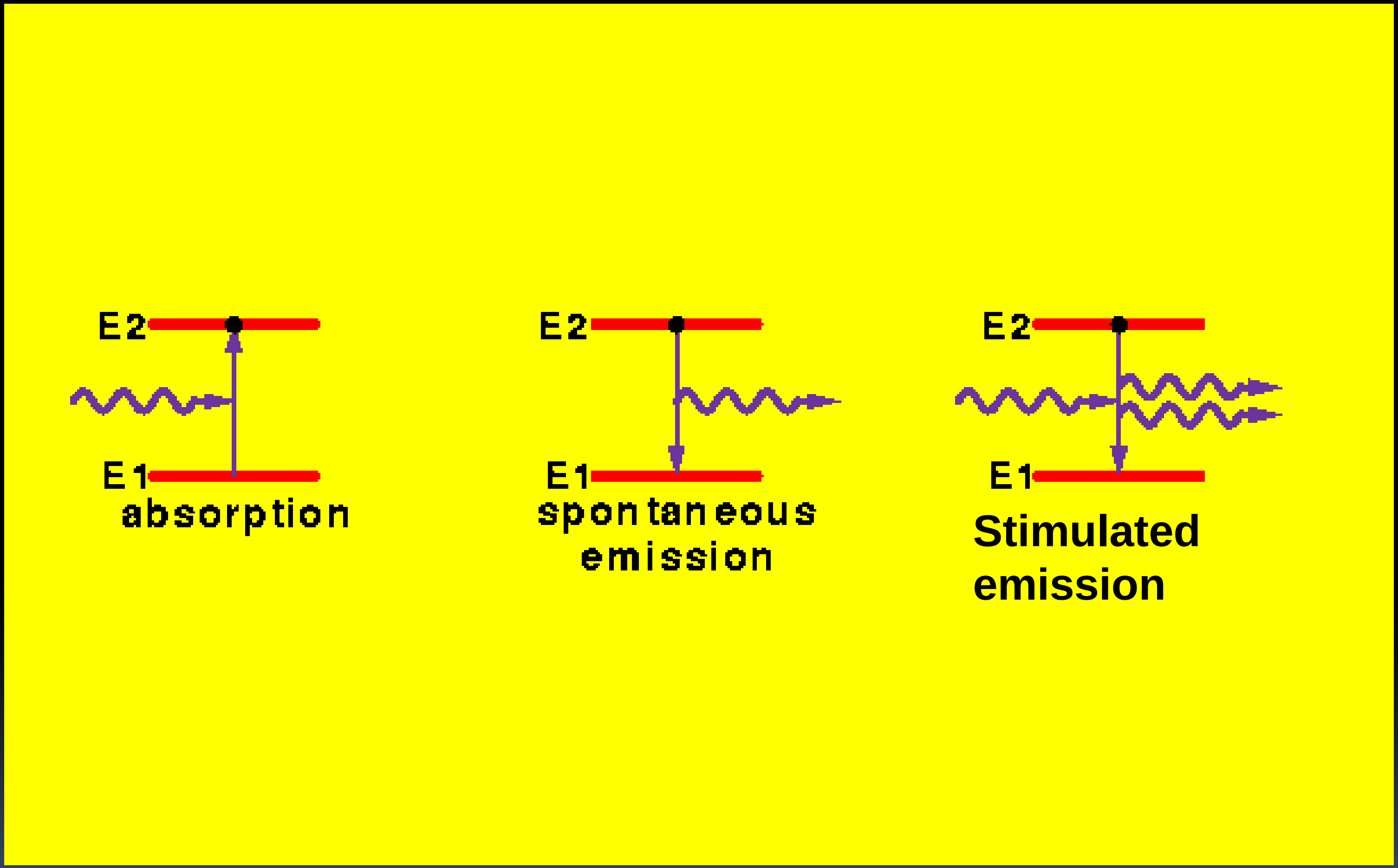
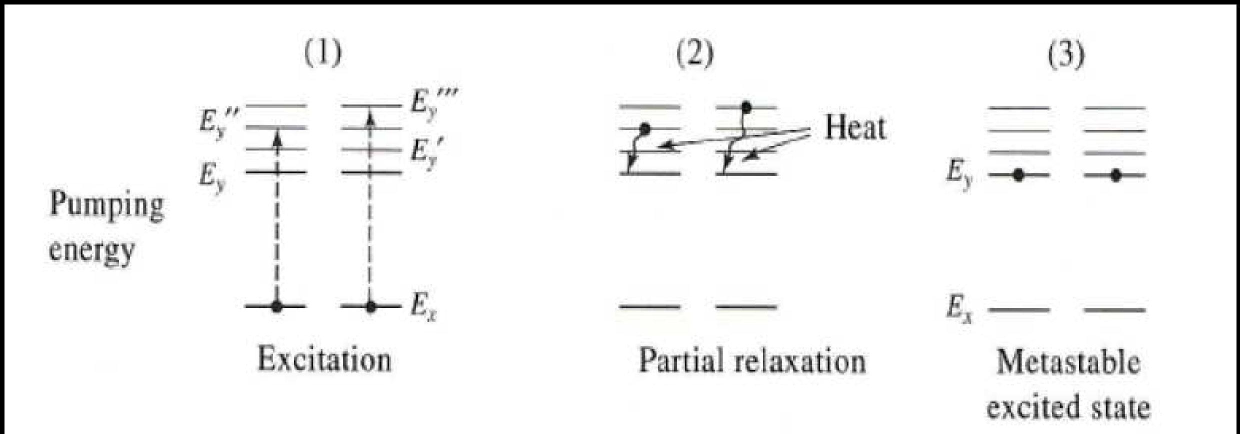
Review of modern physics

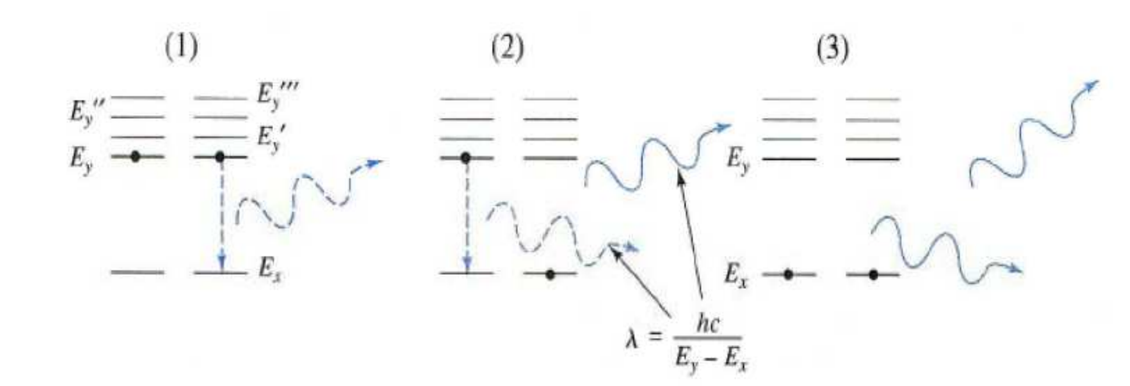
Fundamental processes:



Pumping and Spontaneous emission

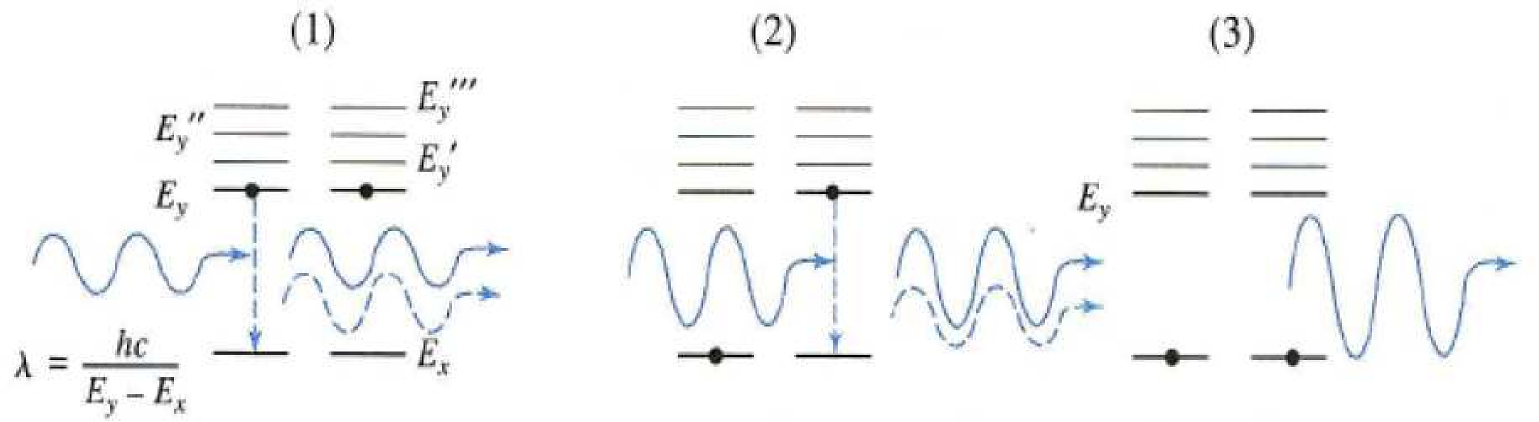


(a) Pumping (excitation by electrical, radiant, or chemical energy)



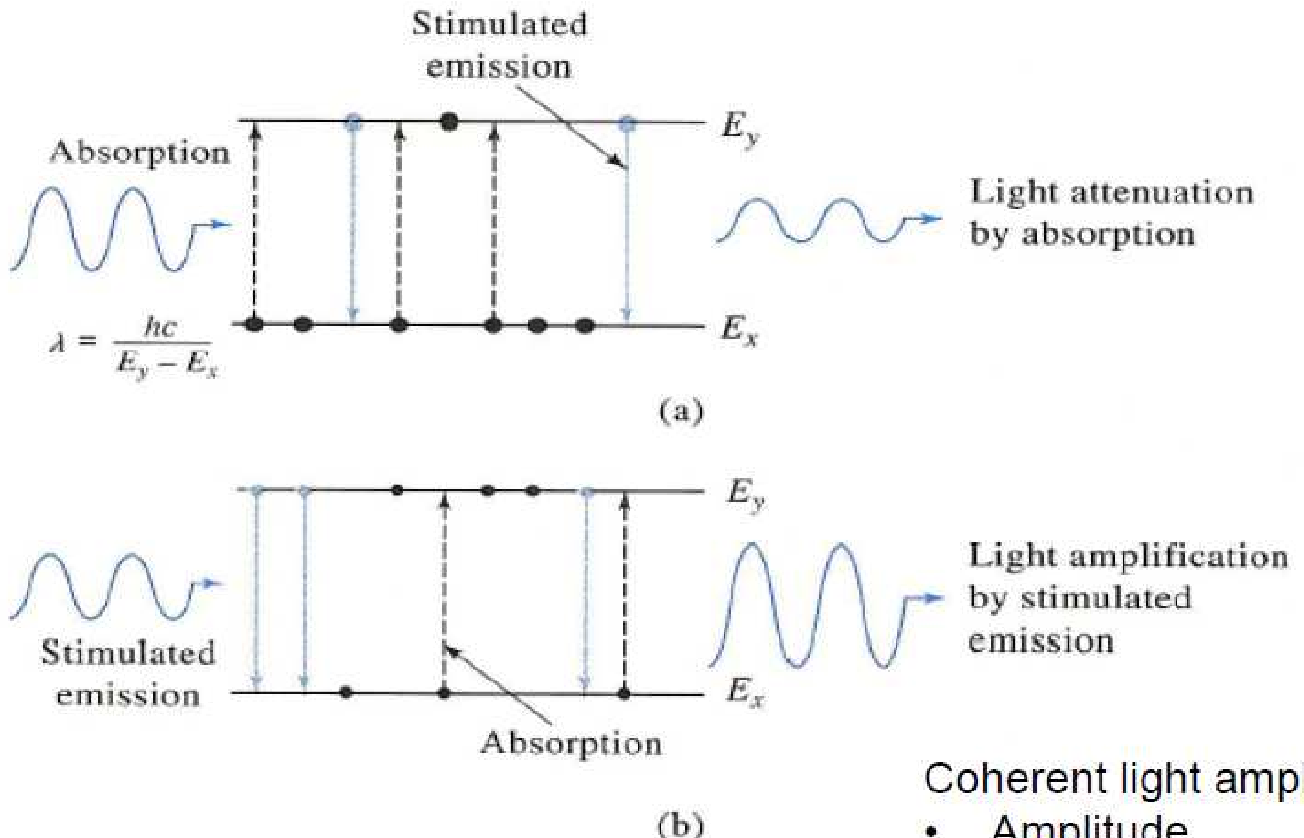
(b) Spontaneous emission

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 $P_{stim} >> P_{spont}$: lasing occurs

Population inversion concept

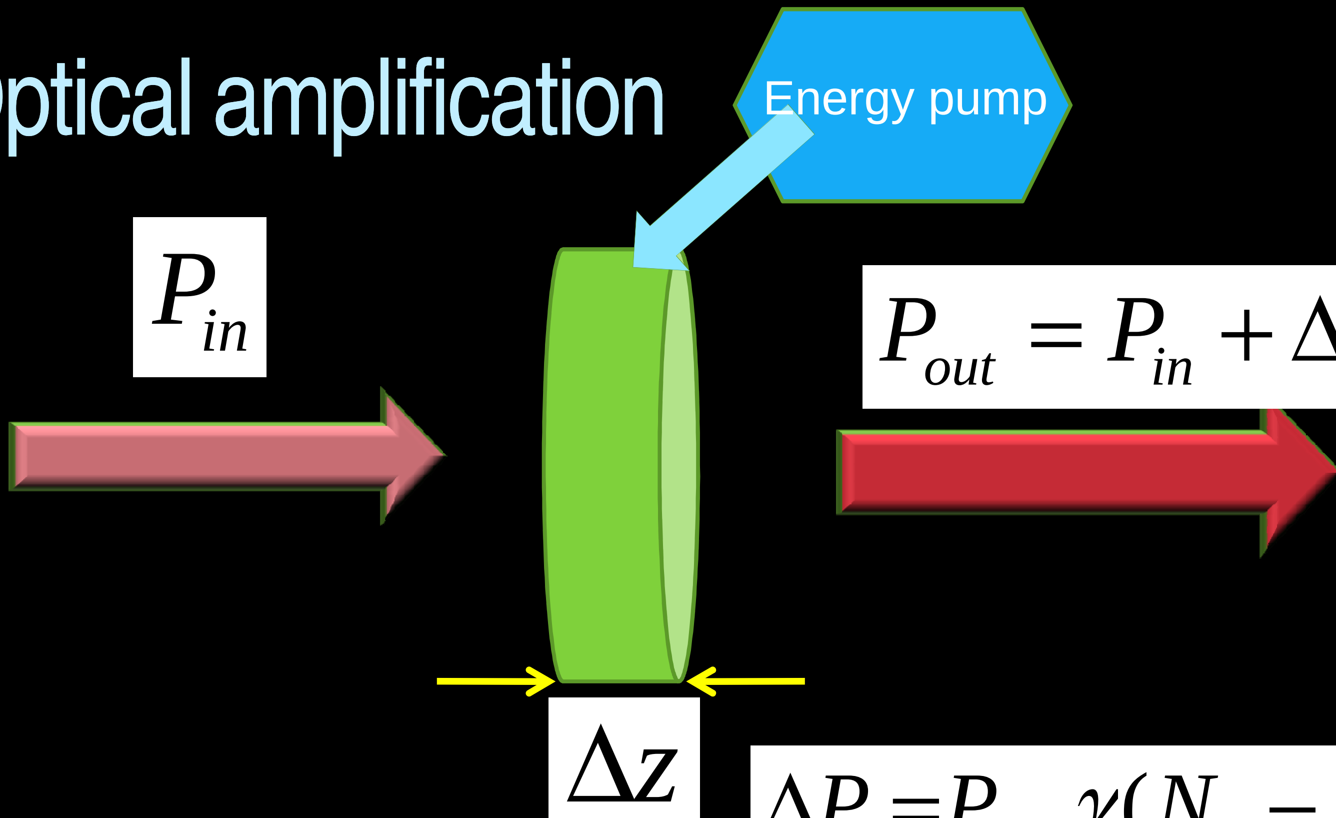
The ration of stimulated emission to absorption is

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

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



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

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

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

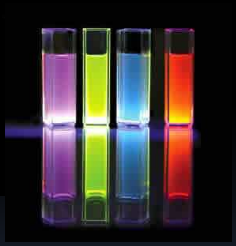
If g>0: Optical gain (else, loss)

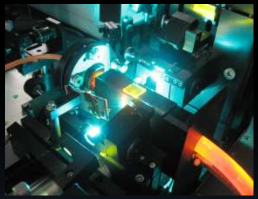
Optically amplified signal: coherent with input: temporally, spatially, and with polarization

Media for optical amplification (and lasers)

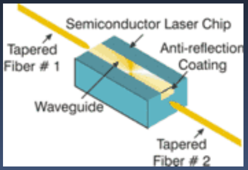
- Gas: atomic, molecular

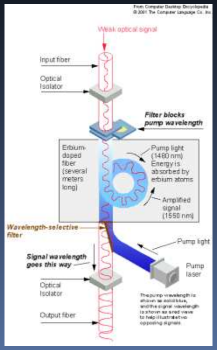
- Liquid: molecules, micro particles in a solution





- Solid: semiconductor, doped materials (EDFA)





Fundamentals of laser

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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

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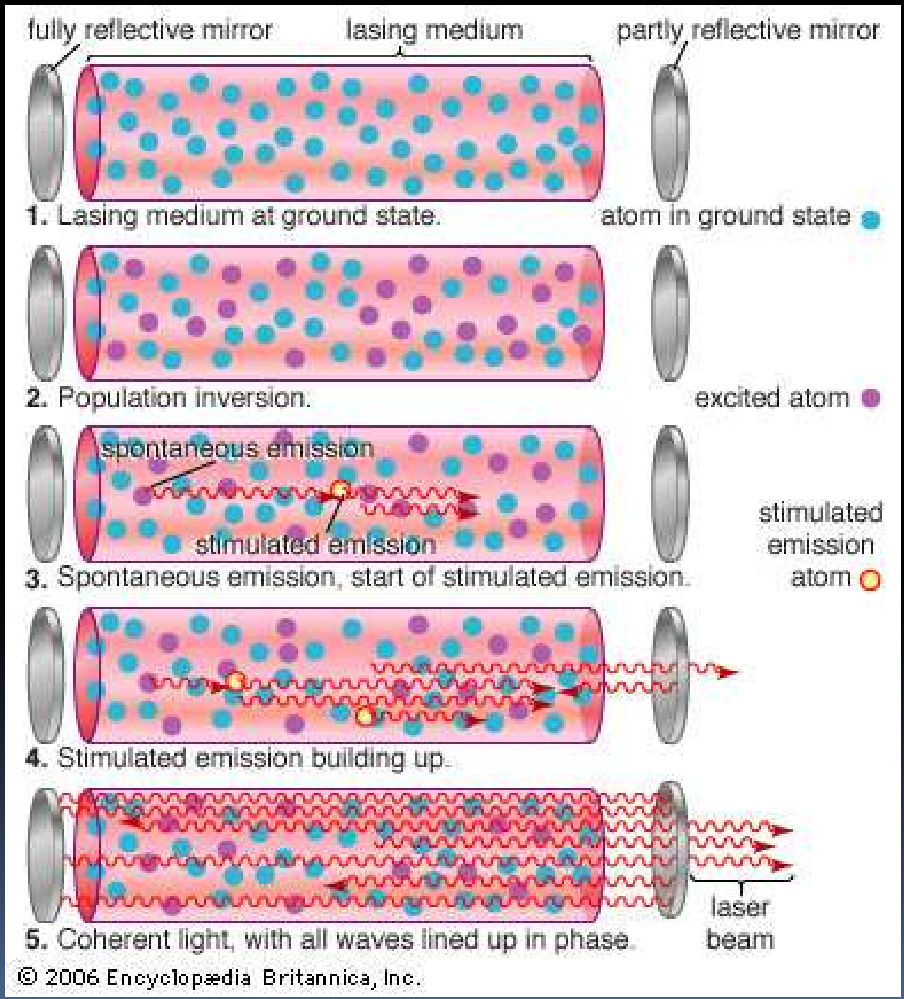
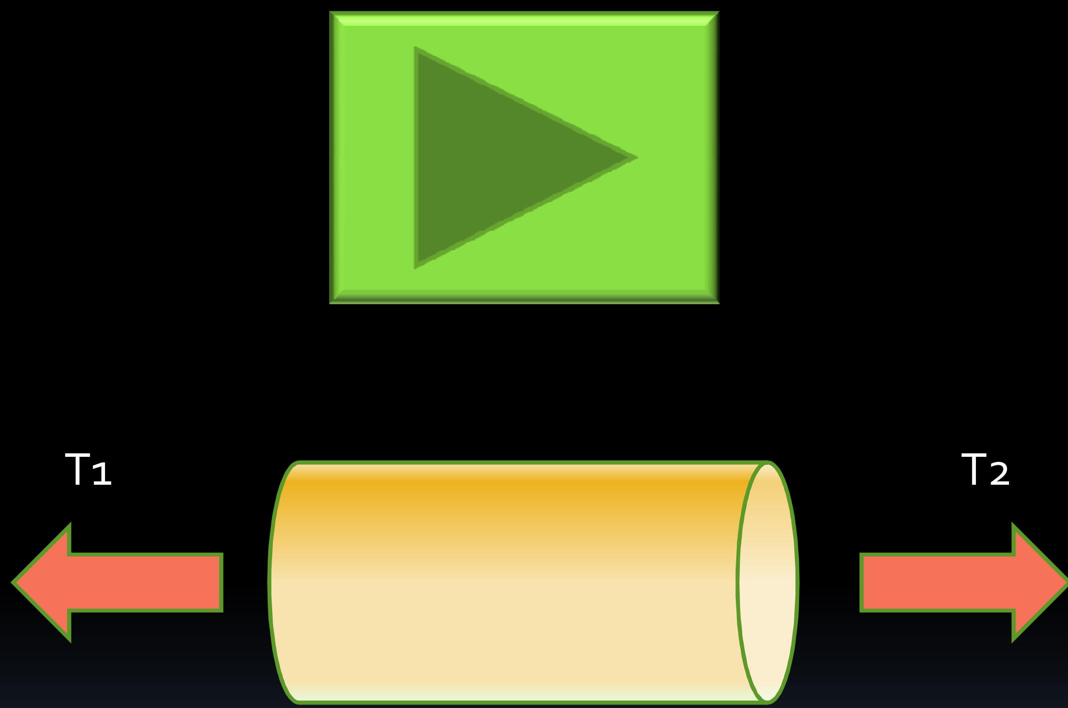
Illustrative concept



Basic laser equation



$$\begin{pmatrix} T2 \\ 0 \end{pmatrix} == \begin{pmatrix} \dfrac{e^{-i\,l\,\beta}\,\mathrm{T1}\left(\mathrm{rp2} - e^{2\,i\,l\,\beta}\,\mathrm{rp1}\,(\mathrm{rm2}\,\mathrm{rp2} - \mathrm{tm2}\,\mathrm{tp2})\right)}{\mathrm{tm1}\,\mathrm{tm2}} \\ \dfrac{\left(e^{-i\,l\,\beta} - e^{i\,l\,\beta}\,\mathrm{rm2}\,\mathrm{rp1}\right)\mathrm{T1}}{\mathrm{tm1}\,\mathrm{tm2}} \end{pmatrix}$$

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**