lasers & Stimulated Emission.

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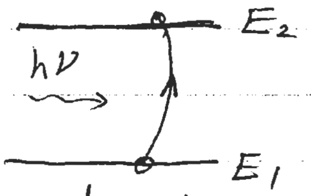
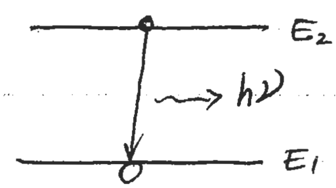
* Spontaneous vs. Stimulated Emission



absorption



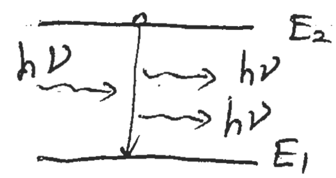
emission (spontaneous)

$$h\nu = E_2 - E_1$$

Explain E_2, E_1 can be that of molecules

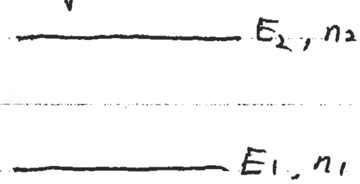
E_c, E_v of semiconductors.

1916 Einstein predicted stimulated emission.



stimulated photon
has same frequency, directi
polarizati as stimulating photon.

proof:



a 2-level system.
(think it as a gas)
inside a blackbody field
at temperature T.

At equilibrium

$$\frac{n_2}{n_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

— Boltzman distribution

$k = 1.38 \times 10^{-23}$ J/K.

At equilibrium: dynamic $\quad -\frac{dn_2}{dt} = \frac{dn_1}{dt}$.

$$\underbrace{\sum}_{\text{all processes}} \frac{dn_1}{dt} = 0$$

absorption: deplete n_1

$$-\frac{dn_1}{dt} = B_{12} n_1 u(\nu, T) \qquad \left(\rightarrow \frac{dn_2}{dt} \neq 0\right)$$

blackbody photons / unit volume $= \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}}-1}$

spontaneous emission:

$$-\frac{dn_2}{dt} = A_{21} n_2 \qquad \left(\rightarrow \frac{dn_1}{dt}\right)$$

does not depend on u.

If just the above 2 processes, cannot reach $\Sigma \frac{dn}{dt} = 0$

stimulated emission

$$-\frac{dn_2}{dt} = B_{21} n_2 u(\nu, T) \qquad \left(\rightarrow \frac{dn_1}{dt}\right)$$

Detailed balance $\quad \Sigma \frac{dn_i}{dt} = 0$

$$B_{12} n_1 u(\nu, T) = B_{21} n_2 u(\nu, T) + A_{21} n_2$$

$\Rightarrow$

$$B_{12} = B_{21}$$

$$A_{21} = \frac{8\pi h\nu^3}{c^3} B_{12}$$

more general $g_i B_{ij} = g_j B_{ji}$ (degeneracy)

$$A_{ji} = \frac{8\pi h\nu^3}{c^3} B_{ji}$$

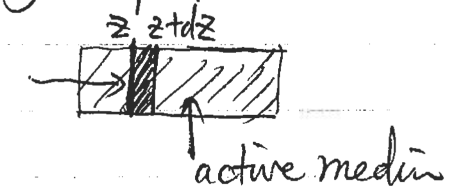
Relative importance of stimulated emission to spontaneous emission

$$m = \frac{B_{21} n_2 u(\nu, T)}{A_{21} n_2} = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Room temperature: $kT \simeq 26$ meV $= 0.026$ eV,

photon: $1\,\mu m = 1.24$ eV $\quad 10\,\mu m \quad 0.124$ eV $\Big\} \; m \ll 1$

Light amplification



(consider again 2-level system)

$I = cu$ (4π factor for spontaneous emission)

$$dI = -h\nu\, B_{12}\, n_1\, u\, dz = -I\,\frac{h\nu B_{12} n_1}{c}\,dz$$

absorption

include stimulated emission

$$dI = -I\,\frac{h\nu B_{12} n_1}{c}\,dz + I\,\frac{h\nu B_{21} n_2}{c}\,dz$$

$$= -\alpha\, I\, dz$$

$$I(z) = e^{-\alpha z}\, I(0)$$

$$\alpha = \frac{h\nu B_{12}}{c}\left(\frac{g_2}{g_1} n_1 - n_2\right)$$

At local equilibrium — Boltzmann statistics

$$\alpha = \frac{h\nu B_{12}}{c}\, n_2 \left(e^{\frac{h\nu}{kT}} - 1\right) > 0$$

If we can make $\alpha < 0$

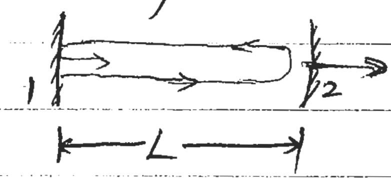
$$\frac{g_2}{g_1} n_1 - n_2 < 0 \qquad I - \text{increases.}$$

└ population inversion (nonequilibrium).

$\gamma = -\alpha$ (γ - gain).

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

Laser cavity



scattering loss

$$I(0)\, e^{2\gamma L}\, e^{-2\beta L}\, R_1 R_2$$

$$= I(0)$$

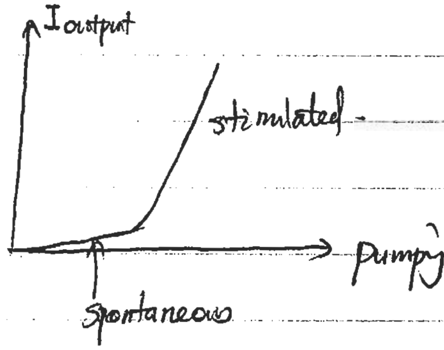
↑ repeat

threshold condition

$$\gamma = \beta - \frac{1}{2L} \ln R_1 R_2$$

one controls through pumping.

fixed pretty much



Pumping: we want $\frac{g_2 n_1}{g_1} - n_2 < 0$

spontaneous decay of level 2

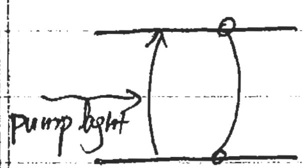
$$-\frac{dn_2}{dt} = A_{21} n_2$$

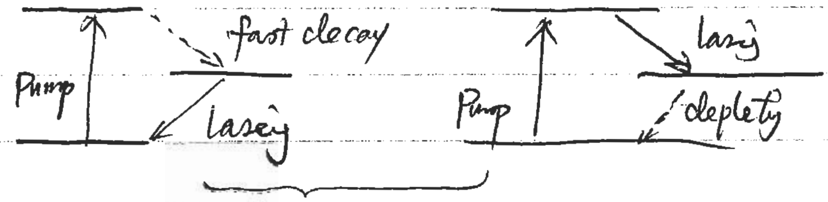
$$n_2 = C e^{-A_{21} t} \qquad \tau_{spon} = \frac{1}{A_{21}}$$

$$= C e^{-t/\tau_{spon}}$$

Need to increase n_2 faster than spontaneous decay

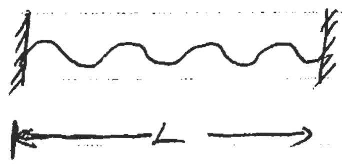
2 level system





3 level system.

Laser Beam Characteristics



cavity standing waves only

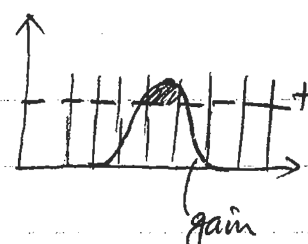
$$\frac{\lambda_q}{2} q = L$$

$$\lambda_q = \frac{2L}{q}$$

$$\nu_q = \frac{c}{\lambda} = \frac{qc}{2L}$$

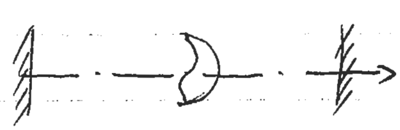
$$\Delta\nu_q = \frac{c}{2L}$$

$L = 1m$, 10^6 modes



$\Rightarrow$ longitudinal modes.

Transverse mode



Notation

TEM_{mnq}

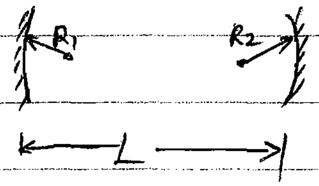
mn — transverse

q — longitudinal — many

TEM00 $\quad$ TEM_{01} $\quad$ TEM_{10} $\quad$ TEM_{11}

Selection of EM waves in cavity.

Typical mirrors

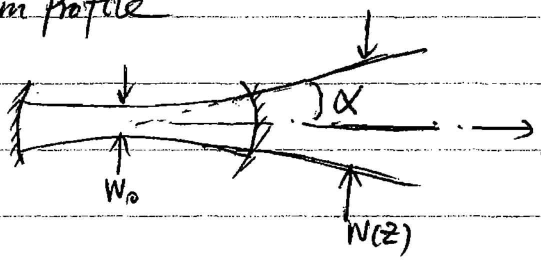


$$0 \le \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \le 1$$

stability criteria

light does not go astray.

Beam Profile



Gaussian

$$I(r,z)=I_0 e^{-2r^2/W(z)}$$

$$W(z)=W_0\left[1+\left(\frac{z}{z_0}\right)^2\right]^{\frac{1}{2}}$$

$$W_0=\left(\frac{\lambda L}{\pi}\right)^{\frac{1}{2}}\left[\frac{(R_1-L)(R_2-L)(R_1+R_2-L)}{L(R_1+R_2-2L)^2}\right]^{\frac{1}{4}}$$

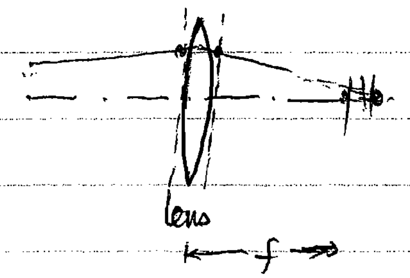
$$z_0=\frac{\pi W_0^2}{\lambda}.$$

divergence $\alpha=\frac{\lambda}{\pi W_0}$

Beam Propagation.

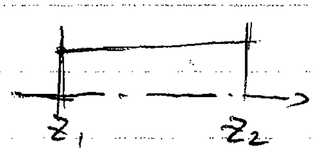
$W(z)$

$\frac{dw}{dz}=W'(z)$



$$\begin{pmatrix} W_{out} \\ W'_{out} \end{pmatrix}=\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}\begin{pmatrix} W_{in} \\ W'_{in} \end{pmatrix}.$$

$$W'_{out}=W'_{in}-W_{in}/f$$



$$\begin{pmatrix} W(z_2) \\ W'(z_2) \end{pmatrix}=\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}\begin{pmatrix} W(z_1) \\ W'(z_1) \end{pmatrix}$$

$$\begin{pmatrix} W_{s+1} \\ W'_{s+1} \end{pmatrix}=\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} W_s \\ W'_s \end{pmatrix}$$

Some Systems

Active media

- Solid-state: Neodymium-YAG ..., Ti-Sapphire.
- Gas: He-Ne, CO_2, Argon, excimer
- Liquid: Dye

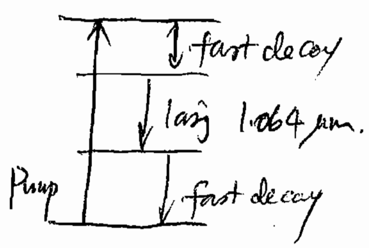
Pumping method

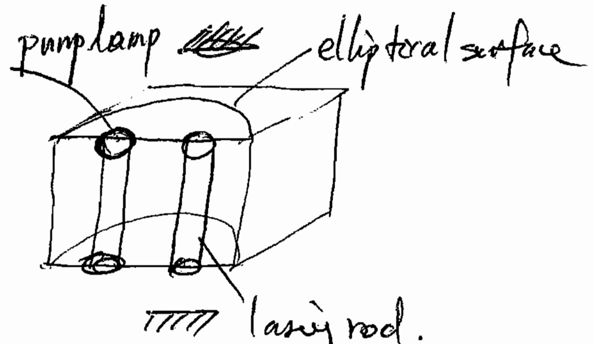
- optical: incoherent, coherent
- current: semiconductor
- electron impact excitation (high voltage)
- free elect laser.

wavelength:
ultraviolet: excimer, frequency tripple/quadruple YAG
visible: He-Ne, double YAG,
near Infrared: semiconductor, YAG
middle & far infrared: CO_2, free electron, quantum cascade

Time scale:
continuum
Pulsed: Q-switched, mode-lock

Nd^{3+}: YAG (Y: Yttrium, A: aluminium, G: Garnet)





Semiconductor