6.013 Electromagnetics and Applications
Spring 2009

LASERS

Representative applications:

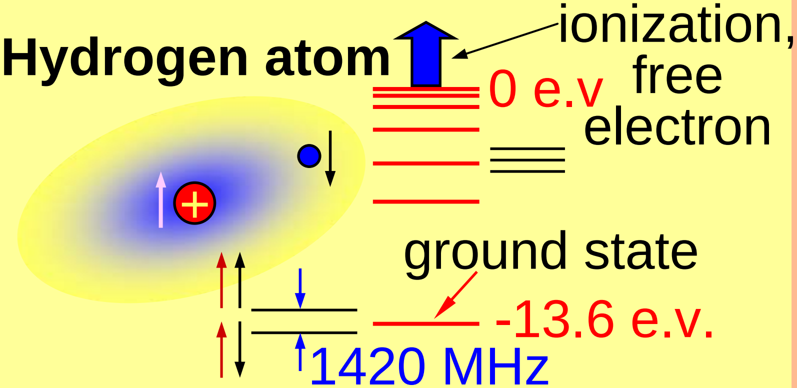
Amplifiers: Broad-band communications (avoid down-conversion)

Oscillators: Frequency/distance reference, local oscillators, illuminators, transmitters, CD/DVD players, sensors

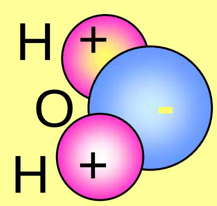
Blasting: Laser machining, labeling, weapons, laser fusion (pellet compression). Peak > 10^{15}W, average > 1kw; high intensity because $I \propto |\sum_i \bar{E}_i|^2$

Energy States:

Hydrogen atom



Water vapor H_2O



States:
electronic (visible, UV)
vibrational (visible)
bending (IR)
rotational (microwave)

Chromium atoms in lattice (e.g. ruby), Erbium atoms in glass

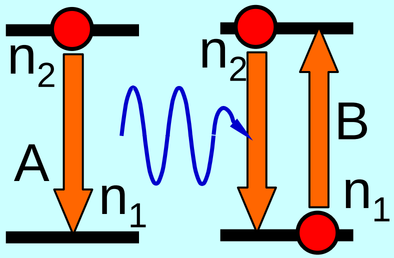
STIMULATED EMISSION AND ABSORPTION

Rate Equation:

Assume: Two-level system, $E_2 > E_1$, and n_i = atoms m^{-1} in state i

Then: $dn_2/dt = -\underbrace{An_2}_{\text{Spontaneous emission}} - \underbrace{B(n_2 - n_1)}_{\text{Induced emission}}$ $[m^{-1}s^{-1}]$ (collisionless system)

Spontaneous emission Induced emission



Spontaneous emission, states i to j:

$A_{ij} = \omega^3 |D_{ij}|^2 (2/3h\varepsilon c^3)$ $[s^{-1}]$ (Decay time $\tau_A = A^{-1}$)

D_{ij} [C m] = quantum dipole moment (electric or magnetic)

Note: $\tau_A \propto \omega^{-3}$ $\Rightarrow$ very brief "visible" τ's, long microwave τ's

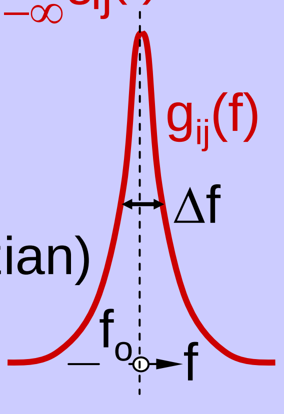
Stimulated emission and absorption:

$$\int_{-\infty}^{\infty} g_{ij}(f)\,df = 1$$

Photon flux density F: $F = \frac{|\underline{E}|^2}{2\eta_o}\frac{1}{hf}$ [photons $m^{-2}s^{-1}$]

B coefficient: $B_{ij} = F\sigma_{ij} \propto F\, g_{ij}(f)\, A_{ij}/\omega^3$

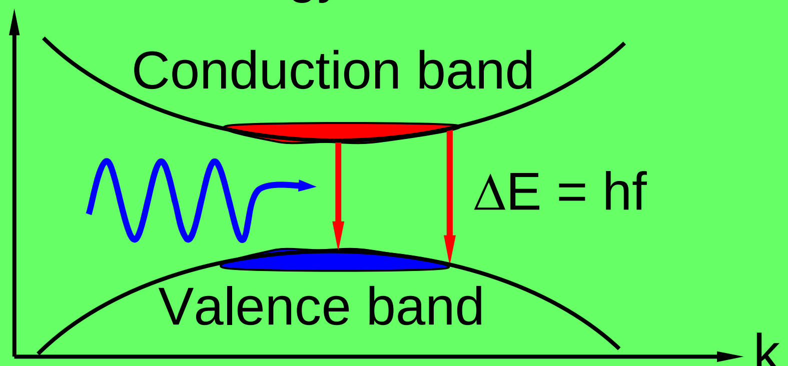
Line shape $g_{ij}(f)$: $g_{ij}(f) = \frac{2}{\pi\,\Delta f}\frac{1}{1 + 4\frac{(f - f_o)^2}{(\Delta f)^2}}$ (Lorentzian)



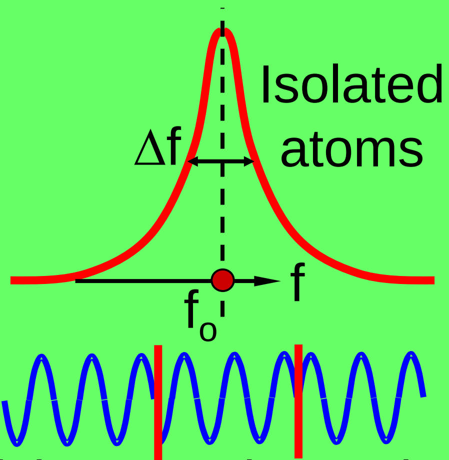
ENERGY LEVEL POPULATION AND WIDTH

Linewidth Broadening Mechanisms:

Electron energy E in semiconductor



Energy band curvature broadens the linewidth



Collisions ⇒ phase changes, Fourier transform ⇒ Δf

Level Populations—Kinetic Temperature T_k:

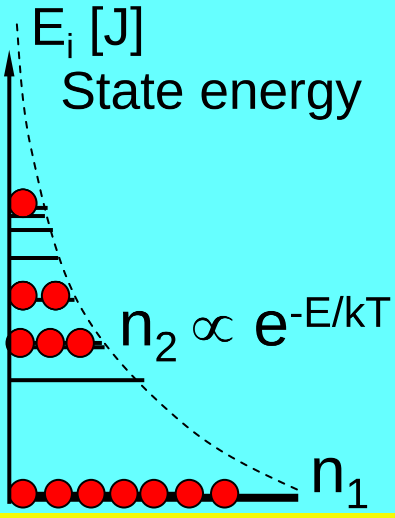
Thermal equilibrium ⇒ Boltzmann distribution:

$$\frac{n_i}{n_j} = e^{-(E_i - E_j)/kT}$$

T = kinetic temperature if collisions dominate

T = radiation temperature if radiation dominates f_{ij}

$\Rightarrow n_i \rightarrow n_j$ if $T_{rad} \rightarrow \infty$, $n_2 > n_1$ if $T_{rad} < 0$

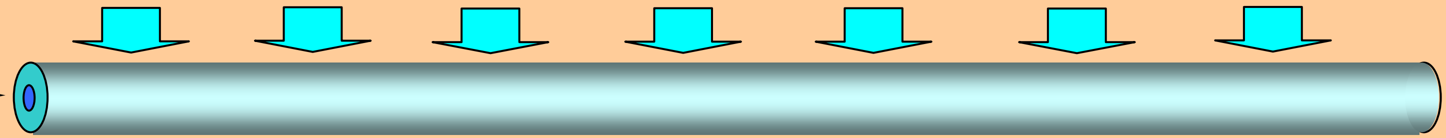


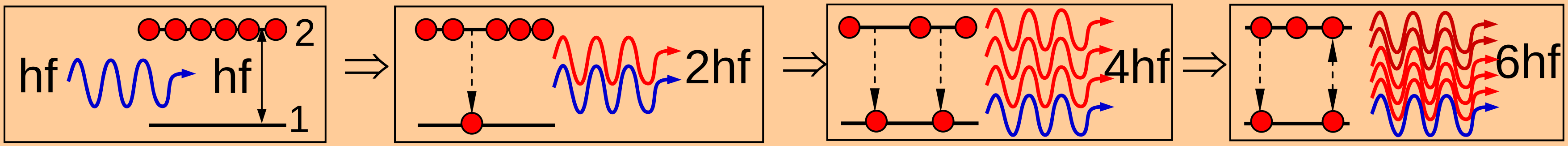
BASIC LASER AMPLIFIER PHYSICS

Amplification Process:

Pump (repopulates level 2)

Optical fiber





input — amplification, exponential growth

Intensity-limited amplification

amplification linear growth

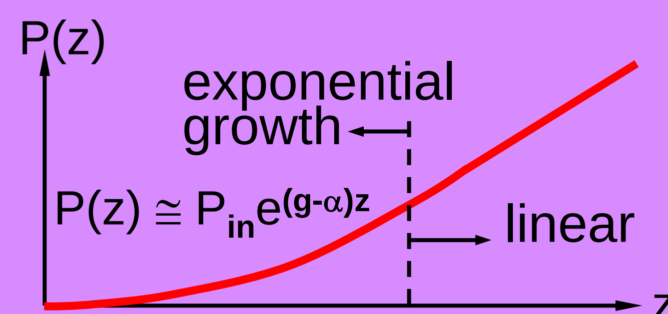
n_2 replacement-rate limited amplification

[Each ● is a separate atom or molecule; need $n_2 > n_1$ for amplification]

Amplification frequency f [Hz]:

$E_2 - E_1 = hf$ [J],

$h = 6.625 \times 10^{-34}$ [Js]

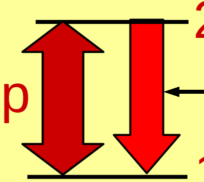


(g is gain, α is attenuation)

PUMPING OF LASERS

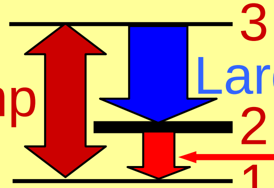
Two-Level Lasers:

Radiation pumping alone never yields $n_2 > n_1$
(some 2-level lasers spatially isolate n_2 group)



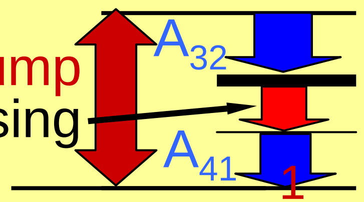
Three-Level Lasers:

Pumping the 1-3 transition yields $n_1 \cong n_3$
Large A_{32} populates L2 so $n_2 >> n_1 \cong n_3 \cong 0$



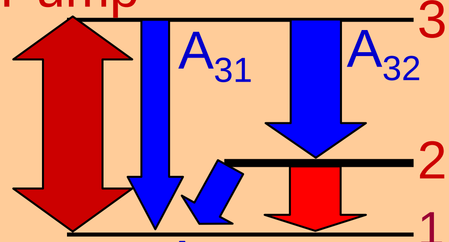
$f_{pump} > f_o$

More levels can utilize transitions with larger A's
Large A_{23} fills L_2, and large A_{41} empties L_4



Laser Power Efficiency (P_{out}/P_{in}):

Intrinsic efficiency: $\eta_i = f_L/f_p$ ($P \propto nhf$ [W]) < 1
B/A efficiency @ 2: $\eta_B = B_{21}/(A_{21}+B_{21}) < 1$
A/A efficiency @ 3: $\eta_A = A_{32}/(A_{31}+A_{32}) < 1$
Total efficiency: $\eta = \eta_i \eta_B \eta_A$



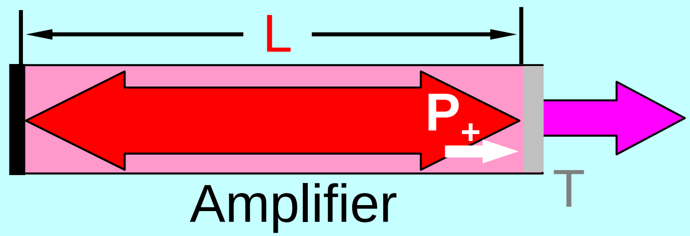
Pump photons $s^{-1} \propto B >> A \propto \omega^3$, so x-ray lasers need pump power $\propto hfB \propto hfA \propto \omega^4$

$dn_2/dt = -An_2 - B(n_2 - n_1)$

LASER OSCILLATORS

Laser Oscillation:

Lossless: With perfect mirrors at both ends a lossless amplifier must oscillate and saturate



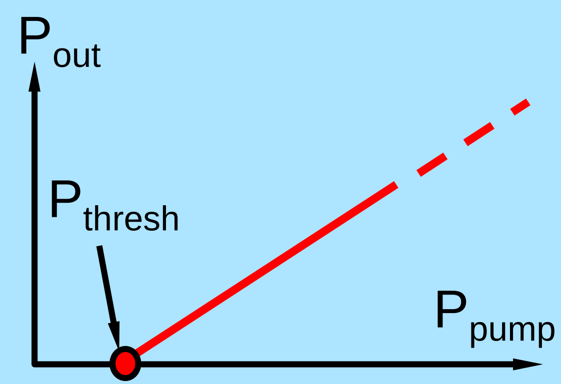
Lossy: Round-trip gain must exceed round-trip loss (threshold condition); gain $\propto$ pump power P_p, so need $P_p > P_{thresh}$

Mirrors: Exit mirror has power transmission coefficient $T > 0$

At threshold, Gain $\cong$ Loss, so: $P_+(1 - T)e^{2(g-\alpha)L} \geq P_+$

$\Rightarrow$ round-trip gain = $e^{2(g-\alpha)L} \geq 1/(1 - T)$ for oscillation

Q-switching: Set mirror reflectivity low $\Rightarrow$ round-trip gain < threshold. When laser is fully pumped, increase mirror reflectivity over threshold, yielding very large "Q-switched pulse"



LASER RESONANCES

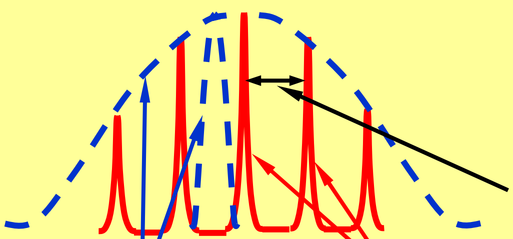
Oscillator Resonant Frequencies f:

Resonances

$$\frac{m\lambda_m}{2} = L \qquad \text{(mirrors} \approx \text{short circuits)}$$

$$\lambda_m = \frac{2L}{m}, \quad f_m = \frac{cm}{2LN} \qquad \text{(N = refractive index)}$$

$$f_{i+1} - f_i = \frac{c}{2LN}$$



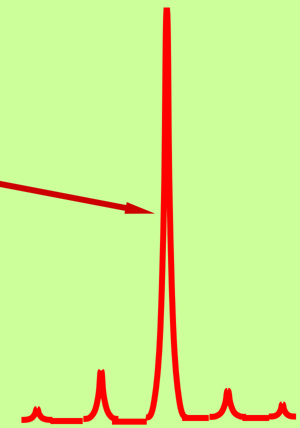
$\cong 10^8$ Hz (100 MHz) for 1-meter fiber;

$\cong$ 50 GHz line spacing for 0.5-mm diodes

Laser Output Spectrum:

If every atom can amplify at all frequencies, then the strongest round-trip gain wins $\Rightarrow$ line narrowing (homogeneous line broadening)

If atoms can amplify only a portion of the band, then all lines over threshold can yield output (inhomogeneous line broadening)



Line narrowing

EXAMPLES OF LASERS

Electrically Pumped Solid-State Lasers:

Forward-biased GaAs p-n junction
injects carriers into conduction band

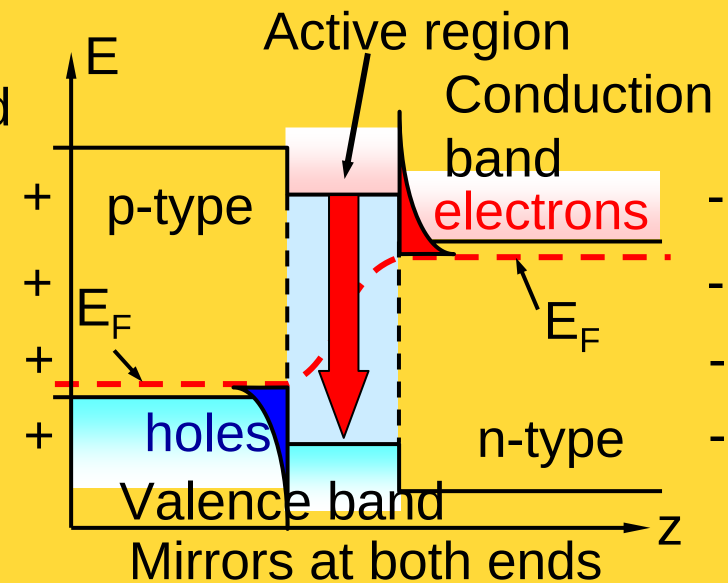
Compact (grain of sand)

~50 percent efficiency

>100 W/cm^2 for arrays

1 $mW/micron^2$ for diodes

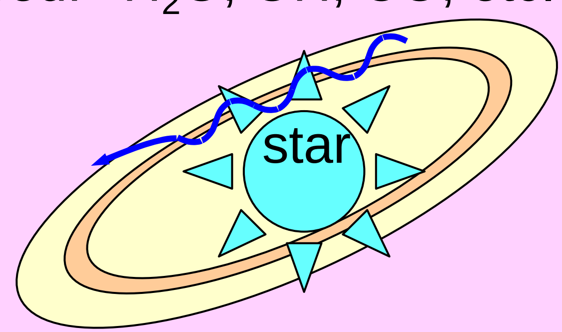
1-1000 mW typical



Astrophysical Masers:

Stellar Pumping: UV-IR pumped: H_2O, OH, CO, etc.

Interstellar collisions: OH, etc.



Chemical lasers:

Weapons (high energy, fast)