LASERS

Applications:

Amplification:	Broad-band communications links (e.g. EFDA; avoids down-conversion)
Oscillator:	Frequency/distance reference, local oscillators, illuminators, sources for fiber communications, CD/DVD players
Focused power:	Laser machining, weapons, laser fusion (pellet compression). Peak > 10^{15}W (10-μm spot ⇒ $\bar{E} \approx 10^{14}\,\mathrm{Vm}^{-1}$ vs 10^{6} in H atom) Average > 1kw; high intensity because $I \propto \lvert\sum_i \bar{E}_i\rvert^2$

Basic Principles:

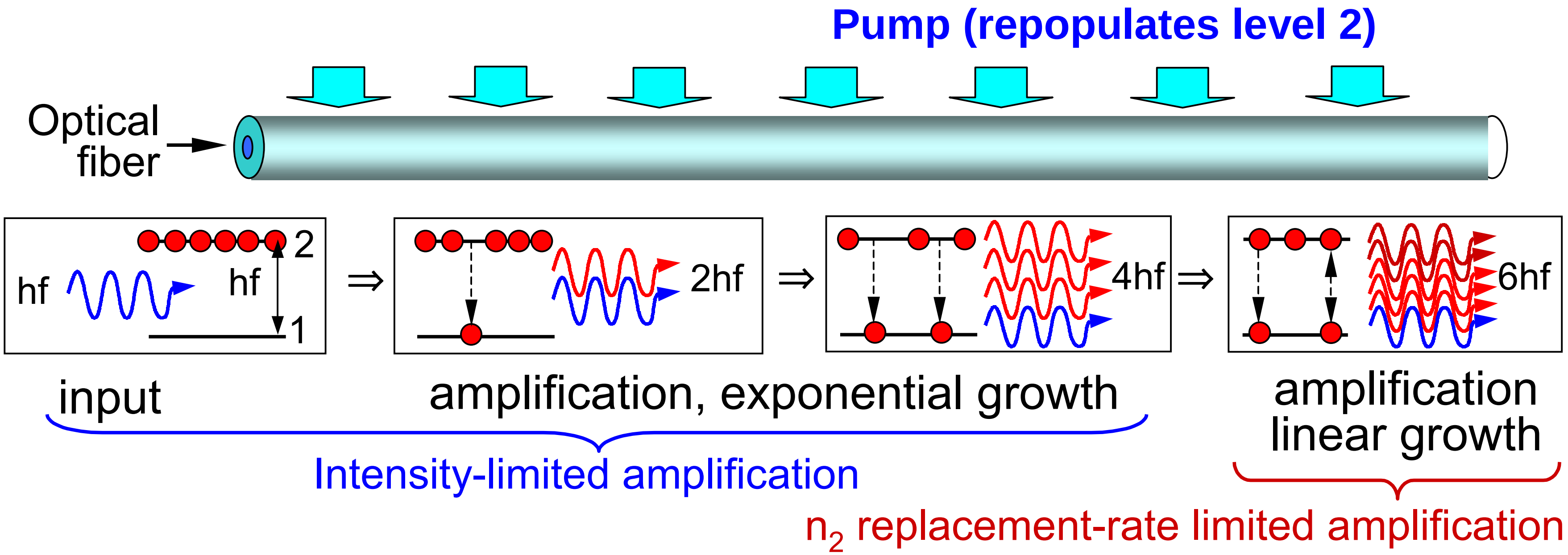
Quantum states characterize atoms and molecules in gases, impurities in solids, and electrons and holes in semiconductors

A transition to a lower state emits a photon coherent with the triggering photon ⇒ amplification (or, with internal reflection, oscillation)

Amplification/lasing requires upper state population to exceed lower state

BASIC LASER AMPLIFIER PHYSICS

Basic Amplification Process:

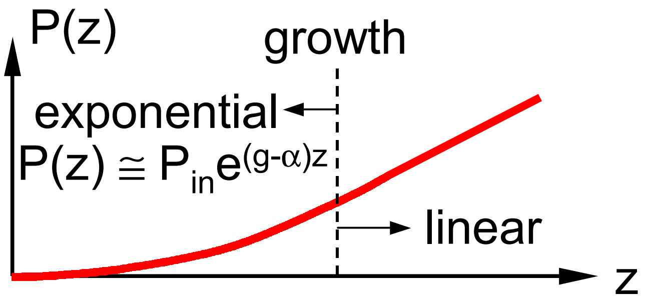


[Each ● is a separate atom or molecule; need $n_2 > n_1$ for amplification]

Amplification frequency f [Hz]:

$$\boxed{E_2 - E_1 = hf\ [\mathrm{J}]}$$

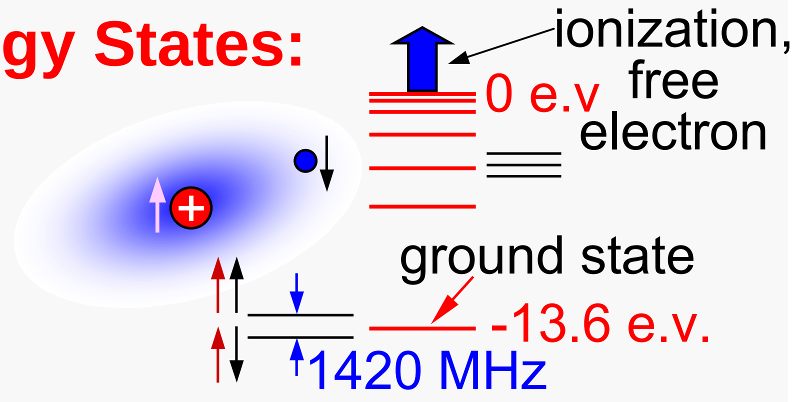
$h = 6.625 \times 10^{-34}$ [Js]



(g is gain, α is attenuation)

ENERGY STATES AND POPULATIONS

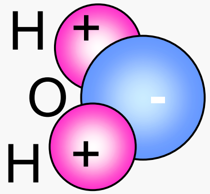
Energy States:



Hydrogen atom (Galactic arms)

States:

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



Water vapor H_2O

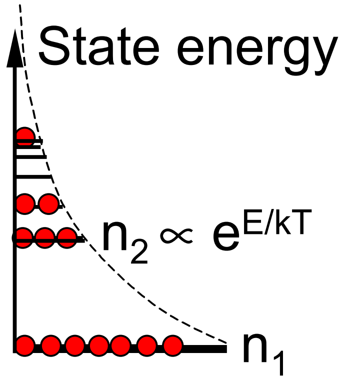
(e.g. water vapor masers around stars)
(electric dipole transitions)

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

Level Populations—Kinetic Temperature T_k:

Thermal equilibrium dominated by collisions

⇒ Boltzmann distribution: $\boxed{\frac{n_i}{n_j} = e^{-(E_i - E_j)/kT_k}}$



If thermal equilibrium dominated by radiation, $T_{i,j}$

⇒ Boltzmann distribution: $\boxed{\frac{n_i}{n_j} = e^{-(E_i - E_j)/kT_{rad}}}$ ⇒ $\boxed{n_i \to n_j \text{ if } T_{rad} \to \infty}$

$n_2 > n_1$ if $T_{rad} < 0$

“A” AND “B” COEFFICIENTS

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 between states i and j:

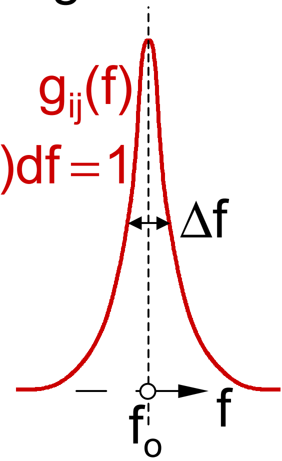
$A_{ij} = \omega^3|D_{ij}|^2\,(2/3h\varepsilon c^3)\ [s^{-1}]$

D_{ij} [Cm] is a quantum mechanical dipole moment (electric or magnetic)

Decay time $\tau_A = A^{-1}$

Note: $\tau_A \propto \omega^{-3}$, so “visible” τ’s are very short, microwave τ’s are long

Stimulated emission and absorption:



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

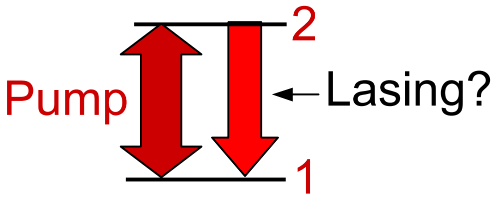
B coefficient: $B_{ij} = F\sigma_{ij} \propto F\, g_{ij}(f)\, A_{ij}/\omega^3$

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

Lorentzian line shape $g_{ij}(f)$: $g_{ij}(f) = [2/\pi(\Delta f)]/[1 + 4(f - f_o)^2/(\Delta f)^2]$

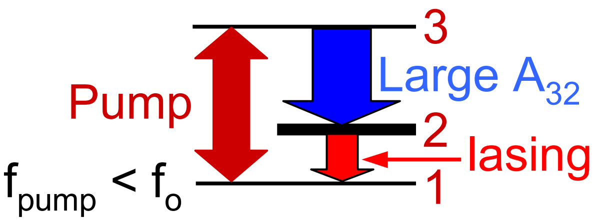
PUMPING LASERS

Two-Level Lasers:



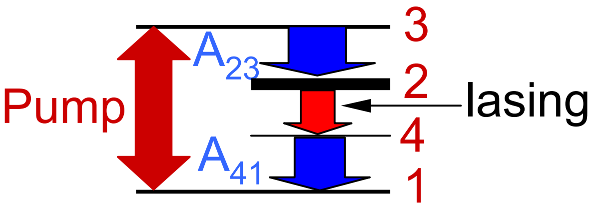
No degree of pumping can yield $n_2 > n_1$
(early 2-level lasers spatially isolated n_2 group)

Three-Level Lasers:

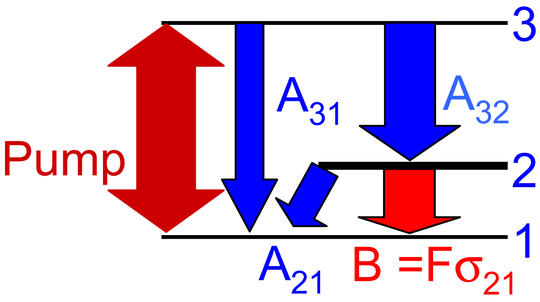


Pump levels 1,3 so $n_1 \cong n_3$
Large A_{32} populates 2 so $n_2 >> n_1 \cong n_3 \cong 0$

More levels sometimes used, e.g. to utilize
quantum states with larger A's →



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

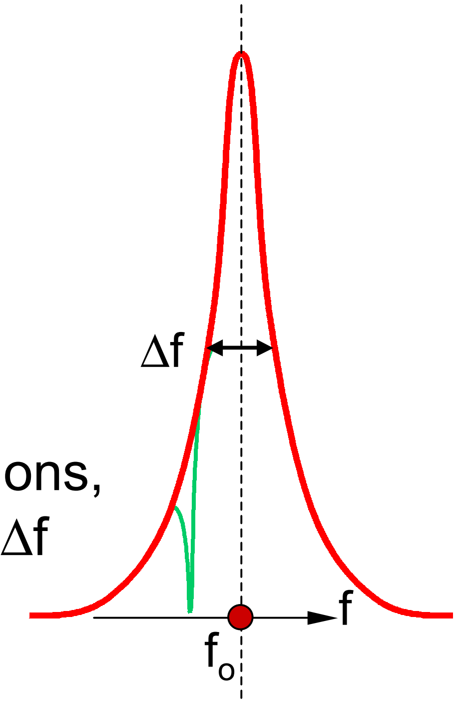


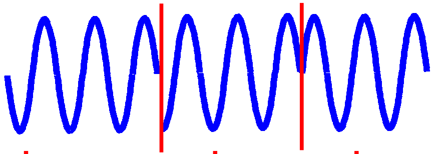
Intrinsic efficiency: $\eta_i = f_L/f_p$ ($P \propto nhf$ [W]) < 1
B/A efficiency: $\eta_B = B_{21}/(A_{21}+B_{21}) < 1$
A/A efficiency: $\eta_A = A_{32}/(A_{31}+A_{32}) < 1$
Total efficiency: $\eta = \eta_i \eta_B \eta_A$
Recall $A \propto \omega^3$; if $B >> A \propto \omega^3$, then x-ray
lasers need very high B (pump values)($B \neq \sim f(\omega)$)

LINE SHAPE

Lorentzian Line Shape and Broadening Mechanisms:

Lorentzian line shape:	$g_{ij}(f) = [2/\pi(\Delta f)] / [1 + 4(f - f_o)^2/(\Delta f)^2]$
$g_{ij}(f)$ has unity integral:	$\int_{-\infty}^{\infty} g_{ij}(f)df = 1$ $g_{ij}(f)/g_o = 0.5$ for $\lvert f - f_o \rvert = \Delta f/2$
Broadening mechanisms:	$\Delta f_o > 1/\tau_A = A \cong 10$ MHz (minimum linewidth); collisions, lattice interactions, Fields ($\overline{E},\overline{B}$), & Doppler all broaden Δf
Homogeneous broadening:	E.g., each atom has $\Delta f \cong 4$ THz; a single frequency can drain G; e.g. EDFA's, most solid-state and semiconductor lasers
Inhomogeneous broadening:	Each narrow-band atom shifted differently, e.g. HeNe; ⇒ hole burning

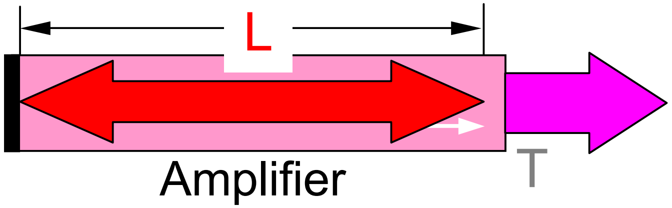




Collisions ⇒ phase changes, Fourier transform ⇒ Δf

LASER OSCILLATORS

Laser Oscillation:



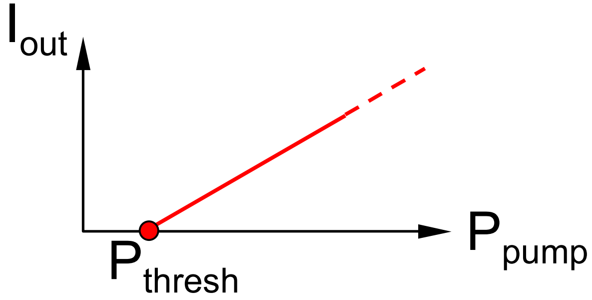
Oscillator: Assume length L, perfect mirrors at both ends;
Closed lossless amplifier must oscillate and saturate

Threshold: Gain m^{-1} must exceed loss (threshold condition)
Gain $\propto$ pump power P_p, therefore P_p > threshold too

Mirrors: Assume one mirror has power transmission coefficient T > 0
Gain $\cong$ Loss: $P_+(1 - T)e^{2(g-\alpha)L} \geq P_+$
$\Rightarrow$ Two-pass gain $e^{2(g-\alpha)L} \geq 1/(1 - T) > 1$ for oscillation ($g > \alpha$)

Output Limit: $P_{out} = \eta P_{pump}$. $P_+ = P_{out}/T$, so $P_+/P_{out} \rightarrow \infty$ as $T \rightarrow 0$

Q-switching: Set T $\cong$ 0 until P_+ peaks,
then set T $\cong$ 1; yields very large
"Q-switched pulse"



LASER RESONANCES

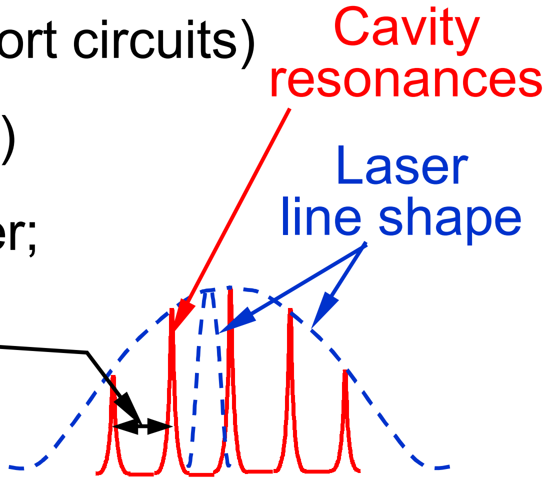
Oscillator Resonant Frequencies f:

Resonances when $\{m\lambda_m/2 = L\}$ (mirrors approx. short circuits)

$\Rightarrow \lambda_m = 2L/m$, $f_m = cm/2LN$ (N = index of refraction)

$f_{i+1} - f_i = c/2LN \cong 10^8$ Hz (100 MHz) for 1-meter fiber;

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



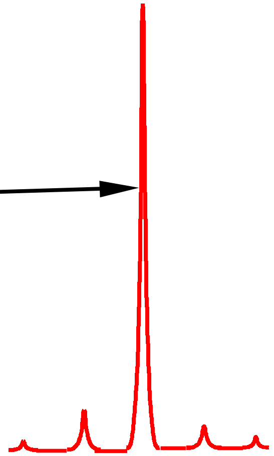
Unsaturated

Laser Output Spectrum:

In saturation, Gain(f) $\cong$ frequency independent

If laser linewidth Δf > line spacing,
dominant line wins if exponential growth

If linewidth Δf < line spacing,
must tune cavity length to f_o

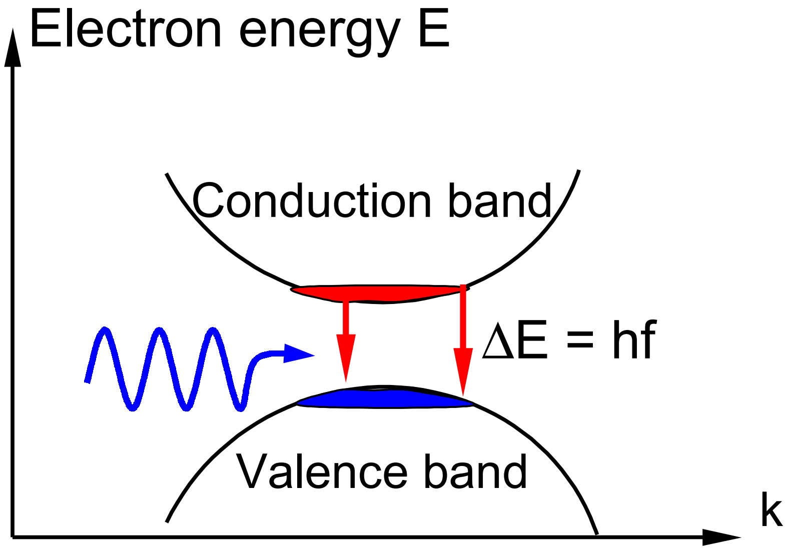


Saturated, line narrowing

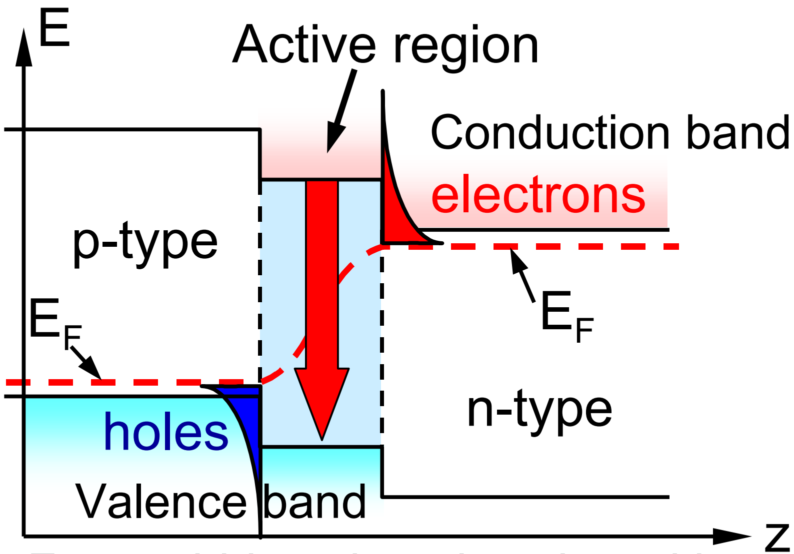
EXAMPLES OF LASERS

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)



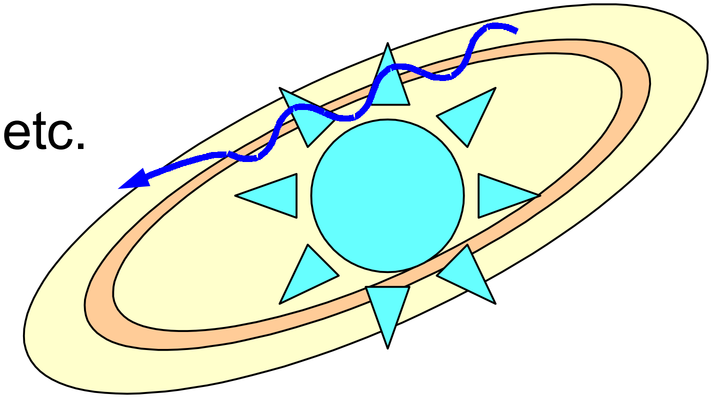
Energy band curvature broadens the laser linewidth



Forward-biased p-n junction with mirrors at ends of transparent region

EXAMPLES OF LASERS (2)

Astrophysical Masers:



Stellar pumped: Water vapor, OH, CO, etc.
Interstellar collisions: OH, etc.

Gas Lasers:

Ammonia (23 GHz): “Pumped” by diverting molecules in ground state
CO_2, HeNe: Pumped by electrical discharges that form energetic plasmas
Chemical: Chemical combustion yields upper-state excess

Externally Pumped Solid-State Lasers

Ruby: Pumped by flash lamps, etc.
EDFA: Pumped by semiconductor lasers