# LASERS

## Representative applications:

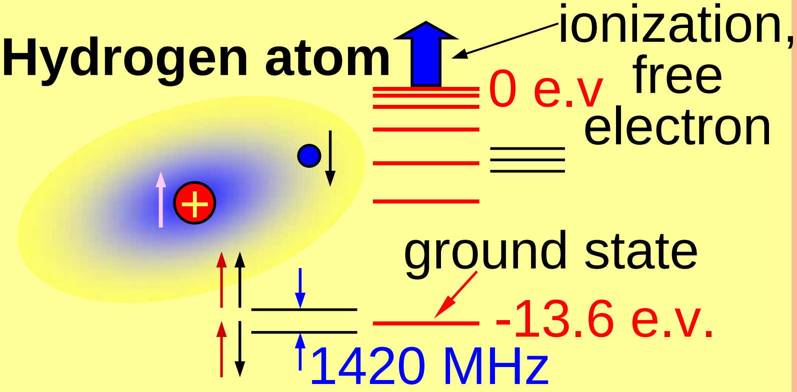
Amplifiers: Broad-band communications (avoid down-conversion)

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

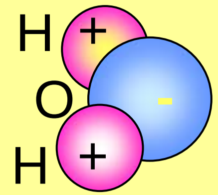
Blasting: Laser machining, labeling, weapons, laser fusion (pellet compression). Peak > $10^{15}$W, average > 1kw; high intensity because $I \propto |\sum_i \bar{E}_i|^2$

## Energy States:

**Hydrogen atom**




**Water vapor $H_2O$**




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

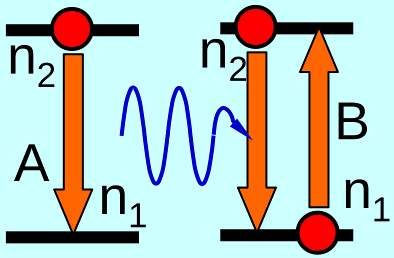
**Chromium atoms in lattice (e.g. ruby), Erbium atoms in glass**

# 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, 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" $\tau$'s, long microwave $\tau$'s

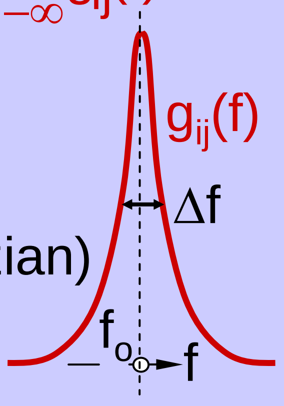
## Stimulated emission and absorption:

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

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

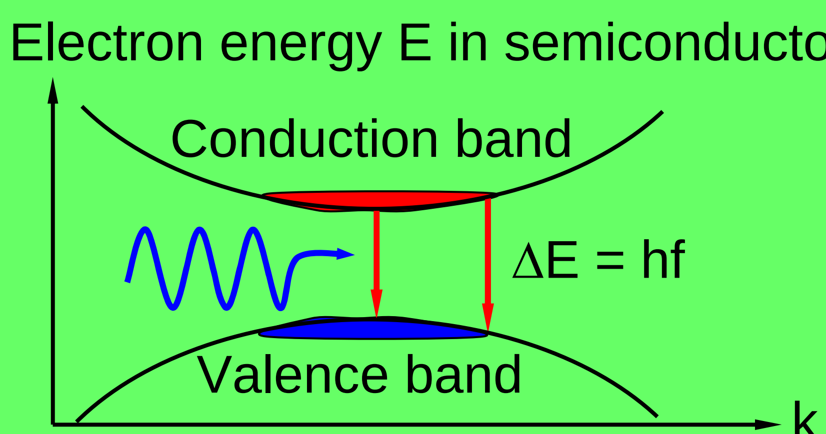
B coefficient: $B_{ij} = F\sigma_{ij} \propto F\, g_{ij}(f)\, A_{ij}/\omega^3$

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)

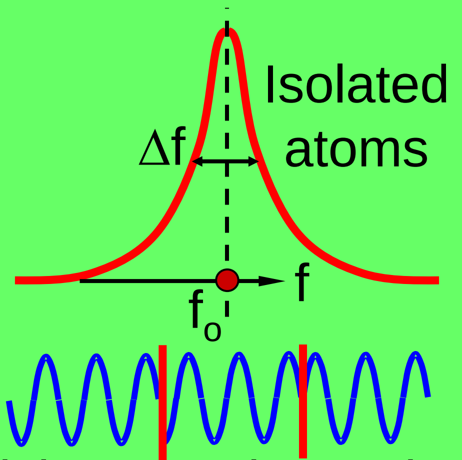


# ENERGY LEVEL POPULATION AND WIDTH

## Linewidth Broadening Mechanisms:




Energy band curvature broadens the linewidth




Collisions ⇒ phase changes, Fourier transform ⇒ Δf

## Level Populations—Kinetic Temperature $T_k$:

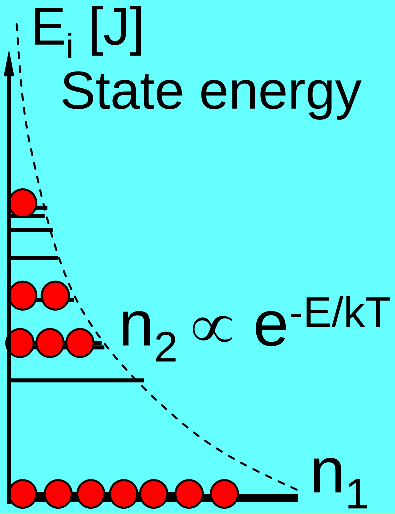
Thermal equilibrium ⇒ Boltzmann distribution:

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

T = kinetic temperature if collisions dominate

T = radiation temperature if radiation dominates $f_{ij}$

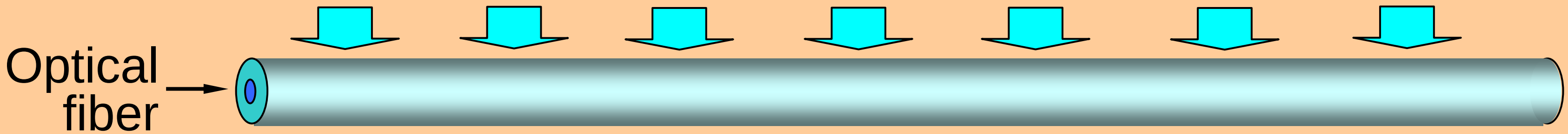
$\Rightarrow n_i \rightarrow n_j$ if $T_{rad} \rightarrow \infty$, $n_2 > n_1$ if $T_{rad} < 0$

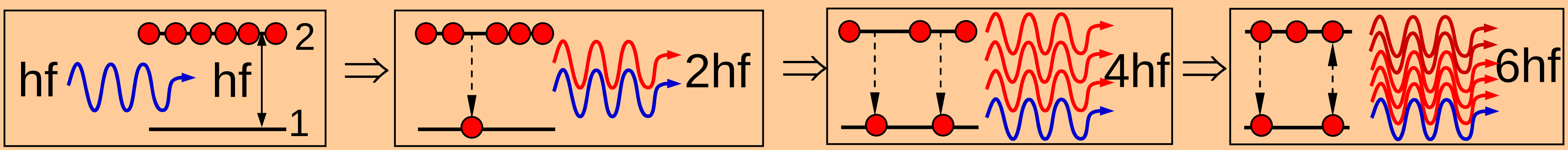


# BASIC LASER AMPLIFIER PHYSICS

## Amplification Process:

Pump (repopulates level 2)




input

amplification, exponential growth

Intensity-limited amplification

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

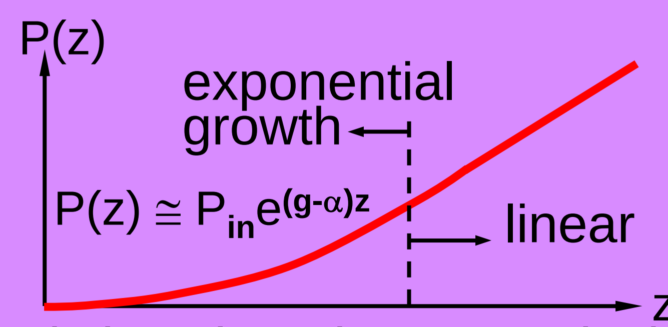
amplification
linear growth

$n_2$ replacement-rate limited amplification

## Amplification frequency f [Hz]:

$E_2 – E_1 = hf$ [J],

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

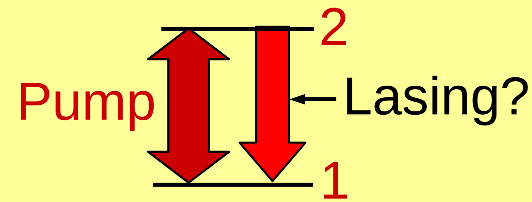



(g is gain, $\alpha$ is attenuation)

# PUMPING OF LASERS

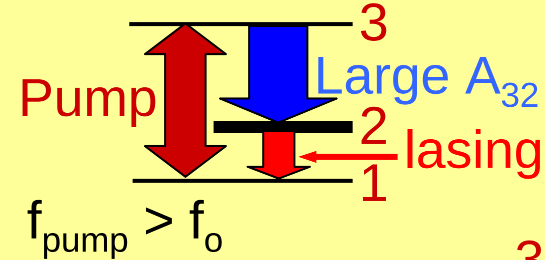
## Two-Level Lasers:

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

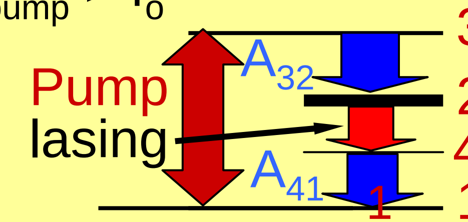



## Three-Level Lasers:

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

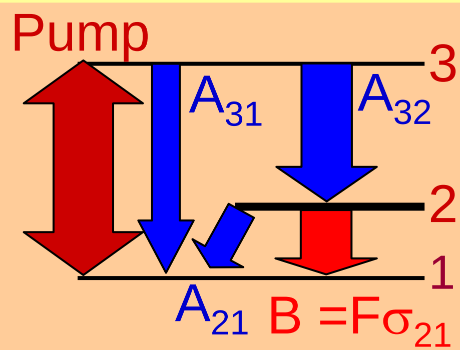



More levels can utilize transitions with larger A's
Large $A_{23}$ fills $L_2$, and large $A_{41}$ empties $L_4$




## 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: $\eta = \eta_i \eta_B \eta_A$



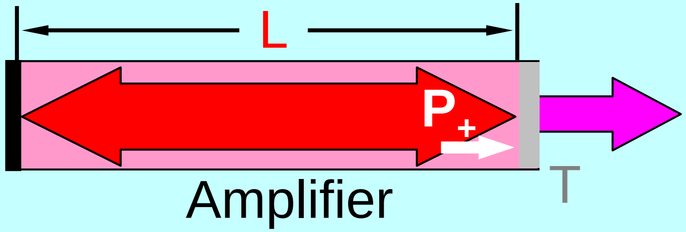

Pump photons $s^{-1} \propto B >> A \propto \omega^3$, so x-ray lasers need pump power $\propto hfB \propto hfA \propto \omega^4$

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

# LASER OSCILLATORS

## Laser Oscillation:

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



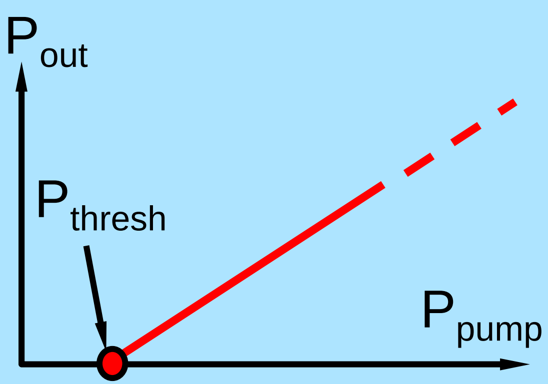

Lossy: Round-trip gain must exceed round-trip loss (threshold condition); gain ∝ pump power $P_p$, so need $P_p > P_{thresh}$

Mirrors: Exit mirror has power transmission coefficient T > 0

At threshold, Gain ≅ 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

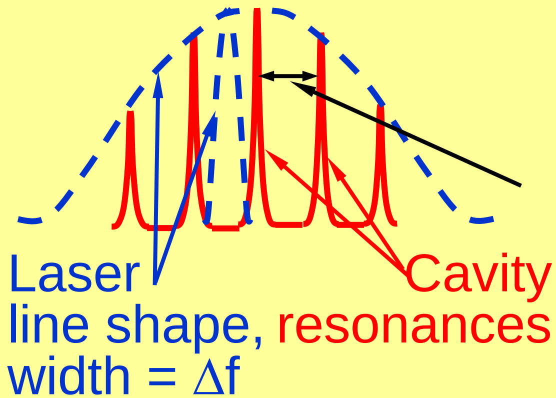
$$\frac{m\lambda_m}{2} = L \quad \text{(mirrors} \approx \text{short circuits)}$$

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

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

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

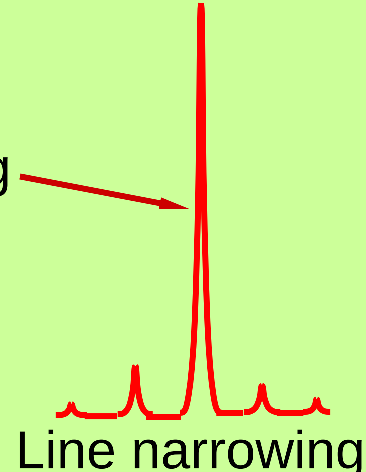
$\cong$ 50 GHz line spacing for 0.5-mm diodes




## Laser Output Spectrum:

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

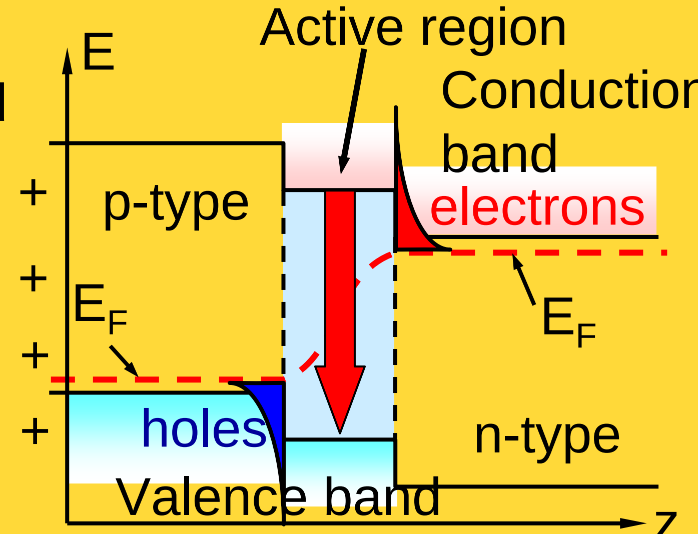
If atoms can amplify only a portion of the band, then all lines over threshold can yield output (inhomogeneous line broadening)



# 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

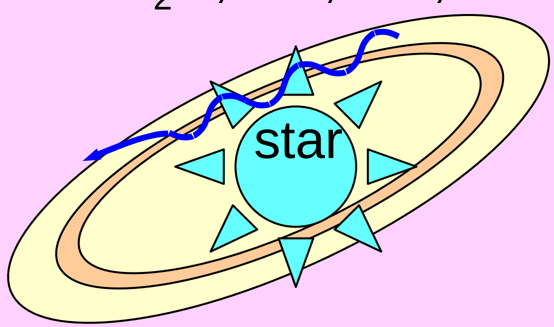



## Astrophysical Masers:

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

## Chemical lasers:

Weapons (high energy, fast)



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