LASERS

Applications:

Amplification: 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, average > 1kw

Note: 10^{15} W in 10-micron spot ⇒ $\bar{E} \cong 10^{14}\left[Vm^{-1}\right]\left(10^{6}\text{ in H atom}\right)$

Basic Principles:

Atoms and molecules in gases, impurities in solids, and electrons and holes in semiconductors have quantum states

A transition to a lower state emits a photon coherent with triggering photon

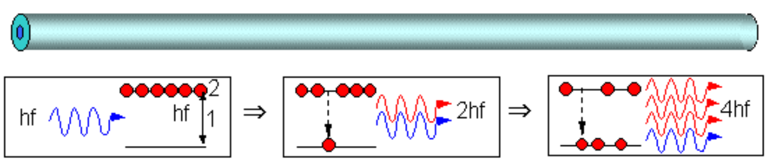
⇒ Exponential spatial amplification or, with internal reflection, oscillation

Amplification/lasing requires upper state population to exceed lower state

L19-1

BASIC LASER AMPLIFIER PHYSICS

Basic Amplification Process:



input

amplification, exponential growth

saturation

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

Basic Equations:

Amplification frequency: $E_2 - E_1 = hf$ [J] $h = 6.625 \times 10^{-34}$ [Js]

Photon increase (no pump): $dn_2/dt = -[An_2 + B(n_2 - n_1)]$ ($n = \#/m^3$)

Wm^{-3} emitted: $P = hf\, d(n_2 - n_1)/dt$ [$Jm^{-3}s^{-1}$]

A,B are the spontaneous and stimulated emission coefficients, respectively

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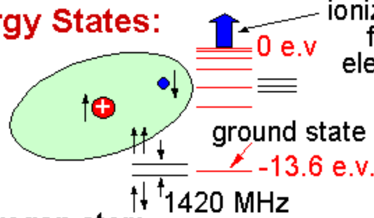
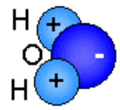
ENERGY STATES AND POPULATIONS

Energy States:



Hydrogen atom
(Galactic arms)

States:

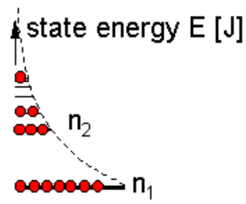


electronic (visible, UV)
vibrational (visible)
bending (IR)
rotational (microwave)

Water vapor H_2O
(e.g. water vapor masers around stars)
(electric dipole transitions)

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

Level Populations—Kinetic Temperature T_k:



Thermal equilibrium dominated by collisions

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

Thermal equilibrium dominated by radiation

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

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

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EINSTEIN "A" AND "B" COEFFICIENTS

Rate Equation: $dn_2/dt = -[An_2 + B(n_2 - n_1)]$ ($n = \#/m^3$, collisionless)

Einstein A Coefficient:

Spontaneous emission: $dn_i/dt = -A_i n_i$ transitions $m^{-3}s^{-1}$

A_{ij} between states i and j: $A_{ij} = k^3|D_{ij}|^2 2/3h\varepsilon$ [s^{-1}]

Dipole strength of transitions: 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 short, microwave τ's are long

B Coefficient:

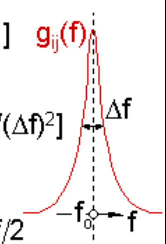
Stimulated emission and absorption: $B_{ij} = Ig_{ij}(f)|D_{ij}|^2 N\pi^2 2/3h^2 c\varepsilon$ [s^{-1}]

Proportional to radiation intensity I: $I = |E|^2/2\eta_o$ [Wm^{-2}]

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

$g_{ij}(f)$ has unity integral: $\int_{-\infty}^{\infty} g_{ij}(f)df = 1;$

[N is refractive index] $g_{ij}(f)/g_o = 0.5$ for $|f - f_o| = \Delta f/2$



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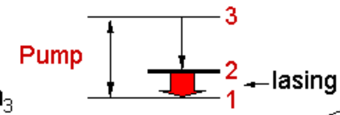
PUMPING LASERS

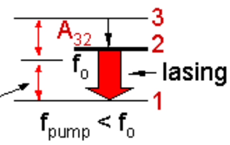
Three-Level Lasers:

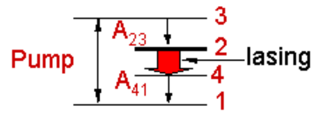


Pump levels 1,3 so $n_1 \cong n_3$

Large A_{32} populates 2 so $n_2 >> n_1 \cong n_3 \cong 0$

More levels sometimes used, e.g. to lower the pump frequency, or to utilize quantum states with larger A's

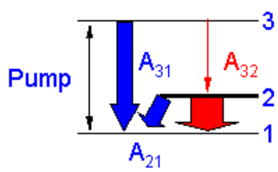




Losses that Limit Short Wavelength Operation:

Key losses: $(n_3A_{31} + n_2A_{21}hf_{31}$ [Pump Wm^{-1}]

Recall $A \propto \omega^3$; if $B >> A \propto \omega^3$, then x-ray lasers need very high B (pump values)



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LASER GAIN

Fiber Amplifier Gain (if n atoms m^{-1} in upper state; ~0 in lower):

dn/dt: $= R - n(A + B) = R - (n/\tau_A) - I_{\#}\sigma n$ (1)

[where R = Repopulation rate s^{-1} of n; $I_{\#}$ = photons $m^{-2}s^{-1}$;
σ = stimulated-emission cross-section [m^2] atom $^{-1}$]

Steady State: $dn/dt = 0, \Rightarrow n = R\tau_A/(1 + \tau_A I_{\#}\sigma) = R\tau_A/(1 + I_{\#}/I_{\#sat})$ [$I_{\#sat} = 1/\tau_A\sigma$] (2)

When B>>A: $dI_{\#}/dz \cong I_{\#}\sigma n$, so that: $I_{\#out} = I_{\#in}e^{\sigma nz} = I_{\#in}e^{gz}$ [gain g (nepers m^{-1})] (3)

Gain $g \cong \sigma n = \sigma R\tau_A/(1 + I_{\#}/I_{\#sat}) \rightarrow 0$ for $I_{\#} >> I_{\#sat}$ [from (2,1)]

$g \cong \sigma n < \sigma n_{max}$ [n_{max} is the number of amplifying atoms m^{-1}]

G(nepers m^{-1}): $g \cong n\sigma = nB/I_{\#} = P_{pump}g_{ij}(f)|D|^2N\pi^2 2/3h^2c\varepsilon A$ for $I_{\#} << I_{\#sat}$ (4)

[from 4,1,2,5, L-19-4]

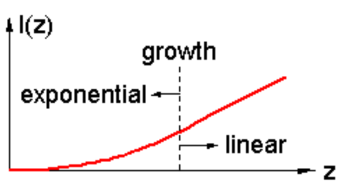
Where: P_{pump} [Wm^{-1}] > hf_pR and $n \cong R/[A(1 + I_{\#}/I_{\#sat})] \cong P_{pump}/[hf_pA(1 + I_{\#}/I_{\#sat})]$ (5)

Laser Gain: $G = I_{out}/I_{in} = e^{\int g(z)dz}$ where

$g(z) \cong \sigma P_{pump}/[hf_pA(1 + I_{\#}/I_{\#sat})]$

(Actually, net gain = $g - \alpha$;

α represents losses)



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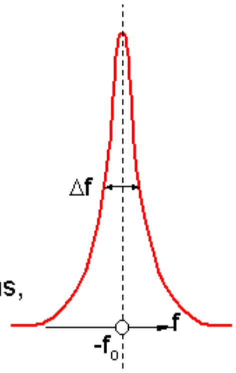
LINE SHAPE

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 $|f - f_o| = \Delta f/2$

Broadening mechanisms: $\Delta f_o > 1/\tau_A = A \cong 10$ MHz (minimum linewidth); collisions, lattice interactions, fields $(\overline{E},\overline{B})$, Doppler

Homogeneous broadening: 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

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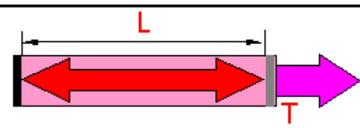
LASER OSCILLATORS

Laser Oscillation:



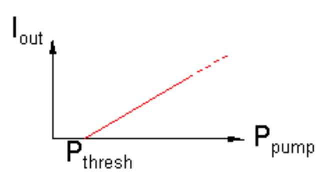
Amplifier: Assume length L, perfect mirrors at both ends;
Closed lossless amplifier must oscillate and saturate
Gain m^{-1} must exceed loss (threshold condition)

Modes: 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;
$\cong 50$ GHz for 0.5 mm semiconductor diodes
If linewidth $\Delta f >$ line spacing, dominant line wins if saturation
If linewidth $\Delta f <$ line spacing, must tune cavity length to f_o

Source: 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 $e^{2(g-\alpha)L} \cong 1/(1 - T)$

Output Limit: Usually $T \cong$ losses $= 1 - e^{-2(\alpha-g)L}$,
and $I \cong I_{sat}$



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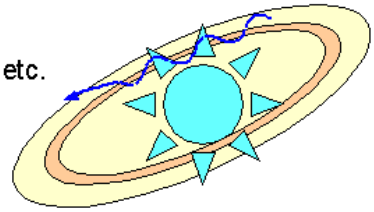
EXAMPLES OF LASERS

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

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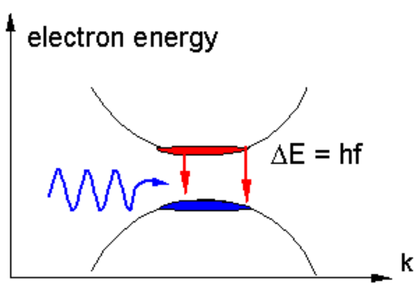
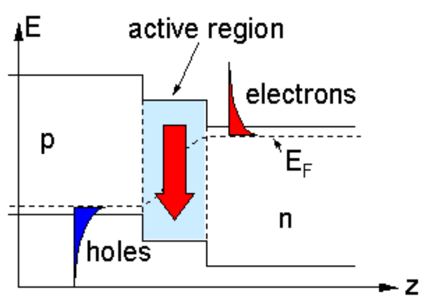
EXAMPLES OF LASERS (2)

Electronically 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)





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