UC San Diego Celebrates ‘Science Nonfiction’ at Comic-Con

FOLLOW @UCSANDIEGO ON INSTAGRAM—WE’RE BRINGING SCIENCE NON-FICTION TO COMIC-CON.

Just up the road from the Comic-Con convention, likeminded “believers” at UC San Diego are busy turning fantasy and science fiction into something very real.
Lecture 6

Laser

[Images of laser applications and diagrams]
In a metal, how does the probability distribution of an electron look like at absolute zero?

![Diagrams showing probability distributions](image)
(Atom) Energy Levels

For atoms, I draw a lower horizontal to indicate its lowest energy state, and another horizontal line higher in energy to indicate its excited state.
What is the probability distribution at zero Kelvin?

At finite temperature?
Occupation of Energy Levels in Thermal Equilibrium

• Boltzmann Distribution

\[
\frac{n_2}{n_1} = \exp \left( - \frac{E_2 - E_1}{k_B T} \right)
\]

At 300 K, for \( E_2 - E_1 = 1 \text{ eV} \), \( n_2/n_1 = 1.7 \times 10^{-17} \)

\( 0.1 \text{ eV} \) \quad 2\%
Optical Processes

spontaneous emission

absorption

stimulated emission

Light Amplification by Stimulated Emission Radiation
In a two-level system, can one achieve population inversion with sufficiently large pumping?

A. Yes
B. No
C. No definite answer
The principle of the LASER. (a) Atoms in the ground state are pumped up to the energy level $E_3$ by incoming photons of energy $h\nu_{13} = E_3 - E_1$. (b) Atoms at $E_3$ rapidly decay to the metastable state at energy level $E_2$ by emitting photons or emitting lattice vibrations; $h\nu_{32} = E_3 - E_2$. (c) As the states at $E_2$ are long-lived, they quickly become populated and there is a population inversion between $E_2$ and $E_1$. (d) A random photon (from a spontaneous decay) of energy $h\nu_{21} = E_2 - E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

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Which do you expect to be easier to be a laser?

• A. 3-level system
• B. 4-level system
• C. Does not matter
Population Inversion

Amplifying medium: $N_2 > N_1$

Input wave: $\bullet$ Atom in upper state 2
Output wave: $\circ$ Atom in lower state 1

Absorbing medium: $N_2 < N_1$

Input wave: $\circ$ Atom in upper state 2
Output wave: $\bullet$ Atom in lower state 1

Legend:
- $E_2$: 2
- $E_1$: 1

Amplification of a traveling electromagnetic wave in (a) an inverted population $N_2 > N_1$, and (b) its attenuation in an absorbing $N_2 < N_1$ medium.

No population inversion

Mirror | Optical resonant cavity | Mirror
What does it take to make a laser?

- Find an appropriate material
- Find an appropriate pumping method
- Find an appropriate optical cavity
Type of Lasers

• **Doped insulator lasers**
  – Ruby laser
  – Nd:YAG laser

• **Gas laser**
  – HeNe laser
  – Argon-ion laser
  – Carbon dioxide laser
  – Excimer laser

• **Semiconductor laser**
Ruby Laser

Components of the first ruby laser

- Power supply
- Switch
- 100%-reflective mirror
- Quartz flash tube
- Ruby crystal
- Polished aluminum reflecting cylinder
- 95%-reflective mirror
- Laser beam

http://universe-review.ca/F13-atom07.htm
Ruby Laser

Xenon-filled flash tube

Heat

~4 millisec

http://universe-review.ca/F13-atom07.htm
Nd:YAG Laser
neodymium ions in yittrium aluminum garnet

How many level (broadly speaking) system is this?

Is it easier to achieve population inversion than a ruby laser? Why?

http://perg.phys.ksu.edu/vqm/laserweb/ch-6/f6s2t2p2.htm
Nd:YAG Laser

neodymium ions in yittrium aluminum garnet

Ophthalmology
Skin cancer removal
Prostate surgery
Hair removal
Engraving
Drilling
Rangefinder
Spectroscopy

He-Ne Laser

He-Ne Laser

http://en.wikipedia.org/wiki/Helium%E2%80%93neon_laser
Carbon Dioxide Laser

Applications of CO$_2$ Lasers

- **Medical, laser scalpel**
  - 80% of soft biological tissue (skin) is water, which absorbs light at $\sim 10$ $\mu$m wavelength.
  - $\Rightarrow$ Penetration length $\sim 50$ $\mu$m.
  - Vaporizes tissue

- **Industrial**
  - Laser cutting ($\sim$100-200 W)
The energy band diagram of a degenerately doped p-n with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

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A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

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Light Output vs. Current (L-I Curve)

Heterostructure Laser

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the p-GaAs layer, the active layer.

(c) Higher bandgap materials have a lower refractive index.

(d) AlGaAs layers provide lateral optical confinement.

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### Common Lasers

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength</th>
<th>Power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium-Neon</td>
<td>632.8nm</td>
<td>0.1-50mW</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Ruby</td>
<td>694.3nm</td>
<td>0.03-100J</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Carbon-Dioxide</td>
<td>10.6µm</td>
<td>3-100W</td>
<td>5-15%</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1.064µm</td>
<td>0.04-600W</td>
<td>0.1-2%</td>
</tr>
<tr>
<td>Argon</td>
<td>488/514nm</td>
<td>5mW-20W</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Dye</td>
<td>400-900nm</td>
<td>20-800mW</td>
<td>10-20%</td>
</tr>
<tr>
<td>Hydrogen-Fluoride</td>
<td>2.6-3µm</td>
<td>0.01-150W</td>
<td>0.1-1%</td>
</tr>
<tr>
<td>Gallium-Arsenide</td>
<td>780-900nm</td>
<td>1-40mW</td>
<td>1-20%</td>
</tr>
</tbody>
</table>
What We Learned

Principles of laser

Population inversion in a 3-level system

Optical cavity

Types of laser

Ruby laser

YAG laser

HeNe laser

Semiconductor laser
How a Laser Works
In a scale of 1 (easy) to 5 (difficult), rate the lecture on laser.

• A. 1 (easy)
• B. 2
• C. 3
• D. 4
• E. 5 (difficult)
QD TV; Detecting Light
cyanophenylcyclohexanes

**Twisted Nematic LC**

A special polymer rubbed on the side of the glass substrate that does not have the polarizing film on it to create microscopic grooves in the same direction as the polarizing film.

Cross-Sectional View of an LCD Panel

Optical Stack in a Color TFT-LCD

fL = foot-lambert, a unit of luminance
CCFL - cold cathode fluorescent lamp

CCFL back light or LED or QD

80.6% of light is lost

http://www.anandtech.com/show/1137/8
TFT/LCD Display
Quantum Dot

- Like a large atom: electrons are confined in all 3 directions
- \( \rightarrow \) discrete electron energy levels, like 1s, 2s, 2p, … of an atom
- \( \rightarrow \) discrete hole energy levels

Colloidal semiconductor nanocrystals (CdS, CdSe, PbS, PbSe, …)
Chemical synthesis
2-5 nm
Quantum Dots

- Narrower potential well width $\rightarrow$ larger confinement energy
- For both electrons and holes
- Larger recombination energy (shorter wavelength)
Quantum Dot Film Sheet for LCD TV

Enhances color

http://www.wired.com/2015/01/primer-quantum-dot/