Engineering Medical Optics  
BME136/251 Winter 2018  

Monday/Wednesday 2:00-3:20 p.m.  
Beckman Laser Institute Library, MSTB 214 (lab)  

Teaching Assistants (Office hours: Every Tuesday at 2pm outside of the BLI library)  
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Web site:  
http://lammp.bli.uci.edu/education/bme136/  

Monday, 1/8 – Optics and Photonic Devices I  
Wednesday, 1/10 – Optics and Photonic Devices II  
Monday, 1/15 – Martin Luther King Day  
Wednesday, 1/17 – Optics and Photonic Devices III: homework 1 handout  
Monday, 1/22 – Laser Microscopy: homework 1 due  
Wednesday, 1/24 – Optical Coherence Tomography: homework 2 handout  
Monday, 1/29 – Endoscopy: homework 2 due  
Wednesday, 1/31 – Midterm  

Monday, 2/5 – Spectroscopy I  
Wednesday, 2/7 – Spectroscopy II: homework 3 handout  
Monday, 2/12 – Spectroscopy III: homework 3 due  
Wednesday, 2/14 – Tissue Optics I  
Monday, 2/19 – President’s day  
Wednesday, 2/21 – Tissue Optics II: homework 4 handout  
Monday, 2/26 – Tissue Optics III: homework 4 due  
Wednesday, 2/28 – Tissue Optics IV: homework 5 handout  
Monday 3/5: homework 5 due  

Group Project Presentations  
Monday, Wednesday, 3/5, 3/7 – Mandatory TA Meetings for Final Group Project Presentations  
Monday, Wednesday, 3/12-3/14 - Final Group Project (Presentations)  

Final Exam – Friday, 3/23, 1:30-3:30 pm
"p" layer: infuse with Group III elements, e.g. B, Ga, Al, In

"n" layer: infuse with Group V elements: e.g. N, P, As, Sb (antimony)
PN Junction – Depletion Approximation
PN Junction – Apply external voltage

Positive voltage (forward, 2-3 V)

Negative voltage (reverse)

Energy bands

Conduction band

Valence band
PN Junctions: LEDs, lasers, solar cells, photodiodes, diodes

Forward-bias (LED/laser)

Reverse-bias (photodetector)

Solar cell
LEDs

GaAs - 880 nm, GaP - 550 nm or 700 nm, GaAsP - 580 nm or 660 nm
AlGaAs – Red/NIR
GaN, InGaN - Green, Blue

Wavelength determined by semiconductor bandgap

~30 nm bandwidth

Ga: recombination produces light; Electroluminescence

Shuji Nakamura, UCSB, 2014 Nobel Prize
HeNe Laser

632.8 nm

~0.002 nm bandwidth

How to get “white” LEDs?

• sources at the three apexes of the color chart

• generate any color

• principle for all color displays

3 dies (chips) on single device
Combine blue LEDs with phosphors that emit other (longer wavelength) colors after excitation with blue light: Cerium(III)-doped YAG (YAG:Ce3+, or Y3Al5O12:Ce3+)

- liquid crystal displays in cellular phones, PDAs, laptops
- not useful as source in filtered light (Liquid Crystal) color displays because color intensity is very non-uniform.

We only sense it as white.
LASER:
Light Amplification by Stimulated Emission of Radiation

- Albert Einstein (1917): *Stimulated emission*
- Nicolaas Bloembergen and Charles Townes (1956): *Development of maser*
- Gordon Gould (1959): "*LASER*” *proposed*
- Theodore Maiman (1960): *First laser demonstrated*
- Charles H. Townes, Nikolay Basov, and Aleksandr Prokhorov (1964): *Nobel Prize in Physics*
Characteristics of Lasers

Compared to conventional light source, laser light has

• *High temporal coherence: monochromatic*
  Extremely small spectral bandwidth

• *High spatial coherence: well collimated beam*
  Extremely small angular broadening: $\lambda / d$

• *High Brightness:*
  *Emitted power per unit area is very high*
Selection of Lasers

• Wavelength
• Energy
• Power
• Pulse Width
• Repetition Rate
LASER
Three Major Components

Pump

Gain Medium

Feedback

Feedback
LASER

Three Major Components

Pump

Gain Medium

Feedback

Feedback
Photon Absorption, Emission

Absorption
\[ \frac{dN_2}{dt} \propto (N_1 - N_2)I(\nu) \]
\[ (N_2 - N_1) < 0 \]
Fast: \( \sim 10^{-15} \) s

Spontaneous Emission
\[ \frac{dN_2}{dt} = -\frac{N_2}{\tau_2} \]

Stimulated Emission
\[ \frac{dN_2}{dt} \propto (N_1 - N_2)I(\nu) \]
\[ (N_2 - N_1) > 0 \]

• Electrons in excited state have a finite average lifetime \( \tau \)
• Photons emitted have random phase and direction

• Presence of excited state atom increases probability of emission of identical photon
• Photons emitted have the same wavelength, phase, polarization, direction
Photon Absorption, Emission

Absorption
\[ \frac{dN_2}{dt} \propto (N_1 - N_2)I(\nu) \]
\[ (N_2 - N_1) < 0 \]

Spontaneous Emission
\[ \frac{dN_2}{dt} = -\frac{N_2}{\tau_2} \]

Stimulated Emission
\[ \frac{dN_2}{dt} \propto (N_1 - N_2)I(\nu) \]
\[ (N_2 - N_1) > 0 \]

In thermal equilibrium, \( N_2 = N_1e^{-(E_2-E_1)/k_bT} \) \(< \) \( N_1 \) \( \rightarrow \) absorption

When \( N_2 > N_1 \) Population Inversion \( \rightarrow \) Stimulated emission
Gain in Laser Medium

Amplifying medium when \((N_2 > N_1)\)

Absorbing medium when \((N_2 < N_1)\)

Gain \(\gamma(\nu) \propto N_2 - N_1\) (population inversion)
Population Inversion: **Three-Level Laser**

Population Inversion: \( \Delta N_{21} = N_2 - N_1 > 0 \)

\[ h\nu = E_2 - E_1 \]

e.g. ruby laser

[Diagram showing three energy levels (E1, E2, E3) with transitions labeled for pump, fast decay, laser transition, and stimulated emission.]
**Four-Level Laser Energy Diagram**

Population Inversion: \( \Delta N_{32} = N_3 - N_2 > 0 \)

\[ h\nu = E_3 - E_2 \]

Nd:YAG Laser

- \( E_1 = 0 \text{ eV} \)
- \( E_2 = 0.26 \text{ eV} \)
- \( E_3 = 1.43 \text{ eV} \)
- \( E_4 = 2.36 \text{ eV} \)

also Ti:Al_2O_3
Pumping

Electrical Pumping
- Argon Ion Laser
- Excimer Laser
- Helium Neon Laser
- Carbon Dioxide Laser
- Semiconductor Laser

Optical Pumping
- Nd:YAG laser
- Ruby laser
- Dye Laser
- Holmium YAG laser
- Titanium Sapphire laser

Diagram:
- Ground State
  - $E_1$
  - $E_2$
  - $E_3$
- Pumping with $hv$ transitions:
  - $E_1 \rightarrow E_2$
  - $E_2 \rightarrow E_3$
  - $E_3 \rightarrow E_1$
Optical Feedback

100% mirror

partial mirror
Optical Feedback

100% mirror

partial mirror
**Optical Feedback**

- Laser cavity (mirrors)
- $E \text{ field} = 0$ at cavity wall, node

**Laser cavity (mirrors)**
Laser Resonant Cavity

\[ \frac{2L}{\lambda} = m \] allowable longitudinal modes; \( m \) integer >>1

100% mirror \hspace{2cm} 30\text{~}99\% \text{ mirror}

Longitudinal cavity modes: determine wavelength (BW)

\[ \Delta \nu = \frac{c}{2L}; \frac{1}{\Delta \nu} = \text{round trip time} \]

Transverse cavity modes: spatial profile (Gaussian)

\[ \text{e.g. for } L = 30 \text{ cm, } \Delta \nu = 0.5 \text{ GHz} \]
**Laser**

**Gain:** Stimulated emission from population inversion due to the pumping

**Loss:** Absorption of the laser medium, partial reflection of the mirrors.

**Laser:** When Gain > Loss

Resonant modes


\[ \nu_0 \]

Laser frequency

\[ \gamma(\nu) \]

Bandwidth (color)

Threshold

For \( L = 30 \) cm, \( \Delta \nu = 0.5 \) GHz; 1.5 GHz BW HeNe laser, \( m = 3 \) modes;

For 128 THz BW TiSa laser \( m = 250,000 \) modes
Ti:Sapphire Laser

http://micro.magnet.fsu.edu/primer/java/lasers/tsunami/

Random Phases: repeat in frequency at 1/round trip transit time c/2L
Ti:Sapphire Laser

http://micro.magnet.fsu.edu/primer/java/lasers/tsunami/

Locked Phases: c/2L
Mode Locking

• Lock cavity modes together, i.e. lock their relative phases.

• Variable loss into the cavity, such as an acousto-optic modulator (external) or saturable absorber (internal) so that the gain of the cavity is modulated at the frequency $c/2L$ (round trip transit time = $2L/c$).

• Interference causes the traveling light waves inside the cavity to collapse into a very short pulse.
Mode Locking

Every time this pulse reaches the output coupler, the laser emits a part of this mode-locked pulse.

Pulse repetition rate is determined by the time it takes for the pulse to make one trip around the cavity (~70-90MHz).

More modes interfere, shorter pulse duration.

Titanium Sapphire Laser: 100 fs modelocked pulses

Diode Lasers

- Modified LED: Heavily doped pn-junctions
- High concentration of e-h pairs, high current densities $10^2 - 10^3$ A/cm$^2$
- Long spontaneous lifetime materials enhance stimulated emission

“p” layer: infuse with Group III elements, e.g. B, Ga, Al, In

“n” layer: infuse with Group V elements: e.g. N, P, As, Sb (antimony)

- Narrow active layer
- Heterostructures, AlGaInP, GaAlAs, InGaAsP: 633, 770, 809 nm, 850, 920, 980, 1.1, 1.3, 1.5 µm
- Powers: few mW's to several W's cw

http://www.mpoweruk.com/semiconductors.htm
Diode Lasers

- Efficiency: 15 to 30%,