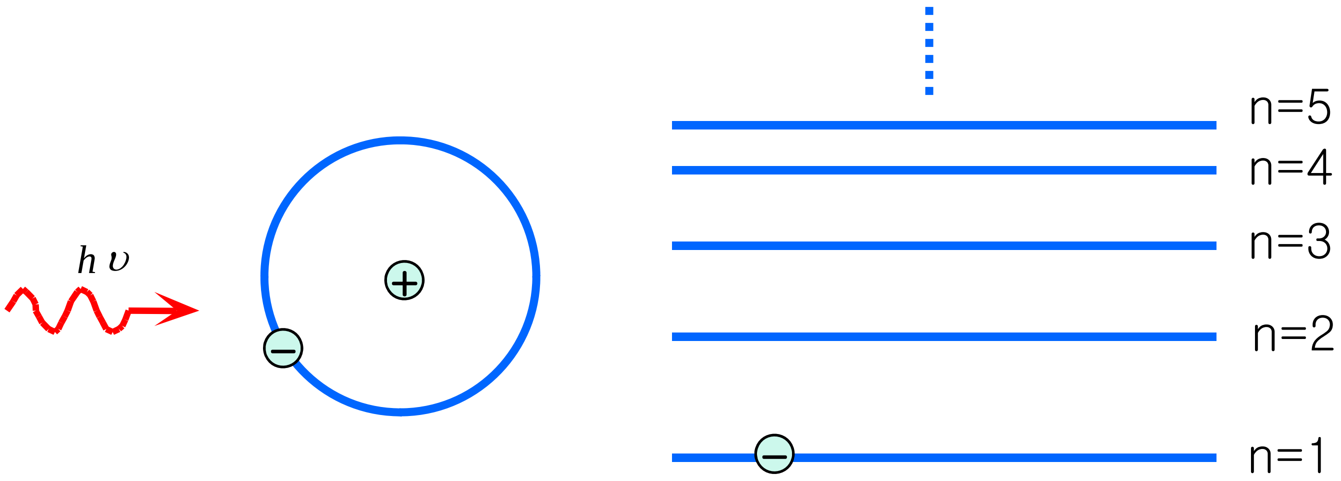
Laser Basics

What happens when light (or photon) interact with a matter?
Assume photon energy is compatible with energy transition levels.

Electron energy levels in an hydrogen atom

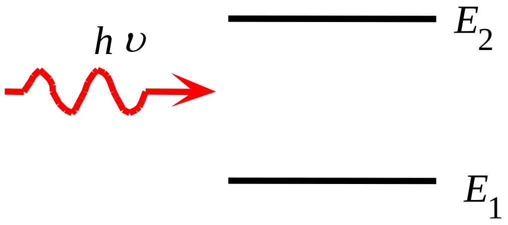


$$E_n = -\frac{13.6}{n^2}[\text{eV}]$$

Energy levels inside every matter are quantized; details depend on the matter

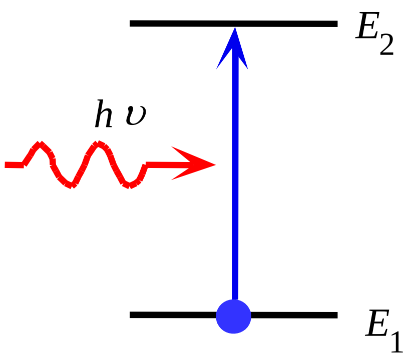
Laser Basics

Consider for simplicity only two energy levels: ground and excited states
Assume $h\nu = E_2 - E_1$

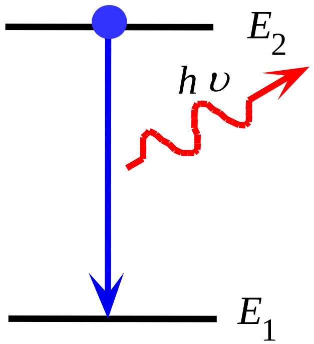


➔ Three interaction processes are possible

Absorption

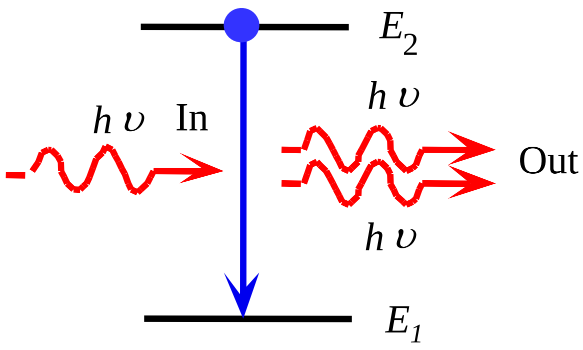


Spontaneous Emission



out photons are
“random”

Stimulated Emission

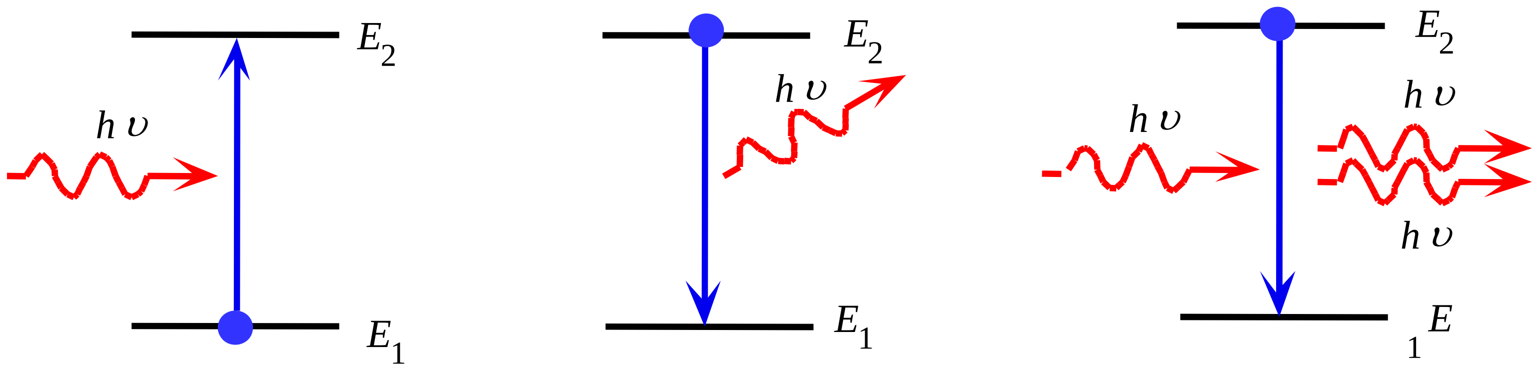


out photons are “identical”
to in photons: amplification

Laser Basics

Determine the rate for each process

Absorption | Spontaneous Emission | Stimulated Emission



$$R_{12} = B_{12} \cdot N_1 \cdot \rho \qquad R_{sp} = A_{21} \cdot N_2 \qquad R_{21} = B_{21} \cdot N_2 \cdot \rho$$

ρ : photon density

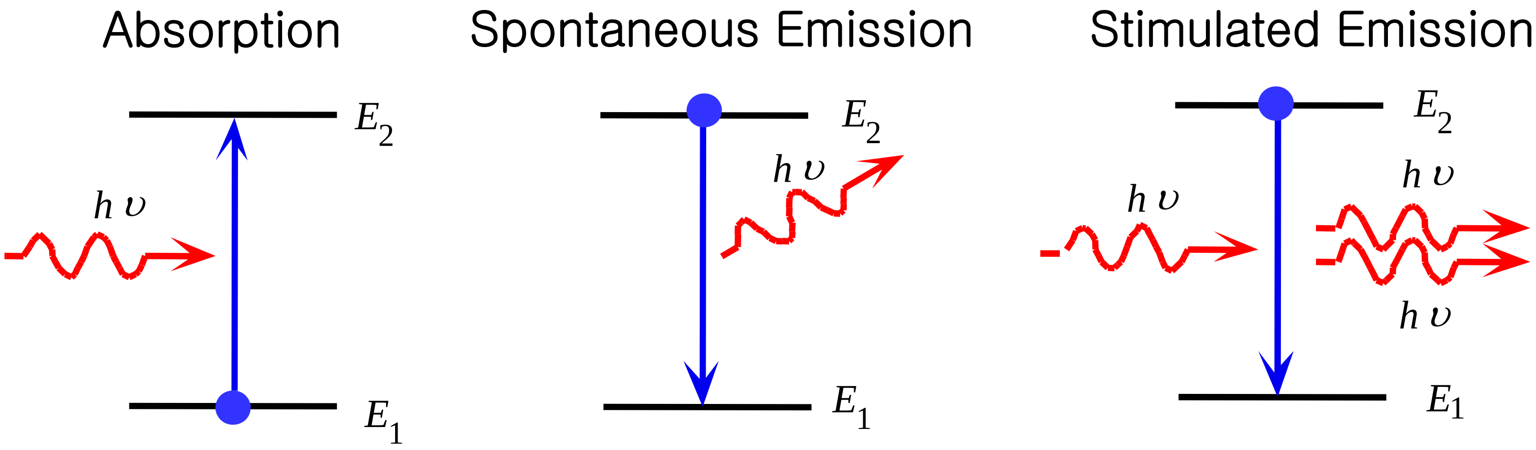
$N_{1,2}$: electron density at $E_{1,2}$

B_{12}, B_{sp}, B_{21} : constants

It can be shown

$$\frac{B_{21}}{B_{12}} = 1 \qquad \frac{A_{21}}{B_{12}} = \frac{8\pi h\upsilon^3}{c^3}$$

Laser Basics


Absorption

Spontaneous Emission

Stimulated Emission

$$R_{12} = B_{12} \cdot N_1 \cdot \rho \qquad R_{sp} = A_{21} \cdot N_2 \qquad R_{21} = B_{21} \cdot N_2 \cdot \rho$$

$$\frac{B_{21}}{B_{12}} = 1$$

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\upsilon^3}{c^3}$$

Interpretations:

–Absorption and simulated emission have the same coefficeint

➔ The only difference is N_1 and N_2

–Spontaneous emission and stimulated emission are intrinsically related

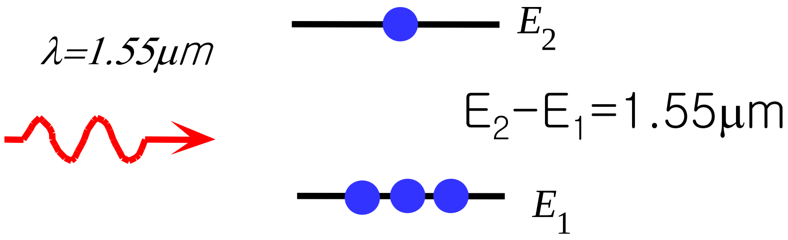
➔ Spontaneous emission is simulated emission due to *vacuum fluctuation*

Laser Basics

Which process is dominant at equalibrium?

Stimulated emission vs. absorption

$$\frac{R_{21}}{R_{12}} = \frac{B_{21}N_2\rho}{B_{12}N_1\rho} = \frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right) << 1$$



$$\frac{R_{21}}{R_{12}} = \frac{N_2}{N_1} = \exp\left(-\frac{0.8eV}{0.04eV}\right) \sim 2\times10^{-9}$$

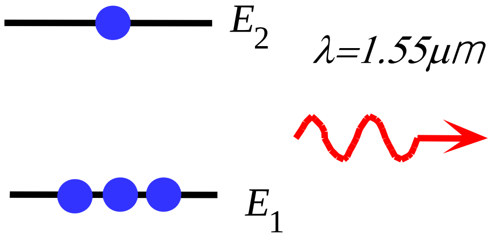
Virtually no possibility for stimulated emission at equalibrium

Laser Basics

Which process is dominant at equalibrium?

Stimulated emission vs. spontaneous emission

$$\frac{R_{21}}{R_{sp}} = \frac{B_{21}N_2\rho}{A_{21}N_2} = \frac{B_{21}}{A_{21}}\rho = \frac{c^3}{8\pi h\upsilon^3}\frac{8\pi h\upsilon^3}{c^3\left[\exp\left(\frac{h\upsilon}{kT}\right)-1\right]} = \frac{1}{\exp\left(\frac{E_2-E_1}{kT}\right)-1}$$

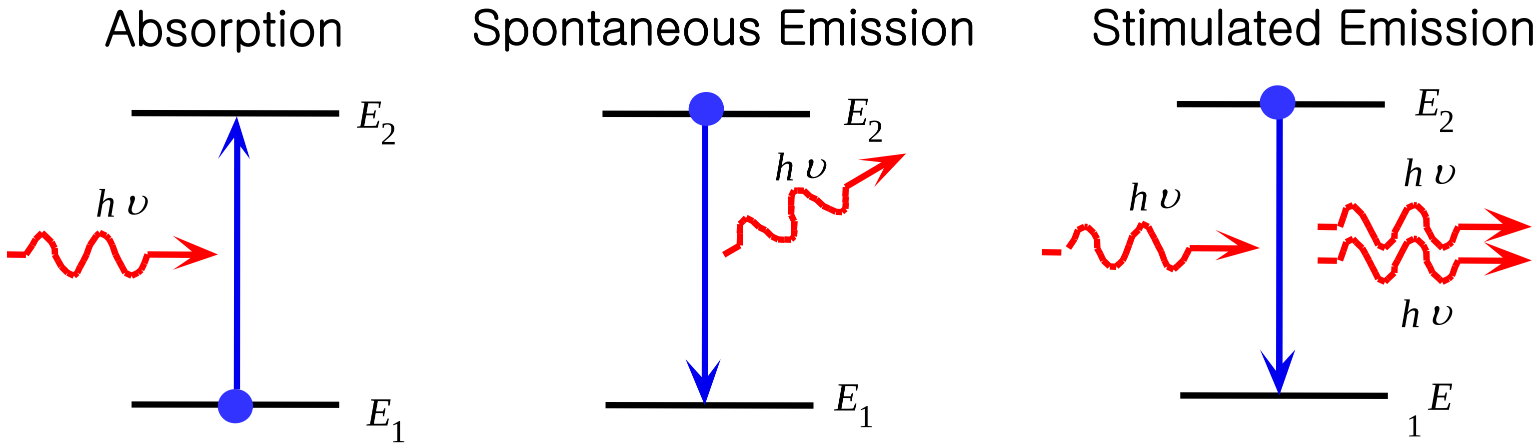


$$\frac{R_{21}}{R_{sp}} = \frac{1}{\exp\left(\frac{0.8eV}{0.04eV}\right)-1} = \frac{1}{4.84\times10^8-1} \sim 2\times10^{-9}$$

Virtually all photon emission is due to spontaneous emission at equalibrium

Laser Basics

How can we induce stimulated emission?



$$R_{12} = B_{12} \cdot N_1 \cdot \rho \qquad R_{sp} = A_{21} \cdot N_2 \qquad R_{21} = B_{21} \cdot N_2 \cdot \rho$$

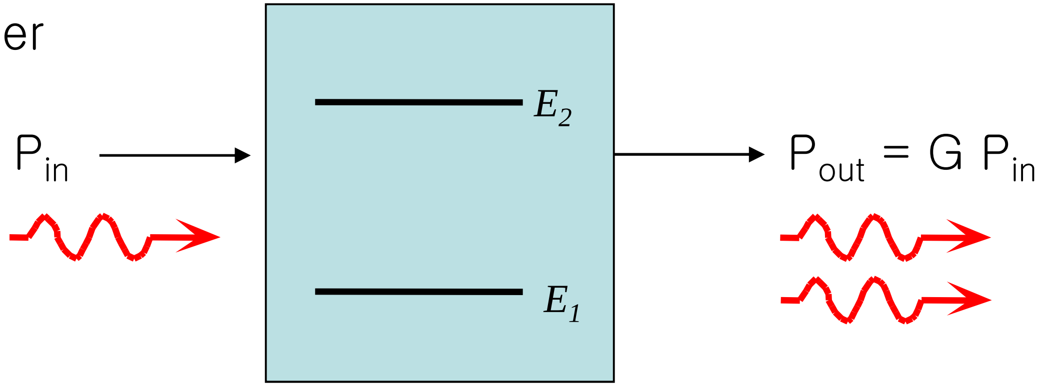
Make N_2 larger than N_1: Break equalibrium and “pump” carriers into E_2

$N_2 = N_1$: transparent

$N_2 > N_1$: population inversion

Laser Basics

Optical Amplifier



Which process is useful for optical amplifier?

How can we make stimulated emission dominant over absorption?

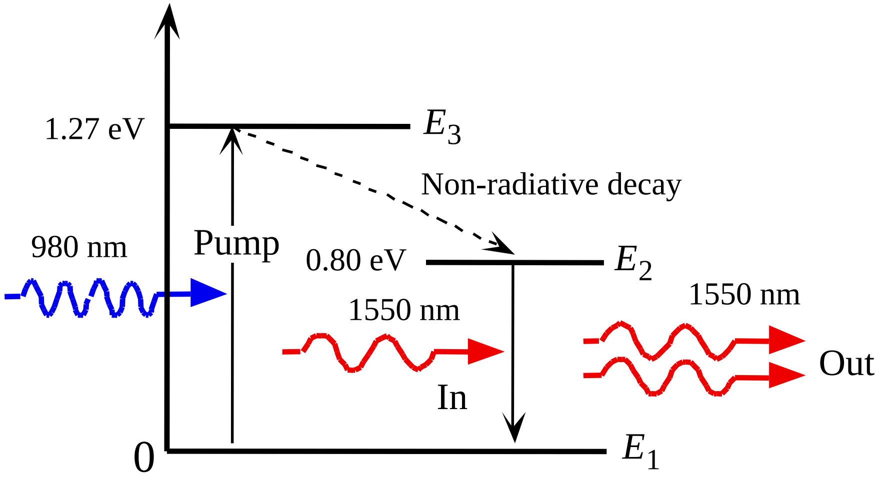
Pump carriers into N_2 so that $N_2 > N_1$

Optical Pumping and Electrical Pumping

Laser Basics

Optical Pumping: Consider Er

Energy levels in Er



- Pump light is absorbed at E_3 generating carriers

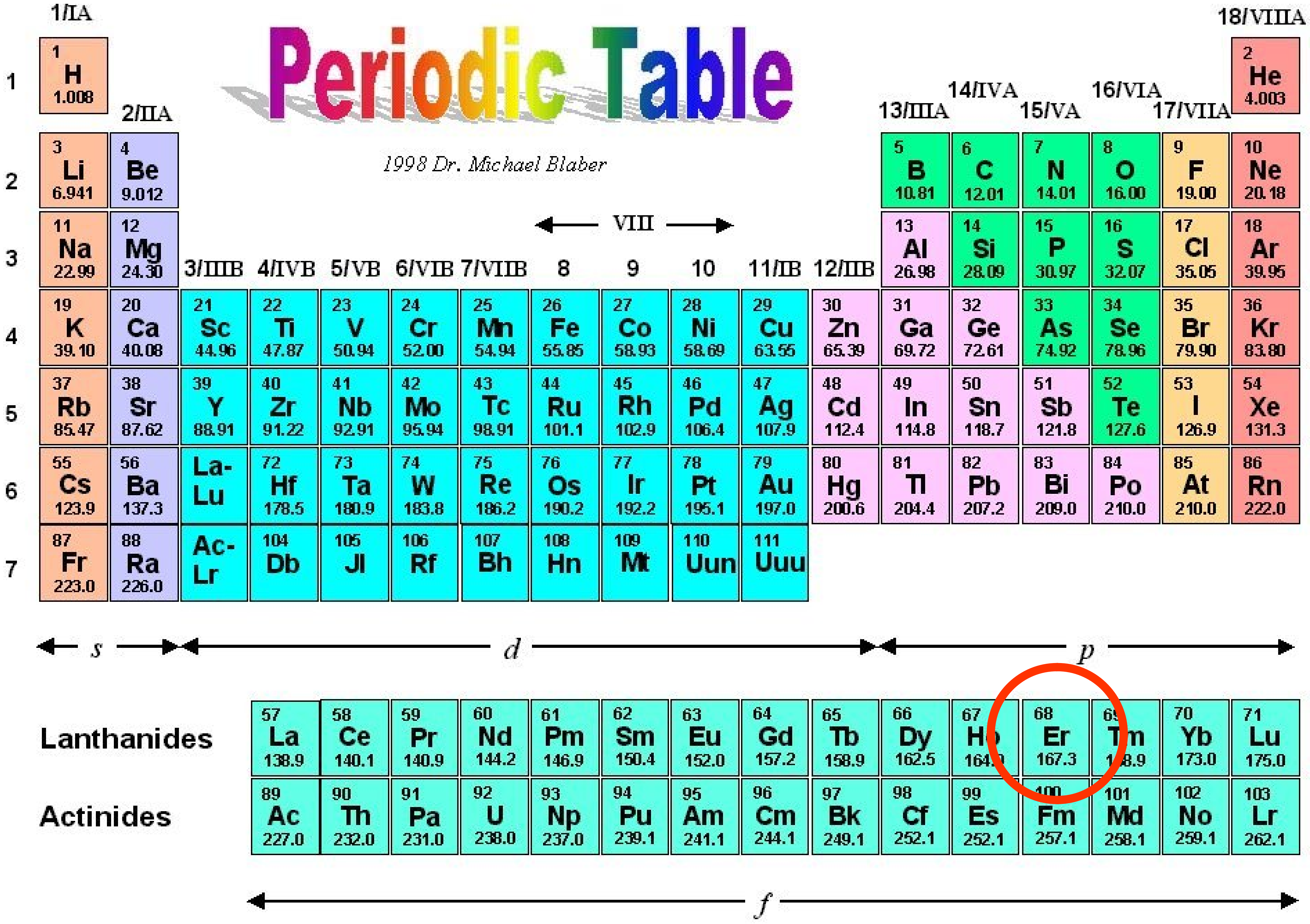
- Carriers at E_3 rapidly transfer to E_2

➔ N_2 builds up

- When $N_2 > N_1$ (population inversion), stimulated emission > absorption for 1550nm light

Er can be easily added to core of Silica fiber

➔ EDF (Er-Doped Fiber)



Periodic Table

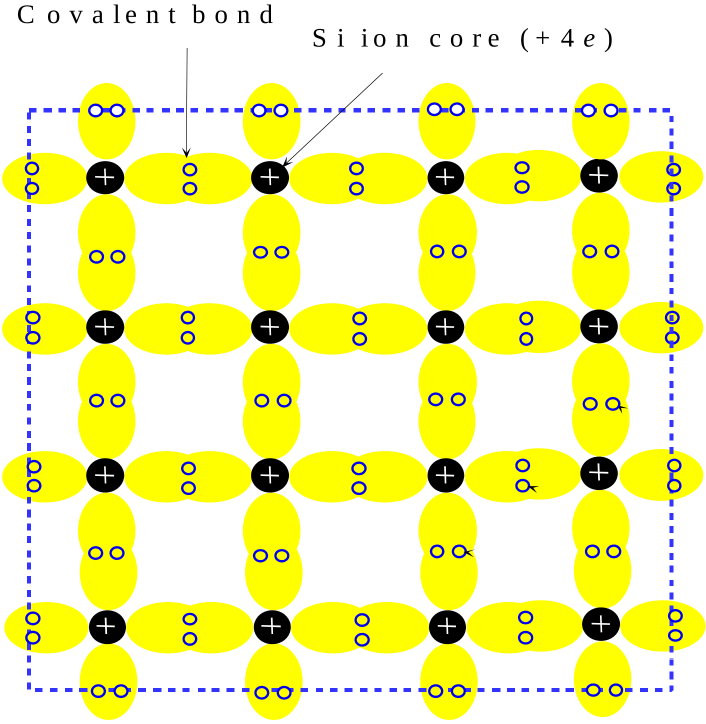
1998 Dr. Michael Blaber

	1/IA	2/IIA	3/IIIB	4/IVB	5/VB	6/VIB	7/VIIB	8	9	10	11/IB	12/IIB	13/IIIA	14/IVA	15/VA	16/VIA	17/VIIA	18/VIIIA
1	1 **H** 1.008																	2 **He** 4.003
2	3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
3	11 **Na** 22.99	12 **Mg** 24.30											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.05	18 **Ar** 39.95
4	19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
5	37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** 98.91	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
6	55 **Cs** 123.9	56 **Ba** 137.3	**La-Lu**	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.8	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** 210.0	85 **At** 210.0	86 **Rn** 222.0
7	87 **Fr** 223.0	88 **Ra** 226.0	**Ac-Lr**	104 **Db**	105 **Jl**	106 **Rf**	107 **Bh**	108 **Hn**	109 **Mt**	110 **Uun**	111 **Uuu**							

Lanthanides	57 **La** 138.9	58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** 146.9	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.2	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 1[illegible]8.9	70 **Yb** 173.0	71 **Lu** 175.0
Actinides	89 **Ac** 227.0	90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** 237.0	94 **Pu** 239.1	95 **Am** 241.1	96 **Cm** 244.1	97 **Bk** 249.1	98 **Cf** 252.1	99 **Es** 252.1	100 **Fm** 257.1	101 **Md** 258.1	102 **No** 259.1	103 **Lr** 262.1

Laser Basics

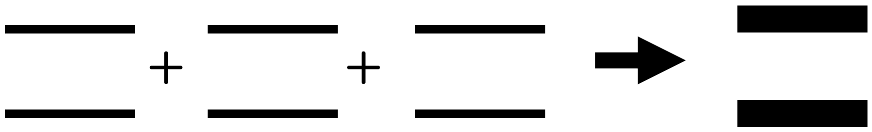
Si lattice structure



Electron energy levels in semiconductors

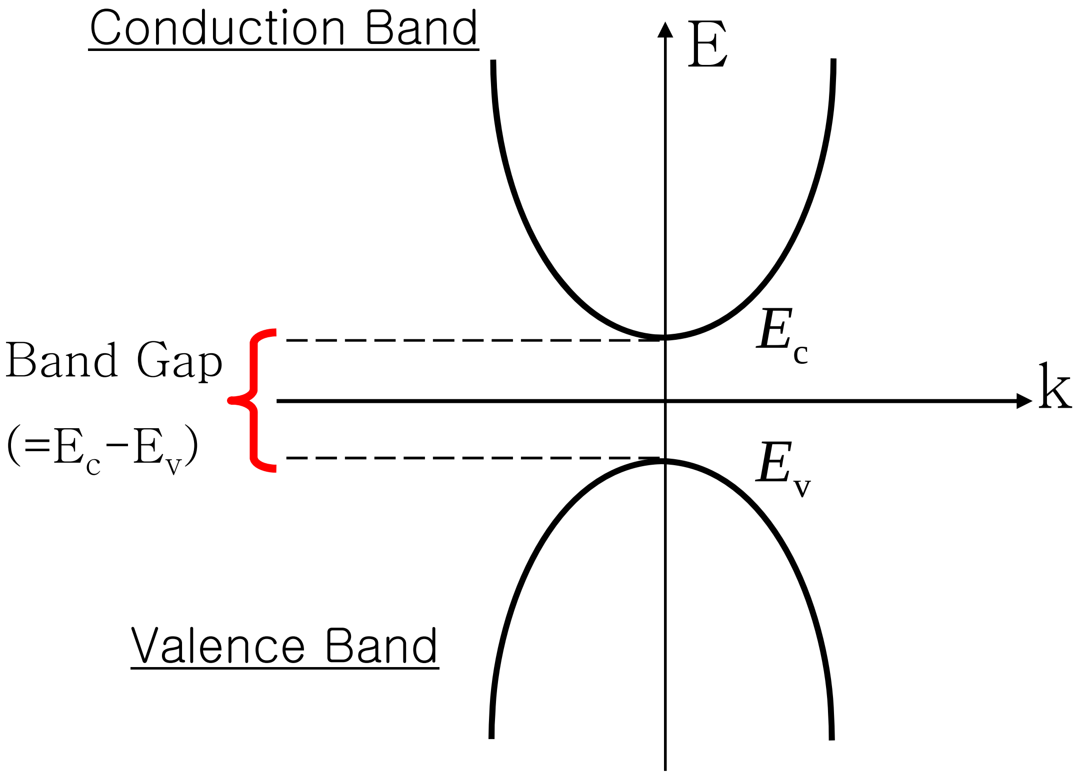
Electrons in each Si atom have discrete energy levels.

But in Si crystal, energy bands are formed.



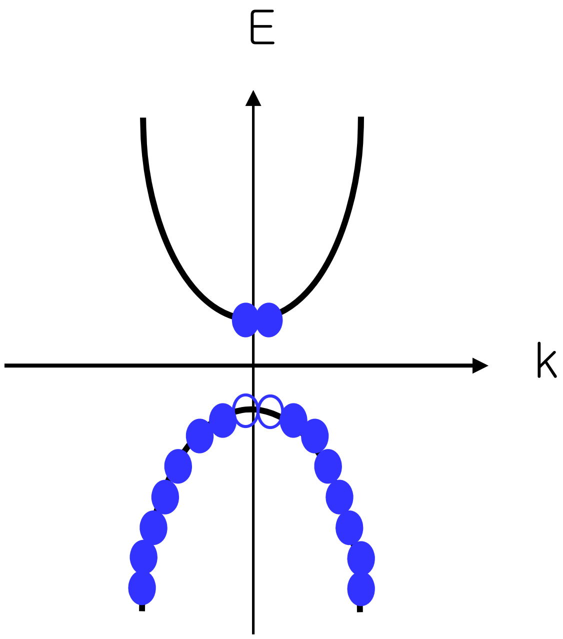
Laser Basics

Band diagram

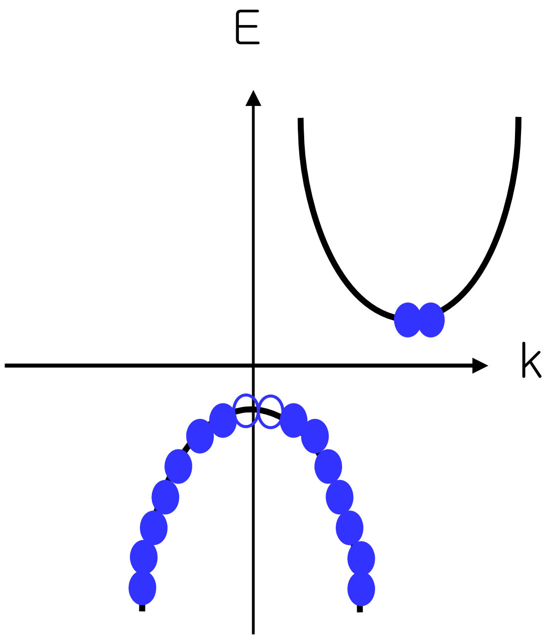


Laser Basics

Direct semiconductor



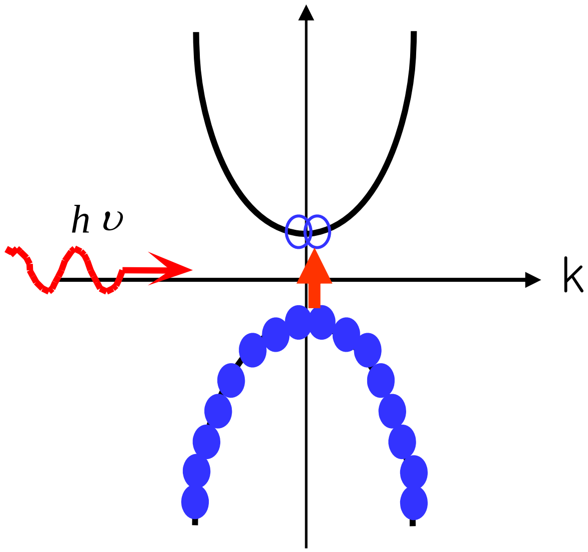
Indirect Semiconductor



Momentum conservation not possible by photon emission
=> No emission (Examaple: Si)

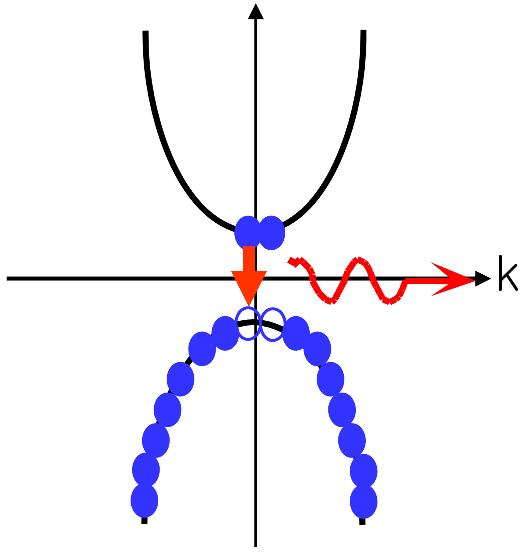
Laser Basics

Absorption



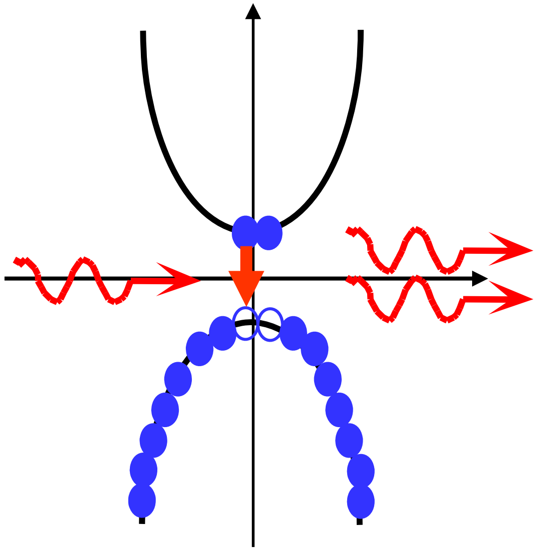
$$R_{12}(h\nu) = B_{12} \cdot N_1(E_1) \cdot P_2(E_2) \cdot \rho(h\nu)$$

Spontaneous Emission



$$R_{sp}(h\nu) = A_{21} \cdot N_2(E_2) \cdot P_1(E_1)$$

Stimulated Emission

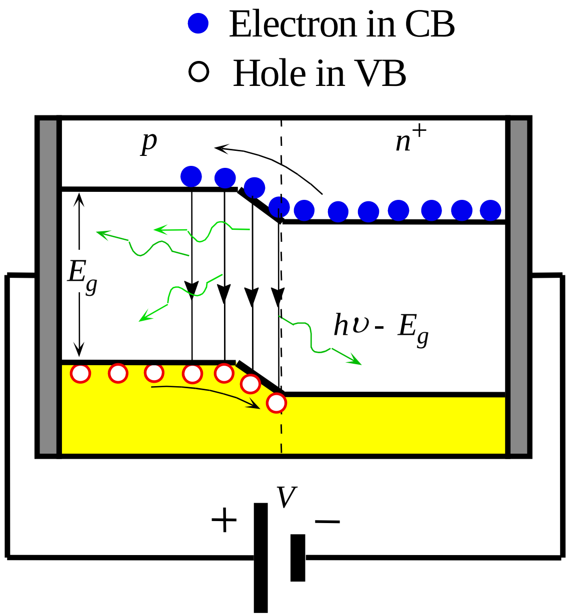


$$R_{21}(h\nu) = B_{21} \cdot N_2(E_2) \cdot P_1(E_1) \cdot \rho(h\nu)$$

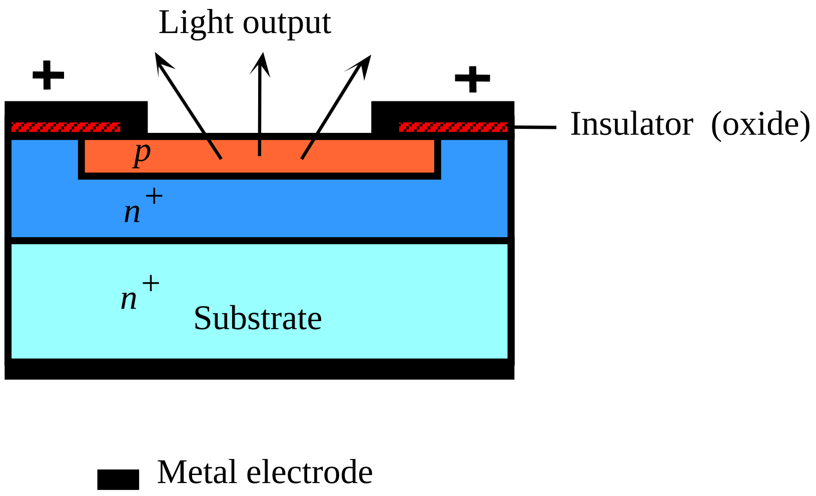
For population inversion, $\dfrac{N_2 \cdot P_1}{N_1 \cdot P_2} > 1$ Electron and hole injection needed.

Laser Basics

How to pump electrons and holes into a semiconductor? Forward-bias PN junctio



Light emitting diode (LED)



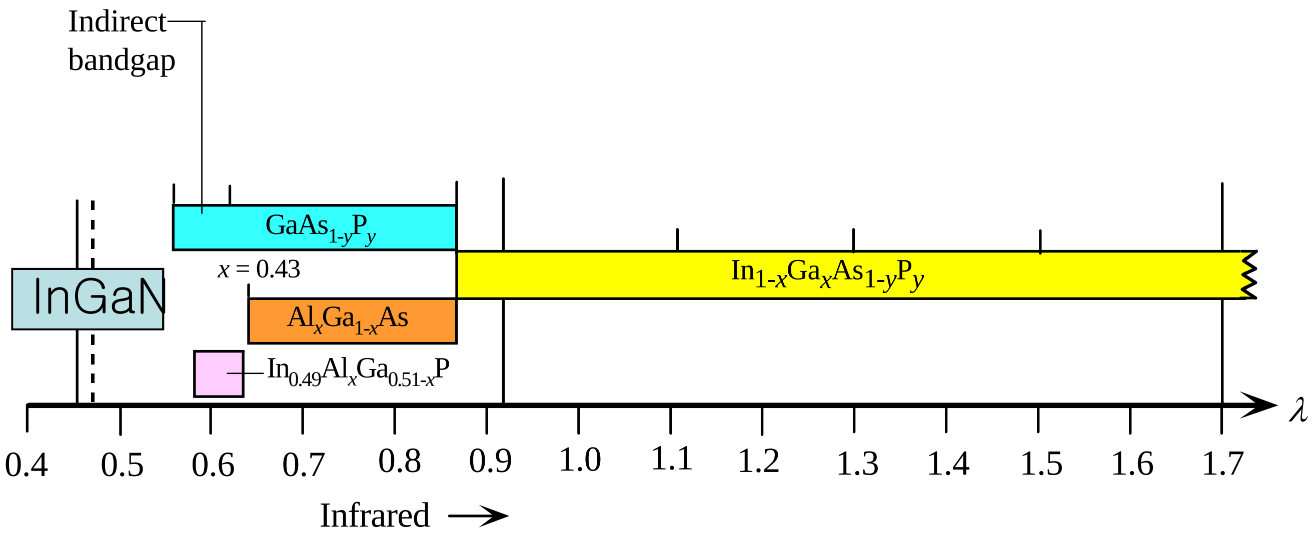
Light emission by spontaneous emission

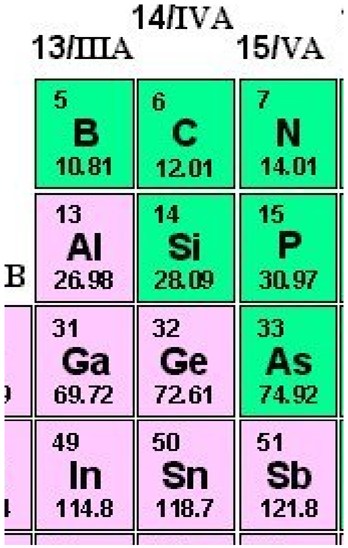
Does any semiconductor emit light?

What determines the color of LED?

Laser Basics

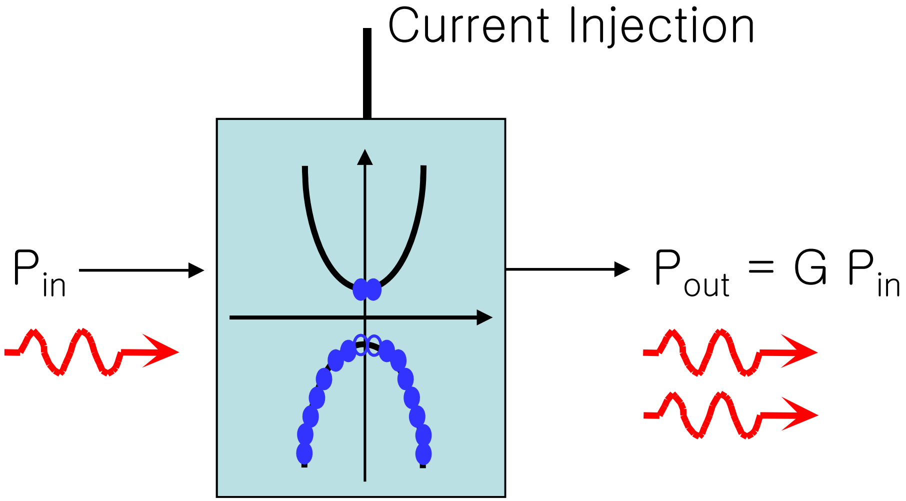
Bandgap energies for major LED materials: III-V compound semiconductor

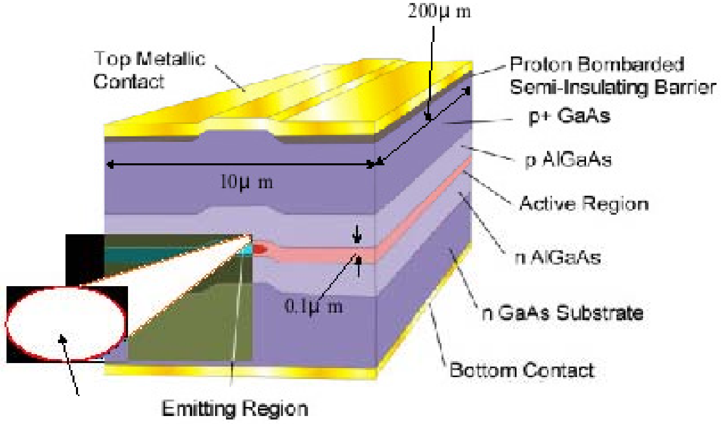


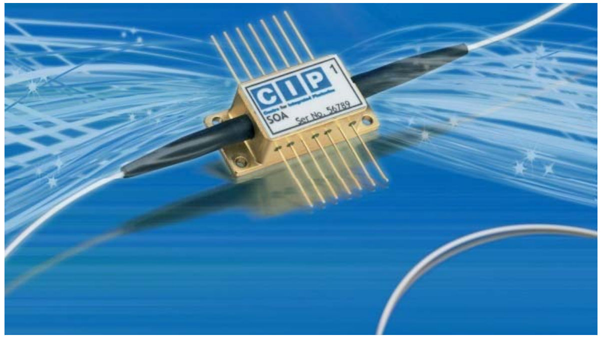


Laser Basics

Current injection into PN Junction can be used for SOA
(Semiconductor Optical Amplifier)

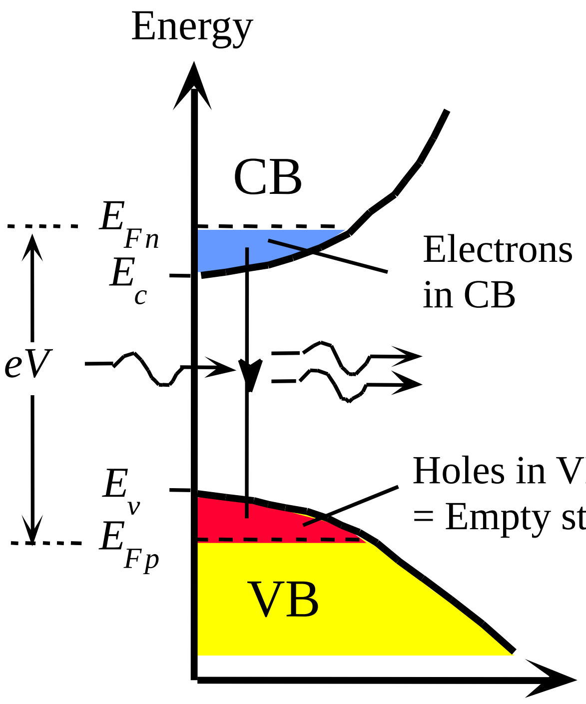


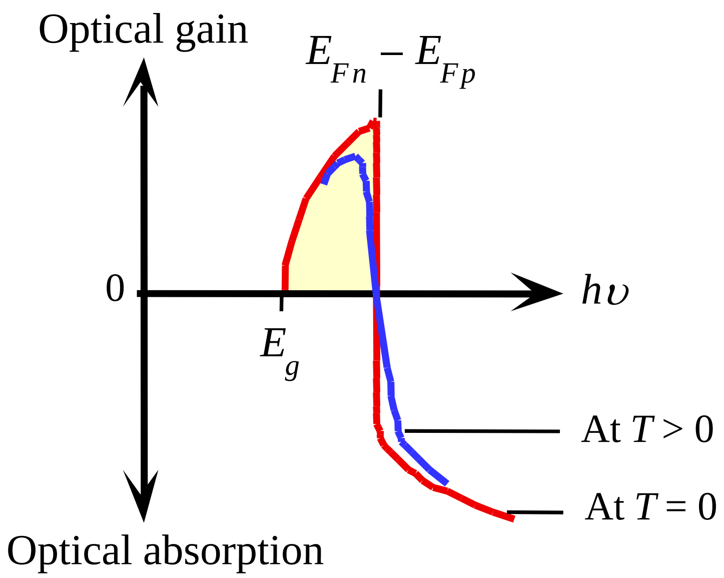




Laser Basics

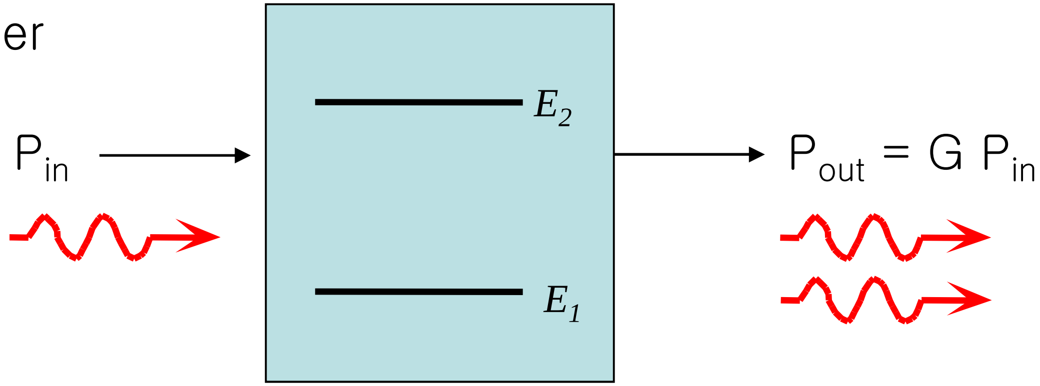
Gain spectrum for SOA





Laser Basics

Optical Amplifier



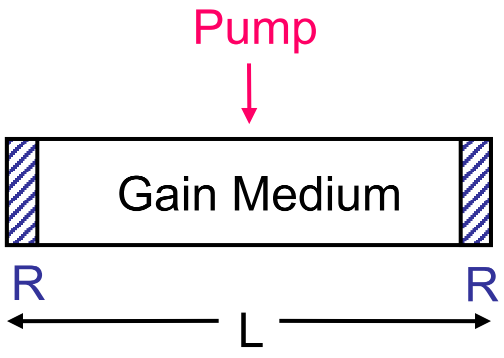
Light source based on stimulated emission?

- Use photons produced by spontaneous emission as initial seeds
- Recycle output photons as seeds for further stimulated emission
- Use mirror for recycling output photons

➔ LASER: Light Amplification by Stimulated Emission Radiation

Laser Basics

LASER: Optical Amplifier + Mirror

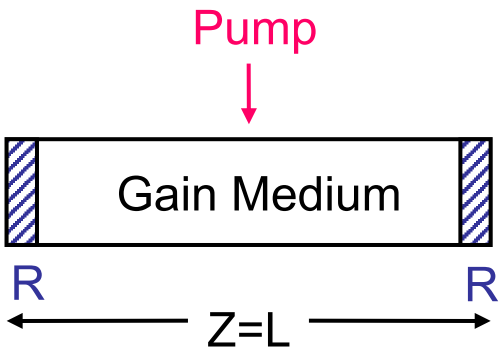


Optical property of gain medium: n, g

$$k = nk_0 + j\frac{g}{2}$$

g depends on λ and the amount of pumping

Laser Basics



$$k = nk_0 + j\frac{g}{2}$$

Assume there is an initial photon moving in z−direction inside gain medium.

What is the condition that this photon is sustained?

➔ No loss after one round trip.

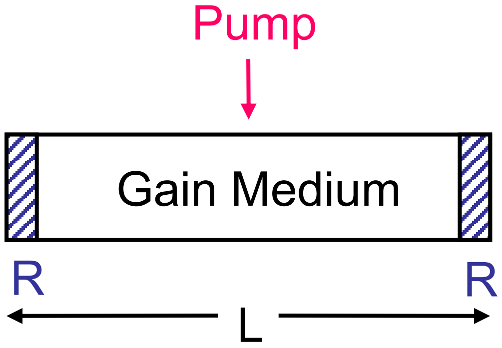
$$E_0 \cdot e^{-jkL} \cdot r \cdot e^{-jkL} \cdot r = E_0$$

$$r^2 \cdot e^{-j2kL} = 1 \qquad e^{-j2kL} = \frac{1}{r^2} = \frac{1}{R}$$

$$e^{-j2nk_0L} e^{gL} = \frac{1}{R} \qquad \therefore\ e^{gL} = \frac{1}{R} \text{ and } e^{-j2nk_0L} = 1$$

Laser Basics

$$e^{gL} = \frac{1}{R} \quad \text{and} \quad e^{-j2nk_0L} = 1$$



From $e^{gL} = \frac{1}{R}, \quad g_{\text{th}} = \frac{1}{L}\ln\frac{1}{R}$

==> Sufficient gain to compensate mirror loss

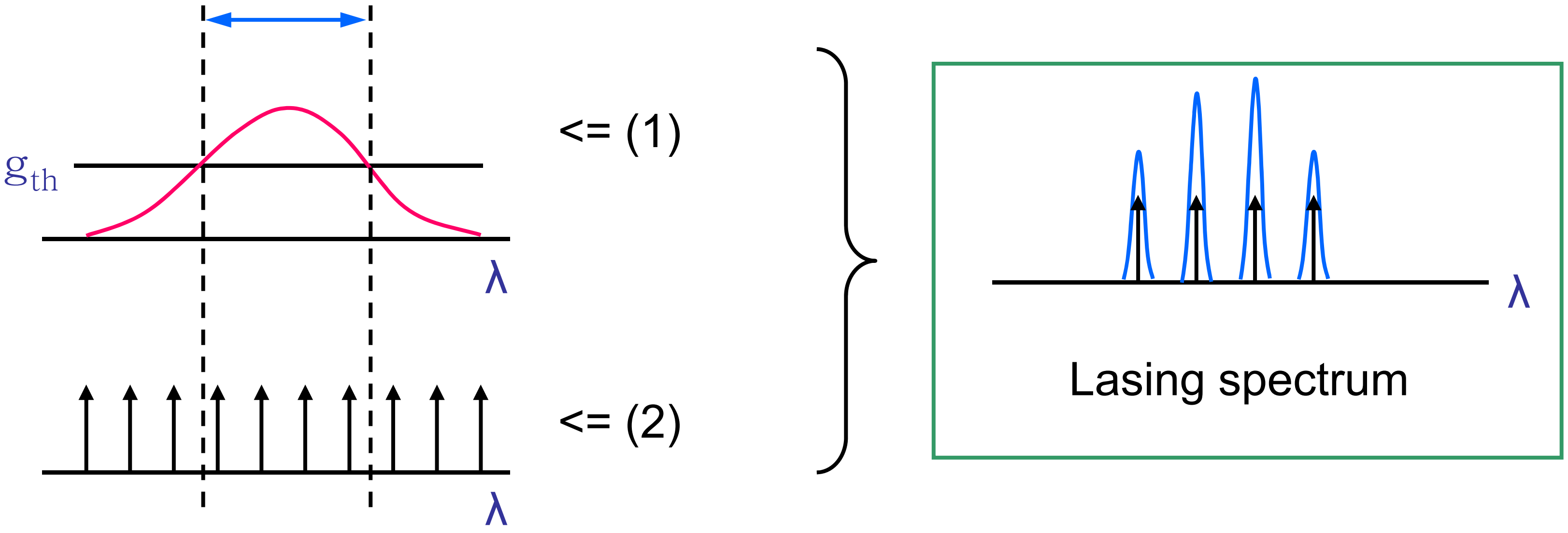
From $e^{-j2nk_0L} = 1, \; 2nk_0L = 2m\pi \quad \Rightarrow \frac{\lambda}{n} = \frac{2L}{m}$ or $L = m\frac{\lambda}{2n}$

cavity length should be multiples of half wavelength

➔ Identical photons are continuously produced at two outputs

Laser Basics

Two conditions for lasing: (1) $g_{th} = \frac{1}{L} \ln \frac{1}{R}$ and (2) $\frac{\lambda}{n} = \frac{2L}{m}$



Lasing peaks (modes) has non-zero linewidth

Laser Basics

Various LASERs

Any optical gain material with mirrors can form a laser

First Laser:

Ruby doped with Cr ($Al_2O_3:Cr^{3+}$)

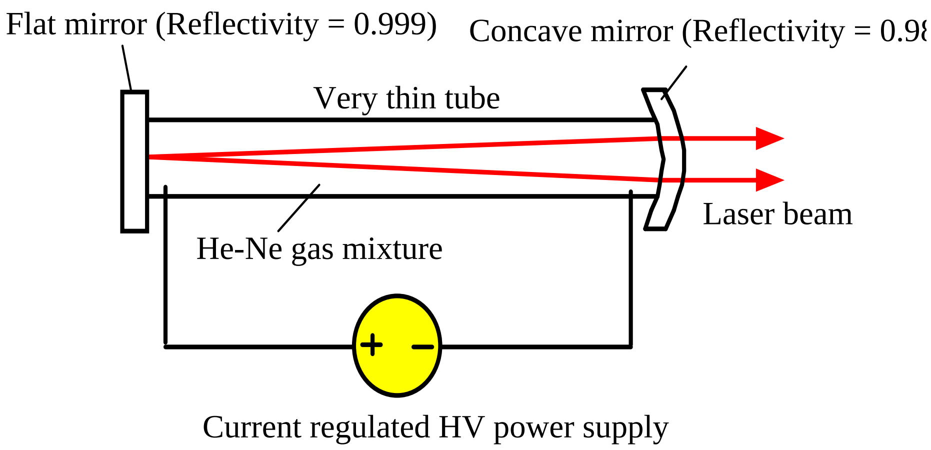
Maiman with first laser in 1960.

Optical Gain: Cr in Al_2O_3

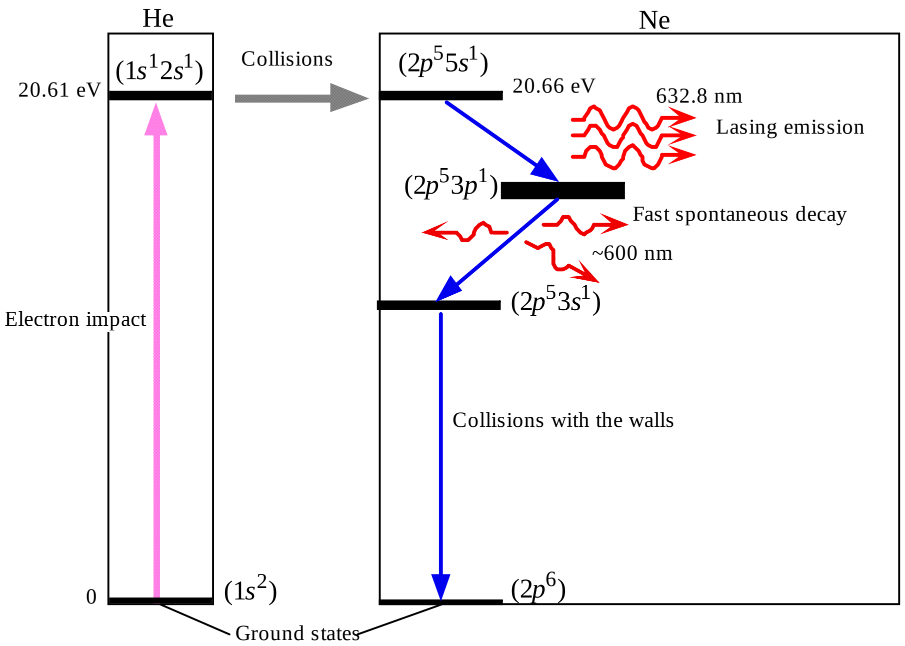
Pump: Flash Lamp

Laser Basics

Gas Laser (HeNe)

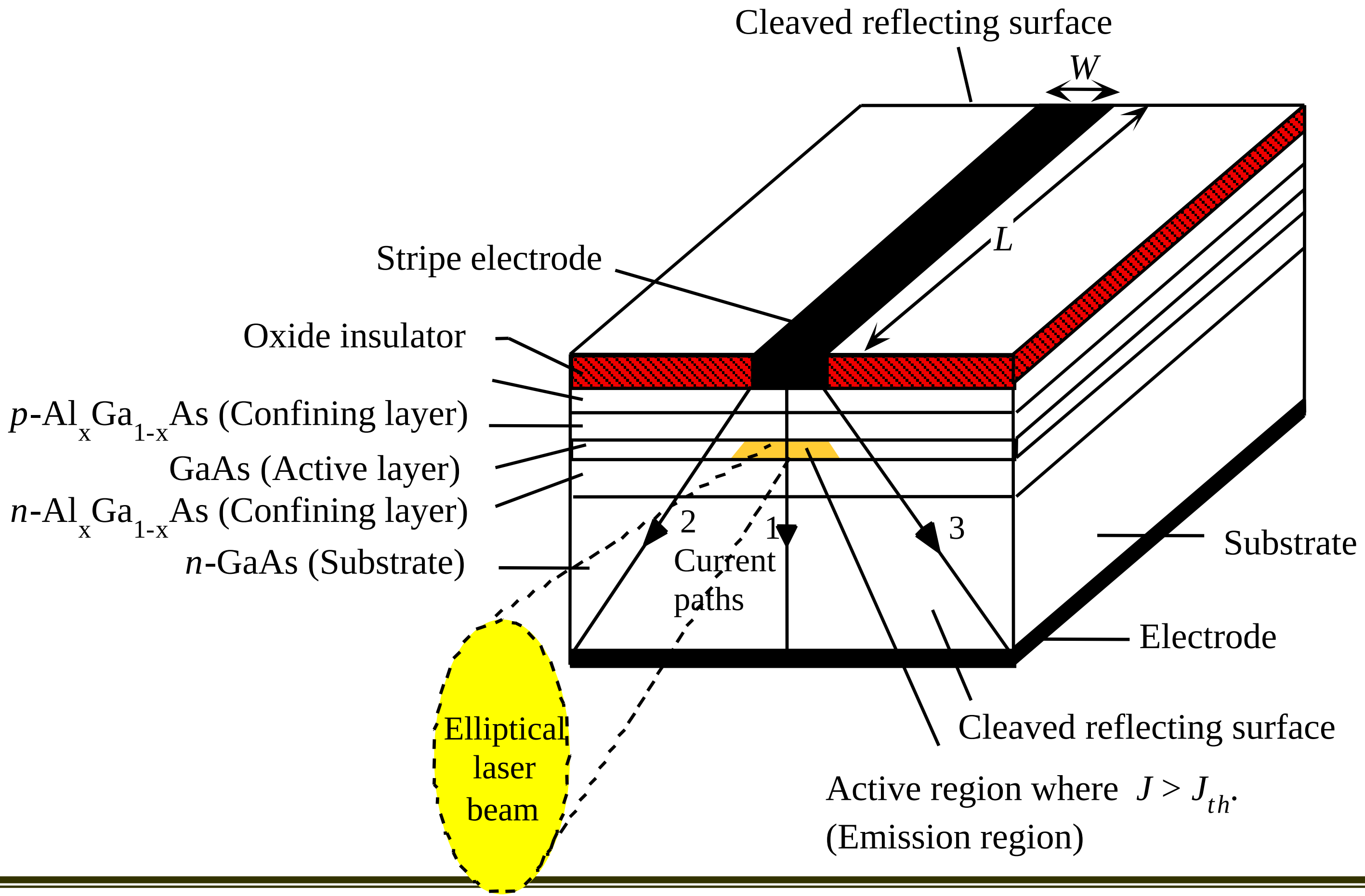


A schematic illustration of the He-Ne laser



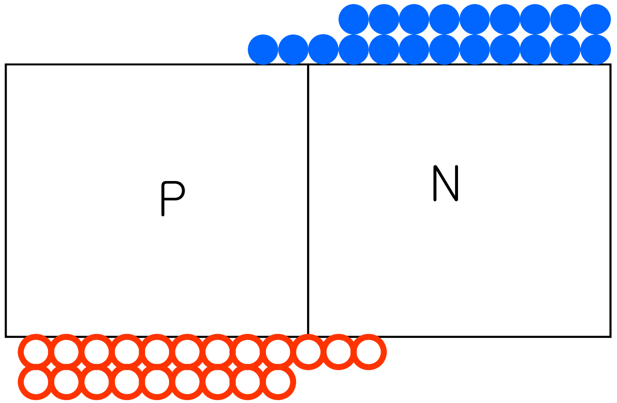
Laser Basics

Semiconductor Laser Structure: PN Junction + Mirror (Cleaved Facets)

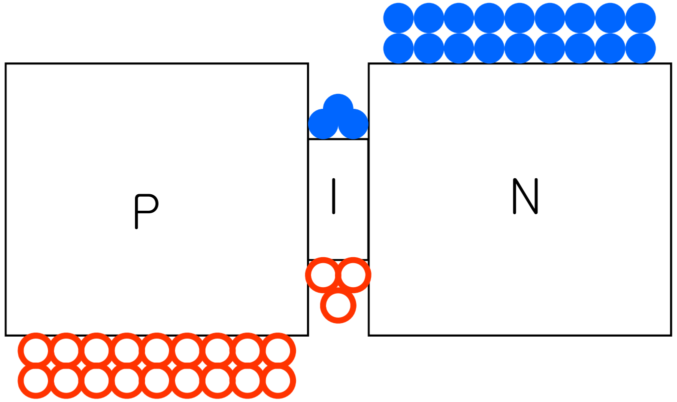


Laser Basics

Efficient carrier confinement: PIN structure with large E_g for P, N regions



Injected carriers are spread-out
=> smaller density

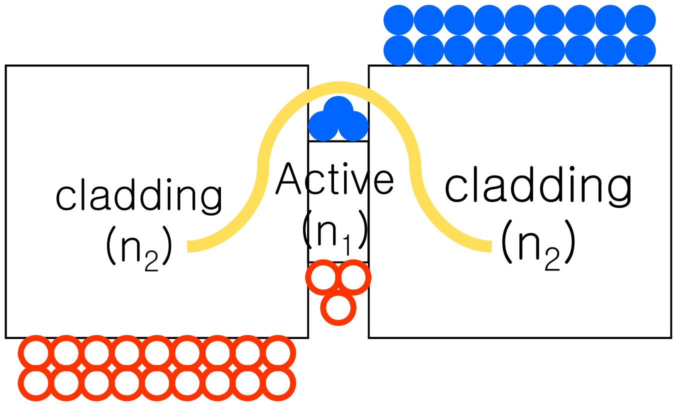


Double heterojunction: Confinement of Injected carriers
=> larger density

For population inversion, $\frac{N_2 \cdot P_1}{N_1 \cdot P_2} > 1$

Laser Basics

Efficient photon confinement: PIN structure with smaller n for P, N regions



Smaller E_g material has larger n (n_1>n_2)

➔ Dielectric waveguide!

=> More photons interacting with injected electrons and holes in the active region

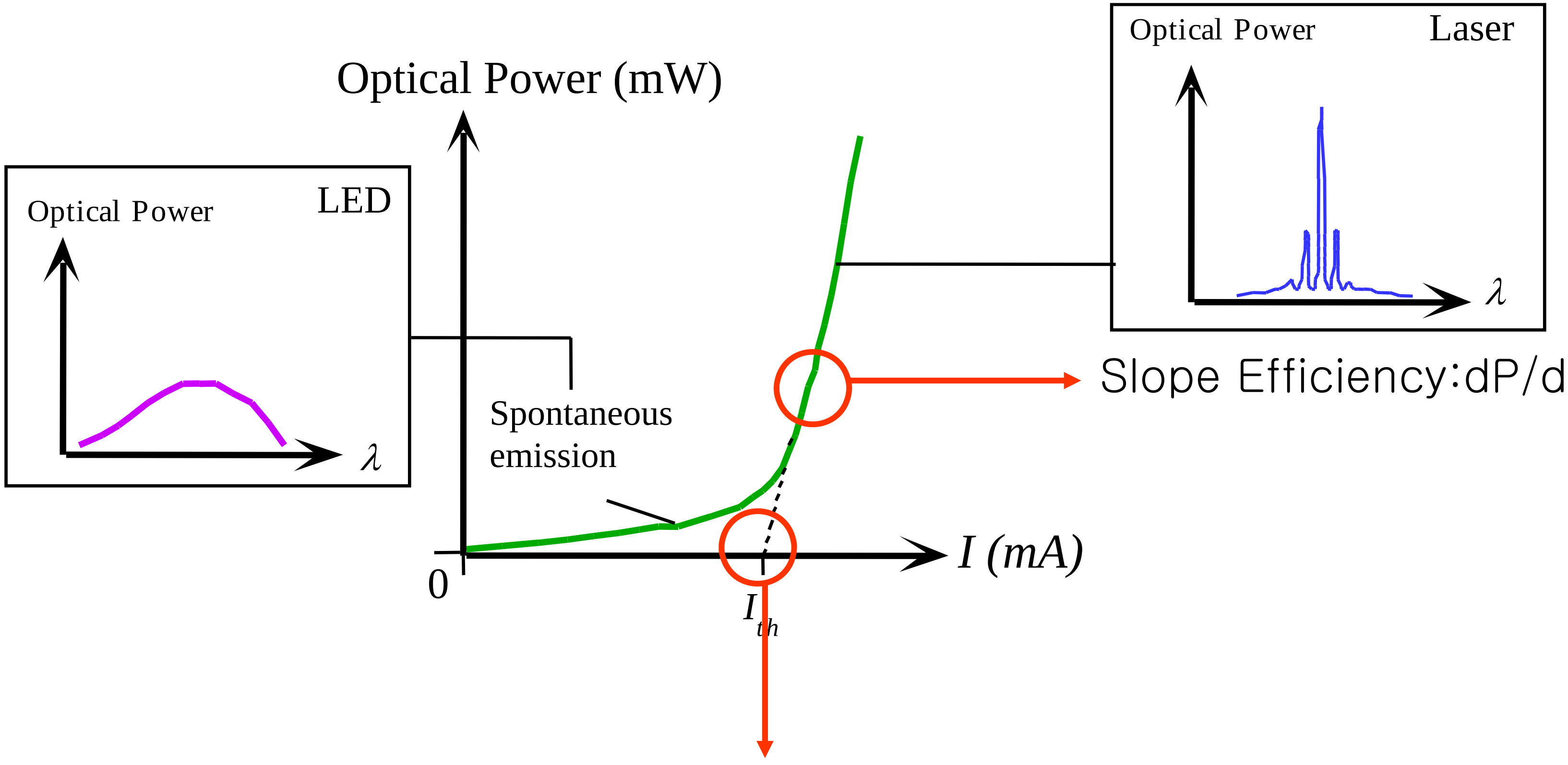
➔ larger Γ

With Γ<1,

$$g_{\mathrm{th}} = \frac{1}{L}\ln\frac{1}{R} = \alpha_{\mathrm{m}}\,(\text{mirror loss}) \quad \Rightarrow \Gamma g_{\mathrm{th}} = \frac{1}{L}\ln\frac{1}{R} = \alpha_{\mathrm{m}}$$

$$\frac{\lambda}{n} = \frac{2L}{m} \quad ==> \frac{\lambda}{n_{\mathrm{eff}}} = \frac{2L}{m}; \quad n_{\mathrm{eff}} = \frac{\beta}{k_0}$$

Laser Basics



Slope Efficiency:dP/dI

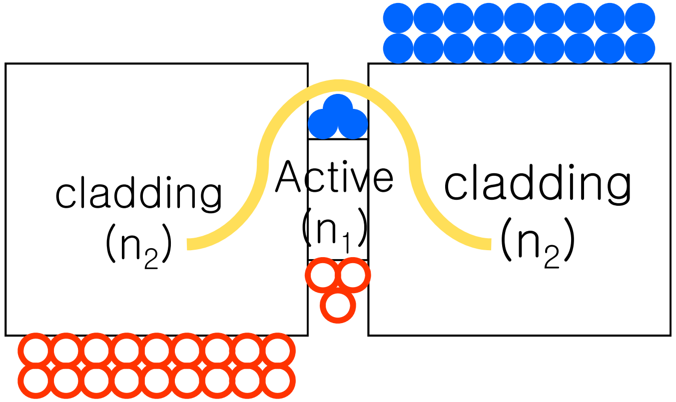
Threshold current: I_{th}

Laser Basics

Two conditions for lasing: (1) $\Gamma g_{\text{th}} = \alpha_{\text{m}} + \alpha_{\text{int}}$ and (2) $\dfrac{\lambda}{n_{\text{eff}}} = \dfrac{2L}{m}$

There can be several lasing modes: several λ's satisfying above conditions.

– Multiple values for n_{eff} if there are multiple waveguide modes



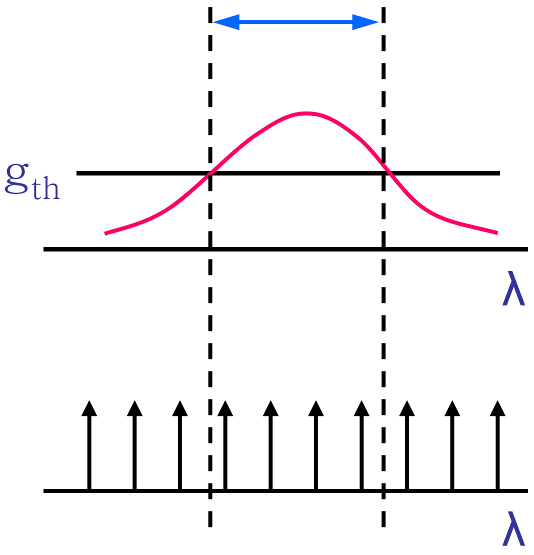
Different modes have different n_{eff}

➔ Design for single guided mode.

TE, TM modes?

Laser Basics

- Multiple cavity modes



$$\frac{\lambda}{n_{\text{eff}}} = \frac{2L}{m} \text{ for } g(\lambda) > g_{\text{th}}$$

Mode separation

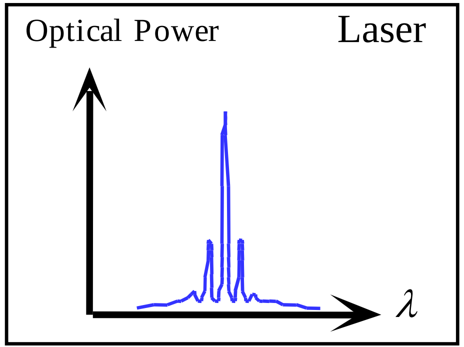
From $e^{-j2nk_0L} = 1 \Rightarrow 2n_{\text{eff}}k_0L = 2m\pi$

$\Delta(n_{\text{eff}}k_0)L = \pi$ => $\Delta(k_0) = \dfrac{\pi}{n_{\text{eff}}L}$

$$\lambda = \frac{2\pi}{k_0} \quad \therefore \Delta\lambda = \frac{\delta\lambda}{\delta k_0}\Delta k_0 = -\frac{2\pi}{k_0^{\ 2}}\Delta k_0 = -\frac{2\pi}{\left(\frac{2\pi}{\lambda}\right)^2}\Delta k_0 = -\frac{\lambda^2}{2n_{eff}L}$$

With typical semiconductor lasers with cleaved facets, Δλ is less than gain bandwidth => multi lasing modes

➔ Fabry-Perot laser



Laser Basics

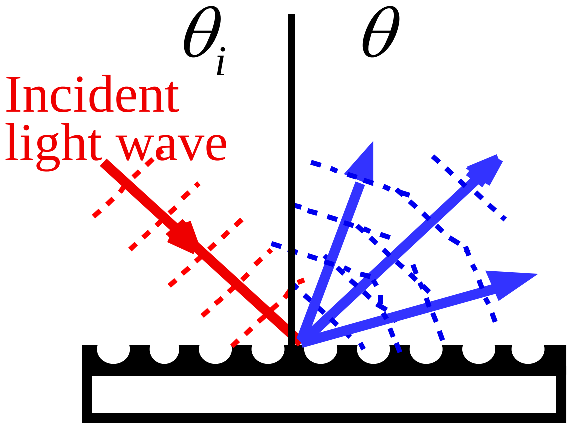
Problems with multi-mode laser?

➔ Modal dispersion even with single-mode fiber

How to make single-mode laser?

Use another type of mirror: Grating

Remember



$$d\left(\sin\theta - \sin\theta_i\right) = m \cdot \lambda$$

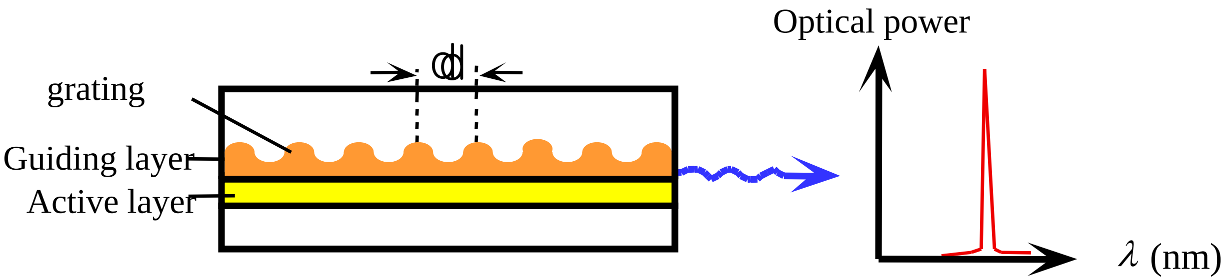
For mirror, $\theta_i = 90^\circ$ and $\theta = -90^\circ$,

$$d = m\frac{\lambda}{2}$$

Laser Basics

How to implement diffraction grating within semiconductor laser?

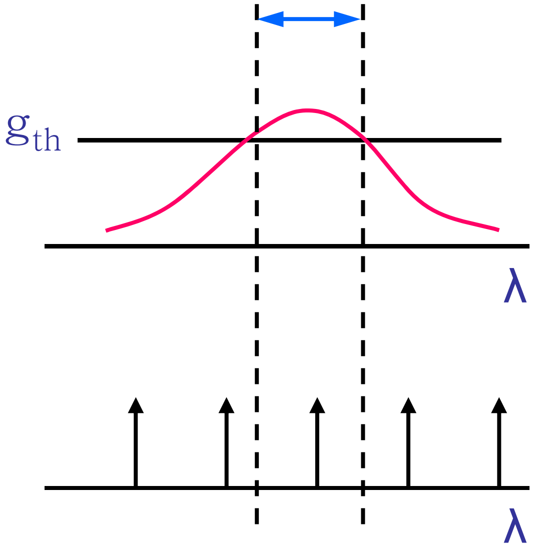
Distributed Feedback (DFB) Laser



$$d = m\frac{\lambda}{2n_{\mathrm{eff}}} \quad \text{(typically m=1)}$$

Laser Basics

Another approach: Make L very small so that
$\Delta\lambda$ larger than gain bandwidth



gain bandwidth: in the order of 10nm

$\lambda:\ 1.5\mu$m

$n_{eff}:\ 3.5$

$L \sim 30\mu$m;

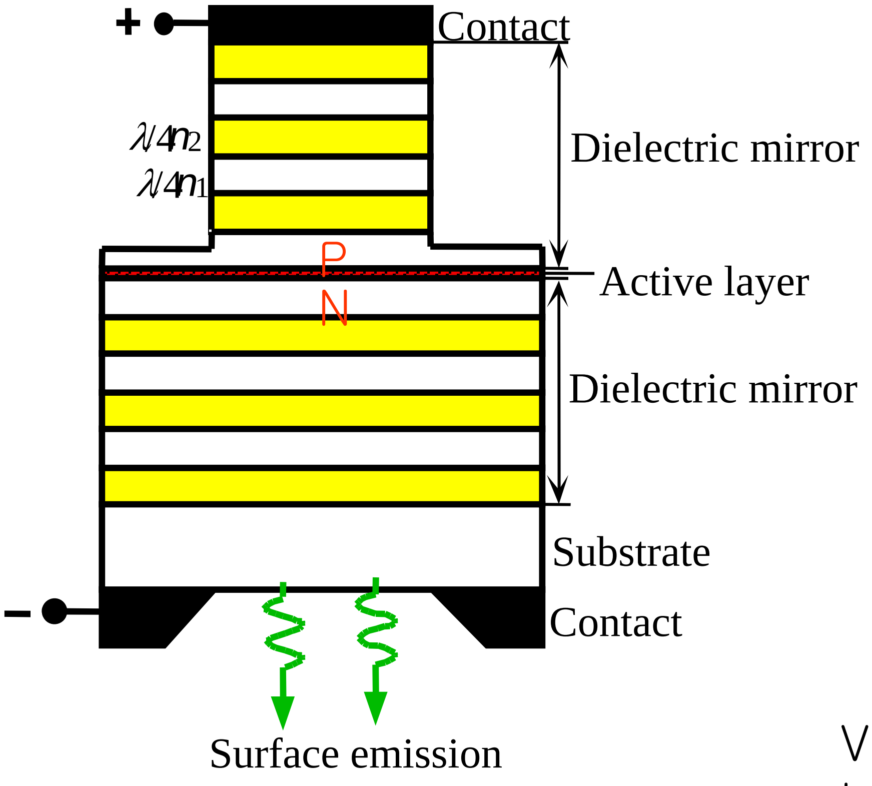
Not easy to fabricate by cleaving

$$\left|\Delta\lambda\right| = \frac{\lambda^2}{2n_{eff}L}$$

From $\alpha_m = \frac{1}{L}\ln\frac{1}{R}$, too much mirror loss

Laser Basics

Solution: Very short cavity vertical lasers with very high reflectivity mirrors
(VCSEL: Vertical Cavity Surface Emitting Laser)



In semiconductor fabrication, vertical thickness can be very precisely controlled.

Dielectric mirror can have high reflectivity approaching R=1.

From $\alpha_m = \frac{1}{L}\ln\frac{1}{R}$,

α_m can be made small if R approaches 1.

VCSELs are cheaper because it is more mass-producible.