LASER

"When God said 'Let there be light' he surely must have meant perfectly coherent light" – Charles Townes, Nobel Laureate (1964)

Syllabus: Radiative and non-radiative transitions. Absorption, spontaneous and stimulated emission, Einstein's A and B coefficients–their interrelation. Idea of metastable state, population inversion. Necessary condition for lasing, threshold population inversion. Two-level system: unattainability of population inversion. Three-level and four-level systems: rate equations and necessary condition for population inversion. Basic components of a laser system — active medium, pumping system and optical resonator. Free spectral range. Line broadening mechanism — natural broadening and pressure broadening (qualitative discussion), Doppler broadening. Ruby laser, He-Ne laser and semiconductor laser working principle.

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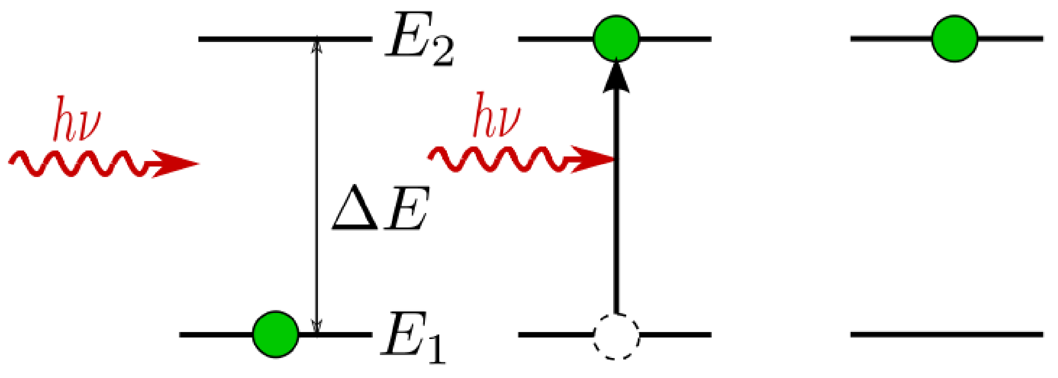
Terminologies

- **Radiative Transition:** Transition between two energy states that involves photon
- **Non-Radiative Transition:** Transition between energy states that does not involve photon – energy exchange may occur in different ways, e.g., via quantum of vibrational energy called phonon
- **Absorption (Radiative):** Excitation to higher energy state by absorption of photon

If N_1 is the population density in lower energy state, the rate of absorption is $B_{12}N_1u(\nu)$

B_{12} (constant) – Einstein's B coefficient

$u(\nu)$ – energy density of radiation at transition frequency ν



$$E_2 - E_1 = \Delta E = h\nu$$

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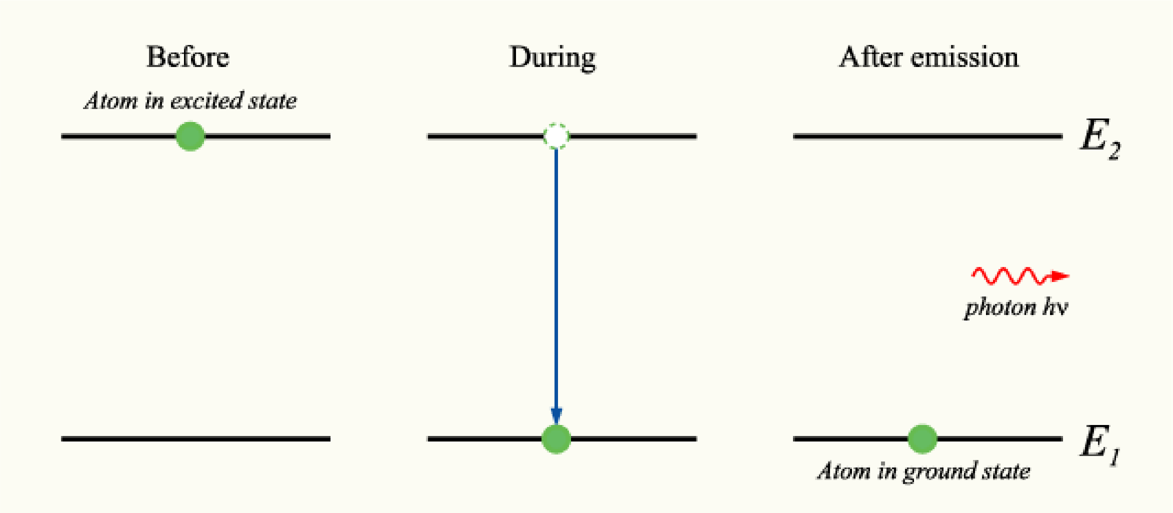
Terminologies

❑ **Spontaneous Emission (Radiative):** Transition from an excited energy state to a lower energy state which occurs at random intervals without regard to the ambient electromagnetic field

❖ If N_2 is the population density in higher energy state, the rate of spontaneous emission is $A_{21}N_2$

A_{21} (constant) – Einstein's A coefficient.

❖ $A = 1/\tau$ where τ is spontaneous lifetime of excited state



❖ The natural linewidth of a spectral line $\Delta\nu = 1/\tau$

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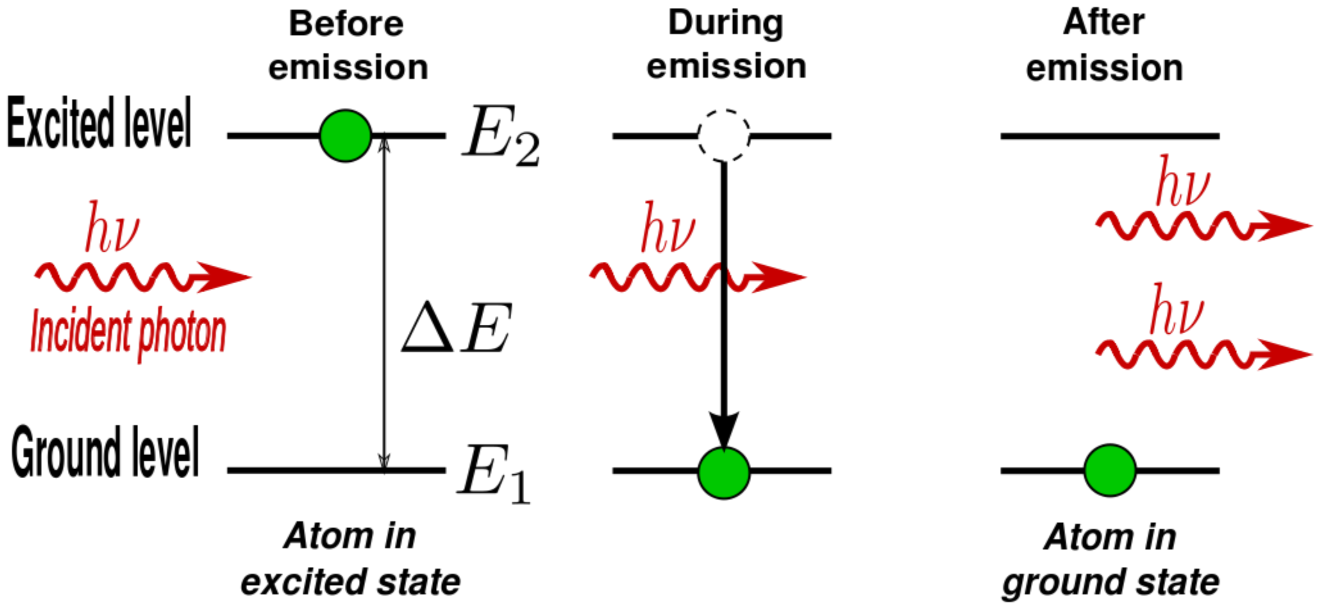
Terminologies

- **Stimulated Emission:** Incident photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level

If N_2 is the population density in higher energy state, the rate of stimulated emission is $B_{21}N_2u(\nu)$

B_{21}(constant) – Einstein's B coefficient



$$E_2 - E_1 = \Delta E = h\nu$$

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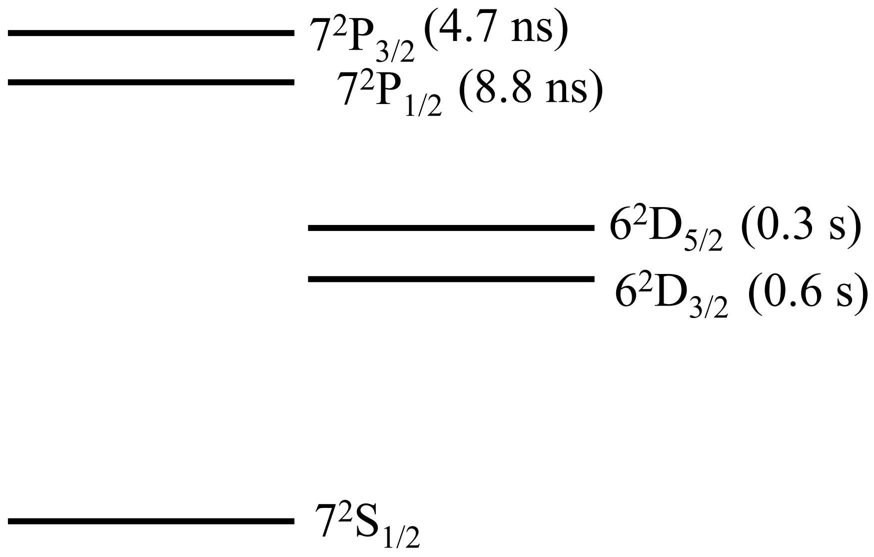
Terminologies

- **Metastable State:** An excited state having longer lifetime (than the ordinary excited states), typically 10 μs – 1 ms. A metastable state may be considered a kind of temporary energy trap, where the population can be gathered, and population inversion can be achieved with respect to a lower excited state of shorter lifetime.



Energy levels of Ra^+

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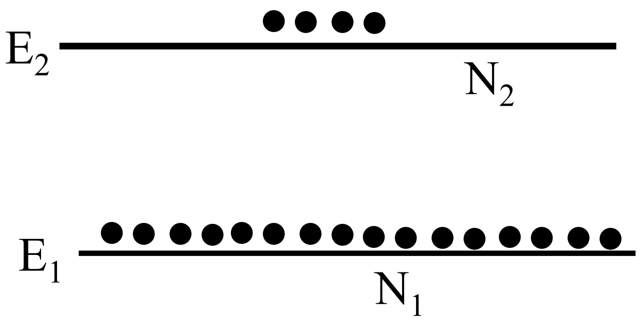
Terminologies

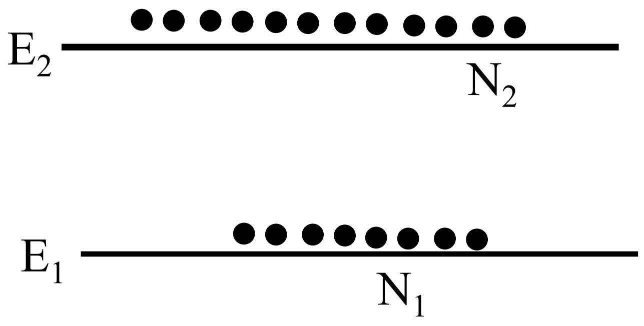
- **Population Inversion:**



$$\frac{N_2}{N_1} = \exp\{-(E_2 - E_1)/kT\}$$

$$\Rightarrow N_2 < N_1$$

$$\Delta N = N_2 - N_1 < 0$$



$$N_2 > N_1$$

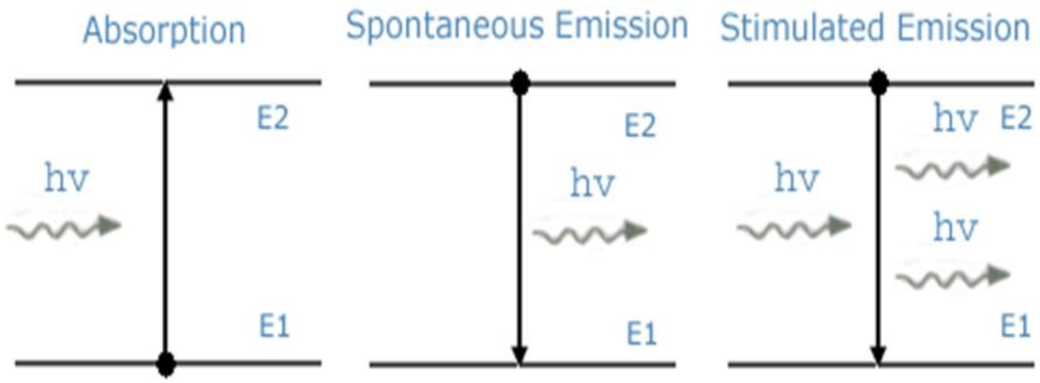
$$\Delta N = N_2 - N_1 > 0$$

E_2 must be a metastable state

Einstein's A & B Coefficients

Rate of change of excited state population

$$\frac{dN_2}{dt} = B_{12}u(\nu)N_1 - B_{21}u(\nu)N_2 - A_{21}N_2 \ldots\ldots (1)$$



Rate of change of population of the ground state is

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = -B_{12}u(\nu)N_1 + B_{21}u(\nu)N_2 + A_{21}N_2$$

In steady state, $dN_1/dt = -dN_2/dt = 0$. From eq. (1)

$$B_{12}u(\nu)N_1 - B_{21}u(\nu)N_2 - A_{21}N_2 = 0$$

$$\Rightarrow u(\nu) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2} = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}}\right)\left(\frac{N_1}{N_2}\right) - 1} \ldots\ldots (2)$$

Einstein's A & B Coefficients

From Maxwell-Boltzmann statistics,

$$\frac{N_2}{N_1} = \exp\{-(E_2 - E_1)/kT\} = \exp\left(-\frac{h\nu}{kT}\right)$$

Substituting in eq. (2)

$$u(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}}\right)\exp\left(\frac{h\nu}{kT}\right) - 1}$$

Planck's formula for radiation energy density:

$$u(\nu) = \frac{8\pi h\nu^3/c^3}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

$$B_{12} = B_{21} = B$$

$$\frac{A_{21}}{B_{21}} = \frac{A}{B} = \frac{8\pi h\nu^3}{c^3}.$$

Einstein's A & B Coefficients

Ratio of the spontaneous to stimulated emission rates:

Rate of spontaneous emission $= AN_2$ & Rate of stimulated emission $= BN_2u(\nu)$

$\therefore$ The ratio of the rate of spontaneous to stimulated emissions is

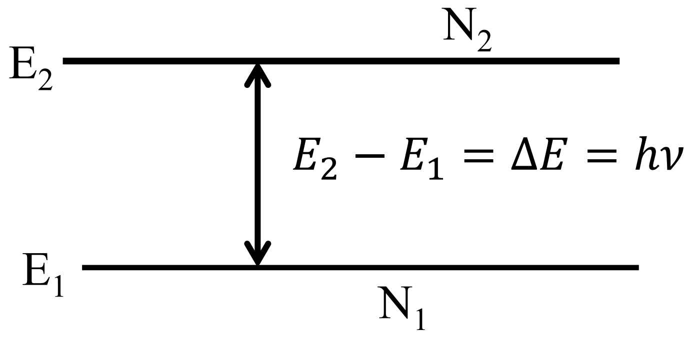
$$R = \frac{AN_2}{BN_2u(\nu)} = \frac{A}{Bu(\nu)} = \left(\frac{8\pi h\nu^3}{c^3}\right)\left\{\frac{1}{\frac{8\pi h\nu^3}{c^3}\frac{1}{\exp(h\nu/kT)-1}}\right\}$$

$$= \exp(h\nu/kT) - 1 = \exp\left(\frac{hc}{\lambda kT}\right) - 1$$

For lower wavelength and at ordinary temperature, $hc/\lambda kT \gg 1$ and hence $R \gg 1$, i.e. the stimulated emission is less probable ($\mathrm{R} = 3.2 \times 10^{12}$ at $\lambda = 500$ nm and $T = 1000$ K while $\mathrm{R} = 4.8 \times 10^{-5}$ at $\lambda = 30$ cm and $T = 1000$ K).

Basic Lasing Action

Necessary Condition:



Rate of absorption $\Gamma_{12} = BN_1 u(\nu)$

Rate of stimulated emission $\Gamma_{21} = BN_2 u(\nu)$

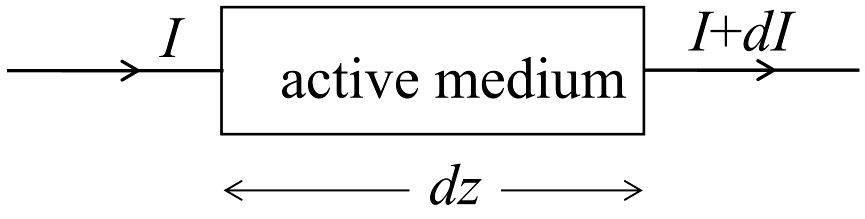
$$dI \propto I$$

$$\propto dz$$

$$\propto (\Gamma_{21} - \Gamma_{12})$$

$$\Rightarrow dI \propto I(\Gamma_{21} - \Gamma_{12})dz$$

or, $dI \propto Bu(\nu)I(N_2 - N_1)dz$



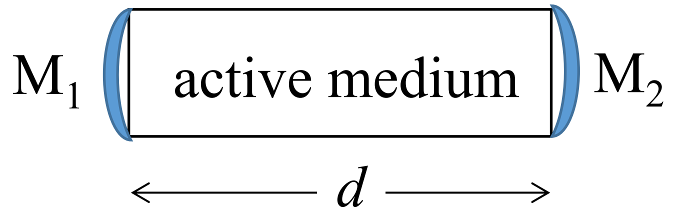
$$\frac{dI}{I} = \sigma(\nu)(N_2 - N_1)dz$$

$$\Rightarrow I = I_0 \exp\{-\sigma(\nu)(N_1 - N_2)z\}$$

$I < I_o$ as $N_2 < N_1$ in normal condition (thermodynamic equilibrium). For $I > I_o$, $N_2 > N_1$ or, $\Delta N = N_2 - N_1 > 0$ i.e. population inversion is the necessary condition for light amplification

Basic Lasing Action

Threshold Condition:



Initial intensity (at an instant, say after reflection from M_1): I_0

Intensity before reflection at M_2:

$$I_1 = I_0 \exp\{-\sigma(\nu)(N_1 - N_2)d\}\exp(-\alpha' d) = I_0 \exp\{(\alpha - \alpha')d\}$$

where, $\alpha = \sigma(\nu)(N_2 - N_1) > 0$

α' accounts for scattering loss and other losses within the medium

Intensity after reflection at M_2: $I_2 = R_2 I_0 \exp\{(\alpha - \alpha')d\}$

Intensity before reflection at M_1: $I_1 = I_2 \exp\{(\alpha - \alpha')d\} = R_2 I_0 \exp\{2(\alpha - \alpha')d\}$

Intensity after reflection at M_1: $I = R_1 R_2 I_0 \exp\{2(\alpha - \alpha')d\}$

where, $\alpha = \sigma(\nu)(N_2 - N_1) > 0$

Basic Lasing Action

Threshold Condition:

Intensity after complete round trip: $I = R_1 R_2 I_0 \exp\{2(\alpha - \alpha')d\}$

For sustained amplification $I \geq I_0$

$$R_1 R_2 I_0 \exp\{2(\alpha - \alpha')d\} \geq I_0 \Rightarrow R_1 R_2 \exp\{2(\alpha - \alpha')d\} \geq 1$$

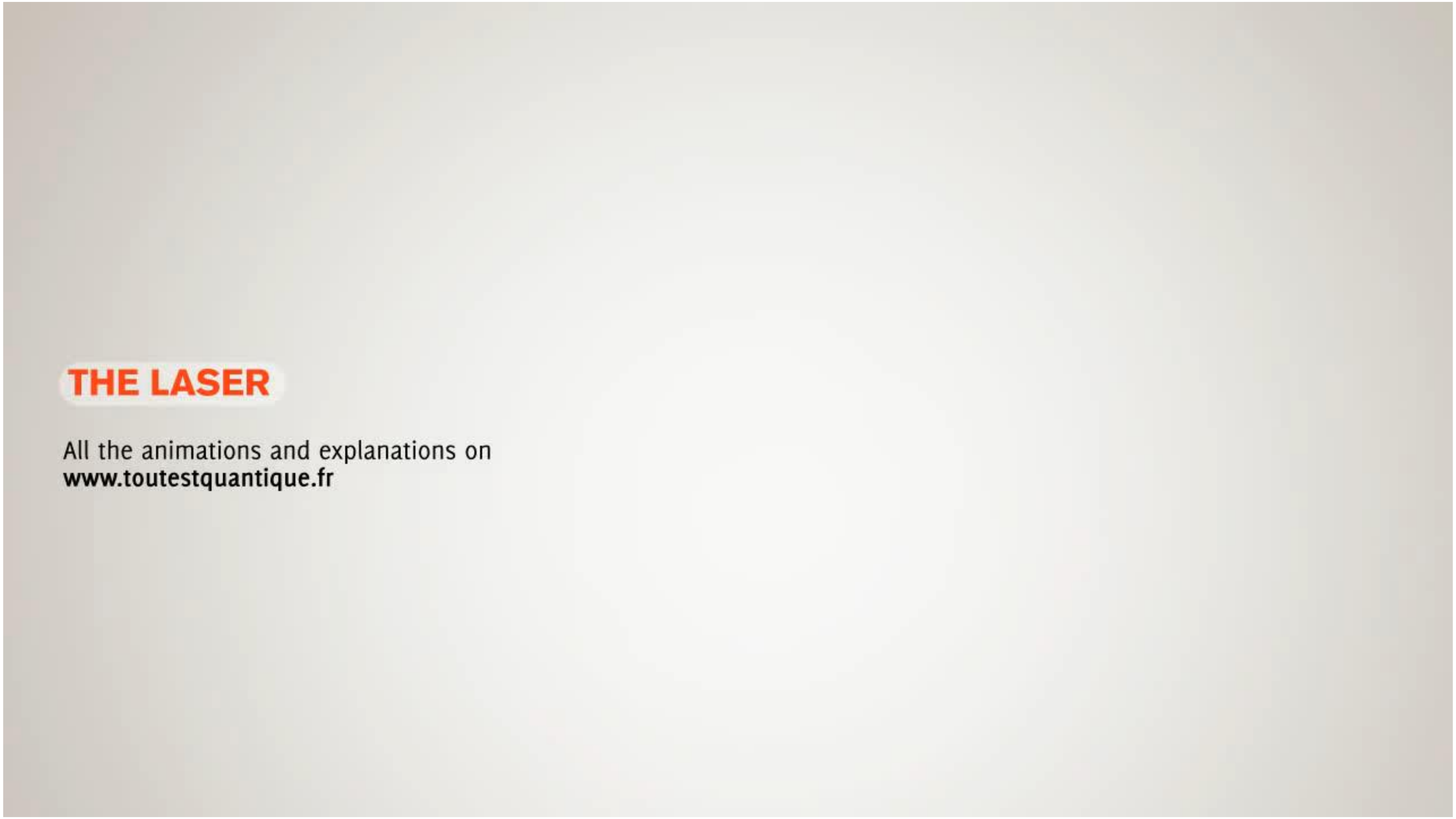
$$2(\alpha - \alpha')d \geq -\ln(R_1 R_2) \Rightarrow \alpha \geq \left[\alpha' - \frac{1}{2d}\ln(R_1 R_2)\right]$$

$$\Rightarrow N_2 - N_1 \geq \frac{1}{\sigma(\nu)}\left[\alpha' - \frac{1}{2d}\ln(R_1 R_2)\right]$$

$$\boxed{\alpha = \sigma(\nu)(N_2 - N_1)}$$

$$\boxed{(\Delta N)_{th} = (N_2 - N_1)_{th} = \frac{1}{\sigma(\nu)}\left[\alpha' - \frac{1}{2d}\ln(R_1 R_2)\right]}$$

Basic Lasing Action

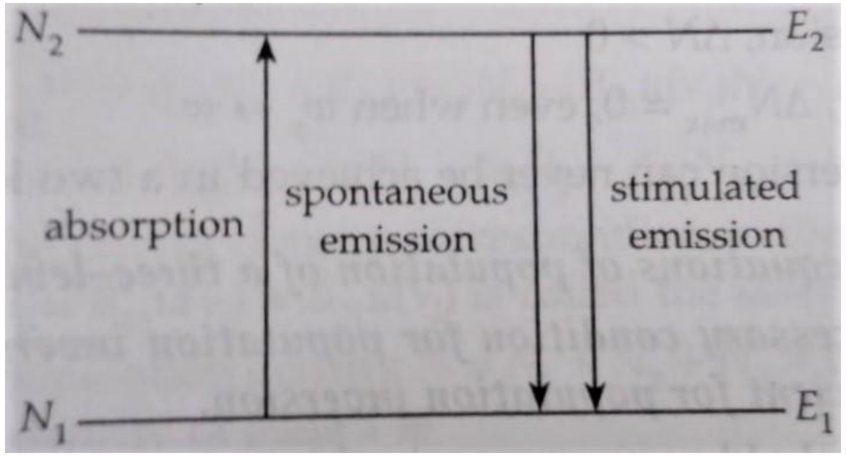


Two-Level System

Rate Equations:

$$\frac{dN_2}{dt} = B_{12}u(\nu)N_1 - B_{21}u(\nu)N_2 - A_{21}N_2$$

$$= w_p(N_1 - N_2) - A_{21}N_2 = -\frac{dN_1}{dt}$$



In steady state, $dN_1/dt = dN_2/dt = 0$

$$\Rightarrow w_p(N_1 - N_2) - A_{21}N_2 = 0$$

$$\Rightarrow N_2 = \frac{w_p}{w_p + A_{21}} N_1$$

$$\Delta N = N_2 - N_1 = \left(\frac{w_p}{w_p + A_{21}} - 1\right) N_1 = -\frac{A_{21}}{w_p + A_{21}} N_1 < 0$$

Population inversion can’t be achieved in two level system, no matter how high the pumping power is.

Three-Level System

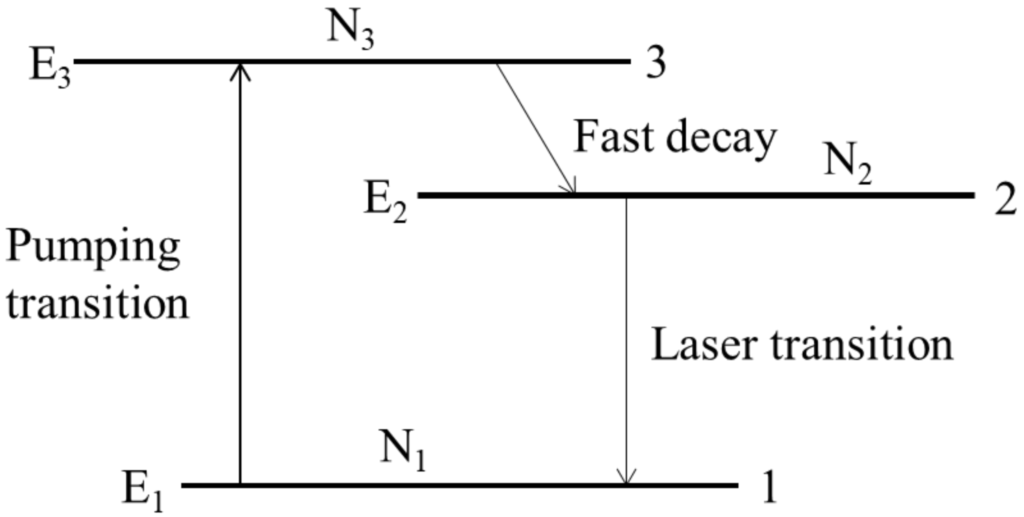
Rate Equations:

$$\frac{dN_3}{dt} = B_{13}u(\nu)N_1 - B_{31}u(\nu)N_3 - A_{32}N_3$$

$$= w_pN_1 - w_pN_3 - A_{32}N_3$$

$$\frac{dN_2}{dt} = A_{32}N_3 + B_{12}u(\nu_l)N_1 - B_{21}u(\nu_l)N_2 - A_{21}N_2$$

$$= A_{32}N_3 + w_lN_1 - w_lN_2 - A_{21}N_2$$



In steady state, $dN_3/dt = dN_2/dt = 0$

$$\Rightarrow\ w_pN_1 - w_pN_3 - A_{32}N_3 = 0$$

$$\Rightarrow\ N_3 = \frac{w_p}{w_p + A_{32}}N_1$$

Three-Level System

Condition for population inversion:

$$A_{32}N_3 + w_l N_1 - w_l N_2 - A_{21}N_2 = 0$$

$$\Rightarrow (w_l + A_{21})N_2 = w_l N_1 + A_{32}N_3$$

$$= \left(w_l + \frac{w_p A_{32}}{w_p + A_{32}}\right) N_1$$

$$\Rightarrow N_2 = \frac{w_l w_p + w_l A_{32} + w_p A_{32}}{(w_l + A_{21})(w_p + A_{32})} N_1$$

$$\Delta N = N_2 - N_1$$

$$= \left[\frac{w_l w_p + w_l A_{32} + w_p A_{32}}{(w_l + A_{21})(w_p + A_{32})} - 1\right] N_1$$

$$= \left[\frac{w_p(A_{32} - A_{21}) - A_{32}A_{21}}{(w_l + A_{21})(w_p + A_{32})}\right] N_1$$

For population inversion, $\Delta N > 0$. Thus, necessary condition for population inversion is $A_{32} > A_{21}$

For $\Delta N > 0$, $w_p(A_{32} - A_{21}) > A_{32}A_{21}$

$$\Rightarrow w_p > \frac{A_{32}A_{21}}{A_{32} - A_{21}}$$

Threshold pump power:

$$w_{pt} = \frac{A_{32}A_{21}}{A_{32} - A_{21}}$$

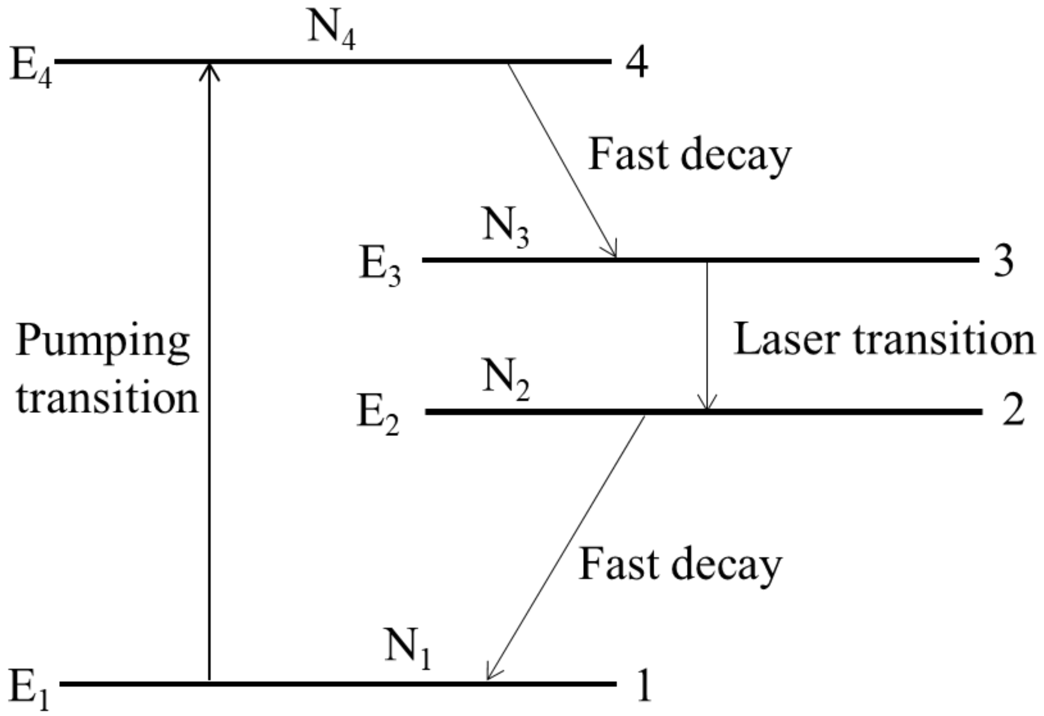
Four-Level System

Rate Equations:

$$\frac{dN_4}{dt} = B_{14}u(\nu)N_1 - B_{41}u(\nu)N_4 - A_{43}N_4$$
$$= w_pN_1 - w_pN_4 - A_{43}N_4$$

$$\frac{dN_3}{dt} = A_{43}N_4 + B_{23}u(\nu_l)N_2 - B_{32}u(\nu_l)N_3 - A_{32}N_3$$
$$= A_{43}N_4 + w_l(N_2 - N_3) - A_{32}N_3$$

$$\frac{dN_2}{dt} = B_{32}u(\nu_l)N_3 + A_{32}N_3 - B_{23}u(\nu_l)N_2 - A_{21}N_2$$
$$= w_l(N_3 - N_2) + A_{32}N_3 - A_{21}N_2$$



Four-Level System

Condition for population inversion:

In steady state, $dN_4/dt = dN_3/dt = dN_2/dt = 0$

$$\Rightarrow w_l(N_3 - N_2) + A_{32}N_3 - A_{21}N_2 = 0$$

$$\Rightarrow N_3 = \frac{w_l + A_{21}}{w_l + A_{32}} N_2$$

$$\Delta N = N_3 - N_2 = \left(\frac{w_l + A_{21}}{w_l + A_{32}} - 1\right) N_2 = \left(\frac{A_{21} - A_{32}}{w_l + A_{32}}\right) N_2$$

For population inversion, $\Delta N > 0$ i.e. $A_{21} > A_{32}$

Components of Laser System

Active Medium: *The medium containing atoms/molecules where the population inversion is achieved and capable of sustaining stimulated emission*

- **Gaseous Medium:** Helium-Neon laser (632.8 nm), Argon ion laser (514.5 nm, 457.9 nm, 488.0 nm), Krypton ion laser (647.1 nm), CO_2 laser (10.6 μm), Nitrogen laser (337.1 nm), Excimer lasers – XeCl (308 nm), XeF (351 nm) etc.
- **Solid State Medium:** Ruby laser (694.3 nm), Nd-YAG laser (1064 nm) etc.
- **Semiconductor Medium:** GaAs (gallium arsenide), AlGaAs (aluminum gallium arsenide), GaP (gallium phosphide), InGaP (indium gallium phosphide), GaN (gallium nitride), InGaAs (indium gallium arsenide), GaInNAs (indium gallium arsenide nitride) etc.
- **Liquid Medium:** Dye laser (organic dye – liquid solution: 300 nm – 1000 nm)

Components of Laser System

Pumping: *Mechanism by which population inversion in a laser system is achieved*

- **Optical Pumping:** Atoms/molecules are exposed to electromagnetic radiation – generally broadband, centering at the transition frequency $\upsilon = (E_2 - E_1)/h$. Atoms/Molecules absorbs the radiation selective and are thus pumped into the excited state. Xenon flash lamp is used for optical pumping in Ruby Laser
- **Electrical Discharge:** Accelerated electrons undergo inelastic collision with atoms/molecules of the active medium and pump them to excited state. – Used mainly in gas laser e.g. He-Ne laser

Components of Laser System

- **Collision:** In a gaseous medium containing different kinds of atoms, say X and Y, electric discharge pumps the atoms in excited states X* and Y*. In case one of these excited atoms, say X*, is in metastable state, and excitation energies of X* and Y* are nearly equal, some of the atoms of Y are pumped to Y* via collision with X*.

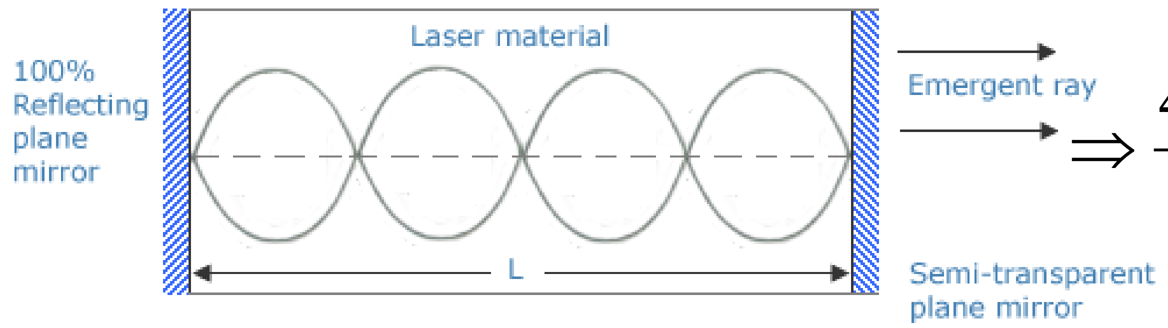
$$X^* + Y \rightarrow X + Y^*$$

For example, Ne atoms in He-Ne laser are pumped via inelastic collision with He*.

- **Injection Current:** Current through the junction of semiconductor diodes creates population inversion in semiconductor diode lasers

Components of Laser System

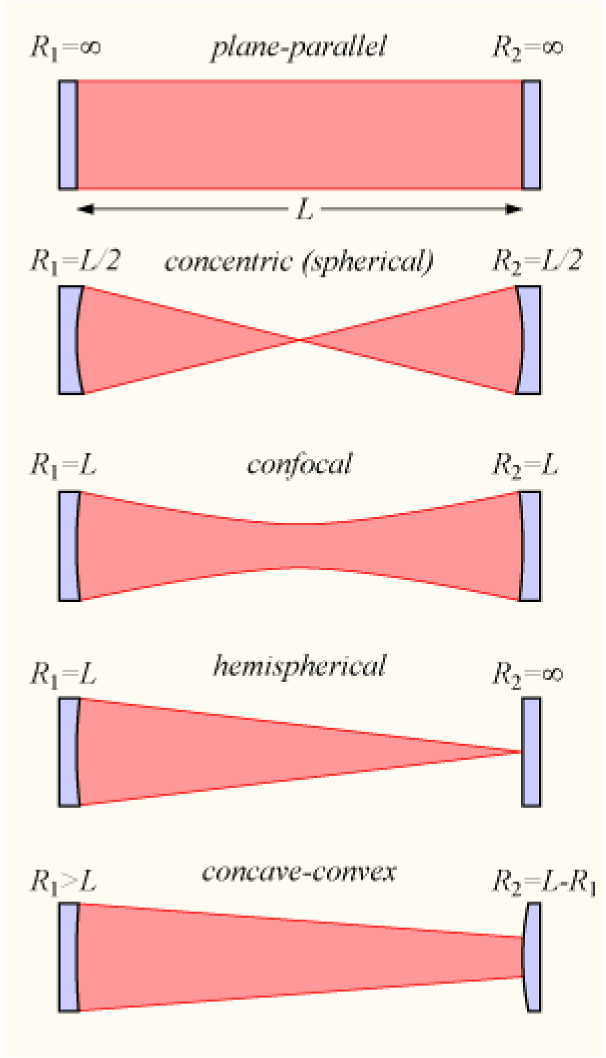
Optical Resonator: *A pair of mirrors that reflects the light back and forth through the active medium thus providing the feedback to amplify and sustain the laser oscillation*



$$\delta = \frac{2\pi}{\lambda_m}\cdot 2L + 2\gamma = 2m\pi$$

$$\Rightarrow \frac{4\pi L}{\lambda_m} = 2m\pi - 2\gamma$$

$$\Rightarrow \nu_m = \frac{c}{n\lambda_m} = m\frac{c}{2nL} - \frac{\gamma c}{2\pi n L}$$



n: Refractive index of active medium

γ: Phase change due to reflection in each mirror

Components of Laser System

Optical Resonator: Free-Spectral Range (FSR)

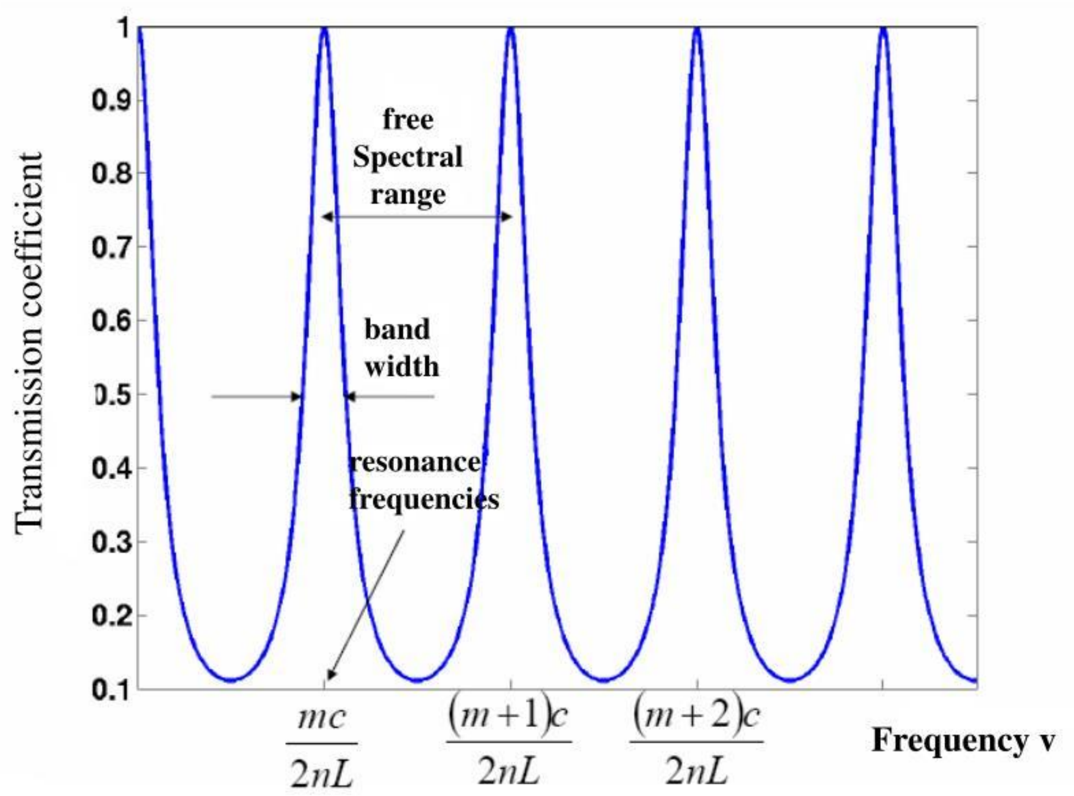
$$\nu_m = m\frac{c}{2nL} - \frac{\gamma c}{2\pi nL}$$

$$\nu_{m+1} = (m+1)\frac{c}{2nL} - \frac{\gamma c}{2\pi nL}$$

$$\Rightarrow \Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{2nL}$$

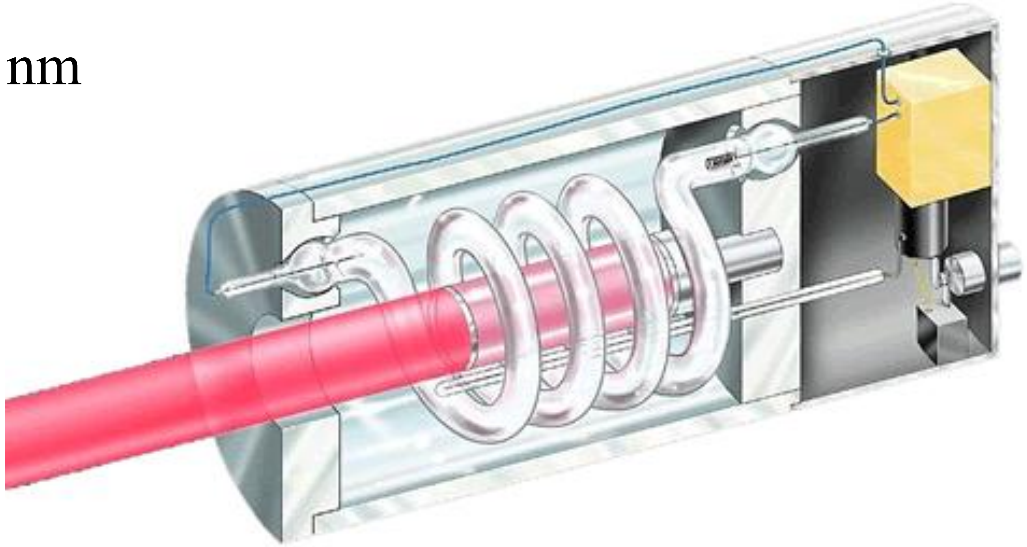
$$\Delta\nu = \frac{c}{\lambda^2}|\Delta\lambda| = \frac{c}{2nL} \Rightarrow |\Delta\lambda| = \frac{\lambda^2}{2nL}$$

$$L = 10\ cm, n = 1, \Delta\nu = 1.5\ GHz$$



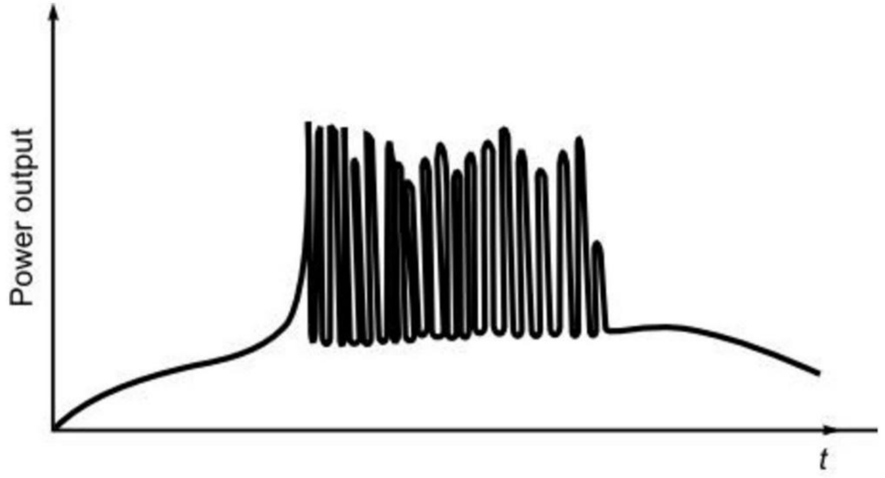
Ruby LASER

- First laser, three level solid state laser system developed by T. H. Maiman in 1960
- Active/Gain Medium: Synthetic ruby crystal grown from sapphire (Al_2O_3) doped with ~0.05% chromium ions (Cr^{+++})
- Pumping Source: Optical pumping – generally by xenon flashtube
- Output Wavelength: 694.3 nm pulsed laser (typical pulse width of the order of microseconds), narrow linewidth of 0.53 nm



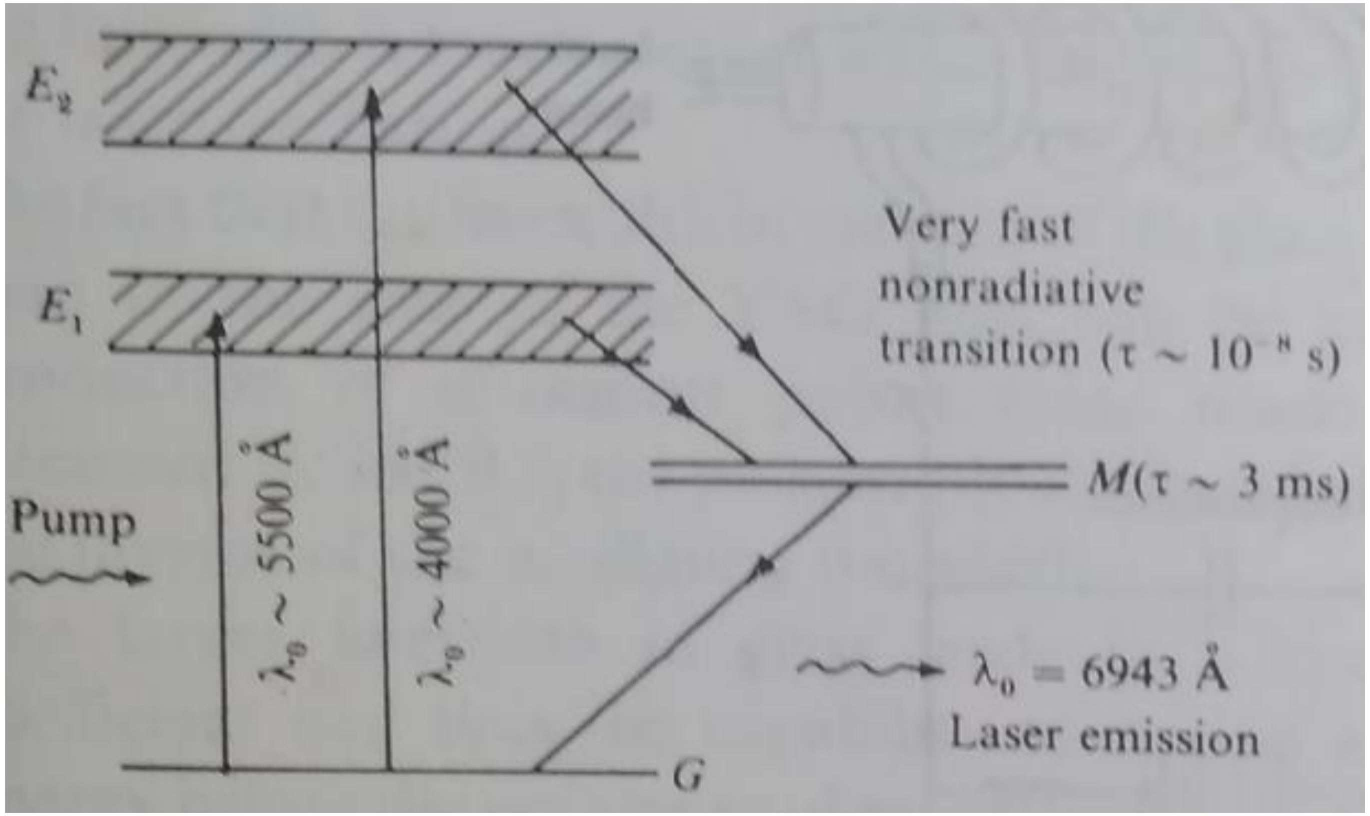
Ruby LASER

- Ruby rod, the active medium, is energized through optical pumping, typically by a xenon flashtube.
- Ruby has very broad and powerful absorption bands in the visual spectrum, at 400 and 550 nm, and a very long fluorescence lifetime of 3 milliseconds.
- Both ends of the ruby rod are polished with great precision (optical flatness typically $\lambda/4$). The finely polished ends of the rod are silvered; one end completely, the other only partially – two ends thus form a resonant cavity



Ruby LASER

- Cr^{+++} ions are excited from ground state (E_1) to the bands E_3 and E_3' which have small lifetime (~nanoseconds)
- Cr^{+++} ions from excited bands undergo non-radiative transition to E_2 which is a metastable state (lifetime ~ 3 ms)
- Population inversion is achieved between the ground state (E_1) and metastable state (E_2) and lasing action starts



Ruby LASER

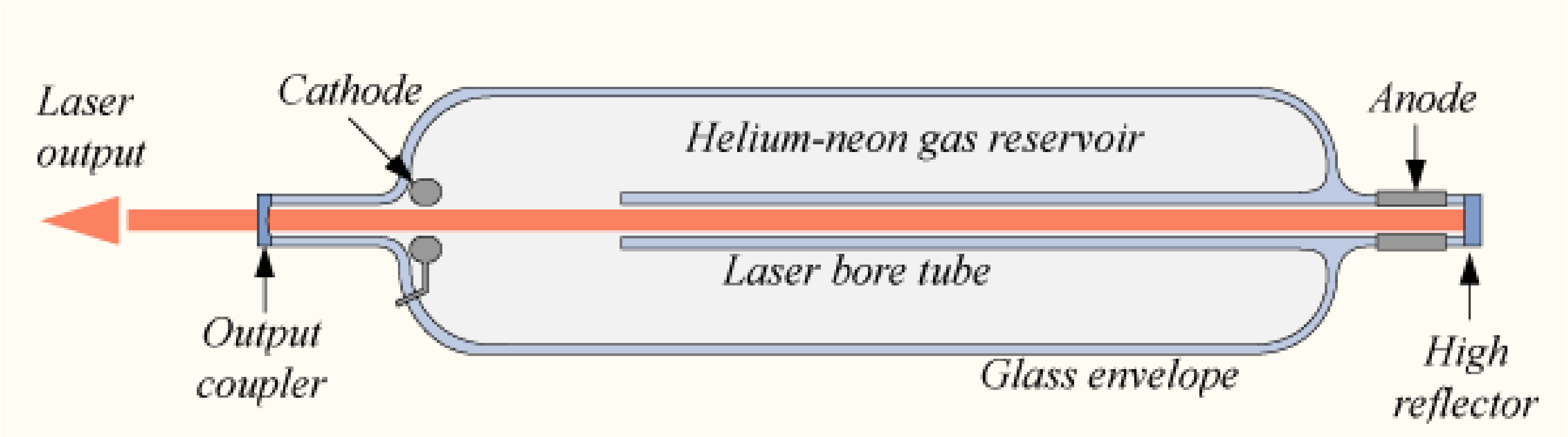
❑ Why pulsed output?

Ruby laser is a three-level laser system where the population inversion is achieved between a metastable state and the ground state. Therefore, it is difficult to maintain the population inversion. This will result in the depletion of upper laser level (E_2) population (due to stimulated emission) more rapidly than it can be restored by the flash light i.e., optical pumping source. The laser emission is made up of spikes of high intensity emissions. *This phenomenon is called spiking of the laser*.

After the depletion of E_2 state population, the laser action ceases for a few microseconds. Since the flash lamp is still active, it again pumps the ground state chromium ions to upper level and again laser action begins. A series of such pulses is produced until the intensity of the flash light has fallen to such a level that it can no longer rebuild the necessary population inversion. So, the output laser will be in the form of pulse in ruby laser or in other words, it will not be continuous.

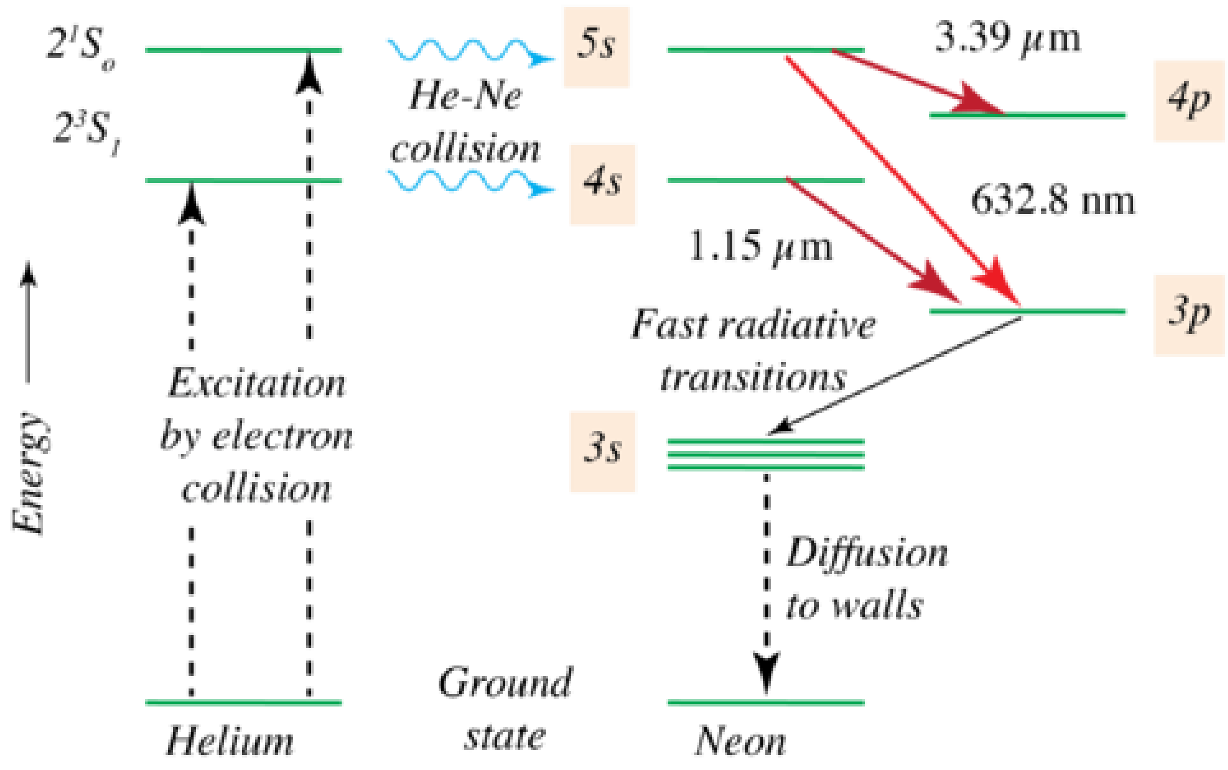
He-Ne LASER

- A four-level gas laser system that produces continuous wave laser at wavelength 632.8 nm
- *Active/Gain Medium*: Mixture of Helium (90%) and Neon (10%) at a total pressure of around 1 torr
- *Pumping Source*: Electrical discharge
- *Output Wavelength*: 632.8 nm (5s→3p transition in neon), 1.15 μm (4s→3p transition in neon), 3.39 μm (5s→4p transition in neon)



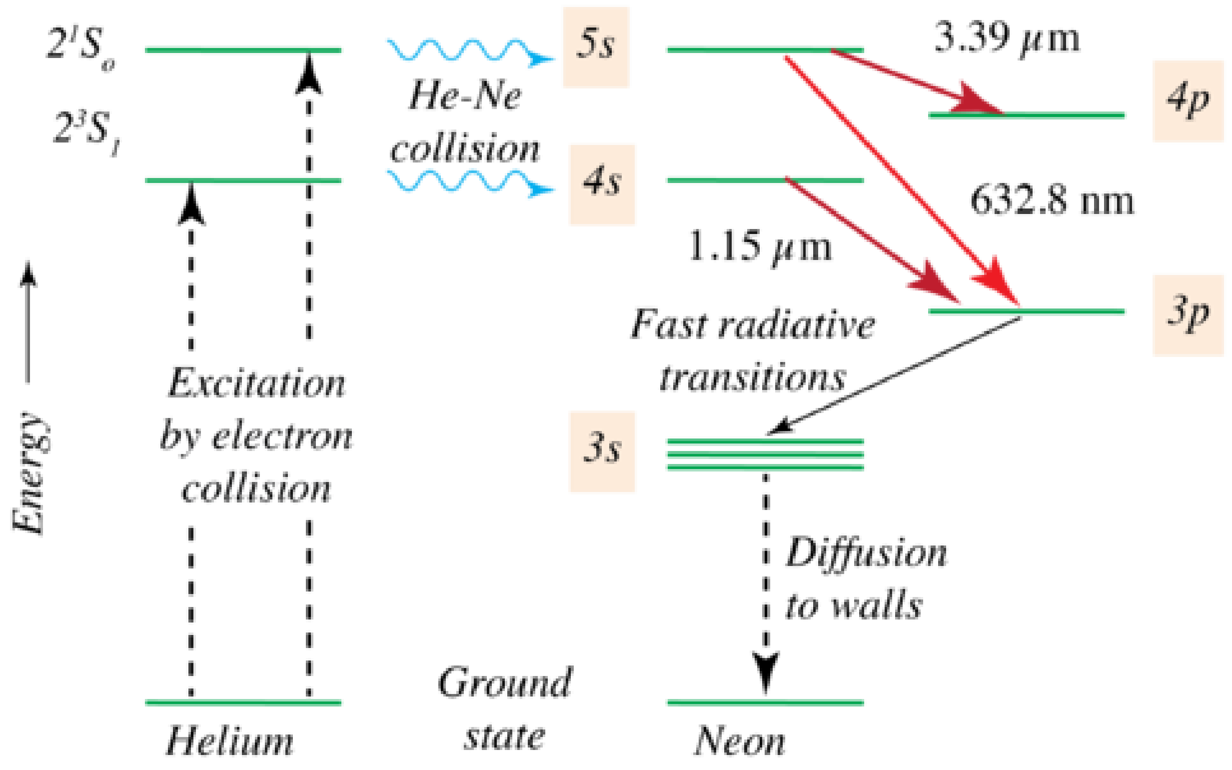
He-Ne LASER

- High voltage electrical discharge excites the helium atoms (inelastic collision with electrons) from ground state to the metastable states 2^1S_0 and 2^3S_1 which have close coincidence with 5s and 4s states of neon
- Collisions between these helium metastable atoms and ground-state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon



He-Ne LASER

- ❑ Population inversion may be achieved between the states 5s → 4p, 5s → 3p, 4s → 3p and the radiation is selectively amplified with the help of resonator cavity
- ❑ CW output corresponds to 5s → 3p transition at 632.8 nm, typical bandwidth 1.5 GHz dominated by Doppler broadening



He-Ne LASER

❑ Why helium atoms and with higher percentage?

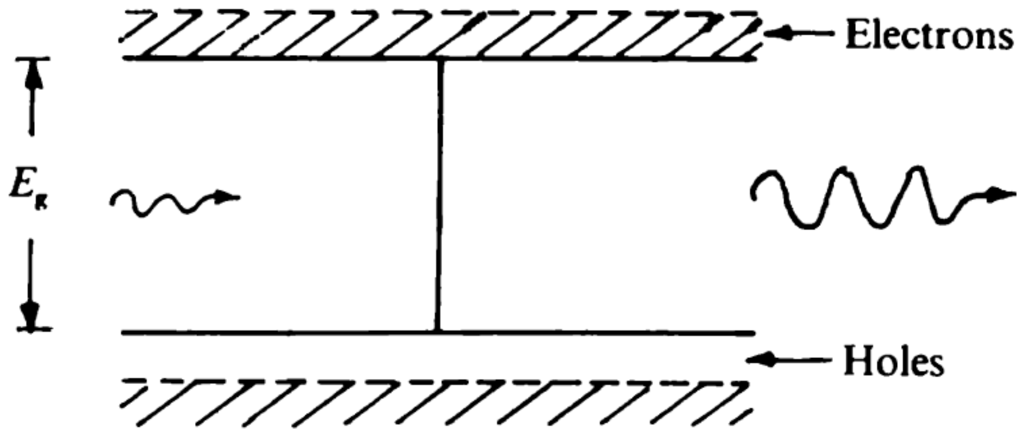
The helium atoms are used for better pumping efficiency i.e. to achieve population inversion in the assembly of neon atoms. Helium, with higher percentage in the mixture, are excited due to the inelastic collision with the electrons from ground state to the metastable states 2^1S_0 and 2^3S_1 which have close coincidence with 5s and 4s states of neon. Collisions between these helium metastable atoms and ground-state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon. Without helium, the neon atoms would be excited mostly to lower excited states that may result in non-laser lines.

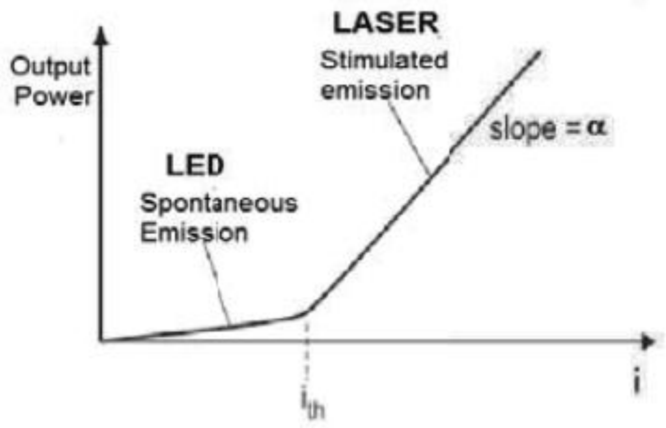
Semiconductor laser

- p-n junction semiconductor diodes (homojunction or heterojunction or double heterojunction) are used as the active medium.
- Electric current is used for pumping electrons from the valence band into the conduction band.
- Semiconductor lasers are widely used because specific advantages like small size, lower cost, direct pumping with conventional electronic circuitry, different wavelengths in the visible and infrared region, capability of monolithic integration, compatibility with optical fibers.
- Working of semiconductor lasers is much similar to that of LED – light emission on electron-hole recombination.
- On absorption on the incident radiation / background radiation, electrons from valence band jumps into the conduction band creating electron-hole pair.

Semiconductor laser

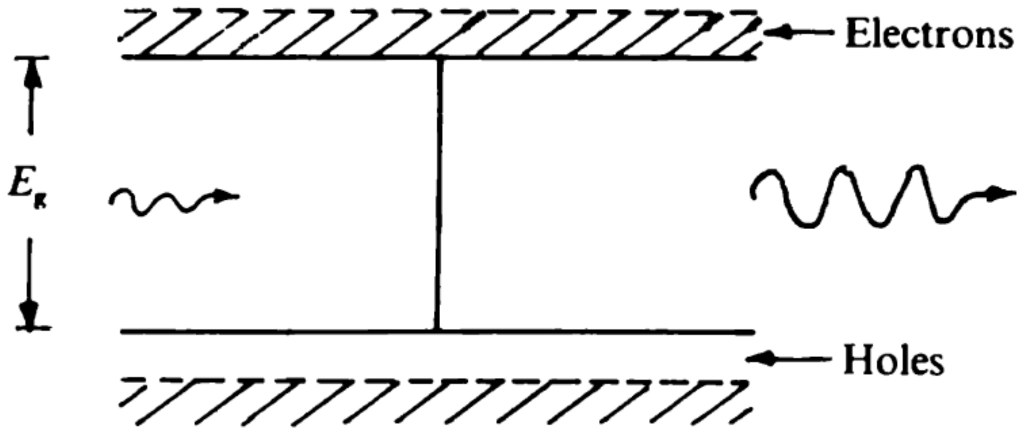
- The electrons from the conduction band may spontaneously come back to the balance band – emits radiation on electron-hole recombination.
- The recombination process may be stimulated by the incident/background radiation – a process of interest in lasing action.
- A large electron density of electrons near the bottom of the conduction band and simultaneously in the same region of space a large density of holes near the top of the valence band are created by some mechanism.

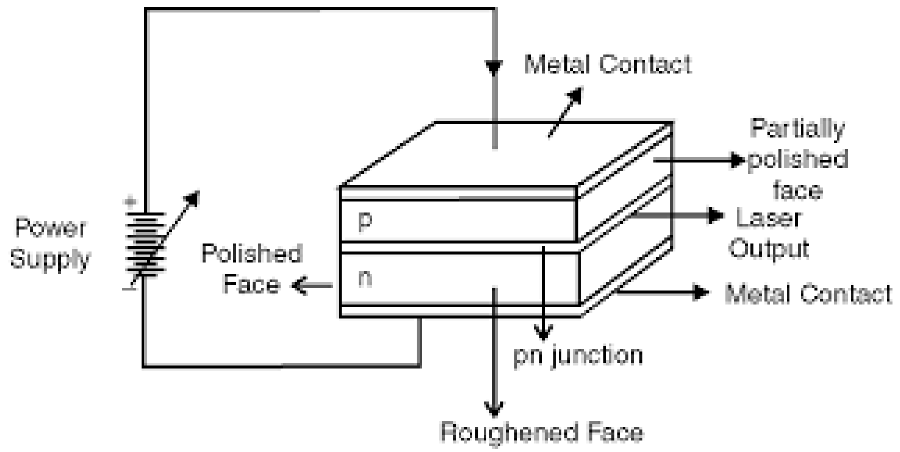




Semiconductor laser

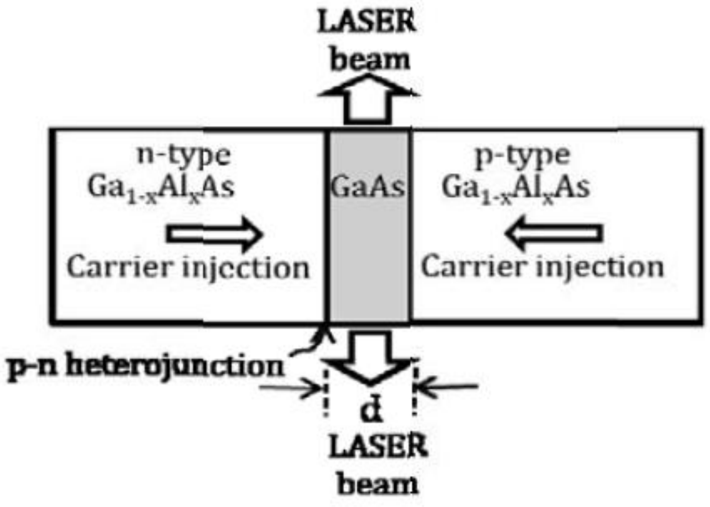
- A radiation of frequency slightly higher than E_g/h will enhance the stimulated emissions as compared to the absorption and thus light amplification can be achieved.
- Optical feedback in laser diodes is usually provided by cleaving or polishing the ends of the diode perpendicular to the junction.

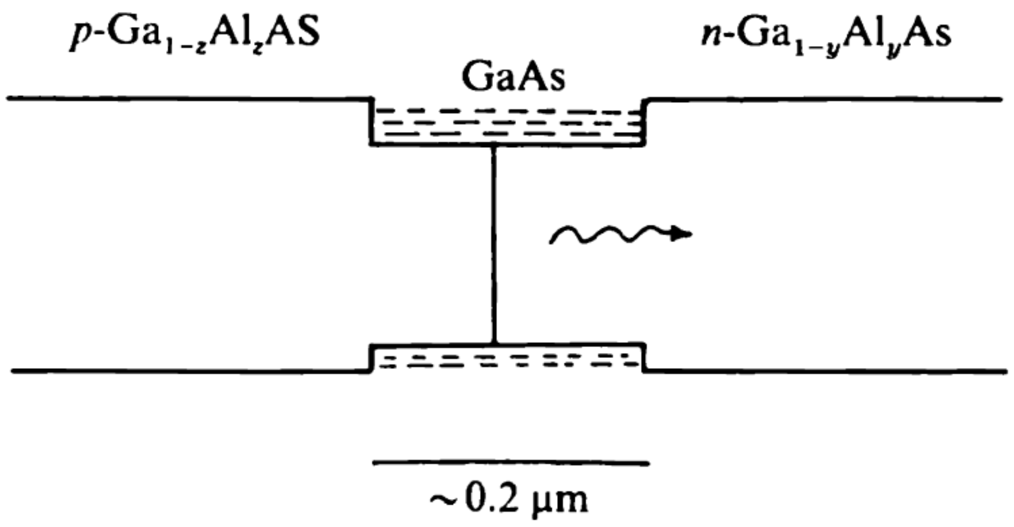


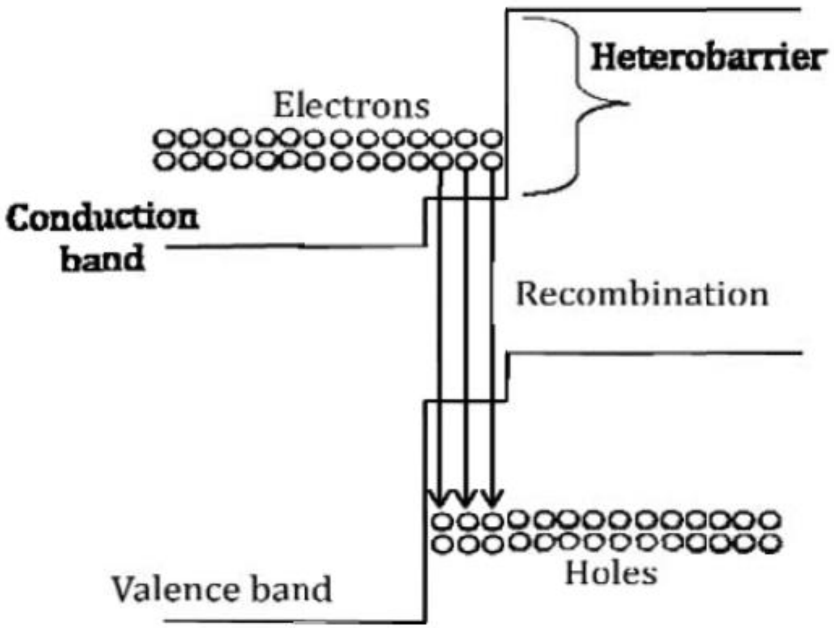


Semiconductor laser

- Threshold current density in homojunction p-n diodes is typically 50000 A/cm^2 which is quite high.
- With the use of heterojunction diodes, the threshold current density is significantly reduced – typically 2000 – 4000 A/cm^2.

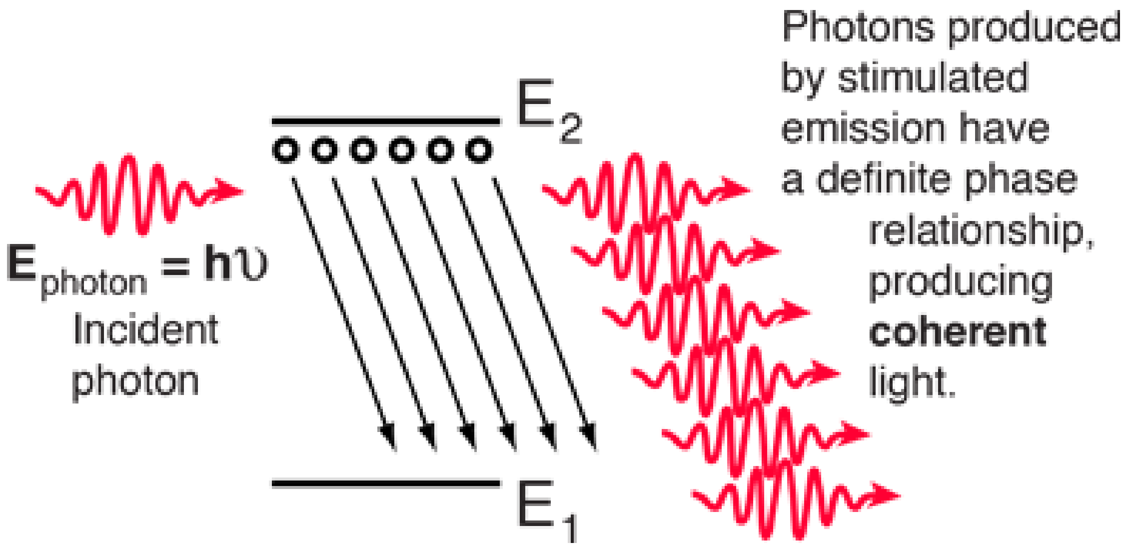






Properties

Coherence: Coherence is one of the unique properties of laser light. It arises from the stimulated emission process which provides the amplification. Since a common stimulus triggers the emission events which provide the amplified light, the emitted photons are "in step" and have a definite phase relation to each other. This coherence is described in terms of temporal coherence and spatial coherence, both of which are important in producing the interference



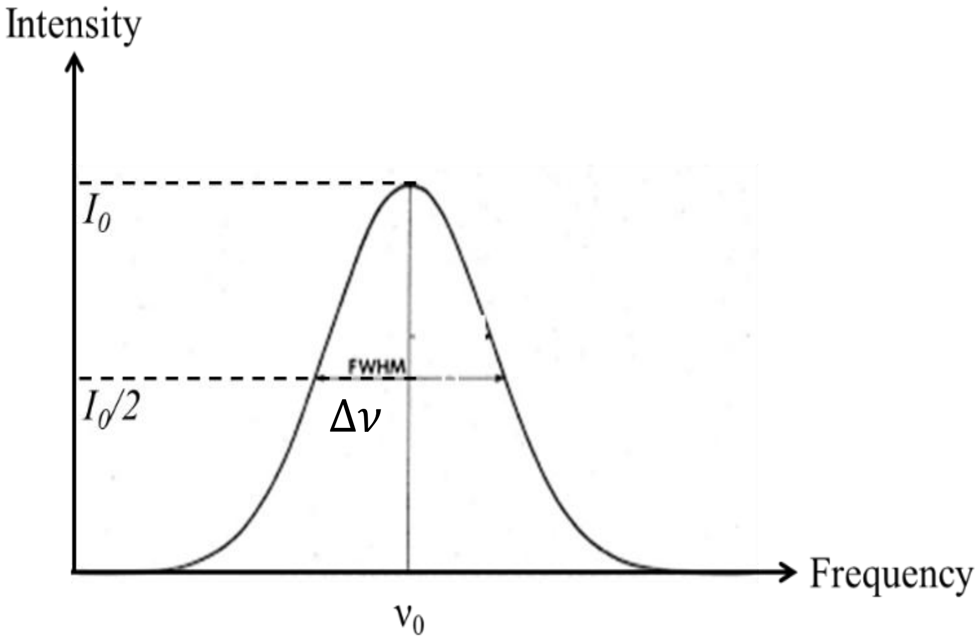
http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/qualig.html

Properties

Monochromaticity: The light from a laser typically comes from one atomic transition with a single precise wavelength. So the laser light has a single spectral color and is almost the purest monochromatic light available. That being said, however, the laser light is not exactly monochromatic. The spectral emission line from which it originates does have a finite width due to Doppler Broadening, Natural Broadening and Collisional or Pressure Broadening

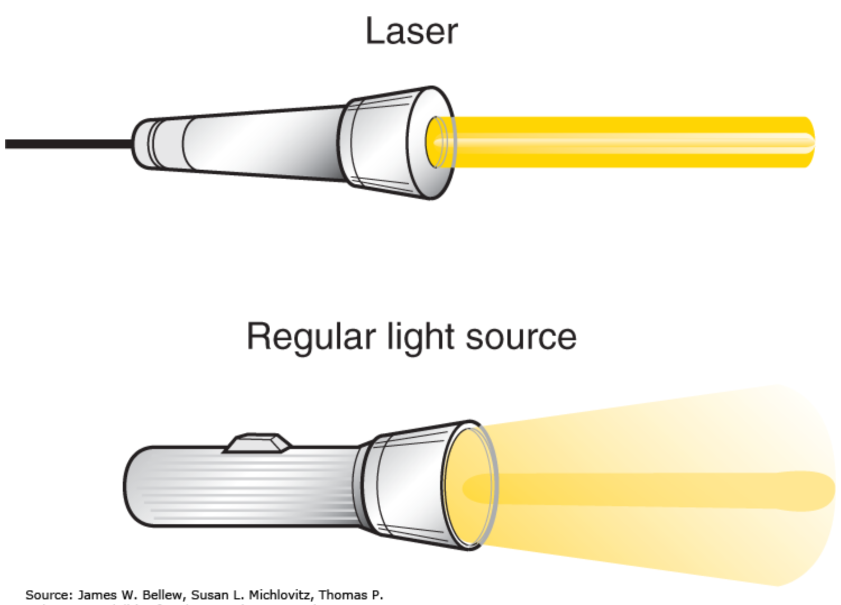
Coherence time: $\tau_c = \dfrac{1}{\Delta\nu} = \dfrac{\lambda_0^2}{c\Delta\lambda}$

Coherence length: $L_c = c\tau_c$

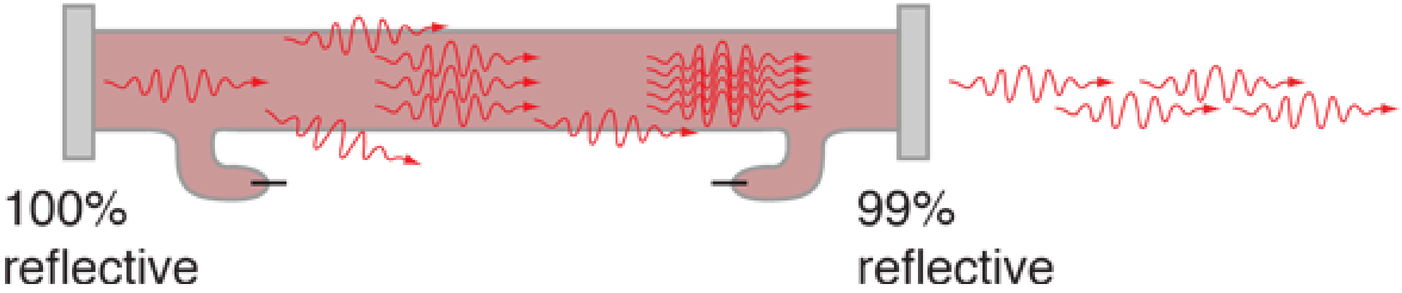


Properties

- **Directionality:** The light from a typical laser emerges in an extremely thin beam with very little divergence i.e. laser beam is highly collimated. The high degree of collimation arises from the fact that the cavity of the laser has very nearly parallel front and back mirrors which constrain the final laser beam to a path which is perpendicular to those mirrors.



Source: James W. Bellew, Susan L. Michlovitz, Thomas P. Nolan Jr.: Modalities for Therapeutic Intervention, Sixth Edition, www.FADavisPTCollection.com



http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/qualig.html

Applications

- **Communications:** Besides fiber-optic communication, lasers are used for free-space optical communication, including laser communication in space.
- **Medicine:** Laser surgery (particularly eye surgery), laser healing, kidney stone treatment, ophthalmoscopy, and cosmetic skin treatments such as acne treatment, cellulite and striae reduction, and hair removal, chemotherapy or radiation therapy. Laser-induced interstitial thermotherapy
- **Industry:** Cutting including converting thin materials, welding, material heat treatment, marking parts (engraving & bonding), additive manufacturing or 3D printing processes like selective laser sintering and selective laser melting, non-contact measurement of parts and 3D scanning, Laser cleaning.
- **Military:** Marking targets, guiding munitions, missile defense, electro-optical counter measures (EOCM), lidar, blinding troops.

https://en.wikipedia.org/wiki/List_of_laser_applications

Applications

- **Law enforcement:** LIDAR traffic enforcement. Lasers are used for latent fingerprint detection in the forensic identification field
- **Research:** Spectroscopy, laser ablation, laser annealing, laser scattering, laser interferometry, lidar, laser capture microdissection, fluorescence microscopy, metrology, laser cooling.
- **Commercial products:** Laser printers, barcode scanners, thermometers, laser pointers, holograms, bubblegrams.
- **Entertainment:** Optical discs, laser lighting displays, laser turntables

https://en.wikipedia.org/wiki/List_of_laser_applications