Laser Theory and Applications

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Outline

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- Absorption
- Spontaneous Emission
- Stimulated Emission
- **LASER** - **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- Interaction of Radiation with Matter
- Blackbody Radiation
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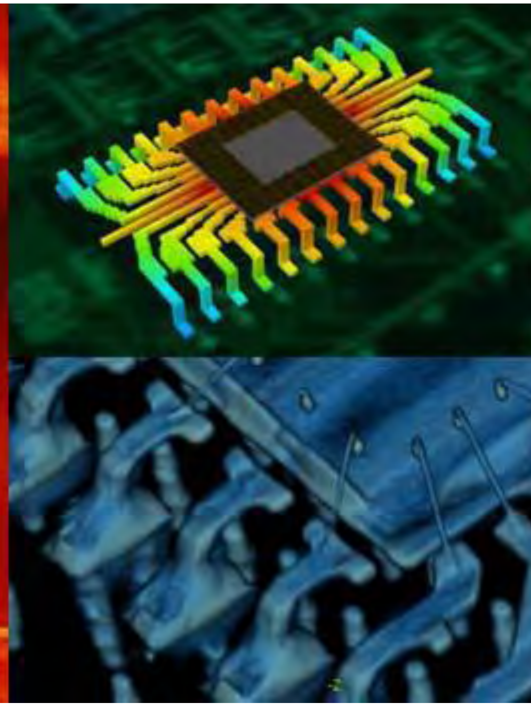
- Einstein Relations - A and B Coefficients
- Population Inversion
- MASER
- 3 and 4 level laser system
- Resonator – stability condition
- Laser – characteristics
- Laser output
- Laser Types
- Applications

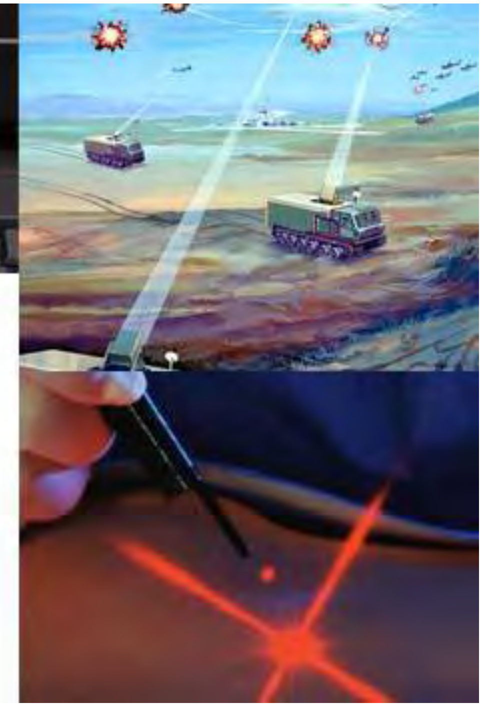
Greatest inventions in last century

Atomic energy



Semiconductor

Computer



Laser

Physicists - laser

Maiman (1960)

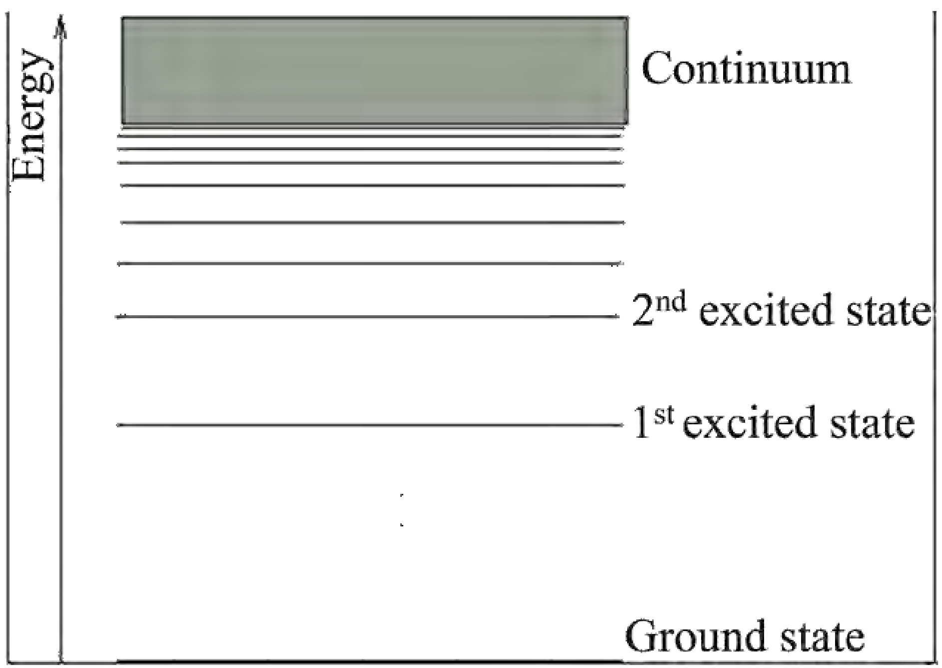
Towens

Prokhorov

Basov

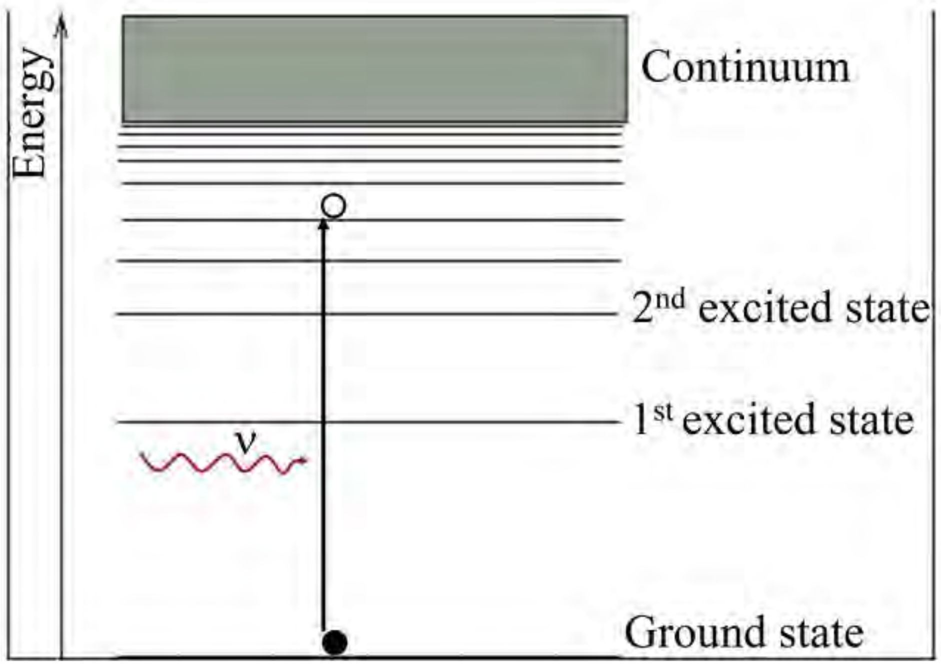
Nobel prize winners for laser

Introduction



- Energy levels - discrete - atom, ions and molecules
- Lowest possible energy level - **ground state** and higher energy levels - **excited states**
- Energy, separation between adjacent energy levels become smaller and smaller until separation becomes so small that energy levels appear continuous - **continuum**

Absorption



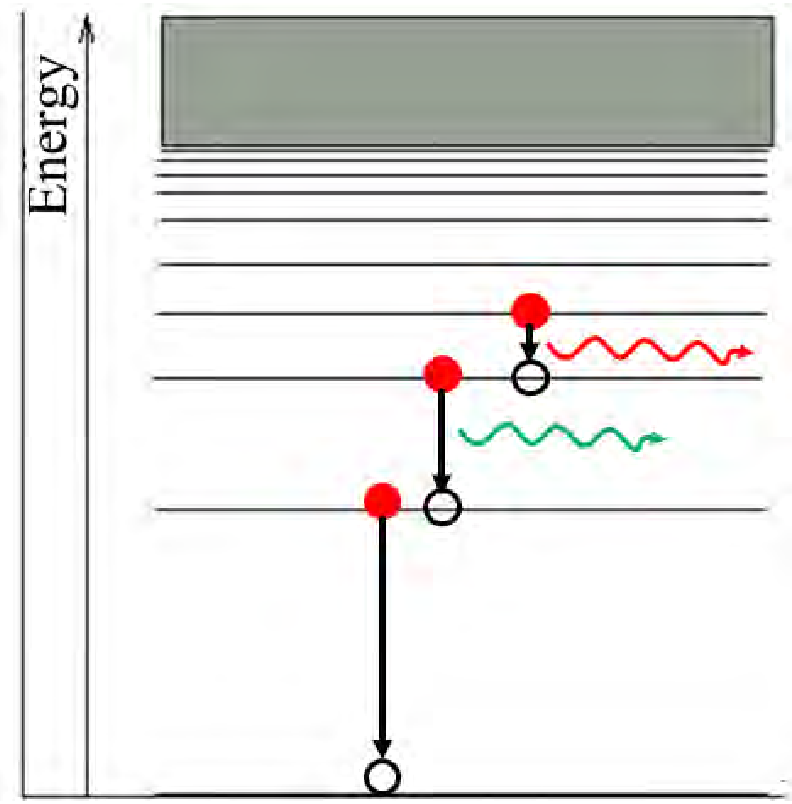
- An electron in one of lower level (**ground state or a lower lying excited state**) with energy E_i can make a transition to a **higher level** having energy E_f by absorbing an incident photon

- **Absorption** can occur only when frequency of incident radiation:

$$\nu = \frac{E_f - E_i}{h}.$$

- Otherwise matter becomes transparent to incident radiation

Spontaneous Emission



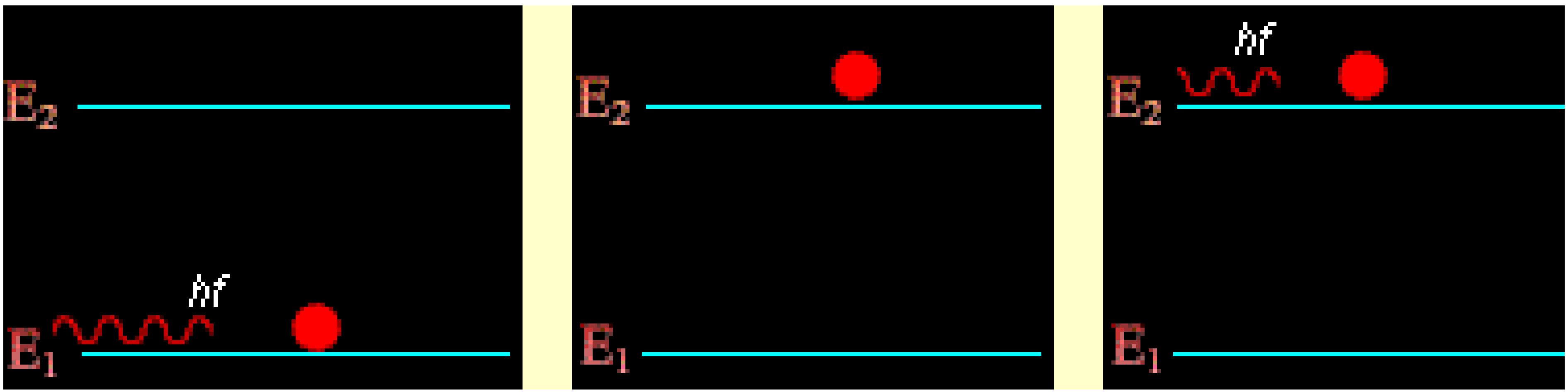
- Atoms in excited states are not in thermal equilibrium with their surroundings
- Such atoms will eventually return to their ground state by emission of a photon
- If E^* energy in excited state and E energy of a lower lying state (which could be ground state), frequency of emitted photon is given by:

$$\nu = \frac{E^* - E}{h};$$

Stimulated Emission

- In 1917, Einstein: Under certain conditions, emission of light may be stimulated by radiation incident on an excited atom
- when electron in excited state E^* and a photon whose energy is equal to difference between E^* and energy E of a lower lying level (could be ground state) is incident on atom
- Incident photon induces electron in excited state to make a transition to lower level by emission of a photon
- Emitted photon travels in same direction as incident photon
- New photon has same energy as that of incident photon and is perfectly in phase with it
- When two waves travel in same direction with a constant phase relationship, they are said to be coherent

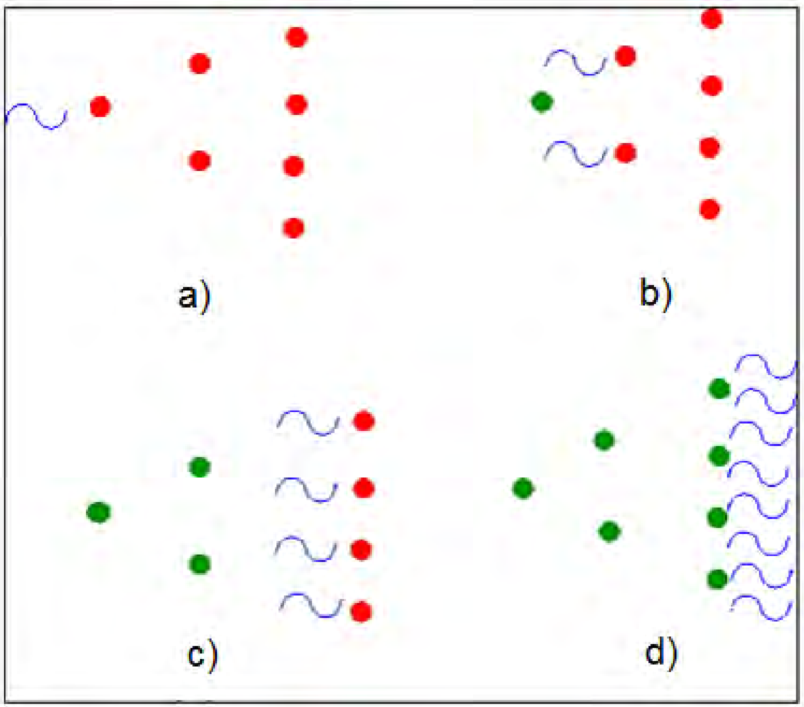
Laser System



LASER - Light Amplification by Stimulated Emission of Radiation

- In 1958, Charles H. Townes and Arthur L. Schawlow - effect of stimulated emission can be amplified to produce a practical source of light, which is **coherent** and can travel long distances without appreciable spread of **beam width**
- Such a light source called **LASER**, an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- Start with one photon which strikes an atom in an excited state and releases a photon, we would have two photons and an atom in the ground state
- These two photons, in turn, may be incident on two more atoms in excited states and give rise to four photons, and so on

LASER



- Electron remains in an excited state ~ 10^{-8} s
- Thus it is difficult to keep atoms in excited states till they are stimulated to radiate a photon
- Excited atom is more likely to de-excite spontaneously
- Photons released through spontaneous processes emitted in random directions and not coherent with incident photon
- Photons incident and generated may be absorbed by atoms in ground states, leading to depletion in number of photons

Interaction of Radiation with Matter

- To have an insight into principle of laser, we need to understand the way radiation field interacts with matter
- In early 20th century, Planck formulated theory of spectral distribution of thermal radiation
- Einstein, by combining **Planck's theory and Boltzmann statistics** gave a theory of stimulated emission - governing principle of lasers

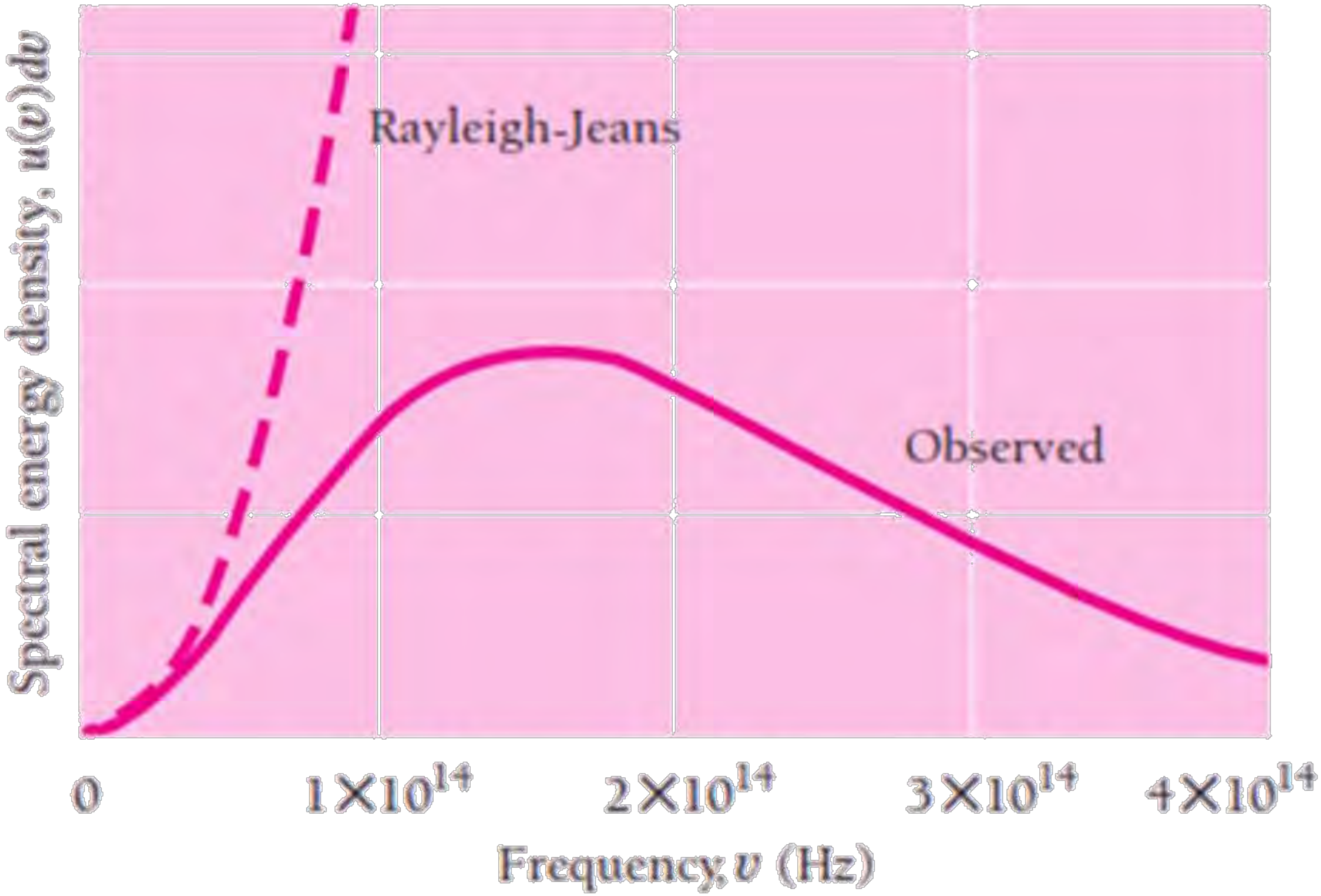
Blackbody Radiation

- Planck's formula gives radiation of radiant intensity when electromagnetic radiation confined to an isothermal cavity - known as **blackbody**
- In classical physics, radiation is considered as waves which form standing wave pattern in cavity with nodes at walls
- Classical formula for radiant energy density $u(\nu)$ at frequency ν in energy interval to $(\nu + d\nu)$: number of modes of electromagnetic waves in this interval $\times$ average energy per mode kT
- Rayleigh- Jeans' Law:

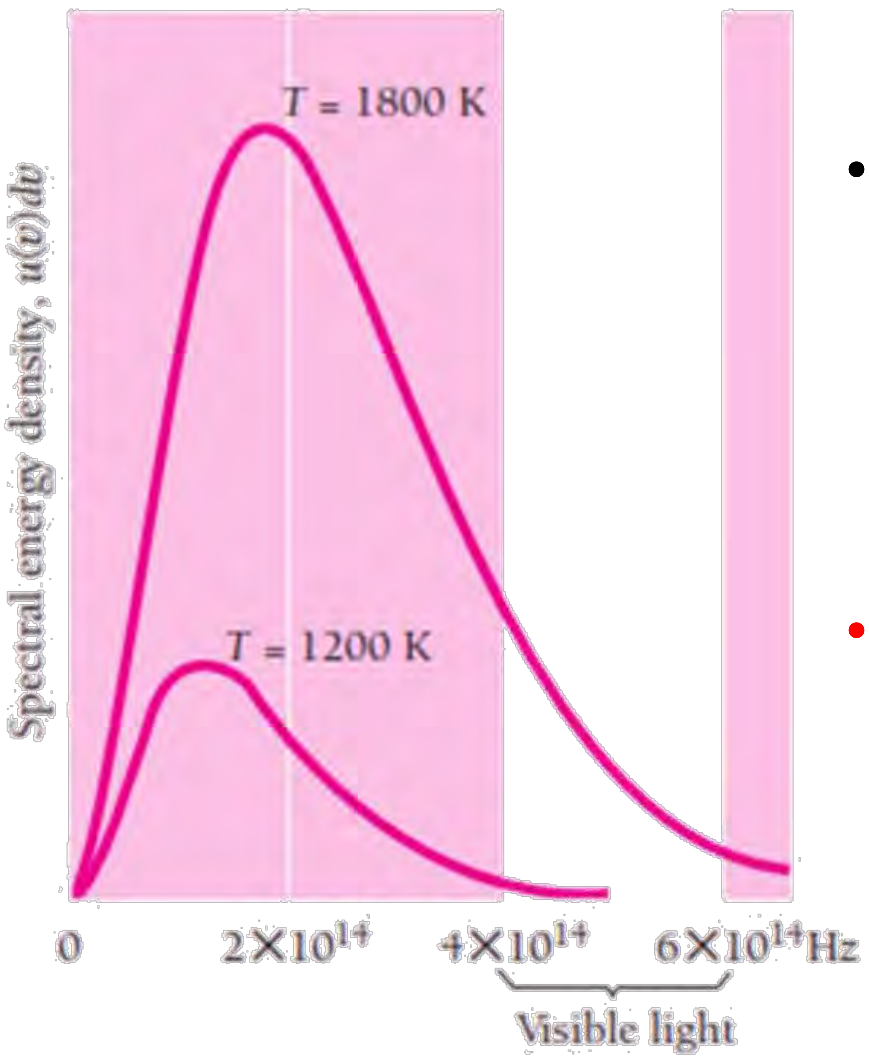
$$u(v)dv = \frac{8\pi kT}{c^3} v^2 dv$$

- Unphysical result in short wavelength region (known as **ultraviolet catastrophe**)

Blackbody Radiation



Blackbody Radiation



- Planck suggested oscillating atoms could emit or absorb energy in tiny bursts called **quanta**, energy of a quantum being proportional to its frequency

- Planck's formula for radiant energy density:

$$u(v)dv = \frac{8\pi h v^3}{c^3}\frac{1}{e^{hv/kT}-1}dv.$$

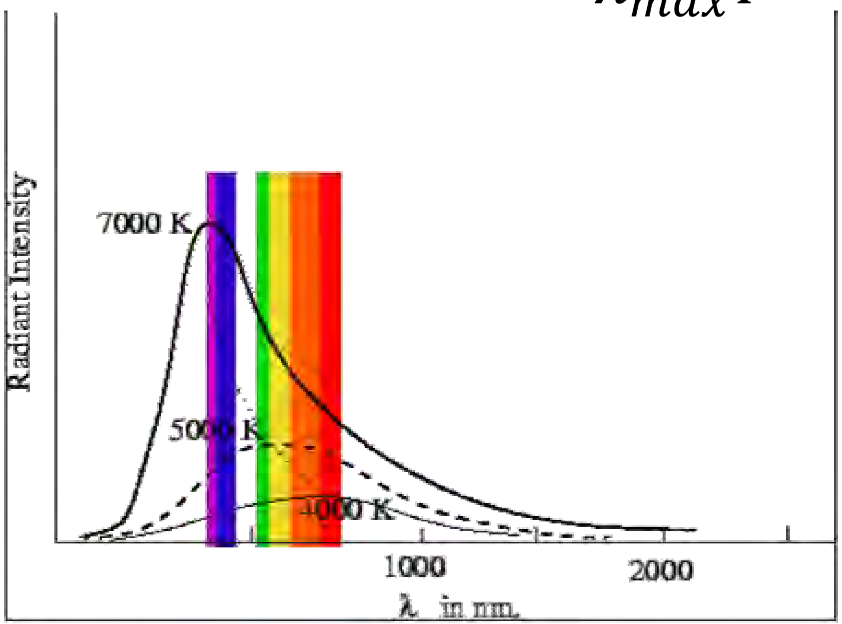
Blackbody Radiation

- Using Planck's law one can show that total power emitted by a blackbody at temperature T is:

$$U = \sigma T^4, \sigma \; - Stefan's\, constant \; - 5.67 \times 10^{-8}\, J - \frac{K^4}{m^2}$$

- Emitted radiation has a peak at wavelength λ_{max} give by Wien's Displacement Law:

$$\lambda_{max} T = 2.9 \times 10^{-8}\, m - K$$



- For instance, a blackbody at a temperature of 5000 K has a radiation peak at 580 nm, which is near middle visible region

Boltzmann Statistics

- **Two level system:** N_1 number of atoms per unit volume in energy level E_1 and N_2 in higher energy level E_2. $E_1 - E_2 = h\nu$
- Total population density in the system: $N_1 + N_2$

- At thermal equilibrium with surrounding at a temperature T, relative population in two levels by **Boltzmann distribution:**

$$\frac{N_2}{N_1} = e^{h\upsilon/kT}$$

- As temperature increases, population of excited states increases
- However, population of an excited state always lies lower than population of ground state, under equilibrium condition
- For large energy gaps such that $h\upsilon \gg kT$, ratio is close to zero so that very few atoms are in upper energy state

Boltzmann Statistics

- When two or more states have same energy, states are said to be degenerate
- Number of states at same energy level is called multiplicity of energy level
- As all states having same energy have same population, we have
-

$$\frac{N_2}{N_1} = \frac{g_1}{g_2} e^{h\upsilon/kT}$$

where g_1 and g_2, respectively, are multiplicities of levels E_1 and E_2

Einstein Relations - A and B Coefficients

- Distribution of atoms in two energy levels will change by absorption or emission of radiation
- Einstein introduced three empirical coefficients to quantify change of population of two levels

- **Stimulated Absorption:** Population of upper level will increase due to absorption of radiation by atoms in lower level
- Rate is proportional to population of atoms in lower level N_1 and to energy density $u(v)$ of radiation in system: $\frac{\partial N_2}{\partial t} \propto u(v)N_1$
- If B_{12} is probability (per unit time) of absorption of radiation, rate of increase of population of excited state:

$$\frac{\partial N_2}{\partial t} = B_{12}u(v)N_1,$$

where B_{12} constant of proportionality ($m^3s^{-2}J^{-1}$)

Einstein Relations - A and B Coefficients

- **Spontaneous Emission:** Population of upper level will decrease due to spontaneous transition to lower level with emission of radiation
- Rate of emission will depend on population of upper level
- If A_{12} is probability that an atom in excited state will spontaneously decay to ground state:

$$\frac{\partial N_2}{\partial t} = -A_{12}N_2,$$

- Solution of eqn.: $N_2(t) = N_2(0)e^{-t/\tau}$ where $\tau = 1/A_{12}$, - average lifetime of an atom in excited level before returns to ground state
- Spontaneous emission depends on lifetime of atom in excited state
- Process is statistical and emitted quanta bear no phase relationship with one another, i.e. the emission is incoherent

Einstein Relations - A and B Coefficients

- **Stimulated Emission:** depends on number of atoms in excited level as well as on energy density of incident radiation
- If B_{21} be transition probability per unit time per unit energy density of radiation, rate of decrease of population of excited state is $B_{21}u(v)N_2$
- Rate equation for the population of the upper level is:

$$\frac{dN_2}{dt} = B_{12}u(v)N_1 - [A_{21} + B_{21}u(v)]N_2$$

- Since $N_1 + N_2$ is constant,

$$\frac{\partial N_2}{\partial t} = -\frac{\partial N_1}{\partial t},$$

- Emitted quanta under stimulated emission are coherent with impressed field
- Spontaneous emission, being incoherent, is a source of noise in lasers

Einstein Relations - A and B Coefficients

- When equilibrium is reached, population of levels remains constant, so that $\frac{dN_2}{dt} = 0$ and rate of emission equals rate of absorption, so that:

$$B_{12}u(v)N_1 = [A_{21} + B_{21}u(v)]N_2$$

- Using the Boltzmann factor,

$$\frac{N_2}{N_1} = \frac{g_1}{g_2}e^{hv/kT},$$

$$u(v) = \frac{A_{21}\frac{g_2}{g_1}}{B_{21}e^{hv/kT} - B_{21}\frac{g_2}{g_1}} = \frac{A_{21}/B_{21}}{\frac{g_1}{g_2}e^{hv/kT}\frac{B_{12}}{B_{21}} - 1}.$$

Einstein Relations - A and B Coefficients

- If we regard matter to be a blackbody and compare above expression for energy density with corresponding energy density expression derived for blackbody radiation:

$$u(v)dv = \frac{8\pi h v^3}{c^3}\frac{1}{e^{hv/kT} - 1}dv$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3}, and\ \frac{B_{21}}{B_{12}} = \frac{g_1}{g_2},$$

- In absence of degeneracy, probability of stimulated emission is equal to that of stimulated absorption
- In view of this, replace two coefficients by single coefficient: B - coefficient
- Spontaneous emission coefficient: A - coefficient.

Einstein Relations - A and B Coefficients

- Ratio of spontaneous emission probability to stimulated emission probability is:

$$\frac{A}{Bu(\upsilon)} = e^{h\upsilon/kT} - 1,$$

- For low temperatures, when $\frac{h\upsilon}{kT} \gg 1$, spontaneous emission is much more probable than induced emission and latter may be neglected
- For high enough temperatures, stimulated emission probability can be significant though for optical frequencies, this requires very high temperature

- For microwave frequencies, stimulated emission processes may be significant even at room temperatures

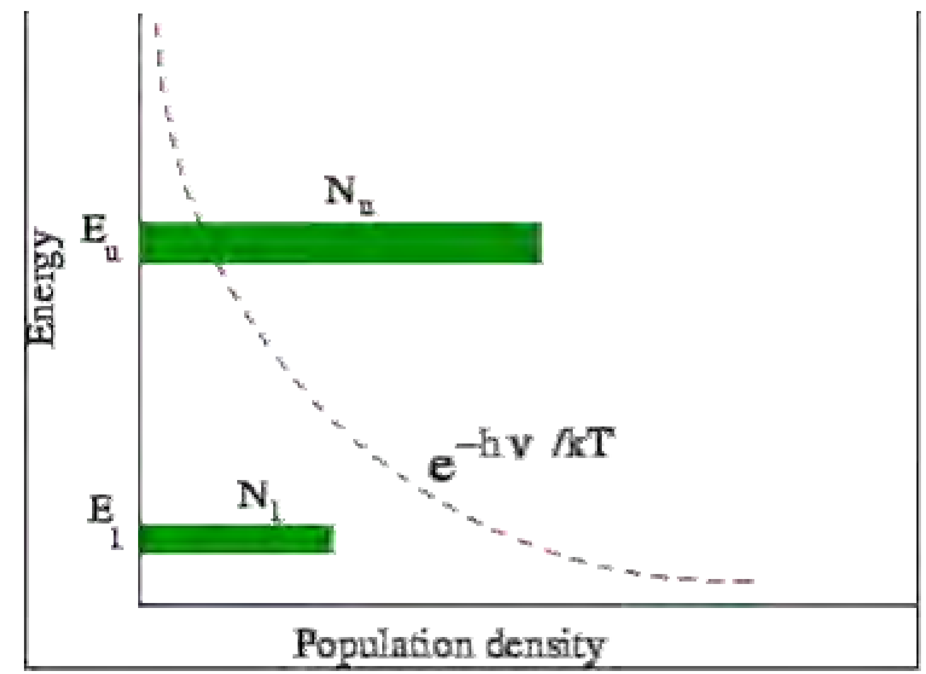
Population Inversion

- When atoms are in equilibrium with surrounding, population of atoms in ground state is more than that in any of excited states
- Population of excited states can be increased by absorption of radiation
- However, life time in excited states being typically of the order of 10^{-8} s, atoms which make transitions to excited states fall back to ground state soon thereafter
- This is also indicated by ratios of Einstein coefficients
- It is, therefore, not possible to keep population in excited states higher than that in ground state

- Basic principle involved in operation of laser is population inversion, a situation in which population of excited state is kept higher than that of ground state

Population Inversion

- When $N_u < N_l$, i.e., the population in upper level is less than that in lower level, number of transitions from lower to upper level with absorption of radiation is more than that with emission and hence radiation is attenuated
- If, on the other hand, $N_u > N_l$, emissions are more than absorption and radiation is amplified as it passes through the material.



MASER

Maser: Microwave Amplification by Stimulated Emission of Radiation

- Townes, 1951, devised method to amplify microwaves Wavelength about 1 cm.
- Townes with PhD student Gordon demonstrated this using ammonia molecules in April 1953.

This was first MASER

MASER

- Frequency of microwave photons is 10^{13} Hz, corresponding to an energy of the order of 0.01 eV
- Energy is of same order as that of thermal energy of air molecules
- In such a case, population of excited states is comparable to that of the ground state at room temperatures
- process of stimulated emission can then be used to amplify microwave signal
- MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation

LASER

16 May, 1960,

Theodore H Maiman, Hughes Labs, generated a laser beam

wavelength 694 nm

from a ruby rod in a coiled flash lamp.

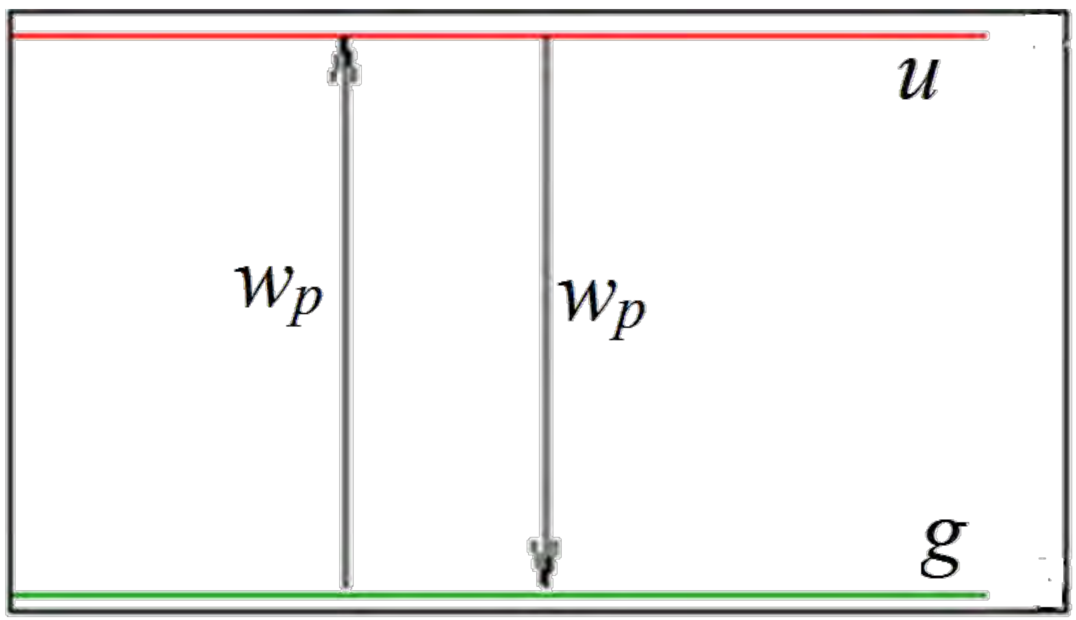
Paper submitted for publication Rejected.

Results announced in New York Times, 8 July 1960.

Paper accepted by “Nature”, appeared 6 August 1960.

Rate Equations for a Two Level System

- A two level system with upper level u and ground level g
- In order that laser transition may occur, we need a population inversion
- As at normal temperatures, population of lower level is more than that at upper level, atoms must be pumped into upper level by providing them energy equal to the energy difference between two levels.



Rate Equations for a Two Level System

- If B_p is pumping induced transition rate for $N_g \to N_u$ or $N_u \to N_g$ and τ is natural lifetime of atoms in upper level, rate equation for two levels:

$$\frac{dN_u}{dt} = -\frac{dN_g}{dt} = w_p(N_g - N_u) - \frac{N_u}{\tau},$$

where $N_g + N_u = N = const$. In the steady state, the time derivatives vanish,

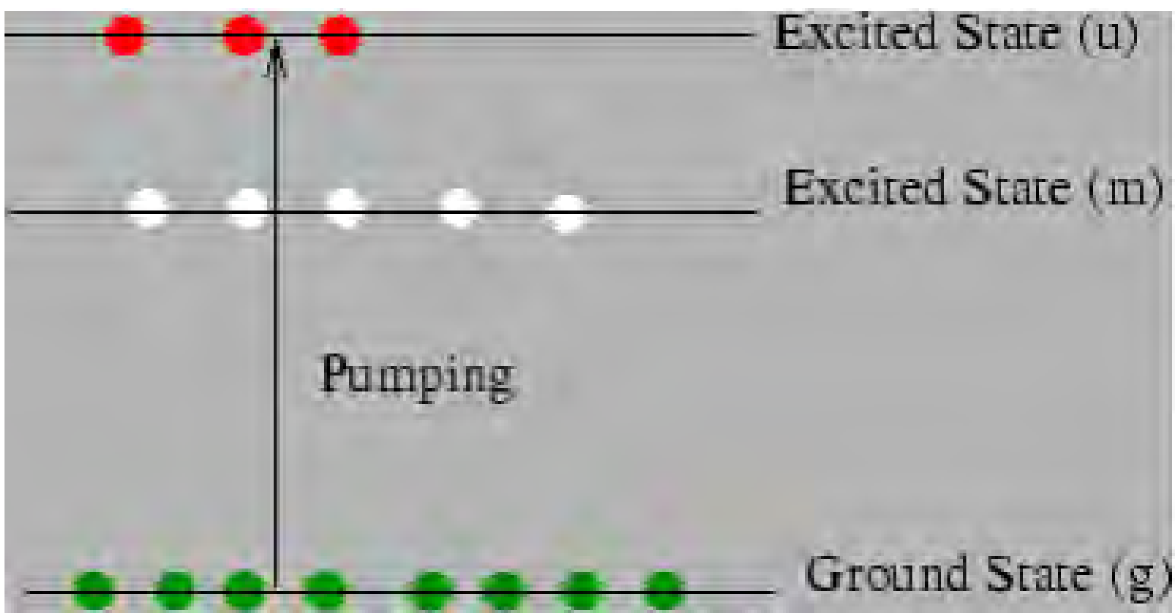
$$N_u = N\frac{w_p\tau}{1 + w_p\tau}.$$

- In order that a population inversion may take place, we must have $N_u > N_g$.

- Thus population inversion is not possible in a two level system

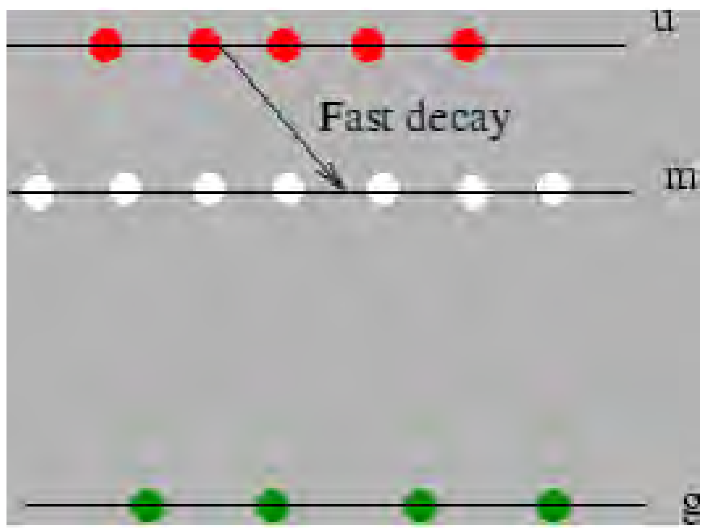
Three Level Laser

- For optical frequencies, population inversion cannot be achieved in a two level system
- In 1956 Bloembergen proposed a mechanism in which atoms are pumped into an excited state u by an external source of energy (such as by an electric pulse or by optical illumination)



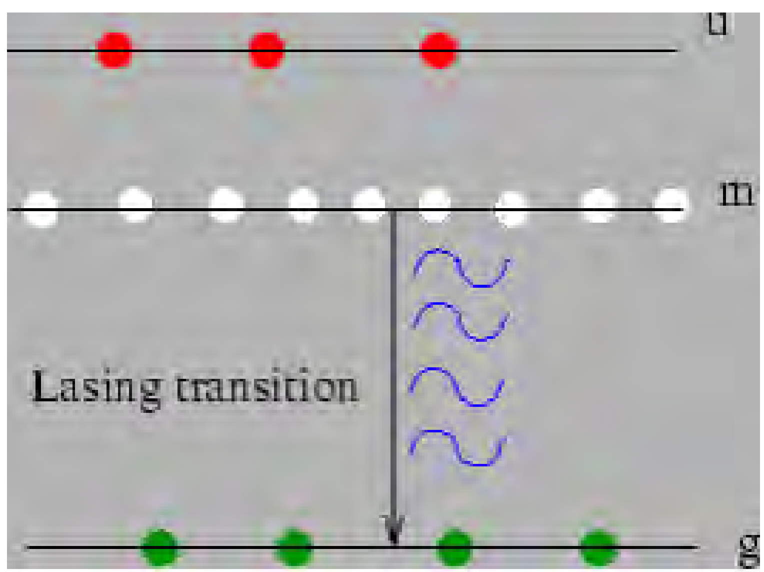
Three Level Laser

- The system, in addition to state u, has an excited state m which is a metastable state, i.e. a state in which atom has a longer life time
- Atoms u decays spontaneously to metastable state m
- Life time in level m is such that rate of spontaneous decay from level m to ground level g is slower than rate at which atoms decay from u to m.
- This results in a population inversion between metastable level and ground state



Three Level Laser

- Emitted photons are confined to a laser cavity to stimulate further emission from excited atoms
- Ruby laser works on principle of a three level system
- pumping power required for such a system is very high because more than half of ground state atoms have to be pumped into upper level to achieve population inversion



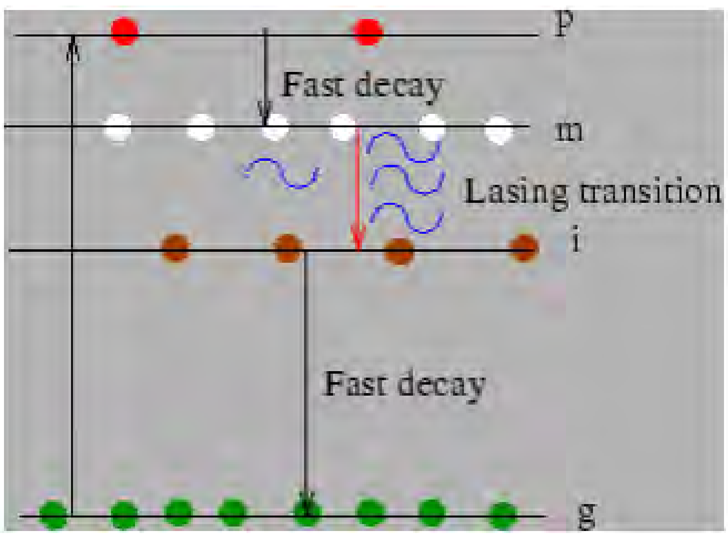
Three Level Laser

- As $N_m \cong N_g = N/2$ and $N_m - N_g << N$, once the population inversion is achieved, power required to maintain it is small
- $u \rightarrow m$ transition is generally radiation less, the energy being given away to lattice
- As more than half of atoms are to be raised to the level m, the probability of spontaneous emission is also much higher
- Laser transition occurs from metastable state to lowest possible state which are well separated

- This leads to low efficiency

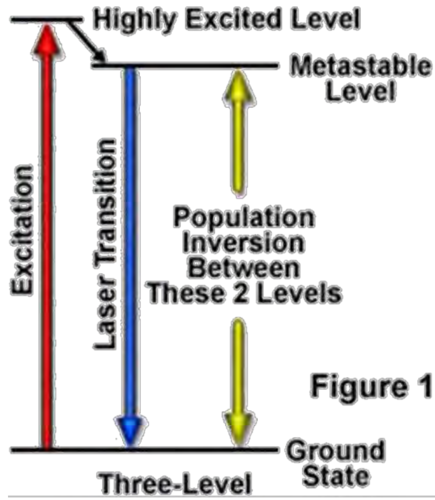
Four Level Laser

- One of most popular and low cost lasers is helium-neon laser, which works on the basis of a four level system with two levels intermediate between the ground state g and pump level p
- Ground state atoms are electrically pumped to a short lived state p
- Atoms from this state undergo fast decay to a metastable state m
- Between m and g, yet another short lived excited state i exists
- A population inversion takes place between this intermediate state i and metastable state m, between which the lasing transition occurs

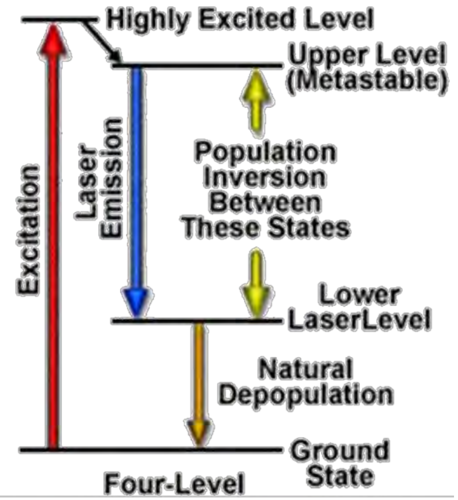


- population inversion occurs even for very small pumping power

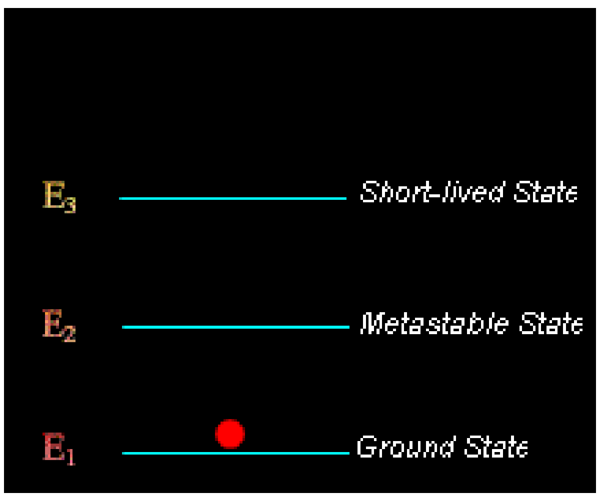
Laser System

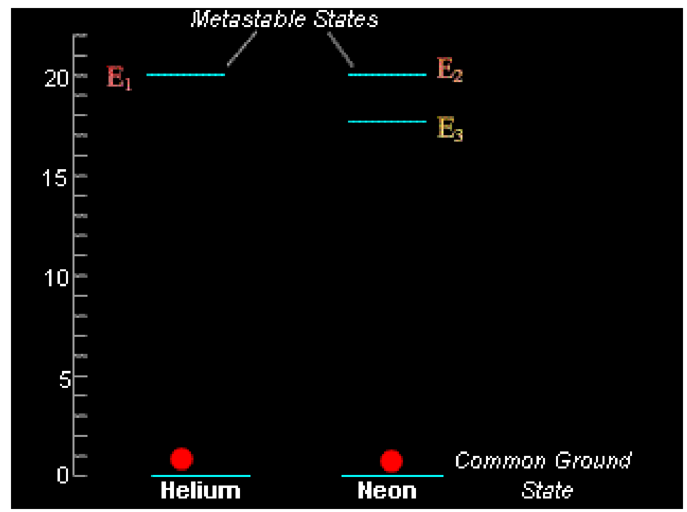


Ruby laser

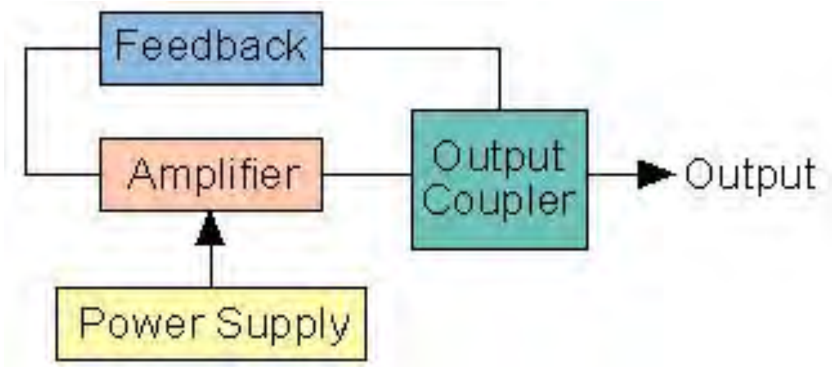


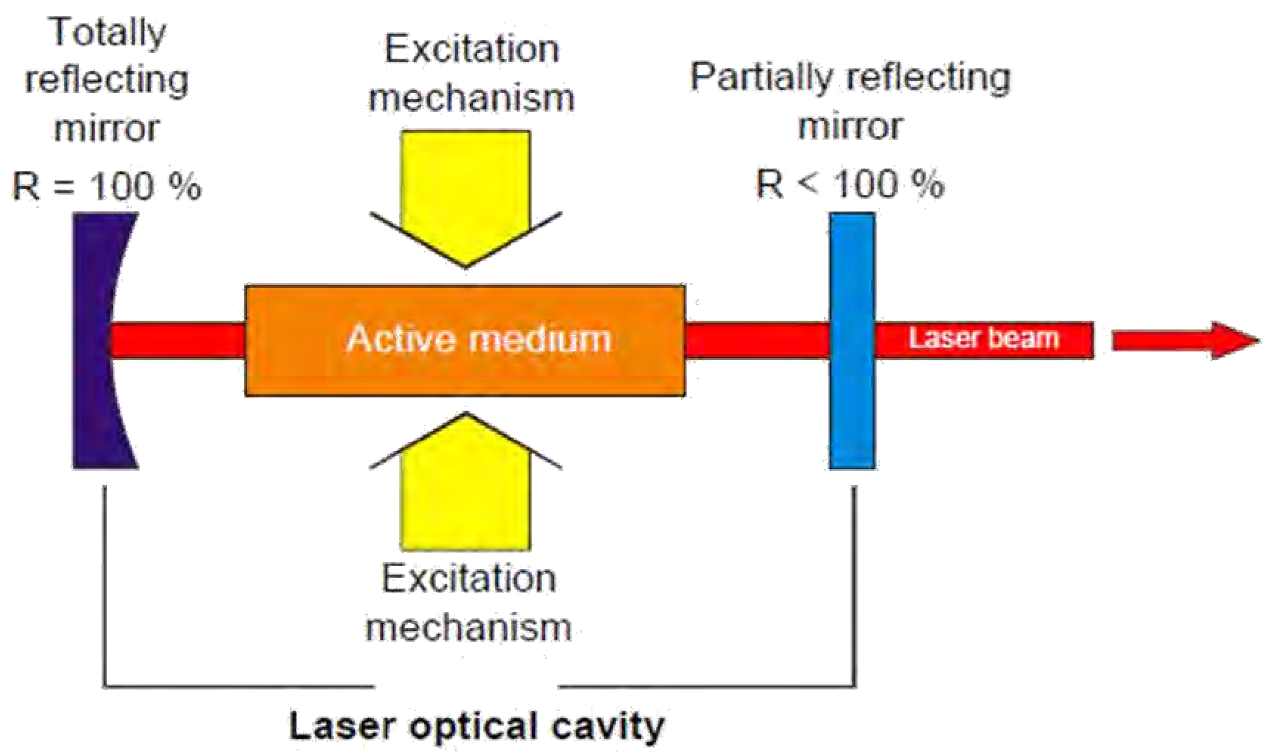
HeNe laser





Laser System



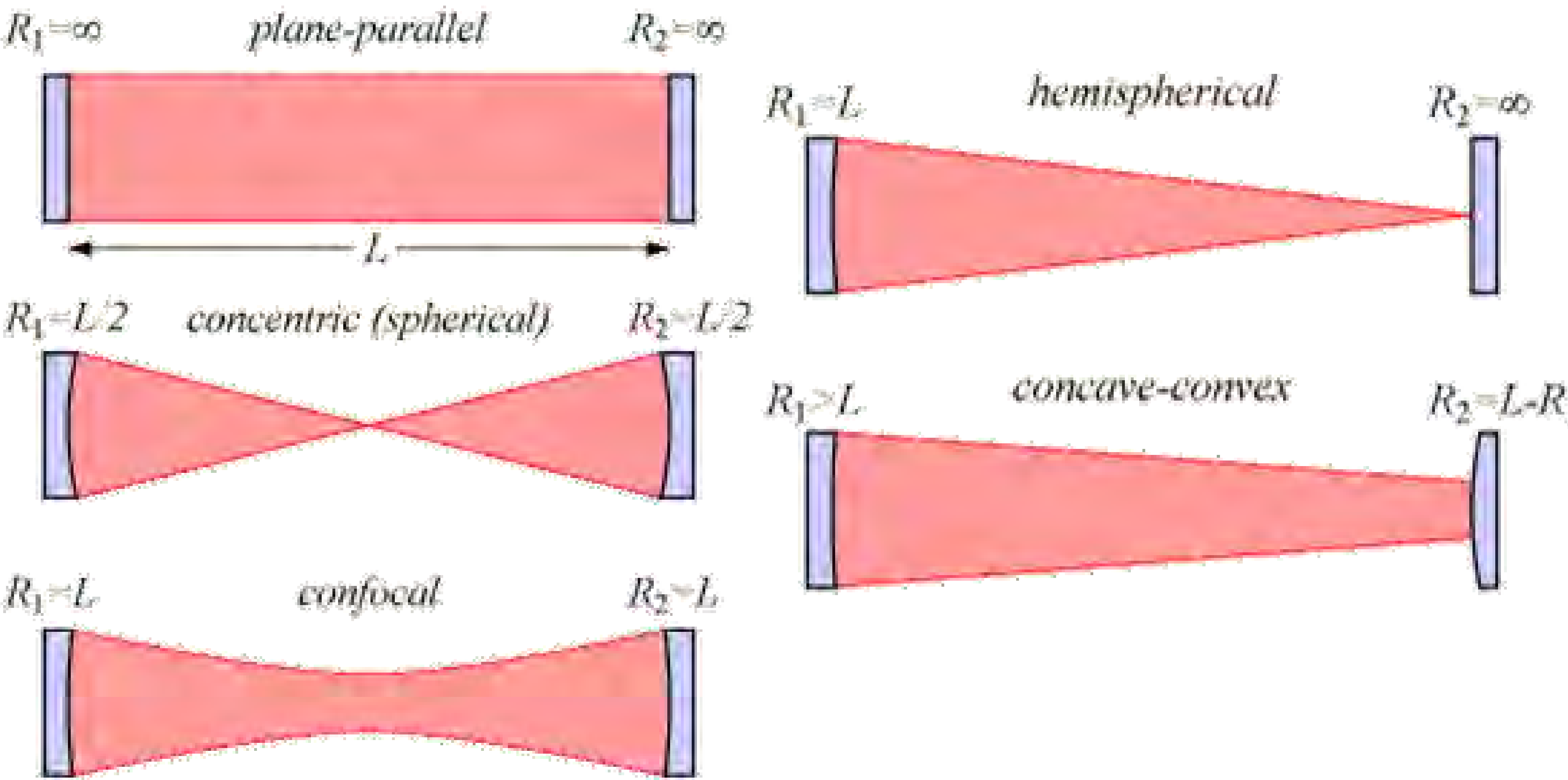


Resonator

Optical cavity, resonating cavity or optical resonator

- Laser radiation can circulate and pass a gain medium which compensates optical losses
- Light confined in cavity reflects multiple times producing standing waves for certain resonance frequencies
- Standing wave patterns produced are called modes; longitudinal modes differ only in frequency
- Transverse modes differ for different frequencies and have different intensity patterns across the cross section of the beam.

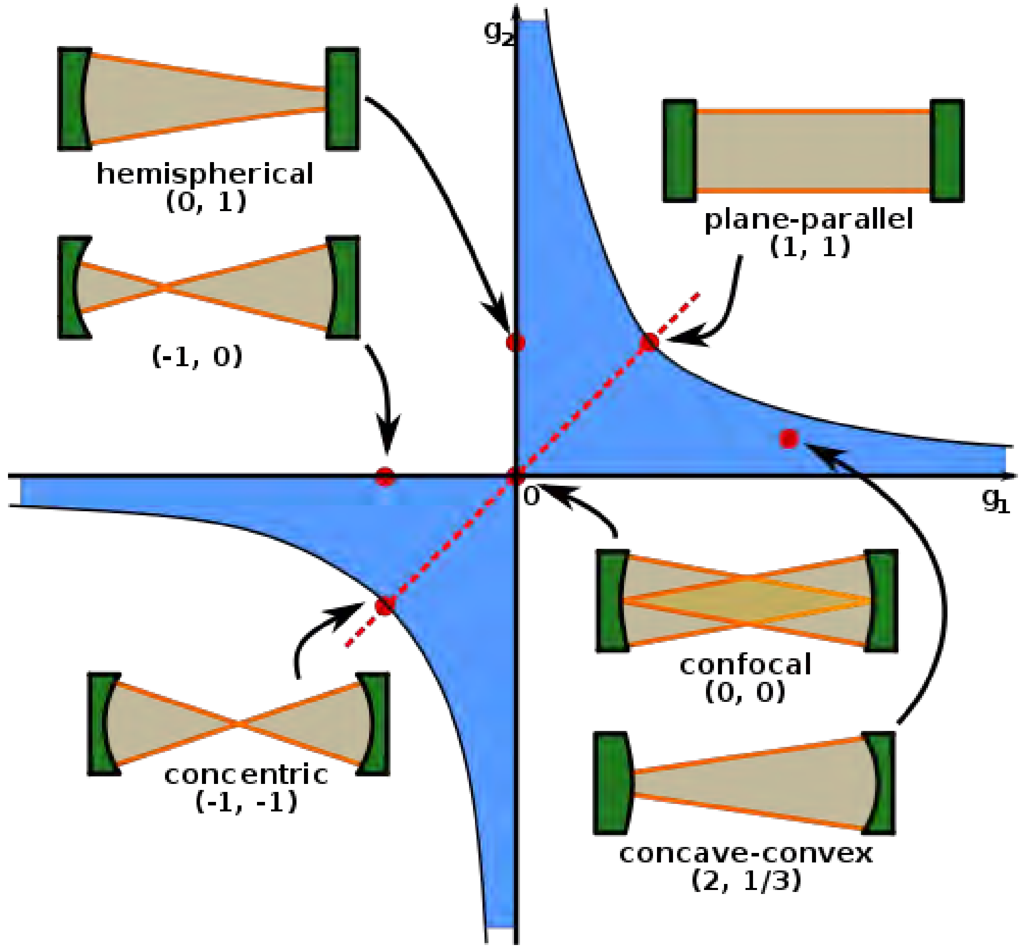
Resonator



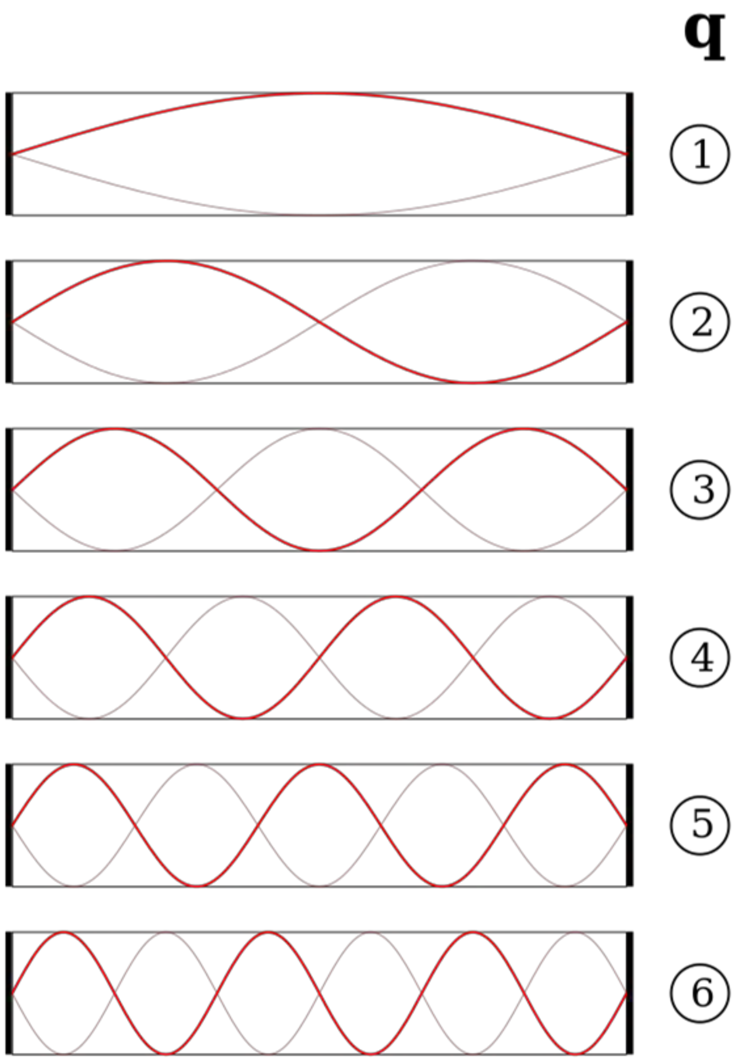
R₁=∞
plane-parallel
R₂=∞
L
R₁=L
hemispherical
R₂=∞
R₁=L/2
concentric (spherical)
R₂=L/2
R₁>L
concave-convex
R₂=L-R₁
R₁=L
confocal
R₂=L

Resonator

$$0 < \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) < 1$$



Resonator – Longitudinal Modes

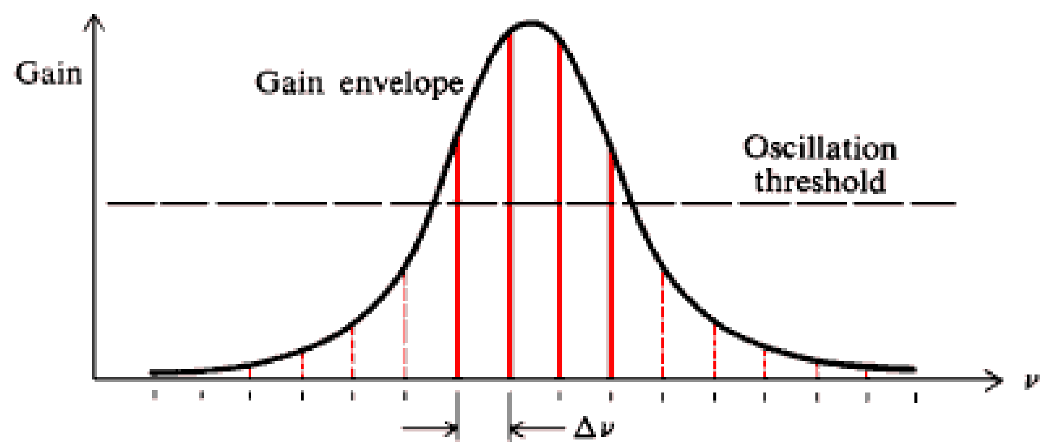


$$L = q\frac{\lambda}{2};$$

$$q\ - integer\ (mode\ order);$$

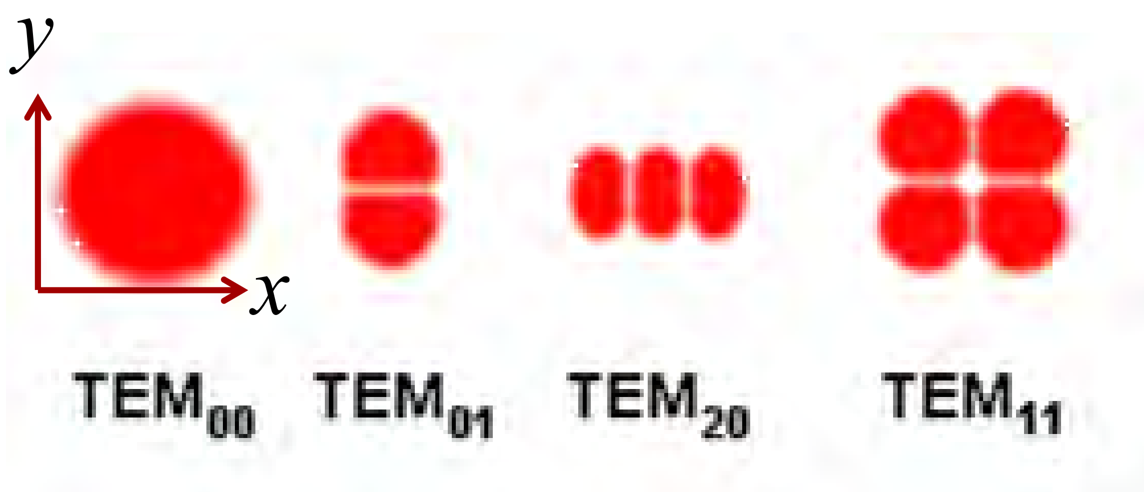
$$\Delta\nu = \frac{c}{2nL};$$

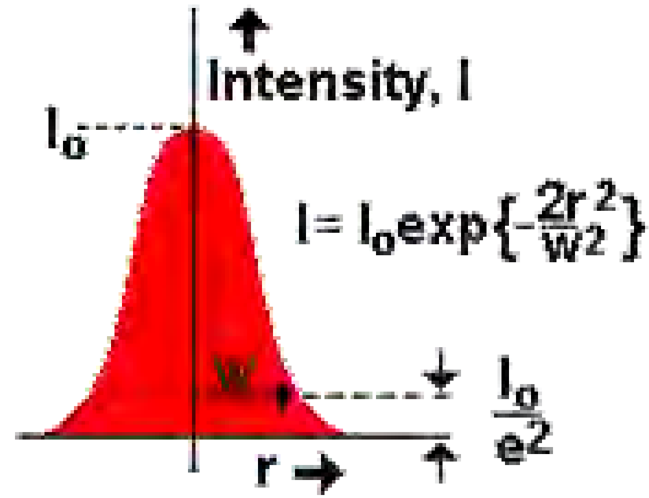
$$\text{n} - refractive\ index$$



Resonator - Transverse Modes

Transverse Electromagnetic Modes (TEM)





TEM$_{00}$ Mode: Gaussian intensity profile and shows lower divergence than higher order transverse modes

LASER

Components

- **Active medium** - solid crystals (Ruby, Nd:YAG), semiconductors, gases (CO_2, He-Ne, Ar-ion), liquid dyes - excitation
- **Excitation Source** – optical (flash lamps), electrical (discharge) – population inversion
- **Resonator** - Highly reflective (100 %) and partially transmissive mirrors (95 %)

Types

- **Solid State lasers** – Ruby laser, Nd:YAG (1.06 μm), Ho:YAG (2.09 μm), Er:YAG (2.94 μm), DPSS-Yb (1.03 μm)

- **Gas lasers** - CO_2 (10.6 μm), ArF (193 nm), KrF (248 nm), XeCl (310 nm)

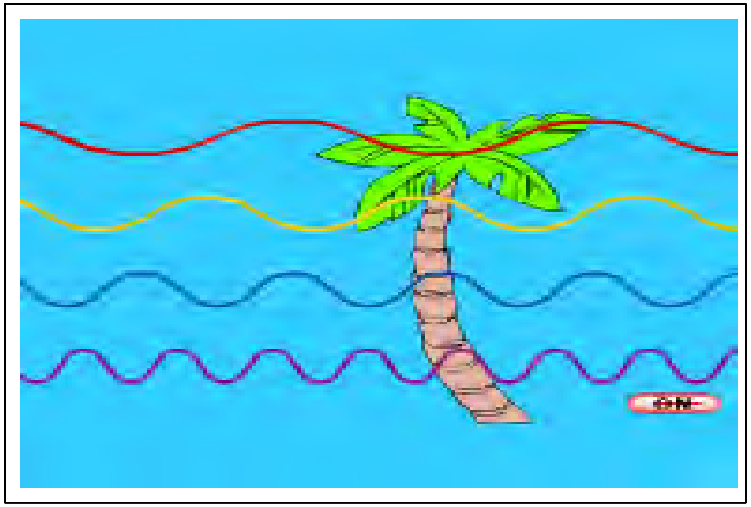
- **Liquid lasers** – Organic dyes – wavelength tunability (IR to UV)

Characteristics

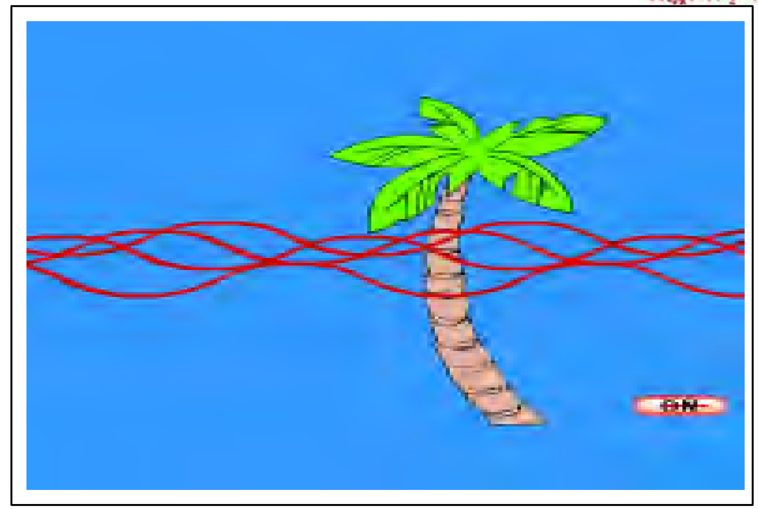
- Monochromatic
- Coherent
- Highly Directional (Less Divergence)
- High Brightness

Characteristics – monochoromatic, coherence

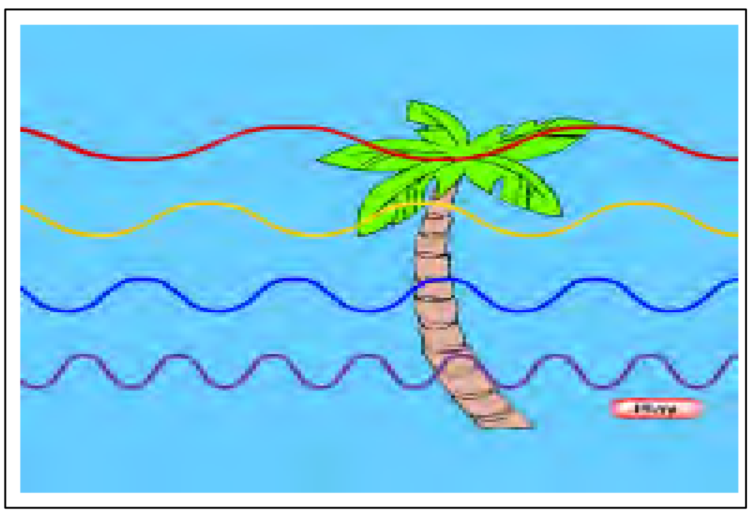
Ordinary Light



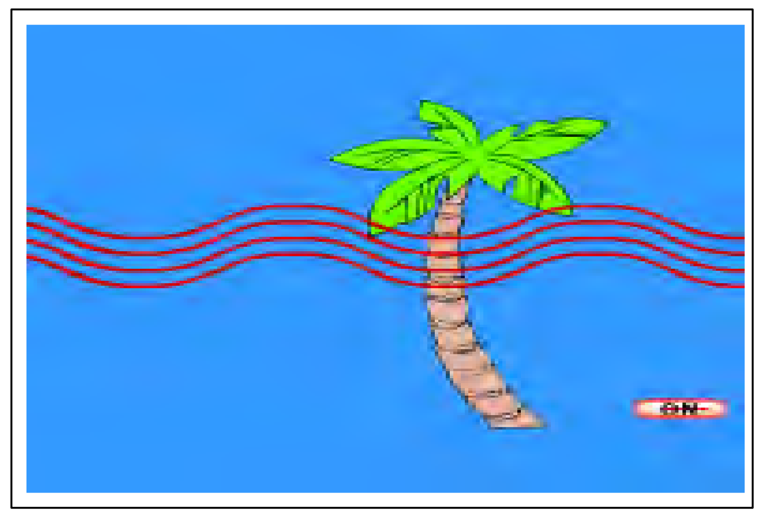
Monochromatic



White Light



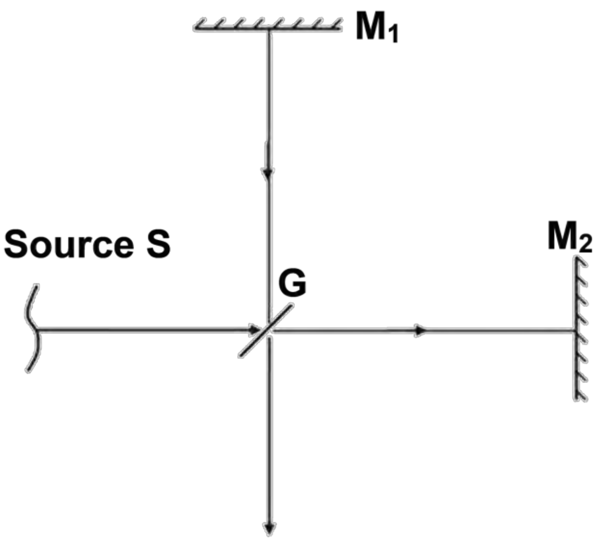
Coherent



Coherence

- Laser beam is highly coherent, i.e, different parts of beam maintain a phase relationship for a long time results in interference effect
- Temporal Coherence ($\Delta\tau$) : Time $\Delta\tau$ after which phase correlation between two waves which were initially in phase (or between two points in same wave which had a known phase difference) drops significantly
- loss of coherence - optical source does not emit a continuous wave for all time to come
- Thermal sources: Typical life time of $\Delta t = 10^{-7}$ s so that a wave which seems continuous, actually consists of a sequence of waves which are typically $c\Delta t \approx 0.3\ m$ long with no phase correlation between parts of one wave train and another

Temporal Coherence



- Temporal coherence: A measure of monochromaticity of beam
- When mirrors $M_1$and M_2 are nearly equidistant from G, i.e, when two waves traversing two different paths take same amount of time, then contrast of interference fringes formed is good
- If M_1 is slowly moved away from G, then for ordinary source of light (sodium lamp), contrast in fringes goes on decreasing and when difference between distances from G to M_1 and M_2 is about few millimeters to few centimeters, fringes are no longer visible

Temporal Coherence

Decrease in contrast of fringes:

- Source S emitting small wave trains of average duration τ_c and there is no phase relationship between different wave trains
- This is in contrast to an infinitely long pure sinusoidal wave train, which is referred to as monochromatic wave
- When difference in time taken by wave trains to travel the paths G to M_1 and back and G to M_2 and back is much less than τ_c, then interference is produced between two wave trains each one being derived from same wave train
- Hence even though different wave trains emanating from S do not have definite phase relationship, since superimposing two wave trains derived from same wave train, fringes of good contrast will be seen

Temporal Coherence

- On the other hand, if difference in time taken is much more than τ_c, then superimposing two wave trains which are derived from two different wave trains, and since there is no definite phase relationship between two wave trains emanating from S, contrast in fringes becomes gradually poorer and eventually for larger distances, fringes disappear
- Hence as mirror M_1 is moved, contrast in the fringes becomes poorer and poorer and for large separations no fringes would be seen
- The time τ_c is referred to as coherence time and length of wave train $c\tau_c$ is referred to as longitudinal coherence length

Temporal Coherence

- For example, Neon 632.8 nm line from a discharge lamp, interference fringes would vanish if the path difference between two mirrors is about a few centimeters
- Thus for this source, $\tau_c \sim 100$ ps
- On the other hand, for the red cadmium line at 643.8 nm, coherence length is about 30 cm, which gives $\tau_c \sim 1$ns
- Non-monochromaticity of light source can also equally well be interpreted as the reason for poor fringe visibility for large optical path differences

Temporal Coherence

- In a laser, in contrast to an ordinary source of light, the optical resonant cavity is excited in different longitudinal modes of cavity which are specified by discrete frequencies of oscillation
- In contrast to $\Delta\nu \sim 10^{10}$ Hz, for ordinary source of light, for a well-controlled laser one can obtain $\Delta\nu \sim 500$ Hz, which gives $\tau \sim 2$ ms
- Corresponding coherence length is about 600 km
- Such long coherence lengths imply that laser could be used for performing interference experiments with very large path differences
- For laser oscillating in many modes, the monochromaticity depends on number of oscillating modes
- For a pulsed laser, minimum linewidth is limited by duration of pulse
- Thus for 1 ps pulse, coherence time is 1 ps and the spectral width would be about 10^{12} Hz

Temporal Coherence

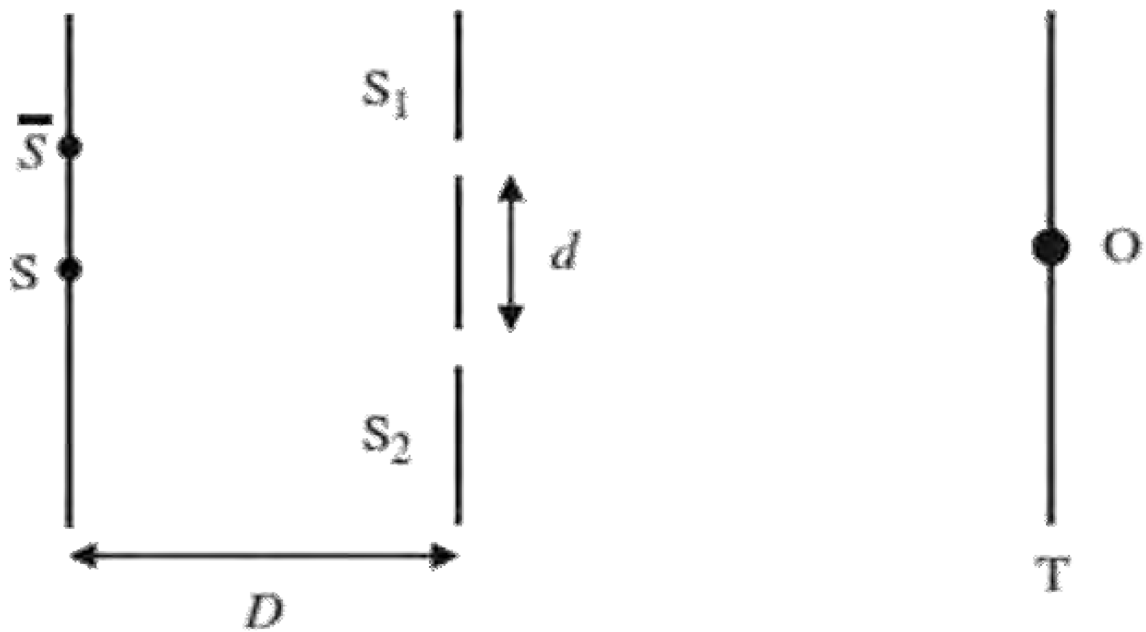
- **Exercise:** A He-Ne laser operating at 630 nm has an emission width of $\Delta\lambda = 10^{-6}$ nm. Calculate the temporal coherence length

- It may be noted that a laser beam is highly monochromatic with the spread of wavelength being very small

- **Exercise:** An Argon laser operating in single mode has a linewidth of 7.5 MHz. Calculate its coherence length

Spatial Coherence

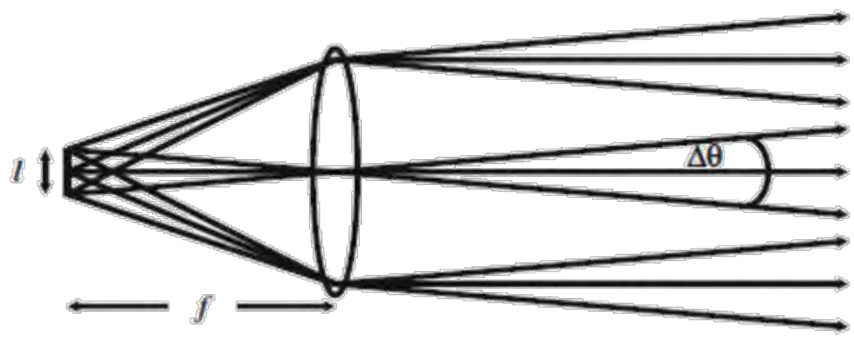
- **Spatial coherence:** Distance over which phase correlation exists between different points in same wave in a direction perpendicular to direction of observation



Characteristics – directionality

Directionality – Less Divergence

- less than 10^{-5} radians (~ 2 s of arc) extremely small divergence
  - surveying, remote sensing, LIDAR, etc.

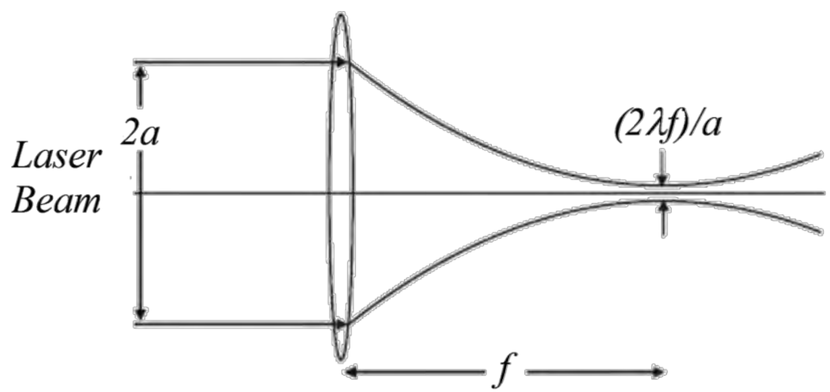


- Divergence of laser beam is primarily due to diffraction
- Most laser beams - spot size (radius of cross section of laser beam) of beam is about few millimeters
- Divergence angle of beam: $\theta \approx \dfrac{\lambda_0}{\pi \omega_0}$, λ_0 – free space wavelength

  ω_0 – spot size

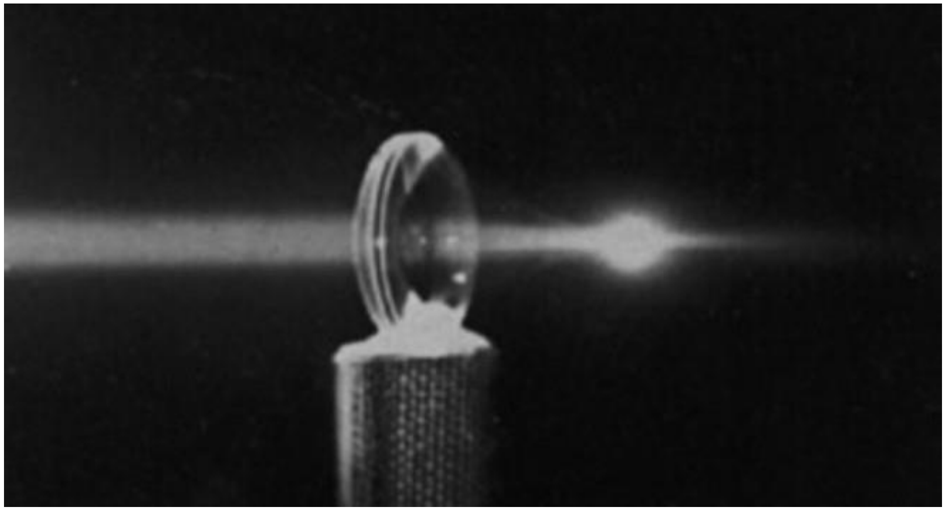
Characteristics – directionality

- Spot size 1 mm and wavelength of 0.6 μm, divergence angle ~ 0.01°
- **Tight Focusing:** focused to very small areas - few (μm)^2 - determined by diffraction effects - Smaller λ - smaller spot size
- surgery, material processing, compact discs
- *F – number = focal length / lens dia.; Camera smaller f – number better resolution*
- laser beam falls on convex lens - radius of focused spot $\propto$ wavelength and *f-number*, (laser beam fills entire lens area)



Characteristics – directionality

- lens *f-number - 2* (i.e., focal length twice lens diameter), then for a laser wavelength of 600 nm the radius of focused spot - 1.5 μm
- Area of focused spot = 7 μm^2
- Power of 1 MW (= 10^6 W), intensity at focused spot would be 14 TW/cm^2 light lead to electric fields of 10^9 V/m – **spark in air**
- very high electric fields inside medium, can change properties medium - **non-linear effects**



Characteristics – directionality

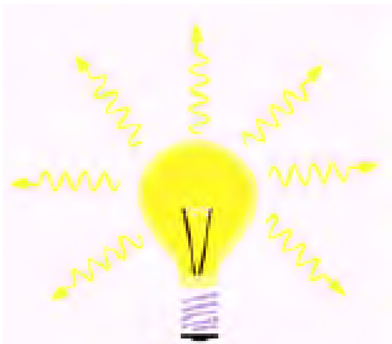
- Low-power (≈ 2 mW) diffraction-limited laser beam incident on eye focused to very small spot - intensity 100 W/cm^2 on retina – damage the retina
- 20 W bulb at 5 m from eye, produces bulb image on retina and produce intensity only 10 W/m^2 on retina - eye surgery and laser cutting
- Directly looking at sun, power density in image 30 kW/m^2
- On earth, about 1.35 kW of solar energy is incident (normally) on 1 m^2
- Energy entering eye is about 4 mW - sun subtends 0.5° on earth, radius of image of sun (on retina) is about 2×10^{-4} m
- If we directly looking at sun power density in image formed is 30 kW/m^2
- Never look into sun; retina will be damaged not only because of high intensities but also because of large ultraviolet content

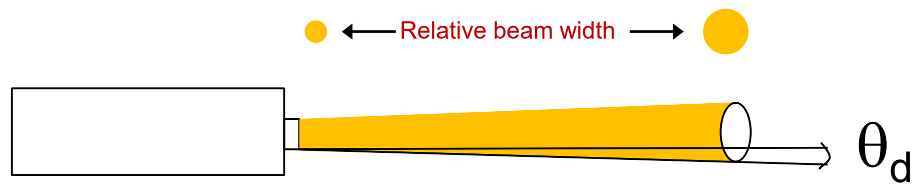
Realization of artificial stars in sky

- At 95 km above earth surface - a layer containing sodium atoms
- Laser beam at 589 nm is sent up, then sodium atoms absorb radiation, get excited to a higher energy level, and then emit spontaneously when they get de-excited
- Some of this radiation is traveling towards earth - resembles a star
- Position of artificial / guide star can be adjusted by changing direction of laser beam
- Pulsed lasers emitting a power of about 20 W and pulse widths of 100 ns are used to create star
- Correction of images formed by telescopes on earth
- Light coming from objects outside earth has to pass via turbulent atmosphere, image of any extra terrestrial object will not be stable
- By looking at image of this artificial star it is possible to determine correction to optical system required in real time for canceling effects of turbulence

Characteristics – directionality

Directionality – Less Divergence





Beam Divergence: $\theta_d = \dfrac{\beta\lambda}{D}$

β ~ 1= f(type of amplitude distribution, definition of beam diameter)
λ = wavelength
D = Beam diameter

Characteristics – Brightness

Brightness of Sun

Surface temperature ~ 6000 K

Stefan's Law $\rho = \sigma T^4 = 5.6696 \times 10^{-8} \times 6000^4$

Energy density $= 7.4 \times 10^7 \; Watt / m^2$

$\therefore$ Brightness = $\rho/4\pi$ = $5.9 \times 10^6 \; Watt / m^2 / Sr$

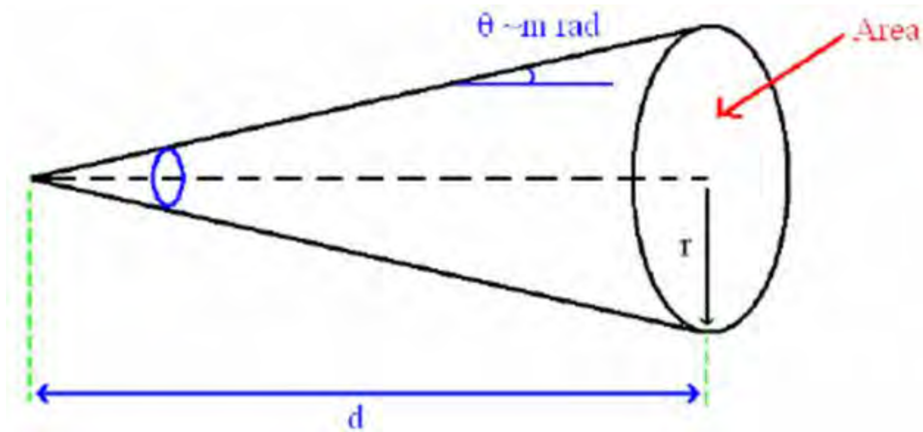
Brightness of He-Ne Laser (632.8 nm, 1 mW, spot size 1 mm, θ_d 0.5 m.rad)

Solid angle $\Omega = \dfrac{\text{Area}}{d^2}, \; r = d \times \theta$

$$\Omega = \pi\theta^2 = 7.85 \times 10^{-7}\,\text{Sr}$$

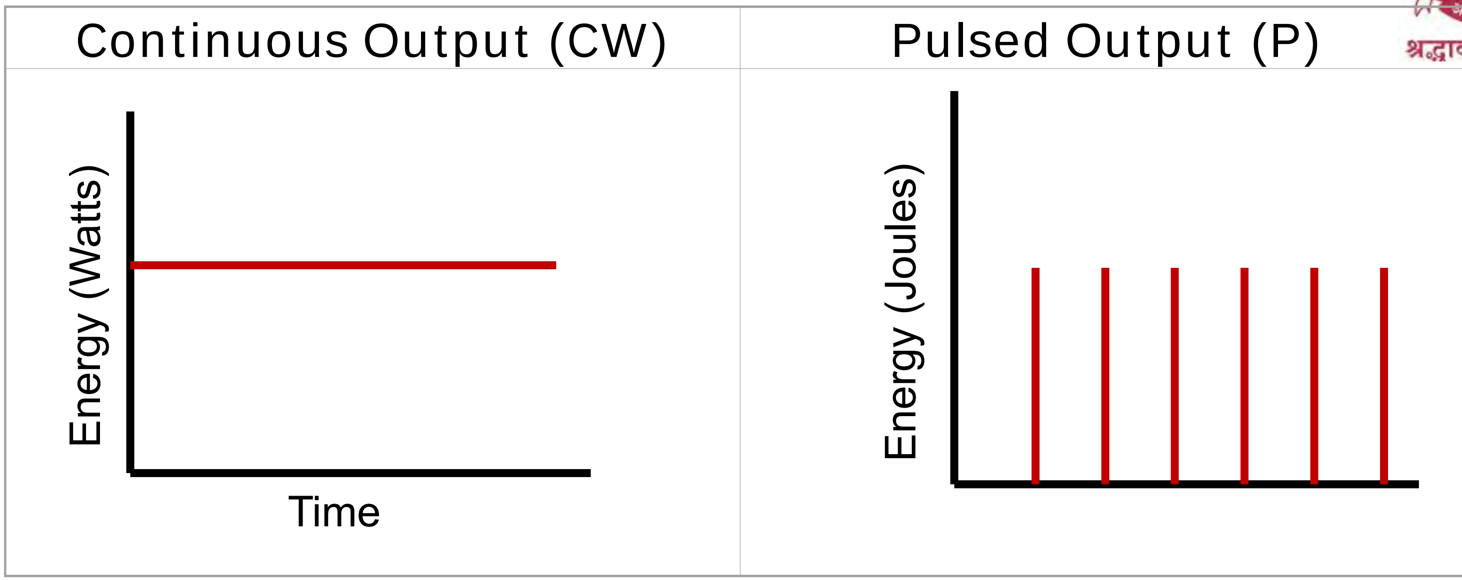
Power density $= \dfrac{1\,\text{mW}}{\pi(5 \times 10^{-4})^2} = 1273\ \text{W/m}^2$

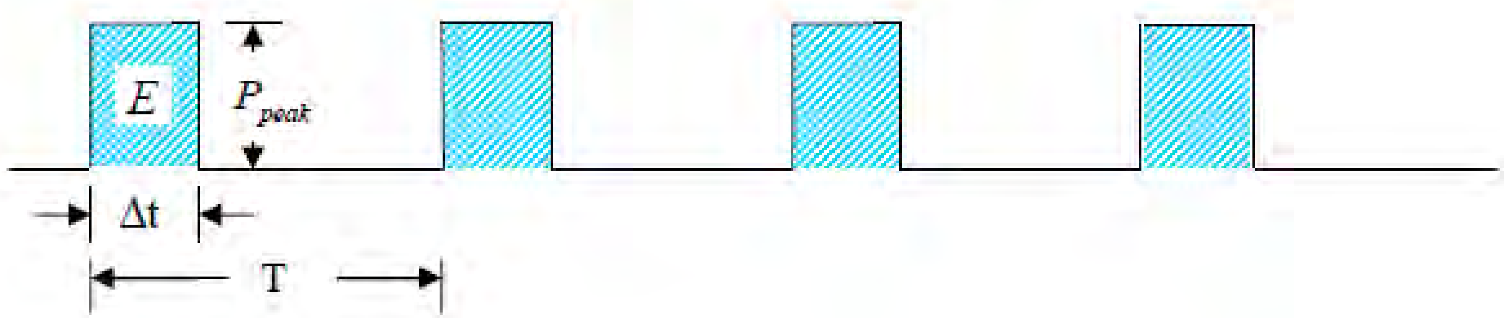
Brightness $= \dfrac{1273}{7.85 \times 10^{-7}} = 1.62 \times 10^9\ \text{W/m}^2/\text{Sr}$



$\therefore$ Brightness of laser ~ 300 times of Sun

Laser Output



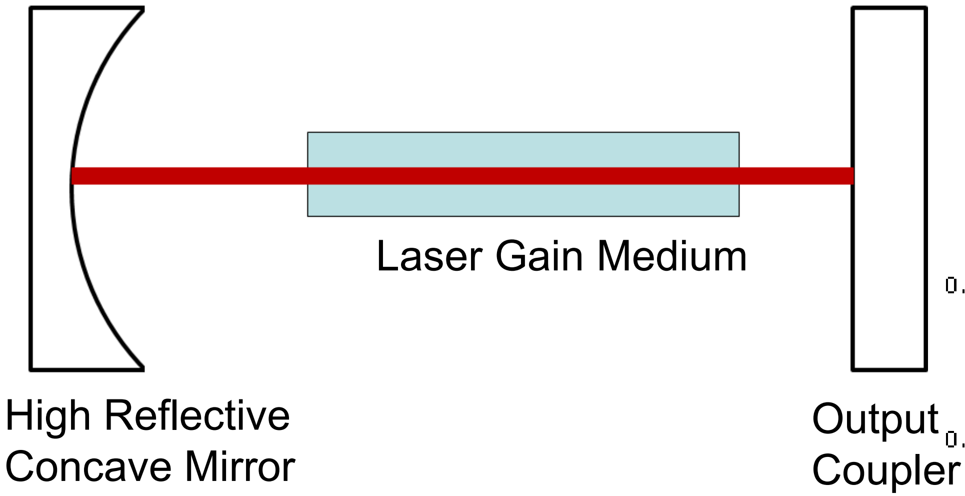


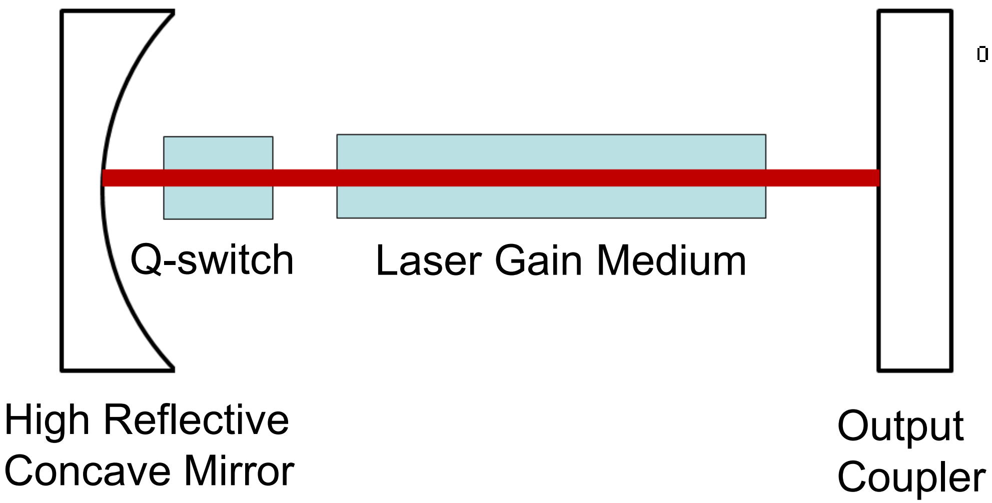
$$P_{peak} = \frac{E}{\Delta t}$$

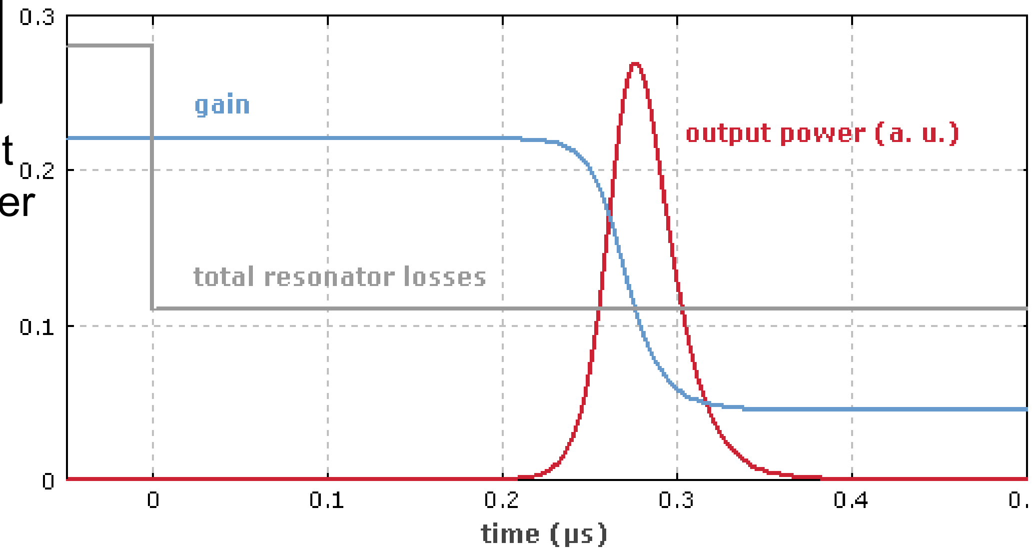
$$P_{avg} = \frac{E}{T} = Ef$$

Fluence = Energy per unit area (J/cm^2)

Laser Output – Q switching







Laser Output – Mode-Locking

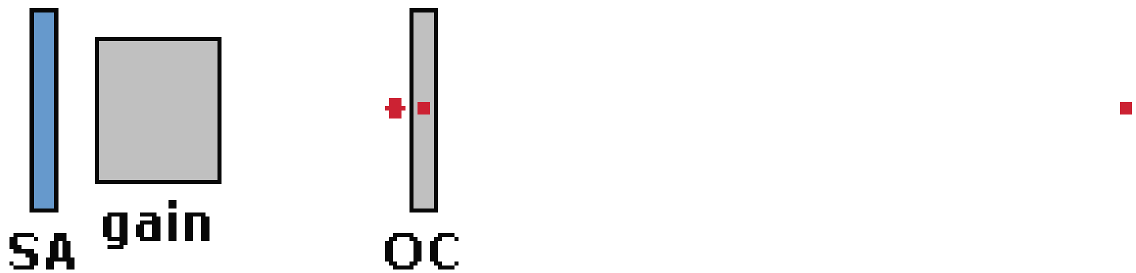
$$\Delta\nu = \frac{c}{2L}$$

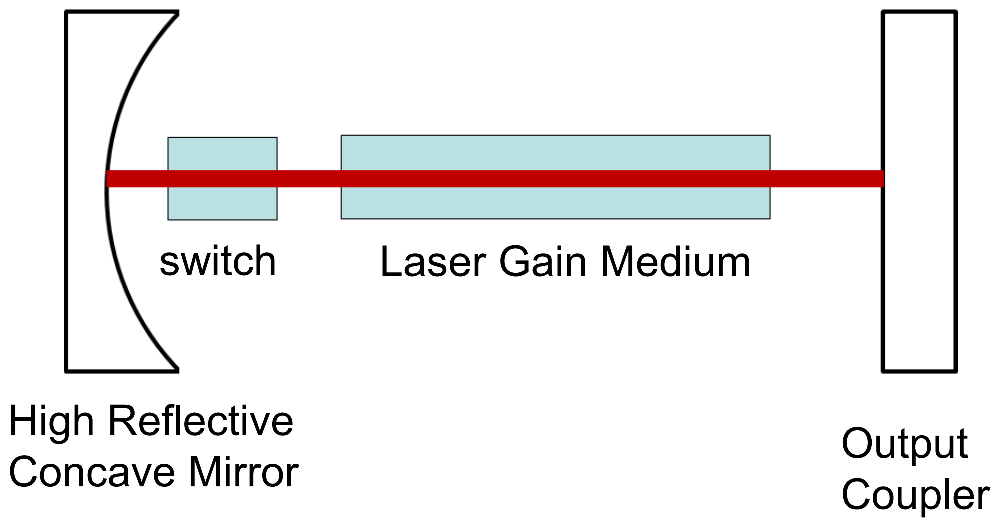
- Small laser L = 30 cm; $\Delta\nu$ = 0.5 GHz – He-Ne laser support 3 longitudinal modes
- 128 THz bandwidth of Ti:sapphire laser support ≈ 250,000 modes - multi-mode operation.
- Modes oscillates independently, no fixed relationship between each other
- Lasers with few oscillating modes, interference between modes cause beating effects - fluctuations in laser output intensity
- Many thousands of modes, interference effects tend to average - near-constant output intensity

Laser Output – Mode-Locking

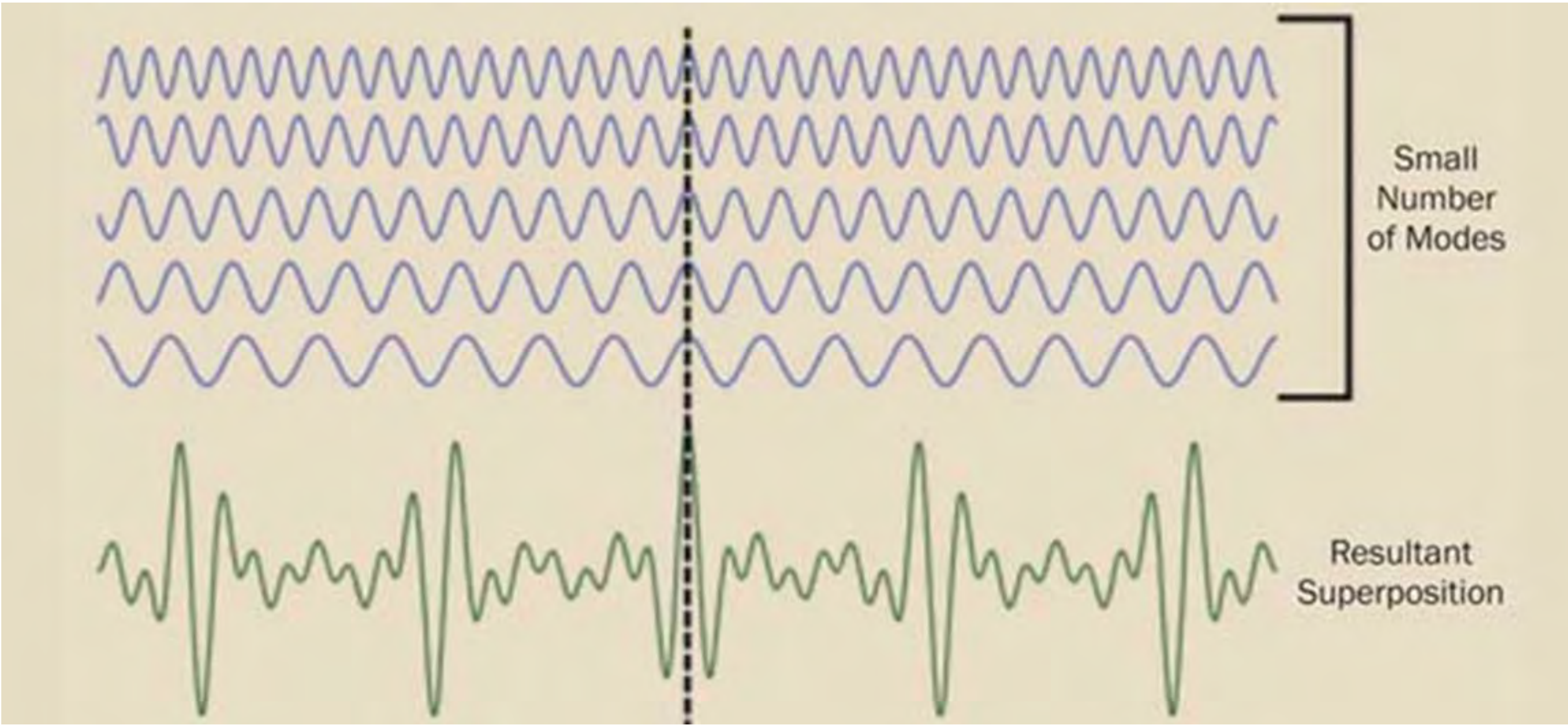
- If each mode operates with a fixed phase between it and other modes - laser output instead of random or constant output intensity,
  - laser modes will periodically all constructively interfere with one another, producing an intense burst or pulse of light.
- Laser is 'mode-locked' or 'phase-locked'.
- Pulses separated in time: $\tau = 2L/c$, where τ time taken for light to make exactly one round trip of laser cavity

Laser Output – ModeLocking

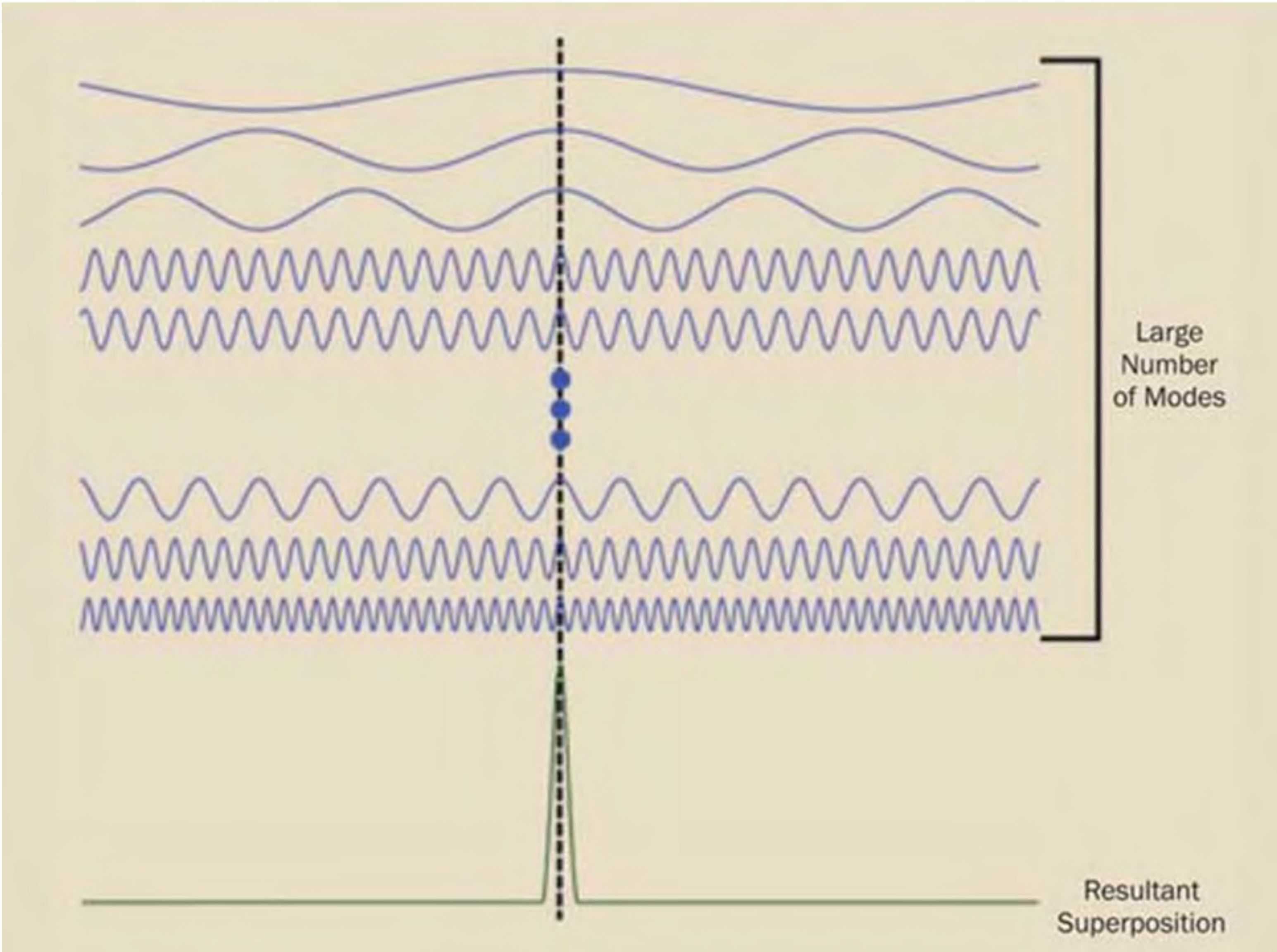




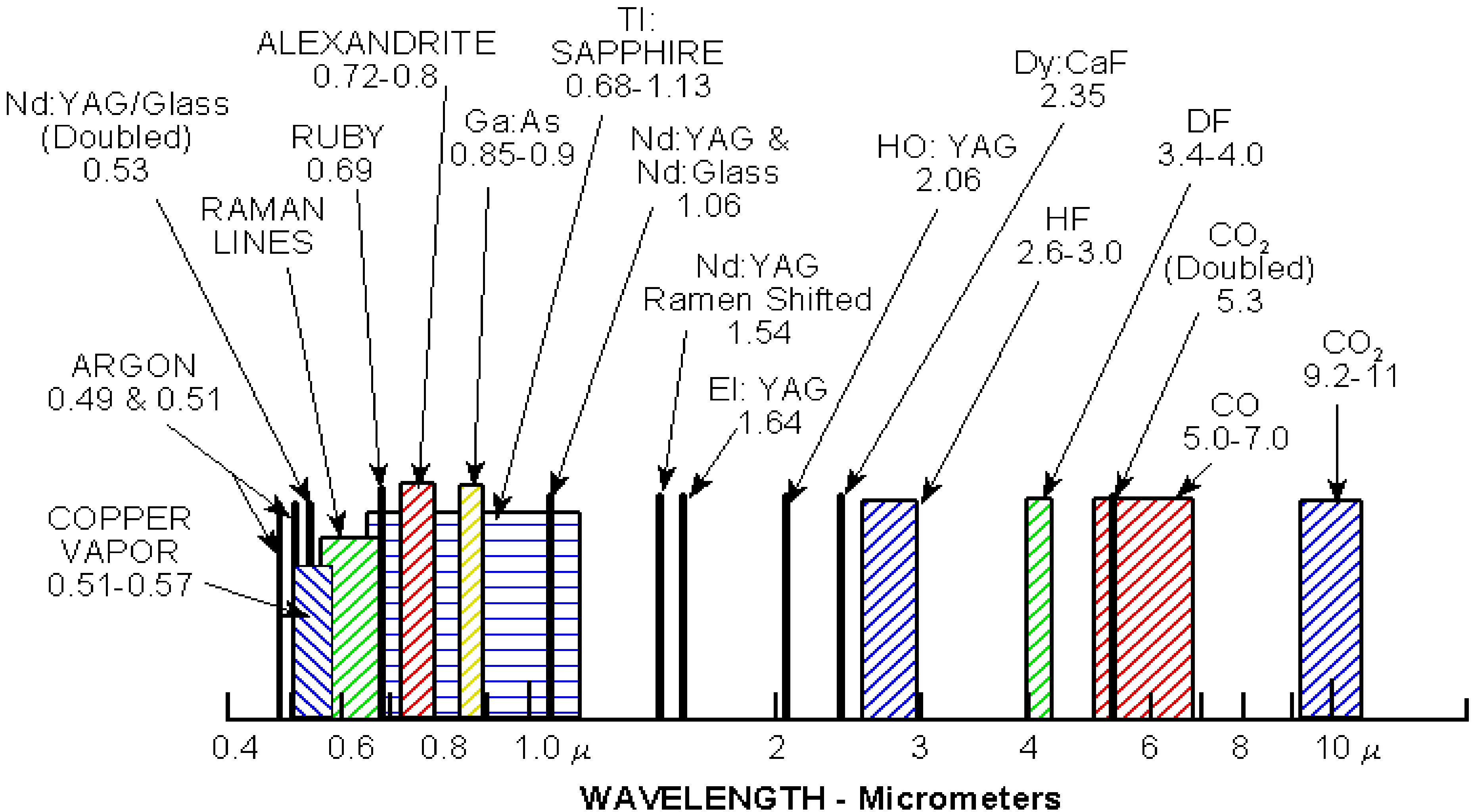
Resonator - Longitudinal Modes



Resonator - Longitudinal Modes



Laser wavelengths



LASER HAZARD CLASSES

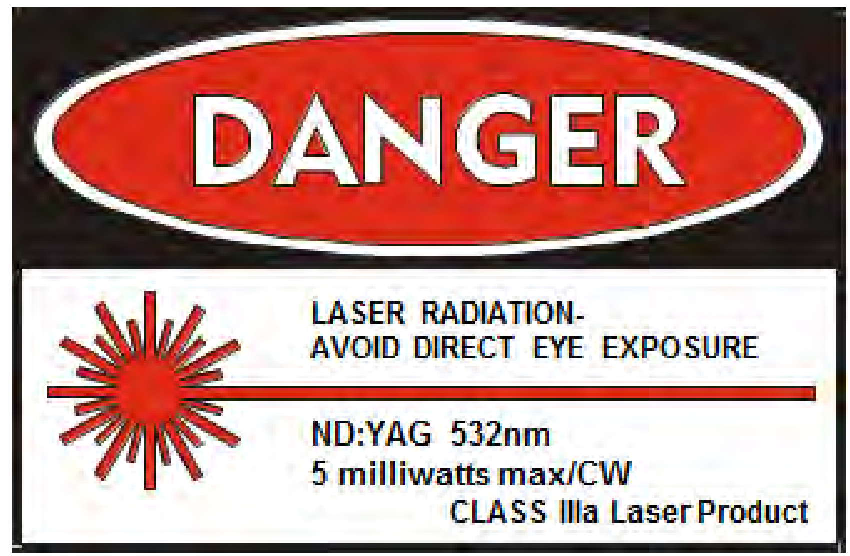
Lasers are classified according to the level of laser radiation that is accessible during normal operation.

CLASS 1: Safe during normal use, Incapable of causing injury, Low power or enclosed beam. Label is not required. Nd:YAG Laser Marker

CLASS 2: Staring into beam is eye hazard, Eye protected by aversion response, Visible lasers only, CW maximum power 1 mW

LASER HAZARD CLASSES

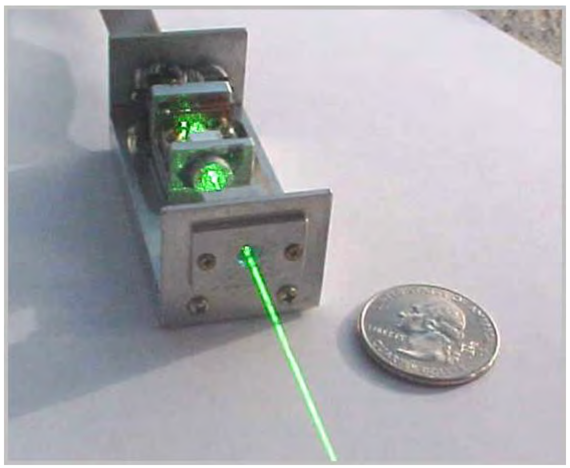
CLASS 3a: Aversion response may not provide adequate eye protection, CW maximum power (visible) 5 mW

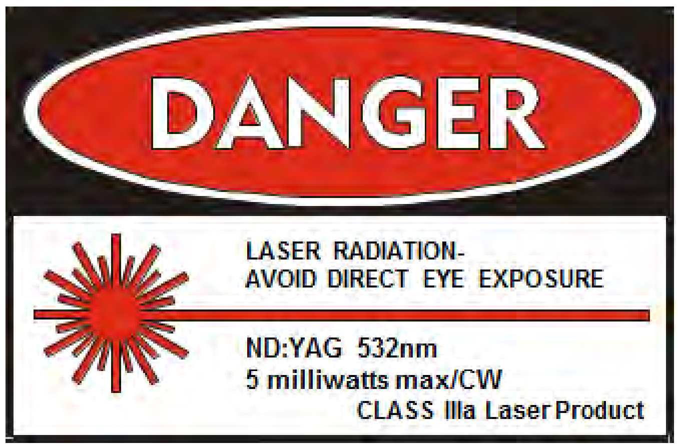


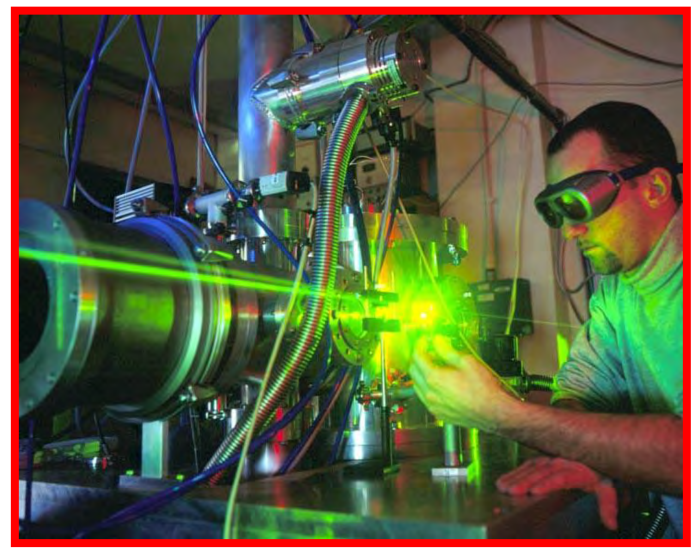
LASER HAZARD CLASSES

CLASS 3b: Direct exposure to beam is eye hazard, Visible or invisible, CW maximum power 500 mW

CLASS 4: Exposure to direct beam and scattered light is eye and skin hazard, Visible or invisible CW power >0.5 W Fire hazard







FEDERAL SAFETY REQUIREMENTS FOR CLASS 1 LASER SYSTEMS WITH ENCLOSED CLASS 3b AND 4 LASERS

Protective Housing

prevents access to laser radiation above safe level.

Safety Interlocks

terminate laser beam if protective housing in opened.

Only authorized personnel may operate laser with interlocks defeated.

Warning Labels

alert personnel if opening the housing might expose a laser hazard.

Viewing Windows and Optics

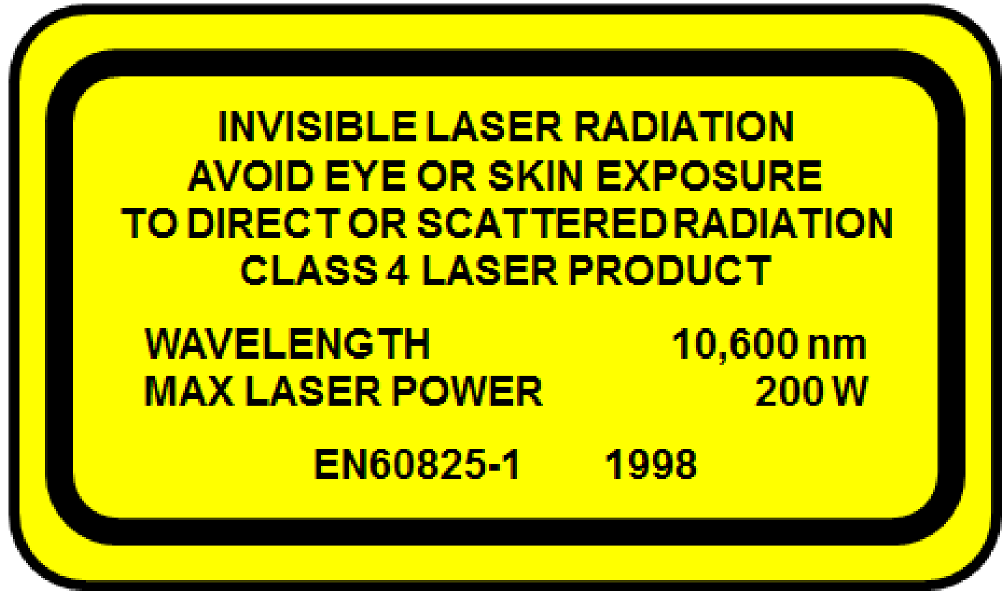
limit laser and collateral radiation to safe levels.

CDRH CLASS WARNING LABELS

Class II
Class IIIa with expanded beam

Class IIIa with small beam
Class IIIb
Class IV

INTERNATIONAL LASER WARNING LABELS



Symbol and Border: Black
Background: Yellow

Legend and Border: Black
Background: Yellow

Controlled Area Warning Sign

Personnel Protective Equipment (PPE) for eyes

- PPE is mandatory to Class 3b or 4 lasers
- Recommended for class 2 or 3a lasers when intentional direct viewing > 0.25 seconds
- Factors for selecting eyewear
  - Wavelength compatibility with laser
  - Attenuation at that wavelength or optical density (OD)
  - Visual transmittance
  - Comfort and fit

$$OD = log_{10}\frac{H_0}{MPE}$$

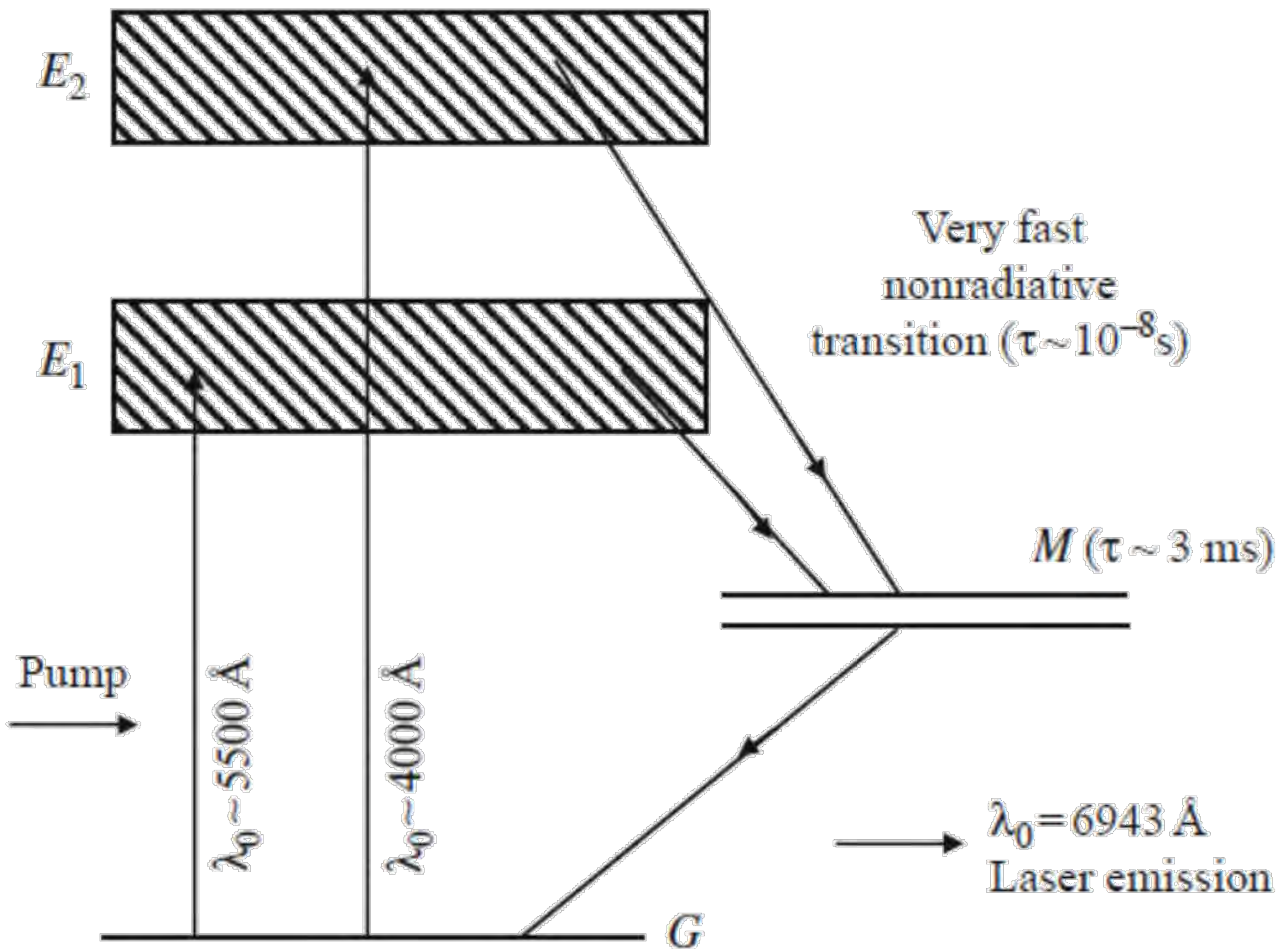
H_0= Anticipated worst-case exposure
[Power/Area] (J/cm^2 or W/cm^2)
MPE= Maximum permissible exposure level expressed in the same units as H_0

Types of Lasers

Ruby Laser

- First laser operated successfully - ruby laser – Maiman 1960
- Lasing medium – Ruby rod (length: 2 – 20 cm, dia: 0.1 – 2 cm) - matrix of aluminum oxide in which some of aluminum ions replaced by chromium ions (~0.05% by weight)
- 3 – level laser. Lasing action - energy levels of chromium ions
- pumping of chromium ions - flash lamp (Input energy 10 – 20 KJ) (e.g., a xenon or krypton flash lamp)
- Chromium ions in ground state absorb radiation around wavelengths of 5500 Å and 4000 Å and excited to the levels marked E_1 and E_2

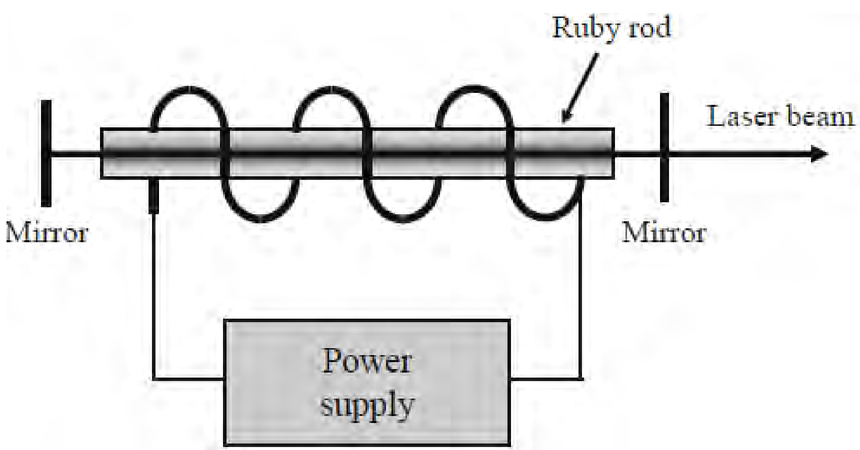
Ruby Laser

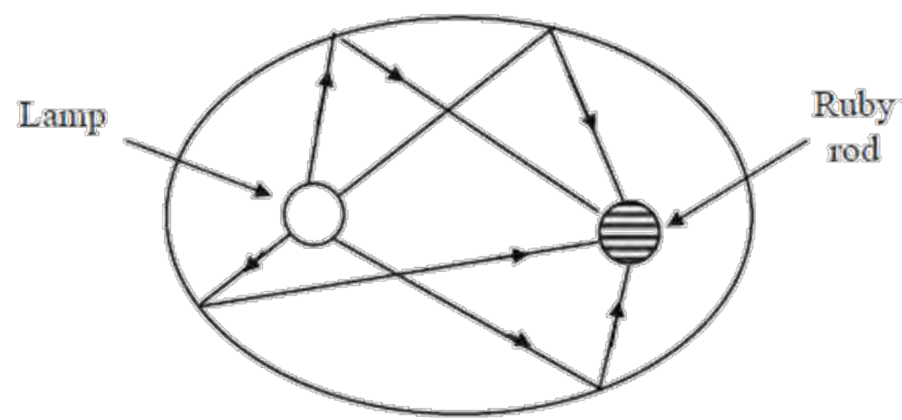


E_2
E_1
Very fast
nonradiative
transition ($\tau \sim 10^{-8}$s)
M ($\tau \sim 3$ ms)
Pump
$\lambda_0 \sim 5500$ Å
$\lambda_0 \sim 4000$ Å
$\lambda_0 = 6943$ Å
Laser emission
G

Ruby Laser

- Flash lamp operation leads pulsed output
- Flash lamp OFF: population of upper level is depleted very rapidly and lasing stops arrival of next flash
- Output is highly irregular function of time with intensity having random amplitude fluctuations of varying duration – laser spiking





Neodymium-Based Lasers

- Nd:YAG laser (YAG stands for yttrium aluminum garnet - $Y_3Al_5O_{12}$) and Nd:glass – 4 level laser
- Energy levels of the neodymium ion take part in laser emission
- Nd ions in YAG or glass host has specific advantages and applications
- Since glass - amorphous structure - fluorescent linewidth of emission is very large leads high laser threshold
- YAG - crystalline - linewidth is much smaller - much lower thresholds for laser oscillation
- Linewidth of glass host is much larger - production of ultrashort pulses using mode locking ($\tau = 1/\Delta\lambda$) and for Q-switching
- Excellent optical quality and excellent uniformity of doping

Neodymium-Based Lasers

- For continuous or very high pulse repetition rate operation the Nd:YAG laser will be preferred
- For high energy-pulsed operation, Nd:glass lasers maybe preferred

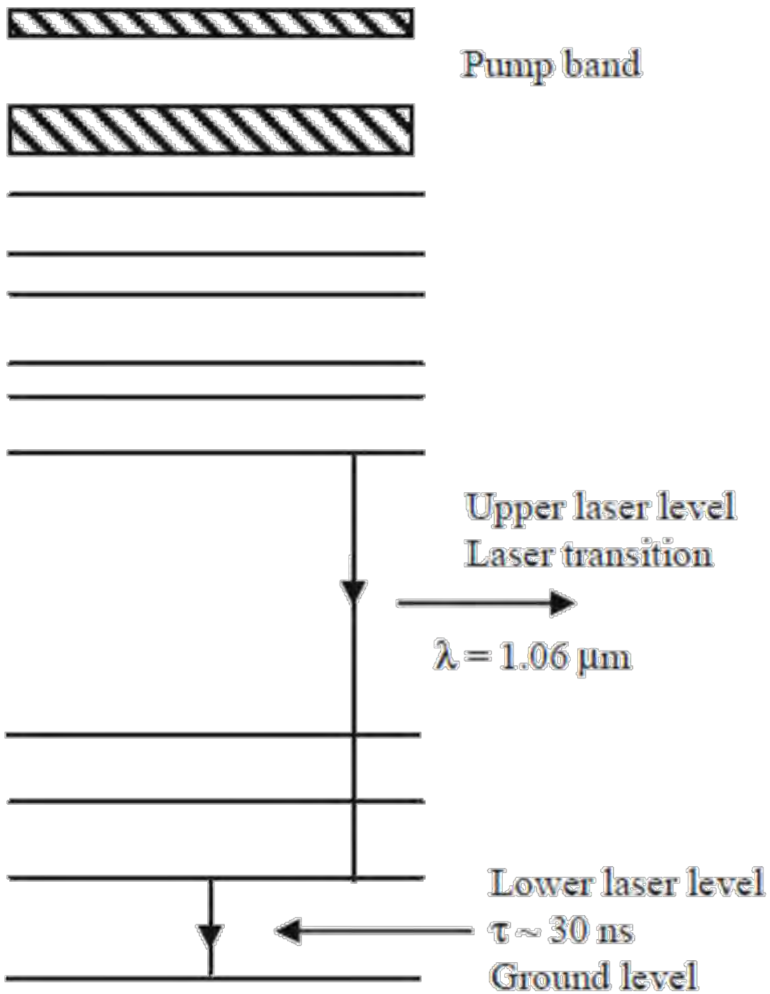
Nd:YAG Laser (1.06 μm):

- Energy difference between the lower laser level and the ground level is ~ 0.26 eV, the ratio of its population to that of the ground state at room temperature (T = 300 K) is $e^{-\Delta E}/kBT \approx e^{-9} << 1$
- Thus the lower laser level is almost unpopulated
- Lower laser level is almost unpopulated and inversion is easy to achieve
- Nd ions pump bands for excitation - 0.81 and 0.75 μm regions pumping using arc lamps (e.g., the Krypton arc lamp)

Neodymium-Based Lasers

- Typical neodymium ion concentrations used are ~1.38×10^{20} cm^{-3}
- Spontaneous lifetime corresponding to laser transition is 550 μs and emission line corresponds to homogeneous broadening and has width $\Delta\nu \sim 1.2\times10^{11}$ Hz which corresponds to $\Delta\lambda \sim 4.5$ Å.
- We have shown in Section 5.4 that Nd:YAG laser has much lower threshold of oscillation than ruby laser
- Efficient pumping of Nd ions to ULL can be accomplished using laser diodes – less heat generation - compact Nd-based lasers
- Intracavity 2nd harmonic generator efficiently convert 1060 to 532 nm (2nd harmonic of 1064 nm of Nd:YAG) leading to efficient green lasers

Neodymium-Based Lasers



- Applications - range finders, illuminators with Q –switched operation giving about 10 – 50 pulses per second with output energies in the range of 100 mJ per pulse, and pulse width ~ 10 ns
- resistor trimming, scribing, micromachining operations, welding, hole drilling, etc.

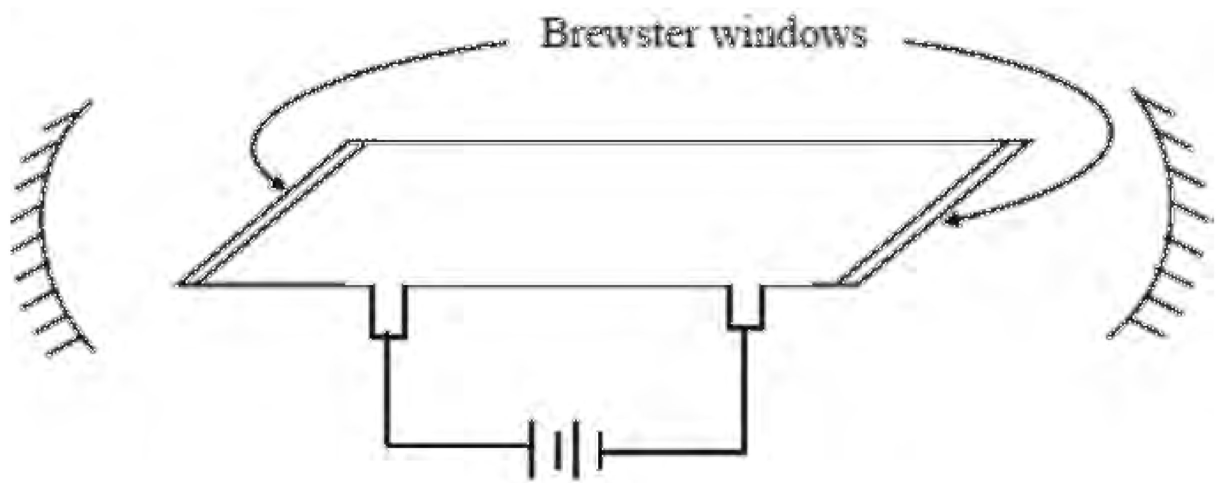
Neodymium-Based Lasers

Nd:Glass Laser (1.06 μm):

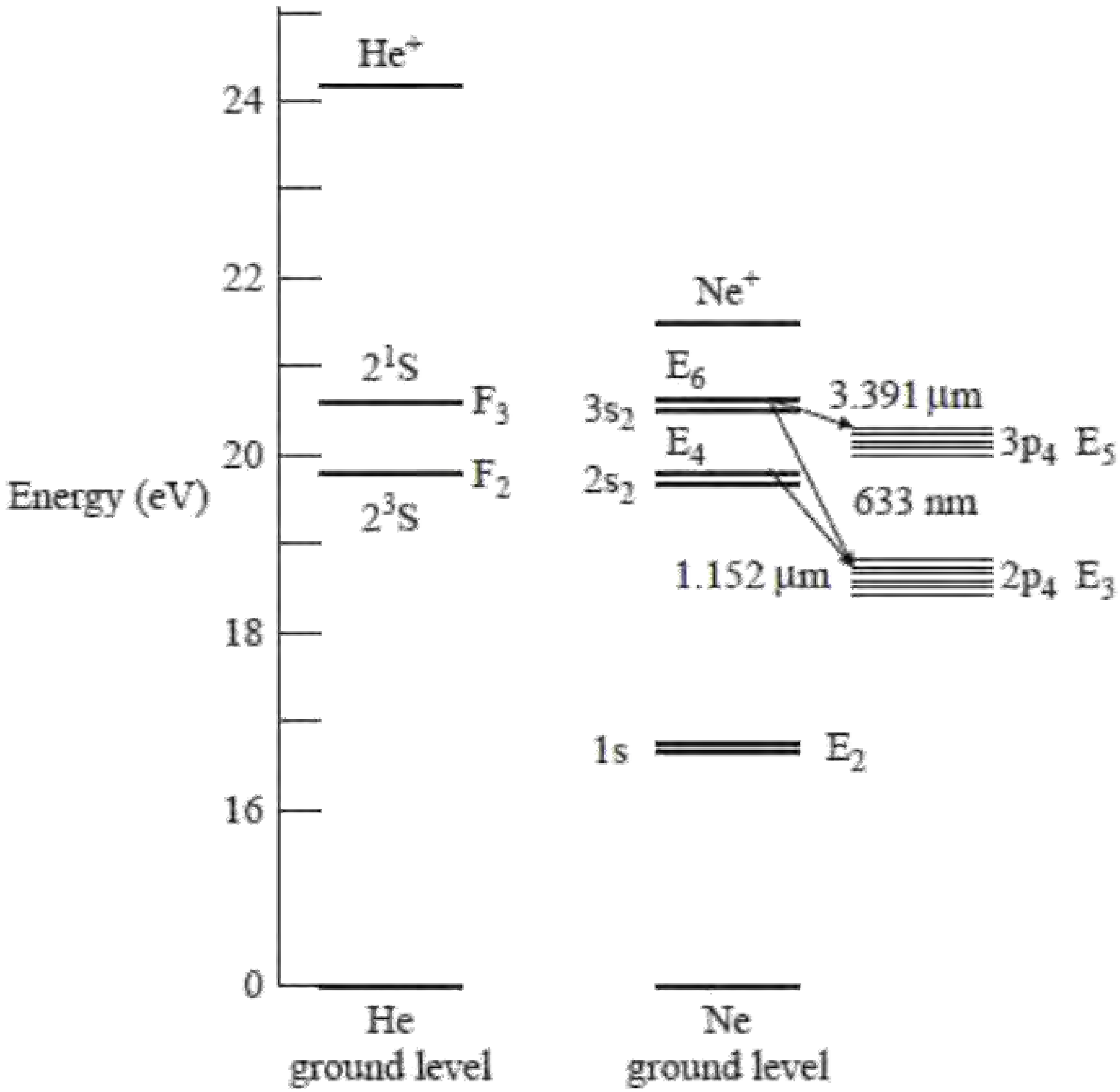
- Nd ion concentrations are $\sim 2.8 \times 10^{20}$ cm^{-3} and various silicate and phosphate glasses are as host material
- Glass has amorphous structure - different neodymium ions situated at different sites have slightly different surroundings - inhomogeneous broadening resultant linewidth $\Delta\nu \sim 7.5 \times 1012$ Hz which corresponds to $\Delta\lambda \sim 260$ Å larger than Nd:YAG laser
- Consequently the threshold pump power is higher
- Nd:glass lasers suitable for high energy-pulsed operation laser fusion where requirement of subnanosecond pulses with an energy content of several kilojoules (i.e., peak powers of several tens of terawatts)

He–Ne Laser – first gas laser

- Atoms characterized by sharp energy levels as compared to solids - electrical discharge to pump atoms
- Long and narrow discharge tube (diameter ~ 2 – 8 mm and length 10–100 cm) filled with helium (1 torr) and neon (0.1 torr)
- Lasing atoms are neon atoms and helium for selective pumping of upper laser level



He–Ne Laser – first gas laser



He–Ne Laser – first gas laser

- Electrical discharge in gas - electrons which are accelerated collide with helium and neon atoms and excite them to higher energy levels
- Helium atoms tend to accumulate at levels F_2 and F_3 due to their long lifetimes of ~ 10^{-4} and 5×10^{-6} s, respectively
- Since levels E_4 and E of neon atoms have almost same energy as F_2 and F_3, excited helium atoms colliding with neon atoms in ground state can excite neon atoms to E_4 and E_6
- Since pressure of helium is ten times that of neon, E_4 and E_6 of neon are selectively populated as compared to other levels of neon

He–Ne Laser – first gas laser

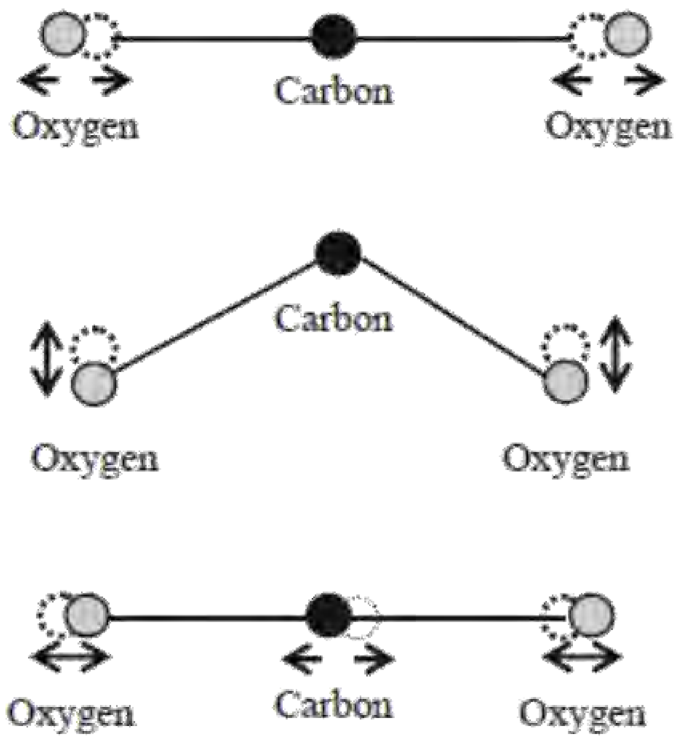
- Transition between E_6 and E_3 produces popular 6328 Å line
- Neon atoms de-excite through spontaneous emission from E_3 to E_2 (lifetime ~ 10^{-8} s)
- Since this time is shorter than lifetime of level E_6 (~ 10^{-7} s) -achieve steady-state PI between E_6 and E_3
- Level E_2 is metastable and thus tends to collect atoms
- Atoms from this level relax back to ground level mainly through collisions with walls of tube
- Since E_2 is metastable it is possible for atoms in this level to absorb spontaneously emitted radiation in $E_3 \rightarrow E_2$ transition to be re-excited to E_3
- This will have effect of reducing inversion. It is for this reason that gain transition is found to increase with decreasing tube diameter
- Other two important wavelengths 1.15 and 3.39 μm, correspond to $E_4 \rightarrow E_3$ and $E_6 \rightarrow E_5$ transitions

He–Ne Laser – first gas laser

- Both 3.39 μm and 6328 Å transitions share same upper laser level
- Laser can be made to oscillate at 6328 Å by either using optical elements in path which strongly absorb 3.39 μm wavelength or increasing linewidth through Zeeman effect by applying an inhomogeneous magnetic field across tube
- If resonator mirrors are placed outside discharge tube then reflections from ends of discharge tube can be avoided by placing windows at Brewster angle
- In such a case beam polarized in plane of incidence suffers no reflection at windows while perpendicular polarization suffers reflection losses leads to polarized output of laser

CO_2 Laser

- Transitions occurring between different vibrational states of CO_2 molecule
- CO_2 molecule - central carbon atom with two oxygen atoms attached one on either side - three independent modes of vibration

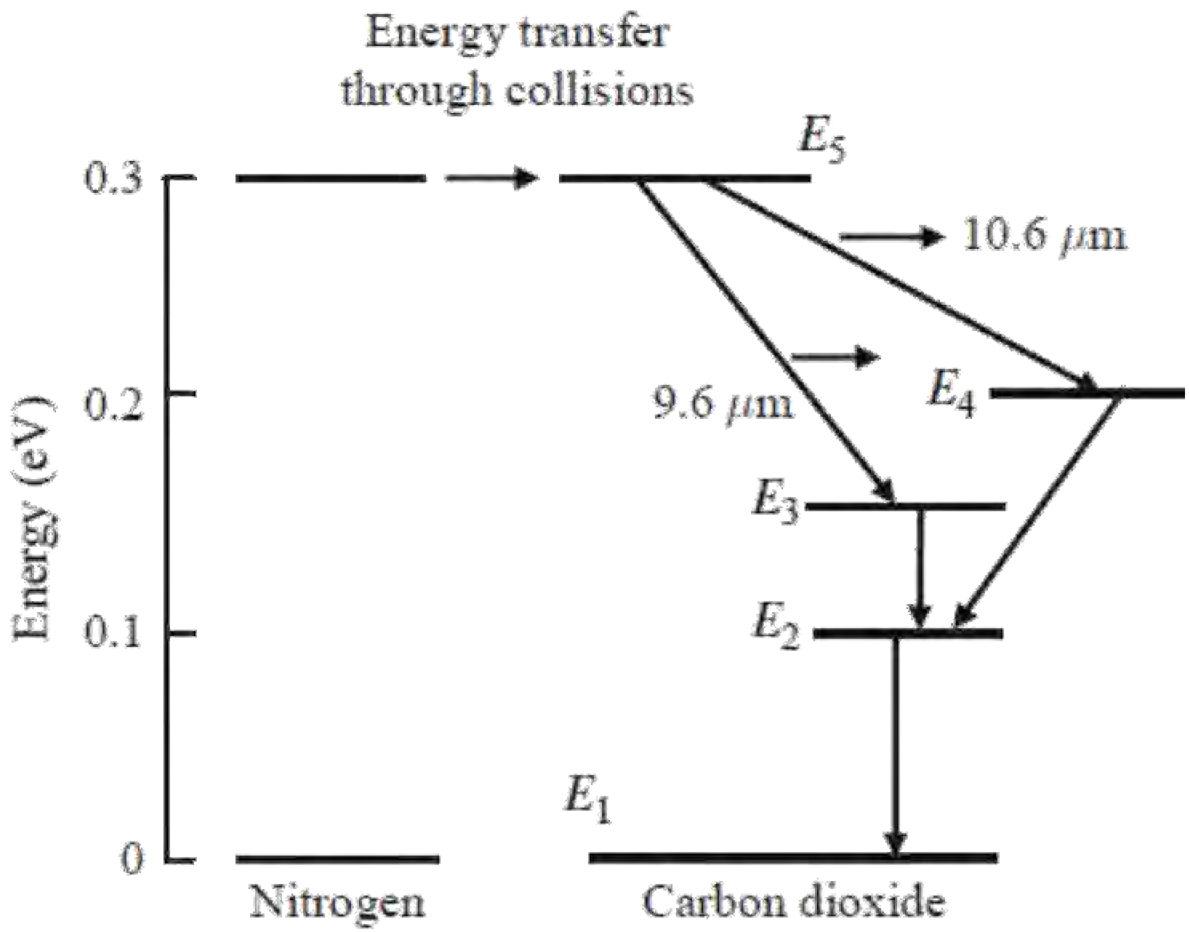


CO_2 Laser

- Symmetric stretch, bending, and asymmetric stretch modes - characterized by definite frequency of vibration
- Vibrational degrees of freedom are quantized, i.e., when a molecule vibrates in any of the modes it can have only discrete set of energies
- ν_1 - frequency corresponding to -symmetric stretch mode then - molecule can have energies of only:

$$E_1 = \left(m + \frac{1}{2}\right) h\nu_1, \qquad m = 0, 1, 2, \ldots$$

CO_2 Laser



Energy transfer through collisions
0.3
0.2
0.1
0
Energy (eV)
E5
E4
E3
E2
E1
10.6 μm
9.6 μm
Nitrogen
Carbon dioxide

CO_2 Laser

- Laser transition at 10.6 µm occurs between (001) and (100) levels of CO_2
- Excitation of carbon dioxide molecules to long-lived level (001) occurs both through collisional transfer from nearly resonant excited nitrogen molecules and also from cascading down of carbon dioxide molecules from higher energy levels
- Efficient pumping to (001) level and also because all energy levels involved are close to ground level
- Atomic quantum efficiency - ratio of energy difference corresponding to laser transition to energy difference of pump transition

CO_2 Laser

$$\eta = \frac{E_5 - E_4}{E_5 - E_1}$$

- η is high (~ 45%) - a large portion of input power into useful laser power
- Output powers of several watts to several kilowatts obtained from CO_2 lasers
- High-power CO_2 lasers: Materials processing, welding, hole drilling, cutting, etc.,
- Atmospheric attenuation at 10.6 μm is low open air communications

Applications

Laser Material Interaction

"Once the lasers were invented, they simply had to be used in materials science"

M. von Allmen

Laser Material Interaction

Medicine ➢ Bloodless surgery, laser healing, laser therapy, kidney stone treatment, eye surgery, dentistry

Industry ➢ Cutting, welding, micro and nano machining, heat treatment of materials, marking parts

Defense ➢ Marking targets, missile guiding, electro-optical counter measures

Research ➢ Spectroscopy, laser ablation, laser annealing, laser scattering, laser interferometer

Commercial ➢ Laser printers, CDs, barcode scanners, laser pointers, holograms

Interaction Mechanisms

Photothermal

- Radiation energy is converted into lattice vibrational energy
- Thermal relaxation time – much shorter than desorption time – ablation through thermal process
- Dominating processes - melting, vaporization and plasma formation.

Photomechanical

- Mechanical stress in the material due to laser irradiation

Interaction Mechanisms

Photochemical

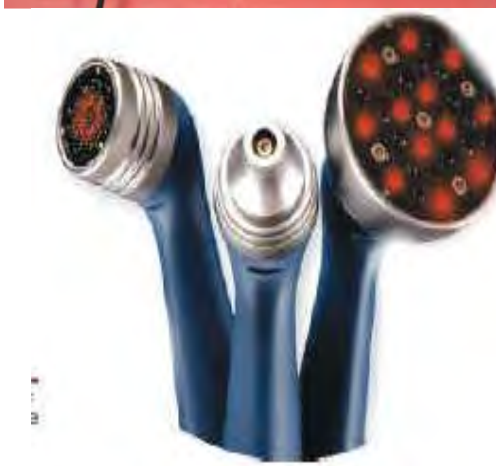
- Polymers processed with UV laser radiation.
- Bond energies in organic molecular solids (O=H [4.8 eV], N=H [4.1 eV], C-O [3.6 eV], C-C [3.6 eV], C=N [3 eV]) - Photon energies of common UV lasers (ArF [6.4 eV], KrF [5 eV], XeCl [4 eV]).
- Photons break chemical bonds in molecules of organic materials - ablation

Medicine

- Dermatology: removing tattoos, scars, stretch marks, sunspots, wrinkles, birthmarks, and hairs,
- Dental procedures: caries removal,
- Procedures, tooth whitening, and oral surgery,
- Endoscopies,
- Eye Surgery,
- "No-Touch" removal of tumors, especially of brain and spinal cord,
- Angioplasty and mechanisms of laser revascularization,
- laparoscopic interventions,
- Acupuncture,

Medicine

- Low Level Laser Therapy (LLLT), 10mW - 200mW
- Low Intensity Laser Therapy (LILT).
  - Generation of heat
  - Initiate chemical change,
  - Disrupt molecular bonds and
  - Produce free radicals
    - Energy Density J/cm^2
    - output power (Watts)
    - irradiation area (cm^2)
    - time (seconds)



Medicine

- Increased cell metabolism
- Altered cell motility, cell membrane potentials, cell potentials
- Increased cellular metabolism,
- Improved localized blood circulation
- Relief from acute and chronic pain
- Reduced localized inflammation
- Stimulation for wound healing and tissue repair
- Stimulation of nerve function
- Activation and proliferation of fibroblasts,

Biostimulation

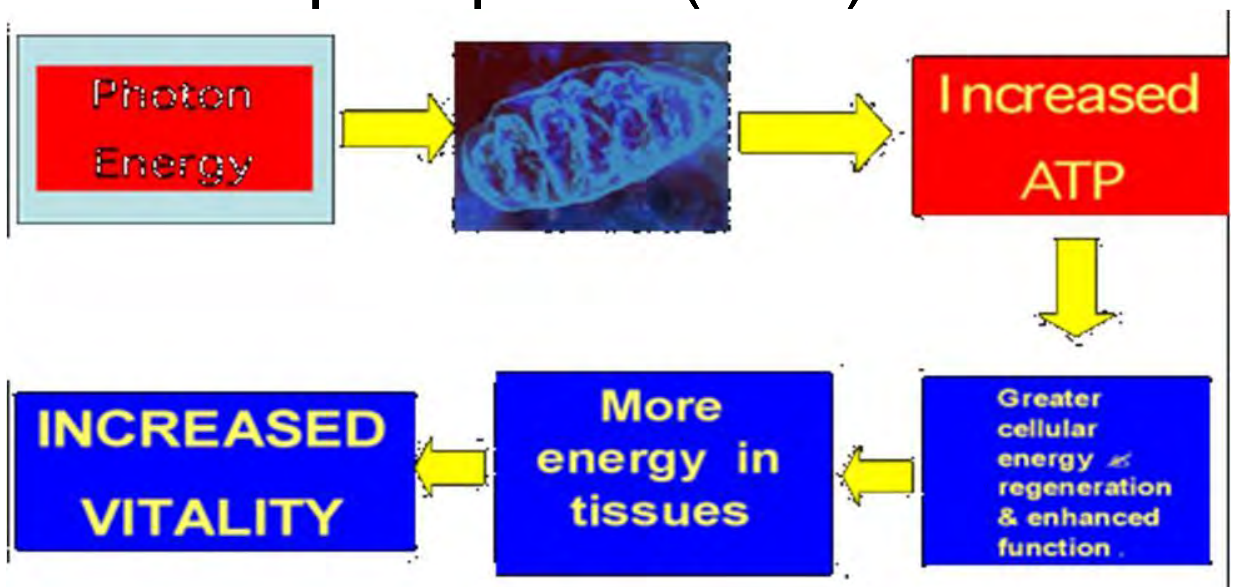
- Energy from laser radiation - stimulate biological function of cells, tissue, and systems and even raise overall vital energy

- Stimulate regeneration of bone, blood, the lining of blood vessels, cartilage, nerve, and muscle

"Bio" stimulation = Life stimulation!

Biostimulation

- Laser therapy adds energy through photon absorption by mitochondria
- Mitochondria absorb laser radiation - activates a series of reactions to increase and store more cellular energy in the form of adenosine triphosphate (ATP)



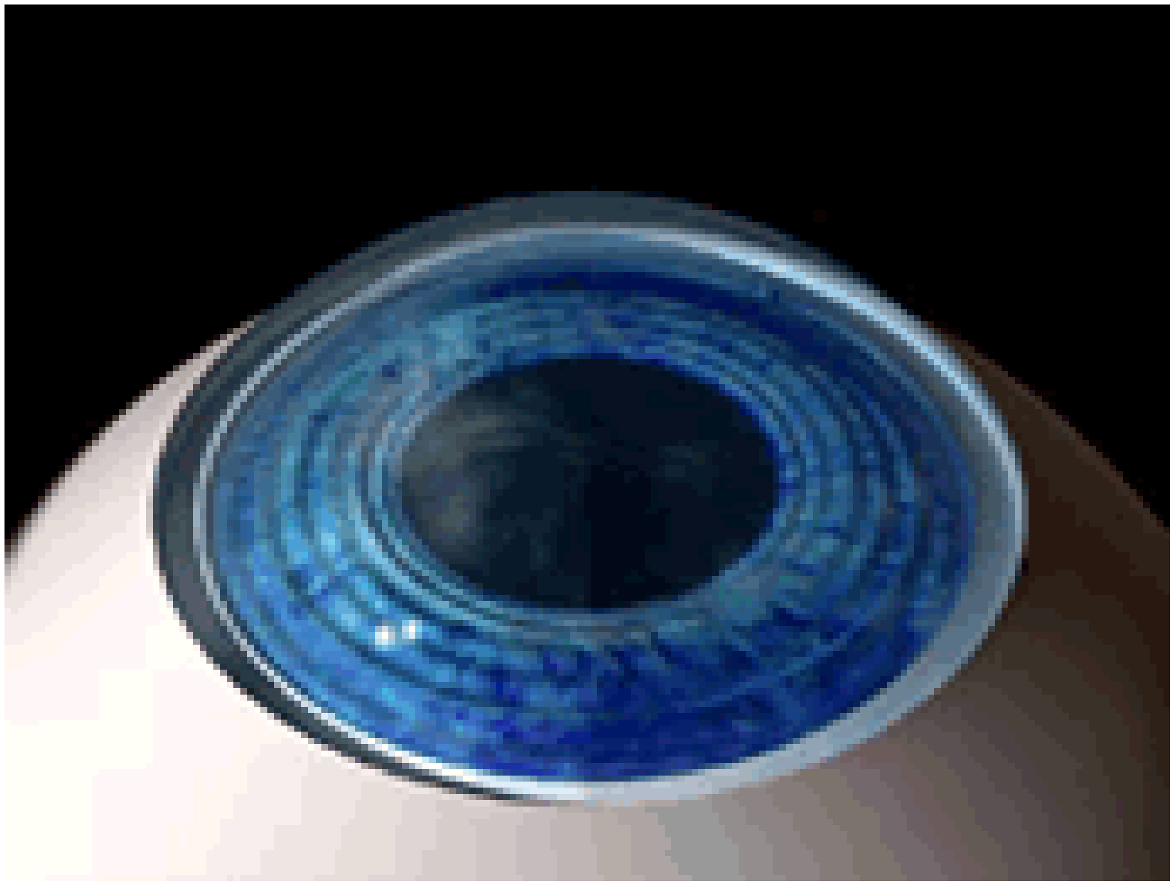
Biostimulation

Skin Rejuvenation

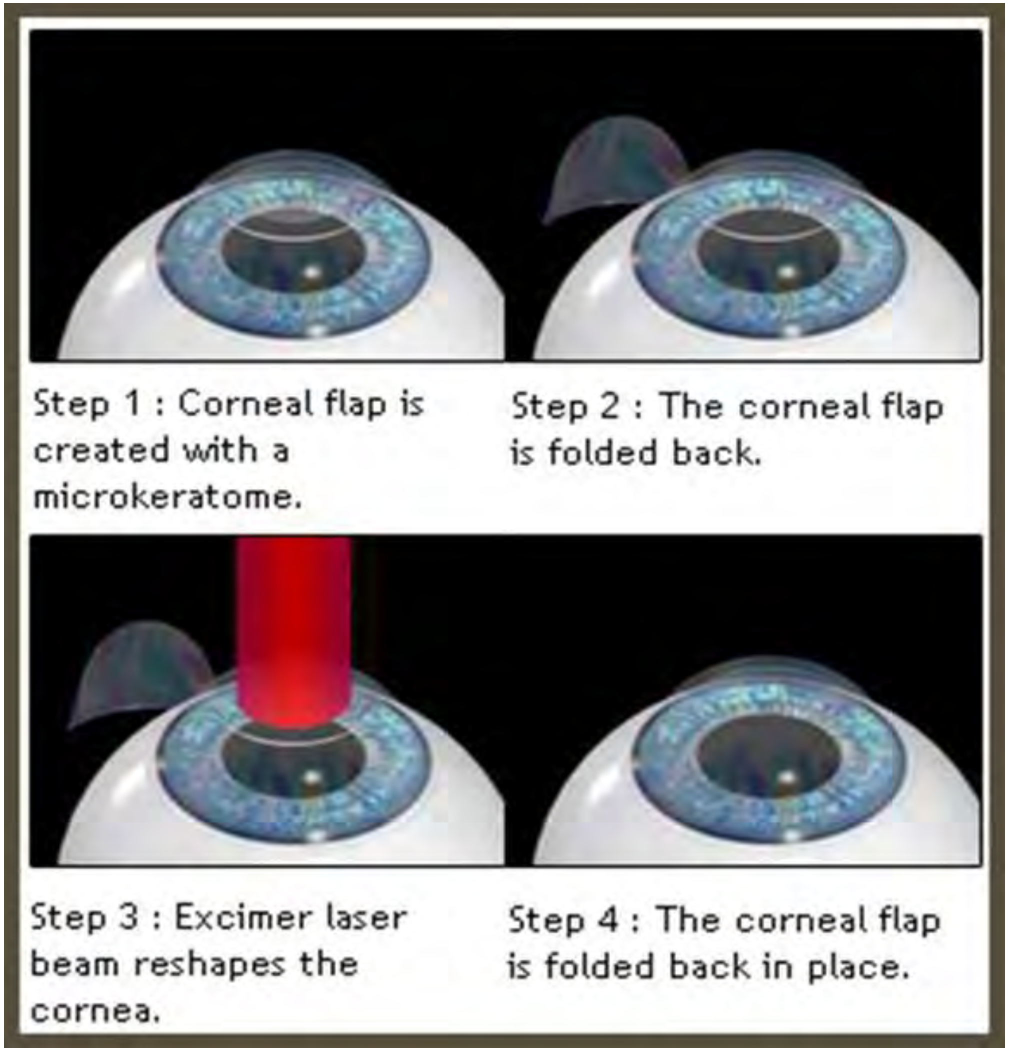
Biostimulation

Skin Rejuvenation

Photoablation



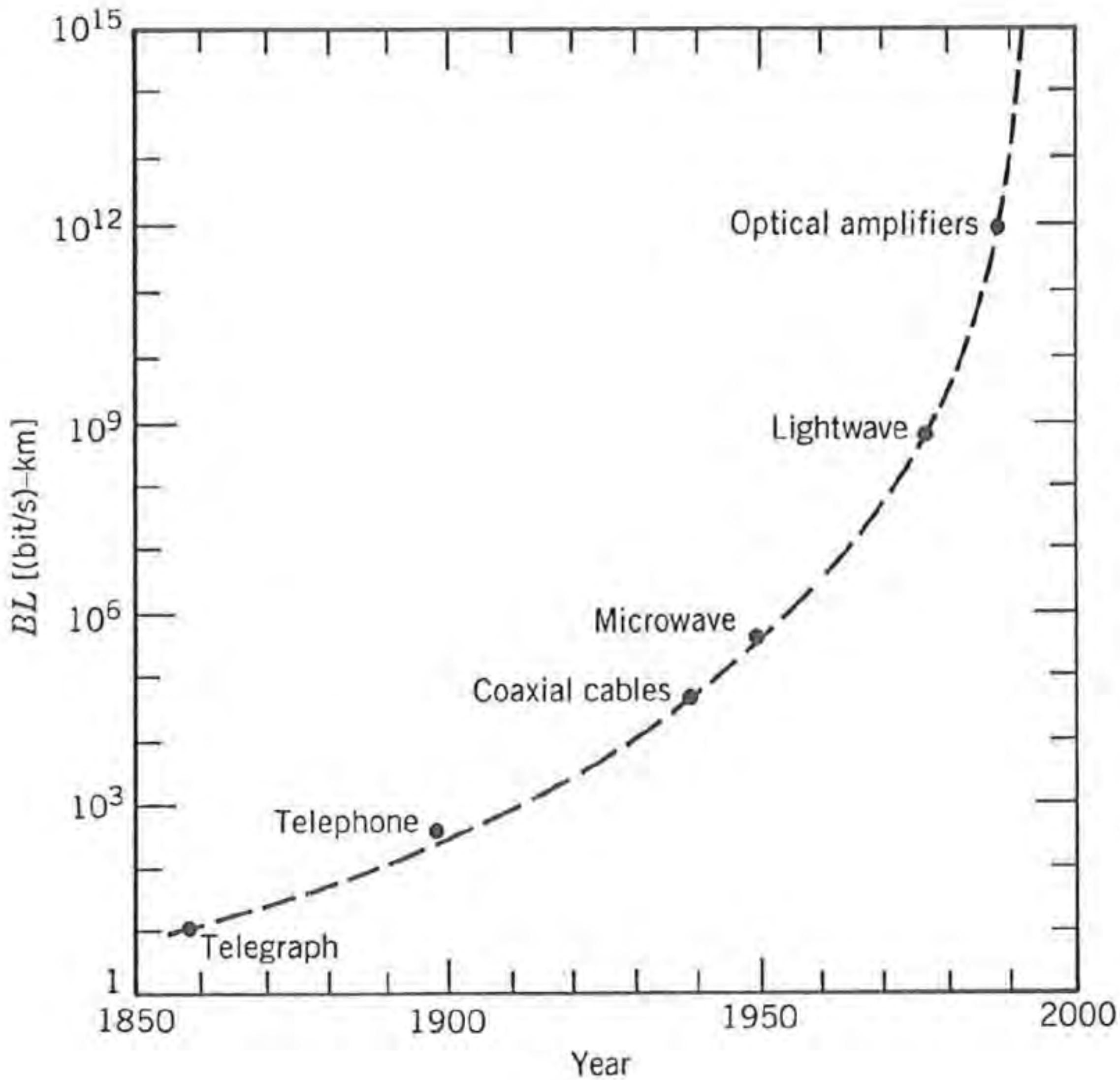
Photoablation



Communication

- Morse telegraph - 1860's, Transmission rate: ~1bit/s
- Distance: Due to application of relay stations: 1000 km
- Invention of telephone 1876.
- First coaxial cable system 1940 with capability to transmit 300 voice channels.
- First microwave system was put into service in 1948 with a carrier frequency of 4GHz. - 100Mbit/s.
- High speed coaxial systems need repeater spacing ~1km.

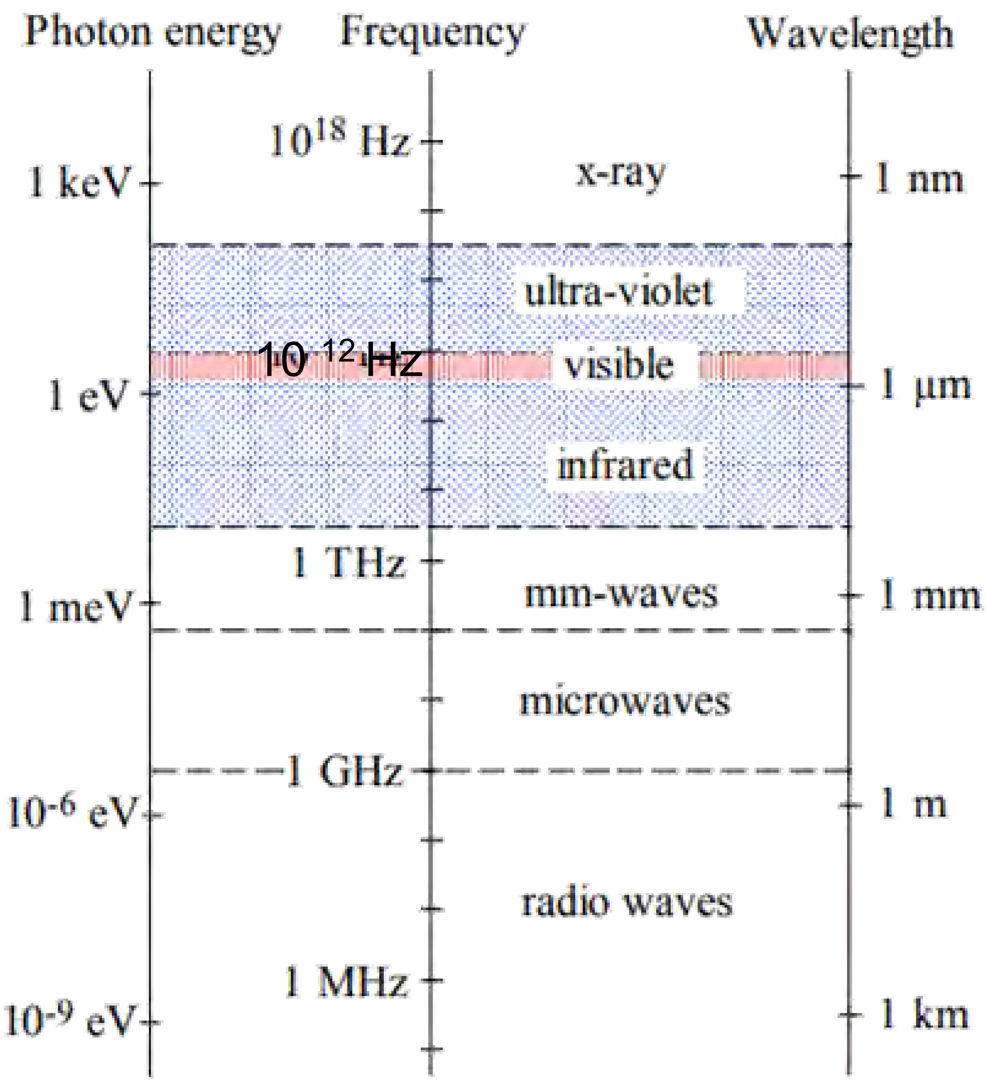
Communication



Increase of bit rate distance product BL for different communication technologies over time

Communication

The electromagnetic spectrum



The carrier frequency is much higher in lightwave systems than in microwave systems

Lightwave systems typically use infrared light

Frequency: $\nu \approx 200$ THz

Wavelength: λ, typ. 1.55 μm

Light velocity in vacuum:

$c \approx 2.998\times10^{8}$ m/s

Laser Material Interaction

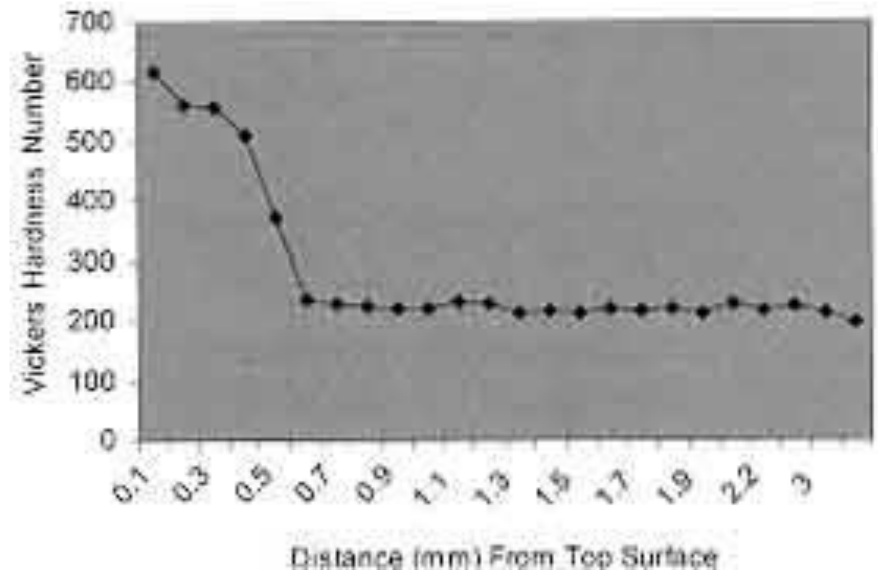
- Laser interaction – absorption, reflection, scattering, transmission
  - Heating, melting, vaporization, plasma formation – laser parameters (wavelength and fluence), material properties (absorption and thermal properties)

- Ablation mechanisms – Photothermal, photomechanical, and/or photochemical

Materials Processing - surface treatment

- **Low power density** - Surface heating - **transformation hardening or annealing**
- **High power density** - Surface melting - to overcome latent heat effect and larger heat conduction losses - homogenisation, microstructure refinement, generation of rapid solidification structures and surface sealing
- **Surface alloying** - melting – mixing into the melt pool - corrosion improvement, wear
- **Surface cladding** – melting – particle injection - fusing on a thin surface melt - alter melting point, thermal conductivity

Materials Processing - surface treatment

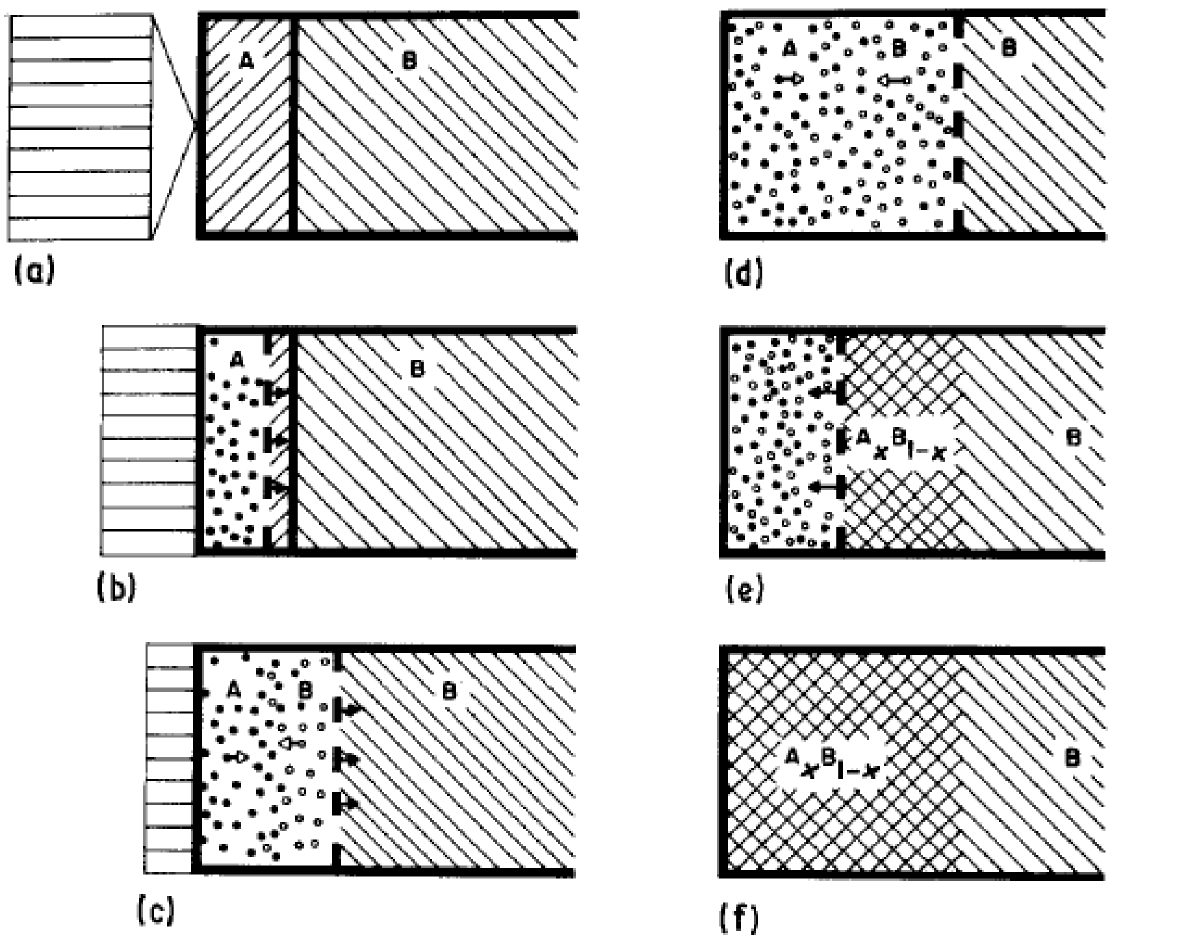


steel surface - transform into austenite during heating and then into martensite during cooling

Materials Processing - surface treatment

- **Surface texturing** – for improved paint appearance
  - microtexturing, nanotexturing
  - For solar cell applications, for improved biocompatibility
- **Cleaning**
- **Non-contact bending**
- High equipment cost, coverage area restricted, absorbent coatings, multiple passes give local tempering

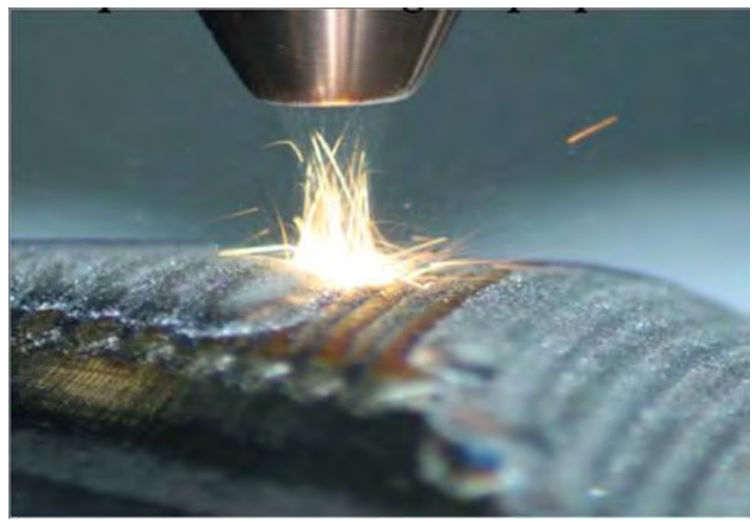
Materials Processing - surface alloying



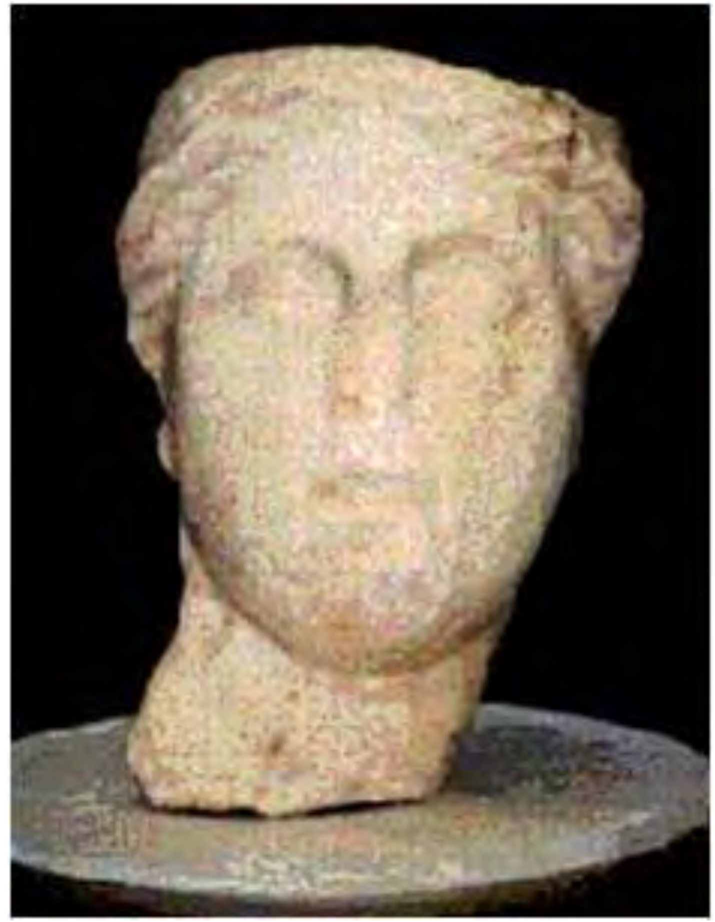
A – thin metal film coating

A – metal substrate

Materials Processing – welding and cladding



Materials Processing – welding and cladding



Introduction / Recording

- Ordinary photograph - a two-dimensional recording of three dimensional scene
- Emulsion on photographic plate - sensitive only to intensity variations
  - phase distribution which prevailed at the plane of photograph is lost while recording
  - dimensional character (e.g., parallax) of the object scene is lost

Introduction / Recording

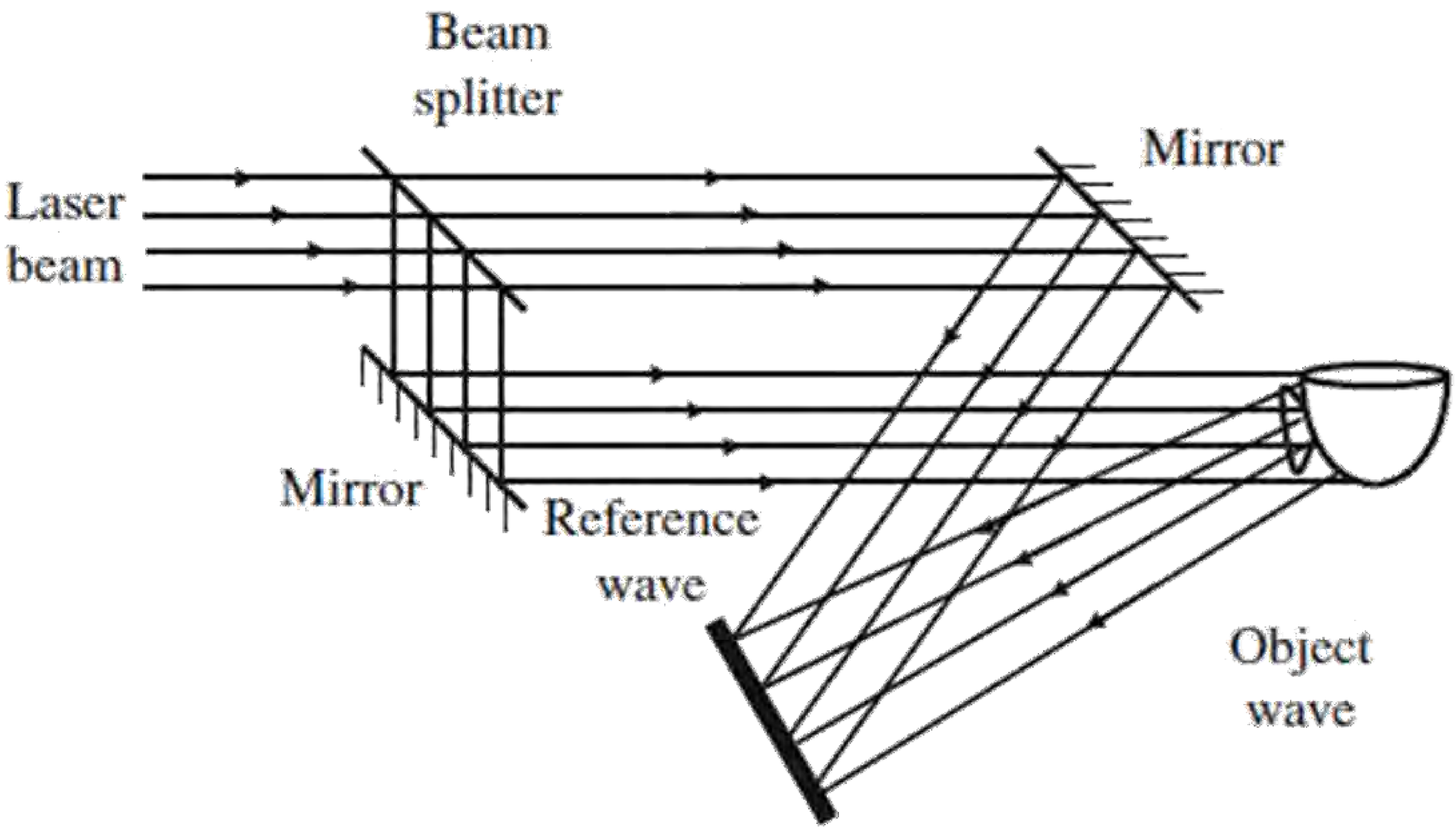
- 1948 - Dennis Gabor - recording not only amplitude but also phase of the wave (practical importance 1960 with lasers)

- Recording: one superimposes on the wave (emanating from the object) another coherent wave called the reference wave

- These two waves interfere in the plane of recording medium and produce interference fringes.

- Interference fringes are characteristic of object and the recording medium records intensity distribution in the interference pattern

Recording



Beam
splitter
Laser
beam
Mirror
Mirror
Reference
wave
Object
wave

Recording

- interference pattern has recorded in it not only the amplitude distribution but also the phase of the object wave
- Field produced due to object wave at the plane of recording medium:

$$o(x,y) = O_0(x,y)e^{i\phi(x,y)},$$

where $O_0(x,y) - amplitude\ part,\ \phi(x,y) - phase\ part$

- Field produced due to the reference wave at recording medium

$$R(x,y) = Ae^{i\Psi(x,y)},$$

Recording

- Reference wave is an obliquely incident plane wave, in which case A is a constant
- Total field produced at the recording medium

$$U(x,y) = O_0(x,y)e^{i\phi(x,y)} + Ae^{i\psi(x,y)},$$

- Intensity pattern recorded by the recording medium

$$I(x,y) = |U(x,y)|^2 = O_0^2(x,y) + A^2 + O_0(x,y)A\, exp\{i([x,y] - \psi)\} + O_0(x,y)A\, exp\{-i[(x,y) - \psi(x,y)]\},$$

omitted a constant of proportionality and carried out time averaging

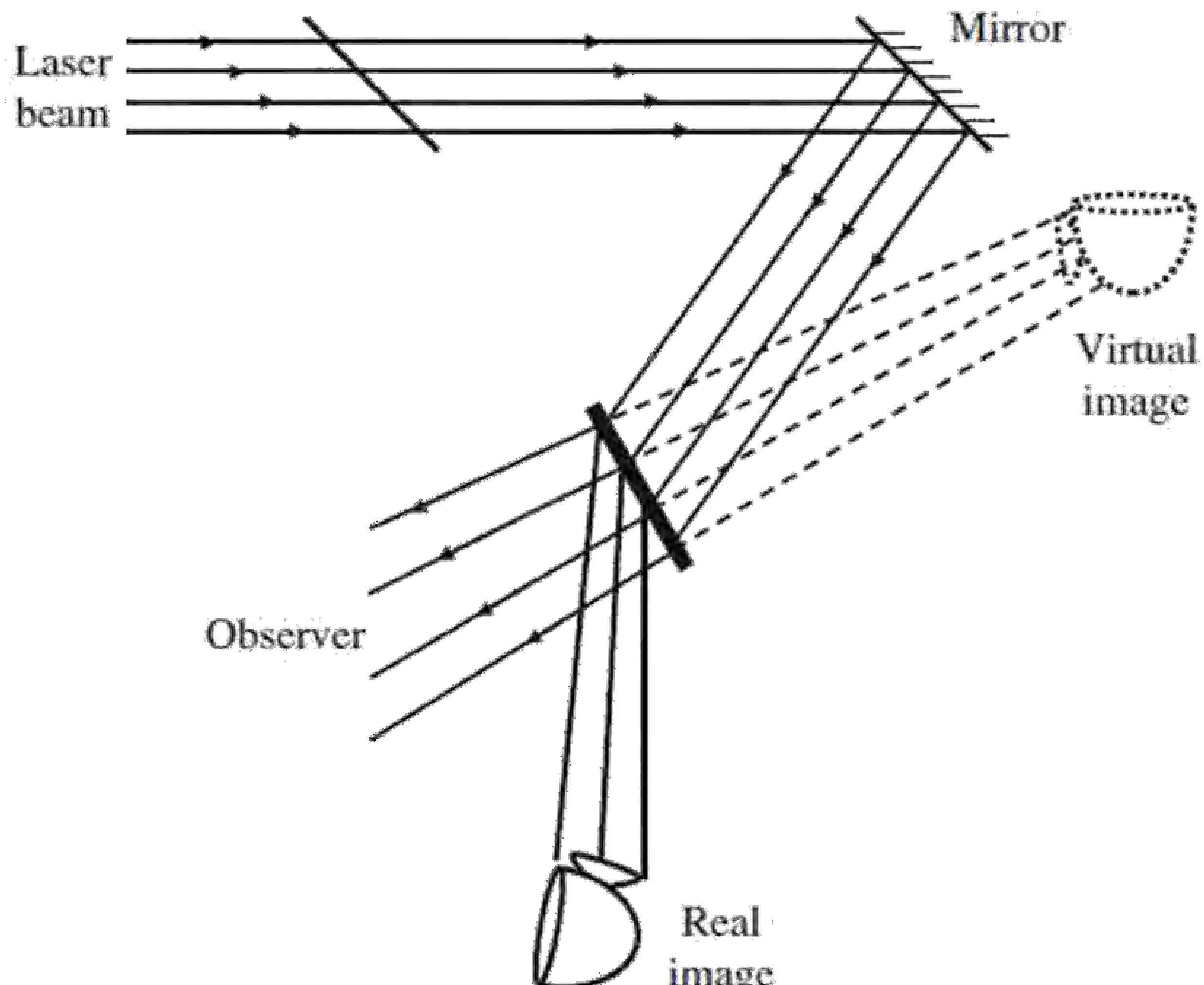
Recording / Reconstruction

- Recorded intensity distribution has the phase of object wave $\varphi(x, y)$ embedded in it
- Hologram has little resemblance to object - a coded form of the object wave is present

Reconstruction

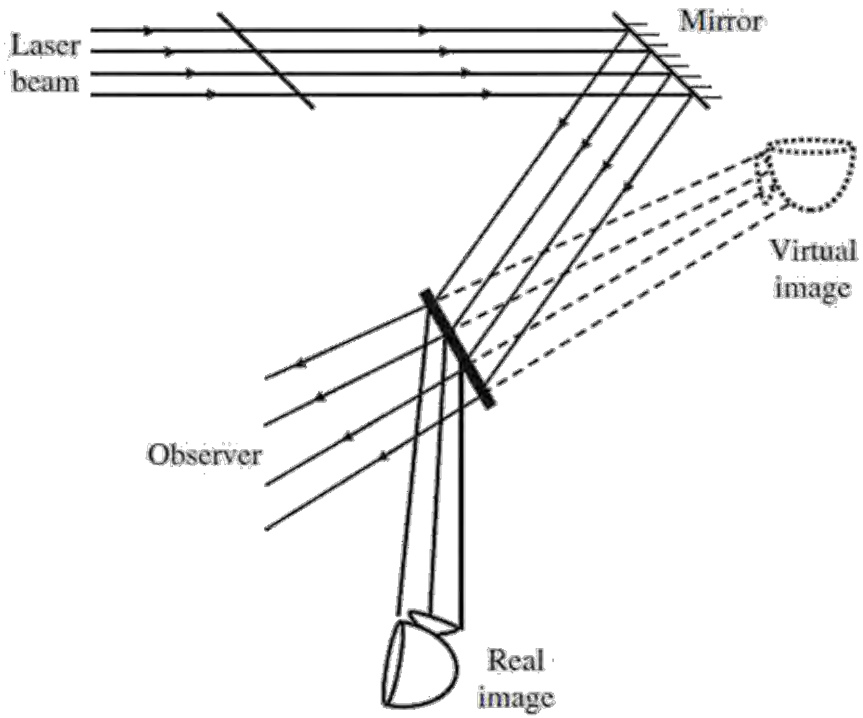
- Technique by which one reproduces the image is termed reconstruction.
- Hologram is illuminated by a wave called the reconstruction wave;
- This reconstruction wave in most cases is similar to the reference wave used for recording the hologram

Reconstruction

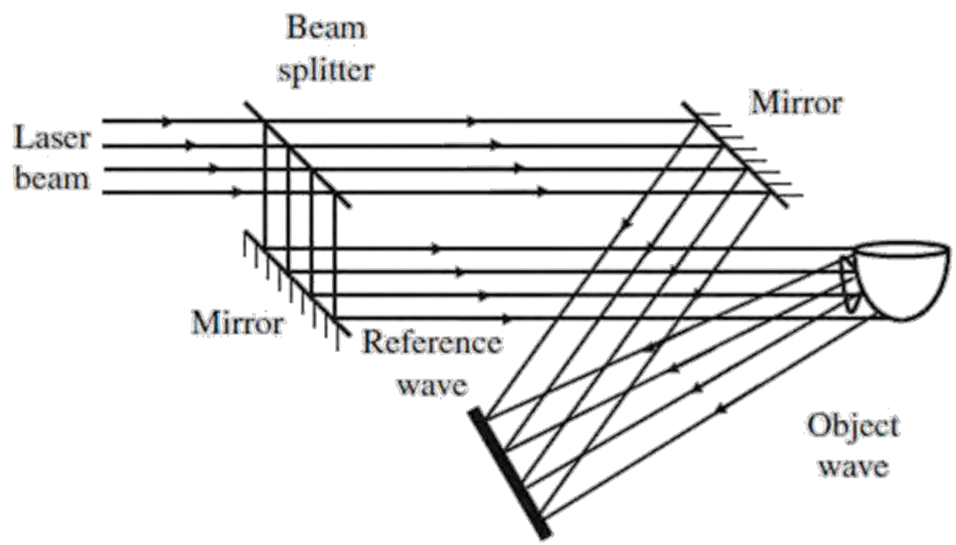


Reconstruction

Recording



Reconstruction



Reconstruction

- When the hologram is illuminated by the reconstruction wave, various wave components emerge from the hologram one of which is the object wave itself.

- When the exposed recording medium is developed, then – in general a transparency, with a certain transmittance is obtained.

- Under proper conditions, the amplitude transmittance of the hologram can be made to be linearly proportional to $I(x, y)$.

Reconstruction

Amplitude transmittance of hologram:

$$t(x,y) = I(x,y),$$

Emerging wave: $t(x,y)Aexp[i\psi(x,y)] = [O_0^2(x,y) +$

2nd term - original object wave apart from the constant multiplicative factor A^2.

1st term - reconstruction wave itself has been modulated in amplitude

last term - complex conjugate of object wave

Three wave components can be spatially separated by a proper choice of reference wave

Reconstruction

- 2^{nd} term - reproduction of object wave (as opposed to an image of the object), is identical to wave that was emanating from object when hologram was recorded

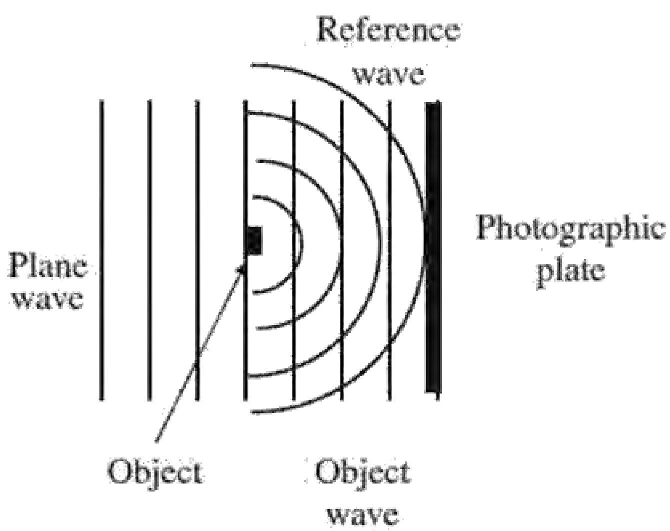
- when one views emerging wave from hologram, - a reconstructed image of object in its true 3-D form is appeared

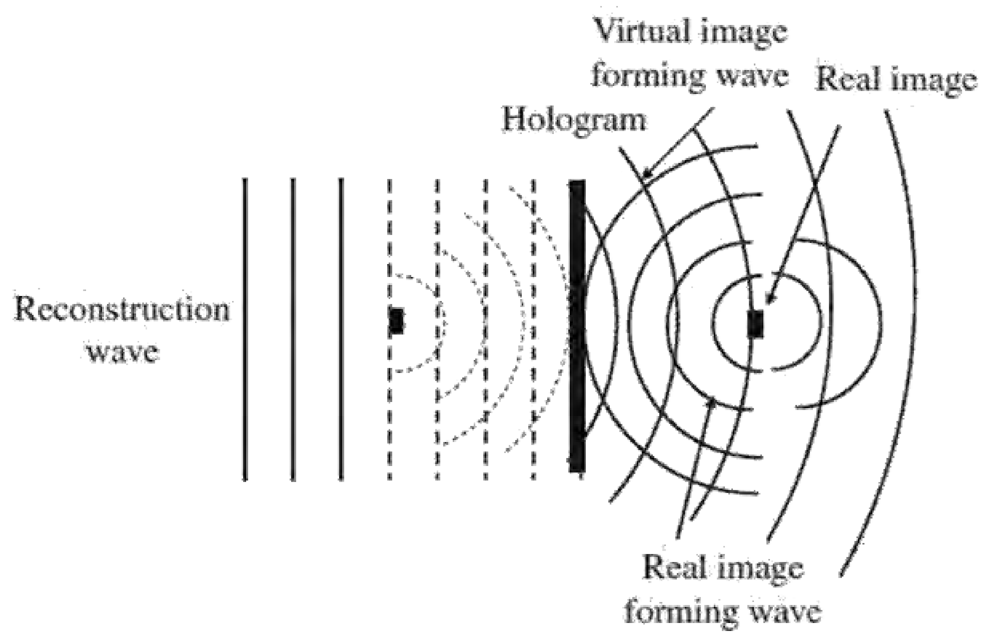
- Thus, as with original object, one can move one's viewing position and look around the object.
- If the hologram has recorded in it sufficient depth of field, one has to refocus one's eyes to be able to see distinctly the objects which are far away.
- A lens can be placed on the path of reconstructed wave and form an image of object on a screen.

Reconstruction

- Reconstruction process generates another image, which is real image represented by 3rd term - can be photographed by placing a suitable light-sensitive medium (like a photographic plate)

- In 1940 before laser in-line holography





Reconstruction

- reference beam is approximately parallel to object wave and the paths traversed by both object and reference waves are almost equal

- because existing sources like mercury discharge lamps had only small coherence lengths.

- disadvantage - waves that form the virtual and real images travel along the same direction.

- Thus, while viewing virtual image, one is faced with an unfocused real image and conversely.

Reconstruction

- 1962 that Leith and Upatneiks - off-axis holography – reference
- Reference beam which falls obliquely on the photographic plate reconstruction process, one obtains well-separated virtual and real images
- Technique was made possible by large coherence length of laser
- Holography is essentially an interference phenomenon – importance of coherence
- it is essential that illuminating wave possesses sufficient spatial coherence, so that wave from every object point may interfere with the reference wave

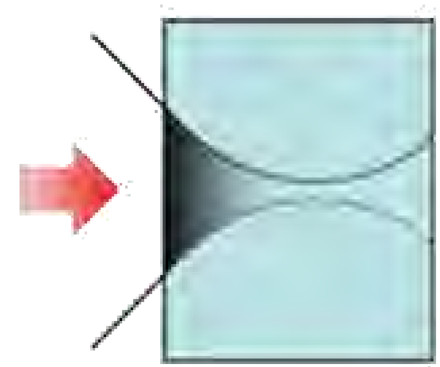
Reconstruction

- For stable interference fringes in the hologram, maximum path difference between reference wave and wave from object must be less than coherence length
- hologram of diffusely reflecting object, each point on object scatters light on the complete surface of hologram.
- Thus, every part of the hologram receives light from all parts of the object.
- If one breaks recorded hologram into various parts, each part is capable of reconstructing entire object; resolution in image decreases as the size of hologram decreases.

Nano and Femtosecond lasers

- 1 mJ pulse - 10 ns - [10 $\times 10^{-9}$ s] - peak power - 0.1 MW
- 1 mJ pulse - 100 fs - [100 $\times 10^{-15}$ s] - peak power - 10 GW
  - Absorption is independent of material properties - process any material

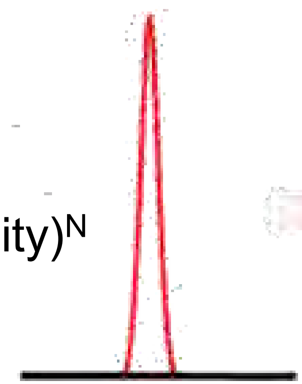
Nanosecond Pulses

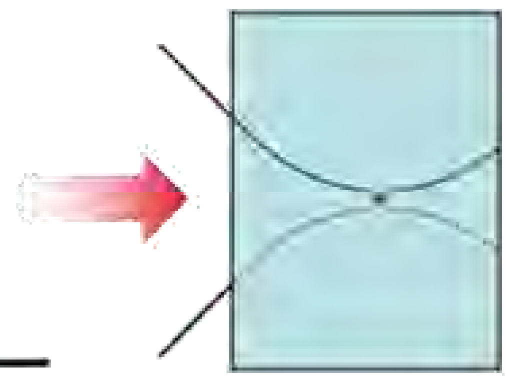


Linear Absorption depends on Intensity

Femtosecond Pulses

Nonlinear Absorption depends on (Intensity)^N





Nano and Femtosecond Laser Interaction

Interaction of ns and fs laser pulses with materials

Thank you