ENGINEERING PHYSICS II (SUBJECT CODE: 303192102)

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CHAPTER 4

Laser and Fibre Optics

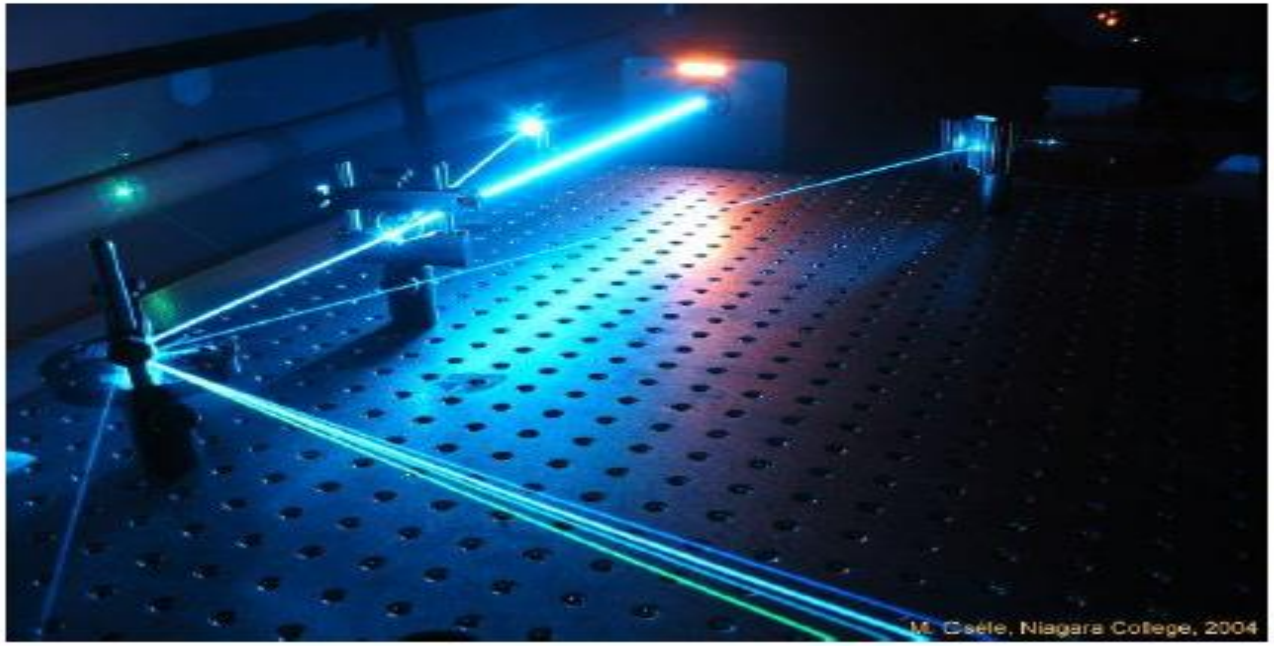
Introduction

Acronymn of LASER is

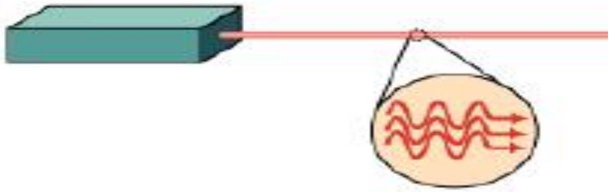
L	LIGHT
A	AMPLIFICATION
S	BY STIIMULATED
E	EMISSION
R	OF RADIATION

The basic scientific principle behind a laser was first put forward by Dr. Charles H.townes in 1954. The efforts of several scientists led to the development of the first laser called pulsed laser in 1960.

Light Amplification by Stimulated Emission of Radiation



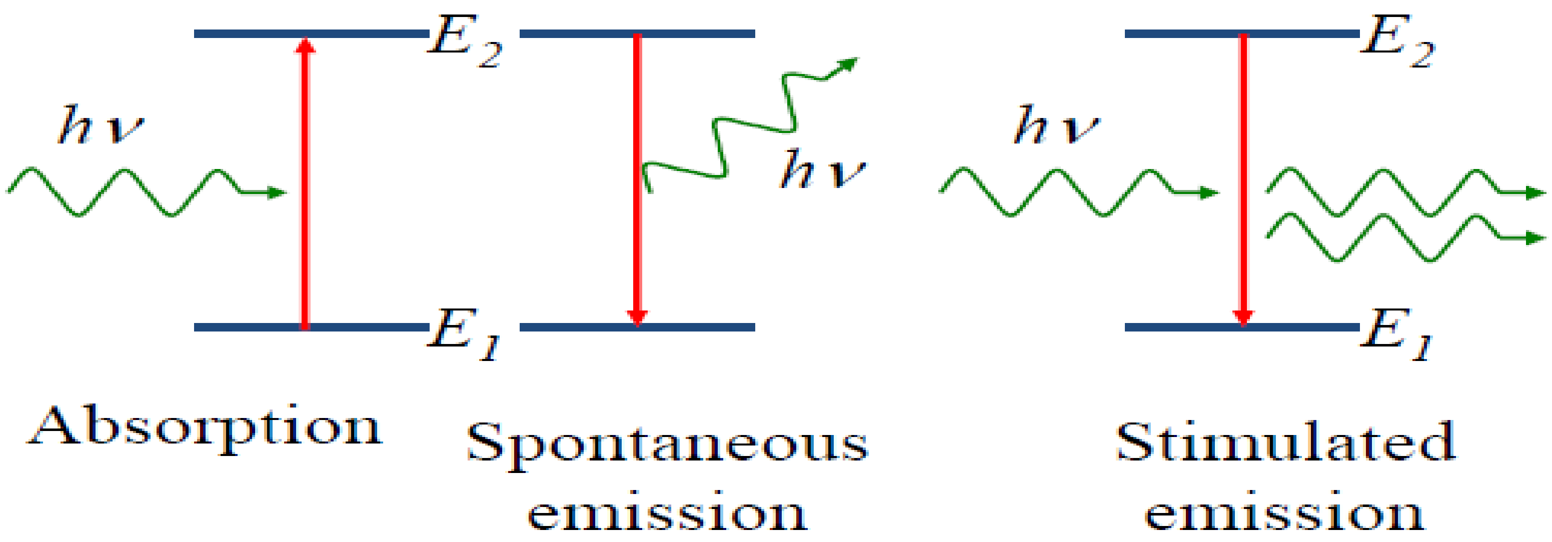
Spontaneous emission



Stimulated emission

•Einstein theory of matter radiation interaction

$$h\nu = E_2 - E_1$$



Einstein Coefficients

Einstein showed the interaction of radiation with matter with the help of three processes called stimulated absorption, spontaneous emission and stimulated emission.

Let N_1 be the number of atoms per unit volume in the ground state E_1 and these atoms exist in the radiation field of photons of energy $E_2 - E_1 = h\nu$ such that energy density of the field is E. Let R_1 be the rate of absorption of light by $E_1 \rightarrow E_2$ transitions by the process called stimulated absorption .

That is $R_1 \propto N_1 E$ Or

$$R_1 = B_{12} N_1 E \qquad (1)$$

Where B_{12} is known as the Einstein's coefficient of stimulated absorption and it represents the probability of absorption of radiation.

Now atoms in the higher energy level E_2 can fall to the ground state E_1 automatically after 10^{-8} sec by the process called spontaneous emission. The rate R_2 of spontaneous emission $E_2 \rightarrow E_1$ is independent of energy density E of the radiation field. R_2 is proportional to number of atoms N_2 in the excited state E_2 thus $R_2 \propto N_2$,

$$R_2 = A_{21} N_2 \qquad (2)$$

Where A_{21} is known as Einstein's coefficient for spontaneous emission and it represents the probability of spontaneous emission.

Continue

Atoms can also fall back to the ground state E_1 under the influence of electromagnetic field of incident photon of energy E_2-E_1 =hv by the process called stimulated emission Rate R_3 for stimulated emission E_2-> E_1 is proportional to energy density E of the radiation field and proportional to the number of atoms N_2 in the excited state,thus

$$R_3 \alpha N_2 E,$$

Or $$R_3=B_{21}N_2 E \qquad (3)$$

Where B_{21} is known as the Einstein coefficient for stimulated emission and it represents the probability of stimulated emission.

Relation between Einstein Coefficients?

In steady state (at thermal equilibrium), the two emission rates (spontaneous and stimulated) must balance the rate of absorption. Thus $R_1=R_2+R_3$, Using equations (1,2, and 3) ,we get

$$N_1B_{12}E=N_2A_{21}+N_2B_{21}E$$

Or $$N_1B_{12}E - N_2B_{21}E=N_2A_{21}$$

Or $$(N_1B_{12}-N_2B_{21})\ E = N_2A_{21}$$

Or $$E= N_2A_{21}/N_1B_{12}-N_2B_{21}$$

$$= N_2A_{21}/N_2B_{21}[N_1B_{12}/N_2B_{21} -1]$$

[by taking out common N_2B_{21} from the denominator]

Or $$E=A_{21}/B_{21}\ \{1/N_1/N_2(B_{12}/B_{21})-1\} \quad (4)$$

Einstein proved thermodynamically,that the probability of stimulated absorption is equal to the probability of stimulated emission. $B_{12}=B_{21}$, Then equation(4)becomes

$$E=(A_{21}/B_{21})\{1/(N_1/N_2)-1\} \qquad (5)$$

From Boltzman's distribution law, the ratio of populations of two levels at temperature T is expressed as

$N_1/N_2=e^{(E_2-E_1)/KT}$, $N_1/N_2=e^{h\nu/KT}$, Where K is the Boltzman's constant and h is the Planck's constant.

Substituting value of N_1/N_2 in equation (5) we get

$$E= A_{21}/B_{21}(1/e^{h\nu/KT}-1) \qquad (6)$$

Now according to Planck's radiation law, the energy density of the black body radiation of frequency ν at temperature T is given as

$$E = 8\pi h\nu^3/c^3(1/e^{h\nu/KT}) \qquad (7)$$

By comparing equations (6 and 7),we get $A_{21}/B_{21}=8\pi h\nu^3/c^3$.

This is the relation between Einstein's coefficients in laser.

Essential component of laser system

- **Active medium or Gain medium :** It is the system in which population inversion and hence stimulated emission (laser action) is established

Active Medium → Pumping Mechanism → Optical resonator

Pumping mechanism : It is the mechanism by which population inversion is achieved. i.e., It is the method for raising the atoms from lower energy state to higher energy state to achieve laser transition.

Optical resonator : A pair of mirrors placed on either side of the active medium is known as optical resonator. One mirror is completely silvered and the other is partially silvered. The laser beam comes out through the partially silvered mirror.

Different Pumping Mechanism

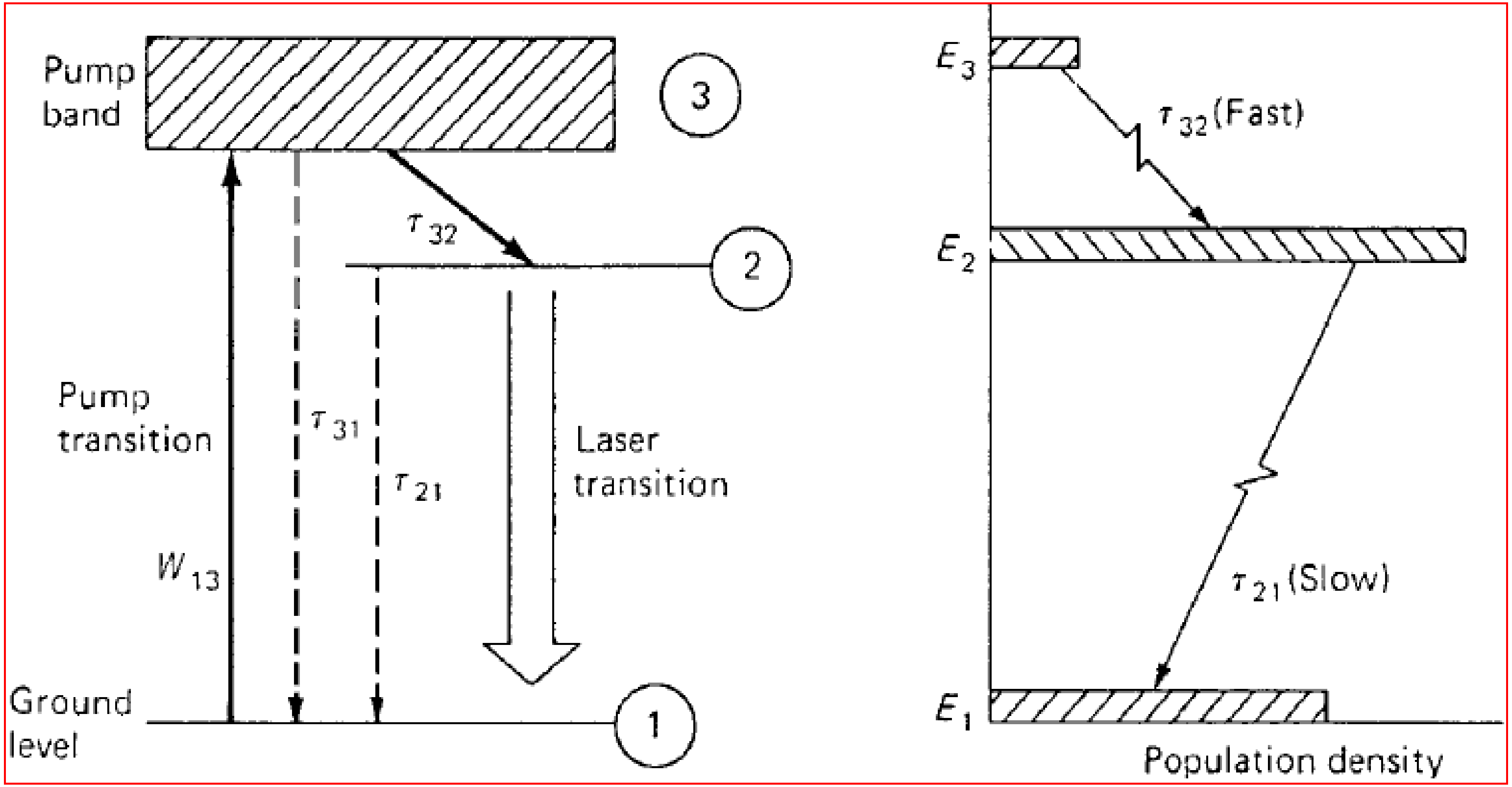
- ***Optical pumping*** **:** Exposure to electromagnetic radiation of frequency $\upsilon = (E_2 - E_1)/h$ obtained from discharge flash tube Suitable for solid state lasers

- ***Electrical discharge :*** By inelastic atom-atom collisions, population inversion is established. Suitable for Gas lasers

- ***Chemical pumping*** **:** By suitable chemical reaction in the active medium, population of excited state is made higher compared to that of ground state Suitable for liquid lasers

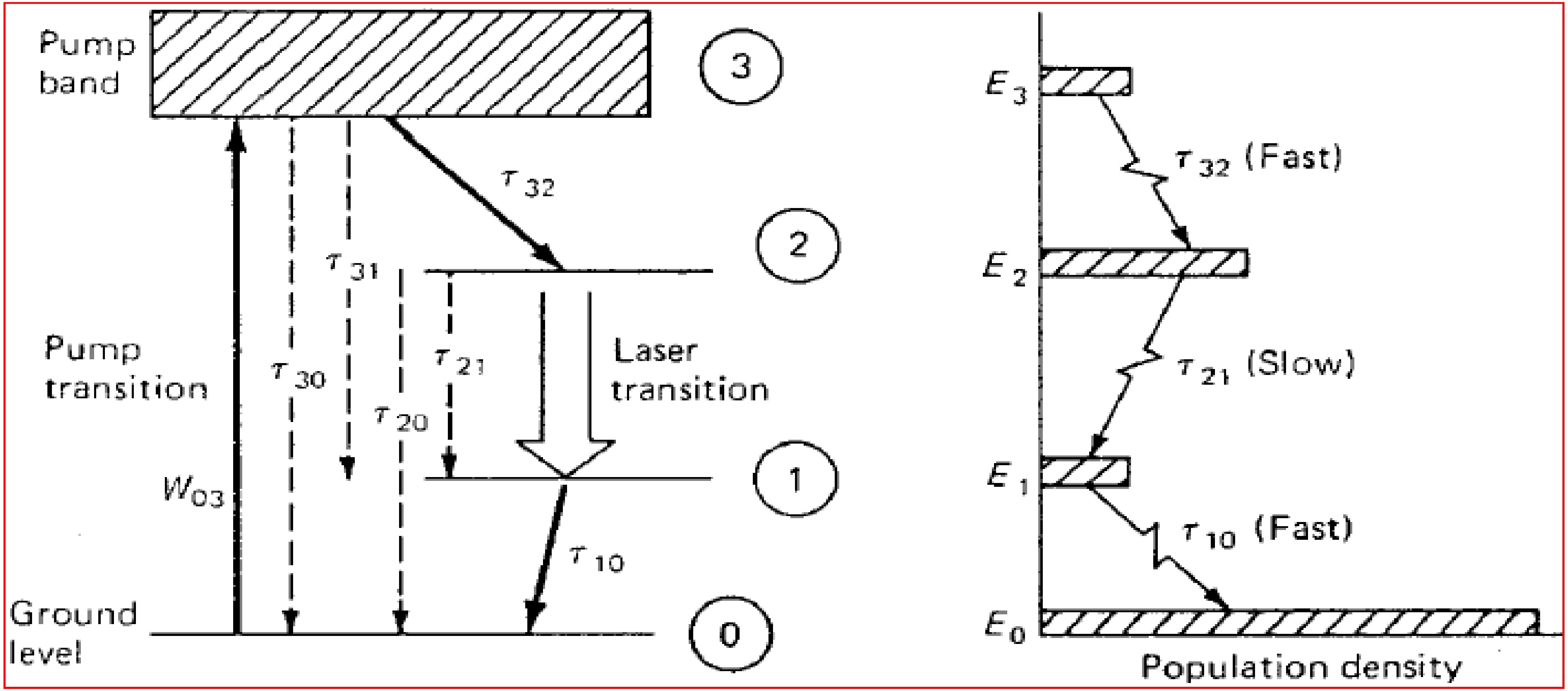
Laser Based on Number of Energy Levels

- Three level system: lasing possible but require high pump energy than four level system Example: Ruby Laser (three level)

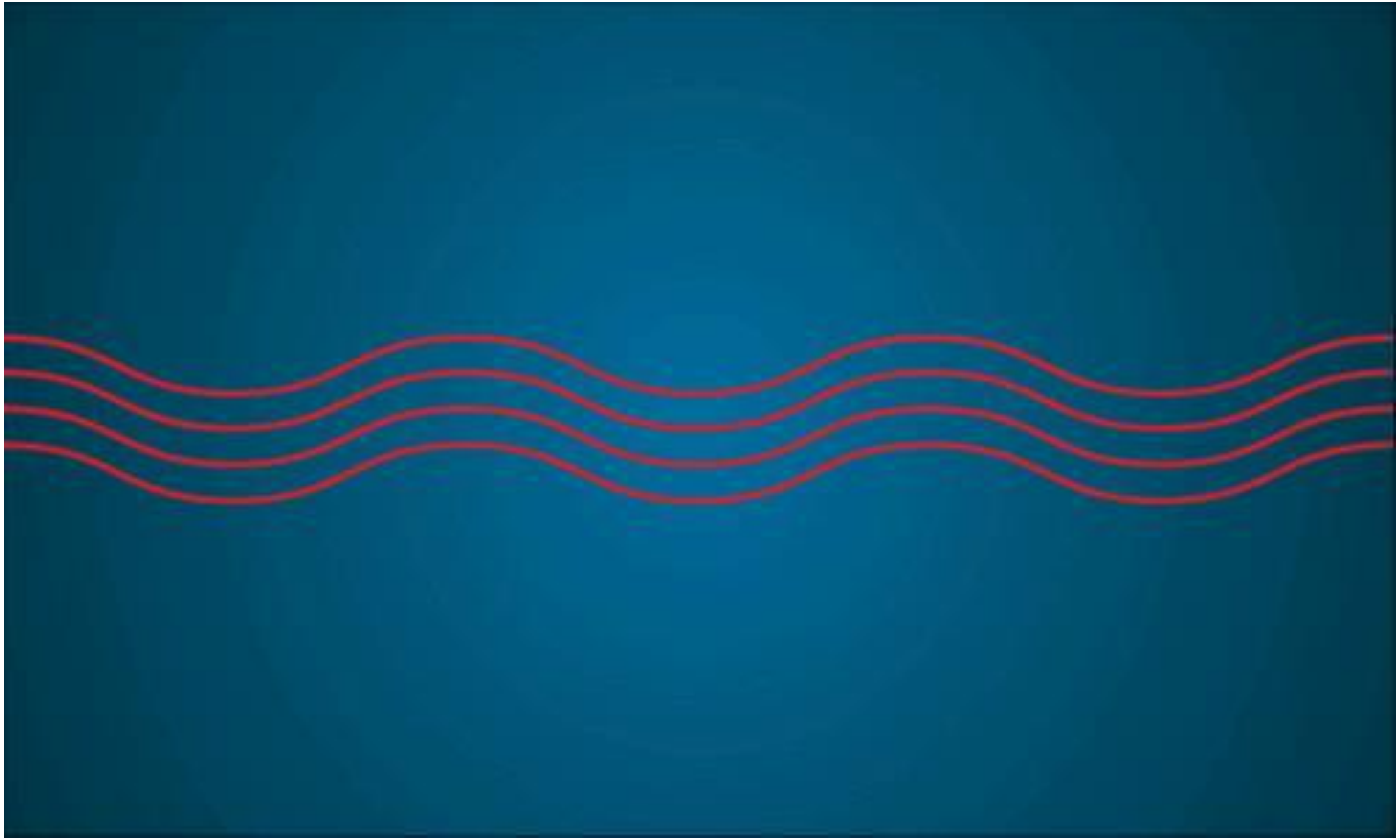


Continue

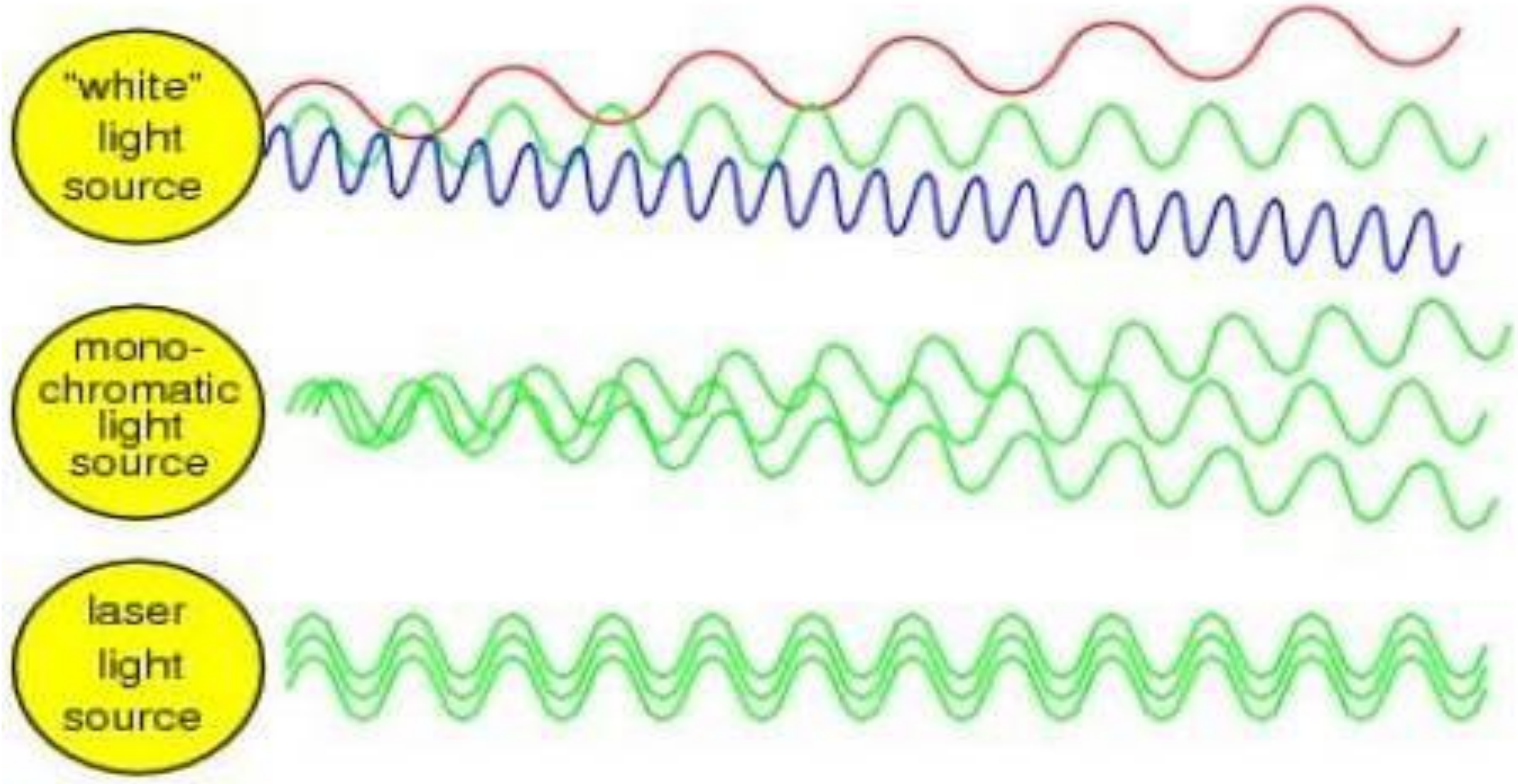
- Four level Laser : Easy to achieve population inversion even by pumping a relatively small number of ions into the upper laser level . Example-He-Ne Laser



Properties of Laser Light (Coherent)



Monochromatic



Pulse Width is Narrow

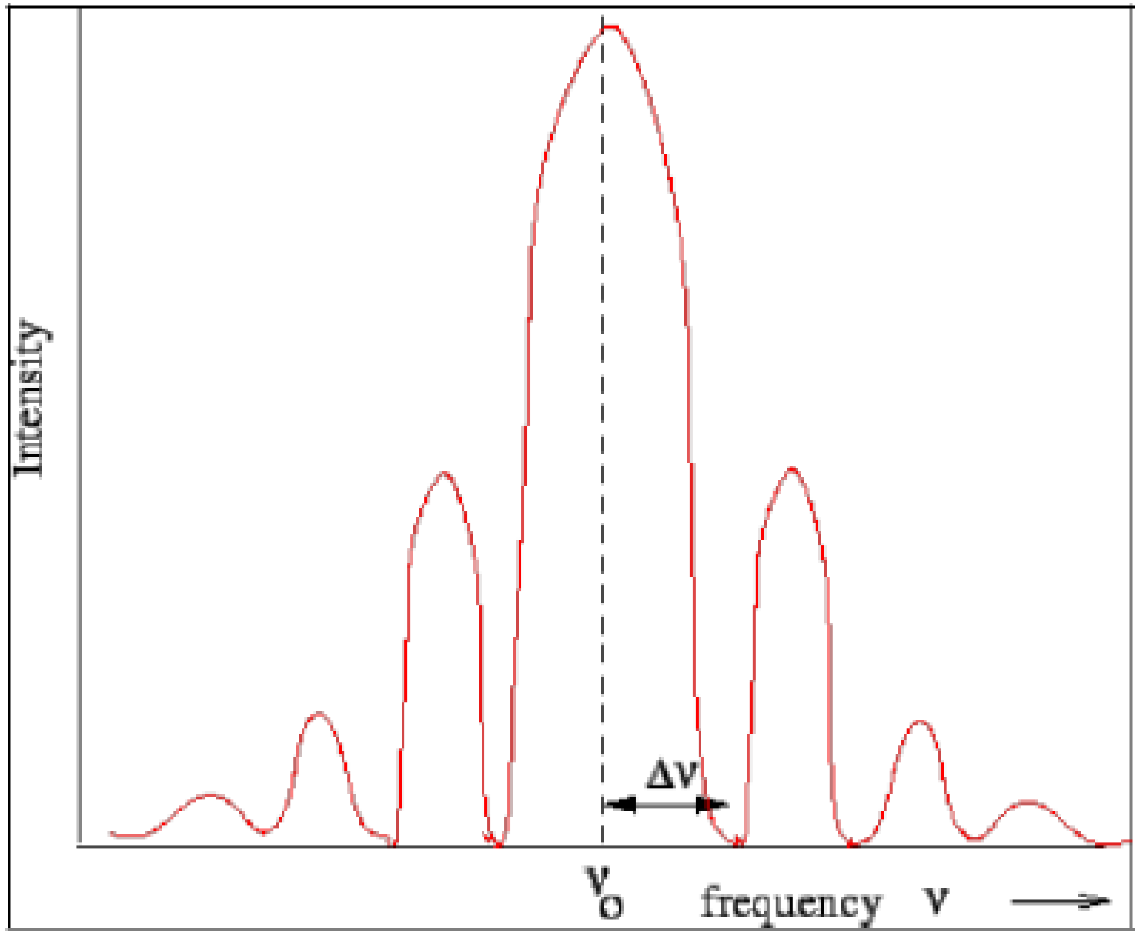
COHERENCE LENGTH

$$l = \frac{c}{\Delta\nu}$$

$$Also\ \nu = \frac{c}{\lambda} \therefore \frac{\Delta\nu}{\Delta\lambda} = \frac{c}{\lambda^2}$$

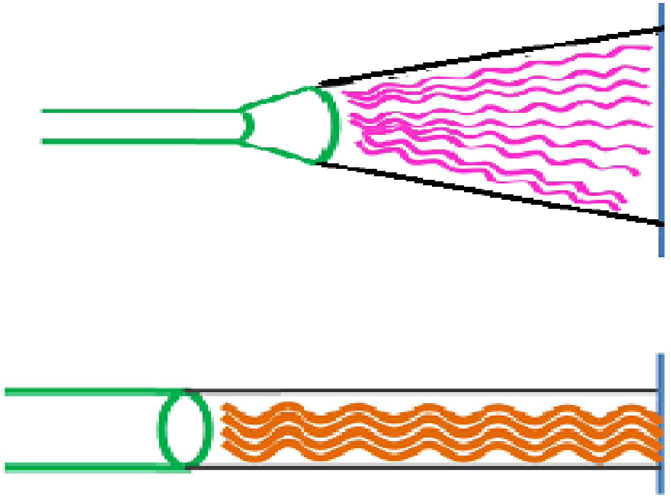
$$\therefore \Delta\nu = \frac{c}{\lambda^2}\Delta\lambda$$

$$l = \frac{c}{\frac{c}{\lambda^2}\Delta\lambda} = \frac{\lambda^2}{\Delta\lambda}$$

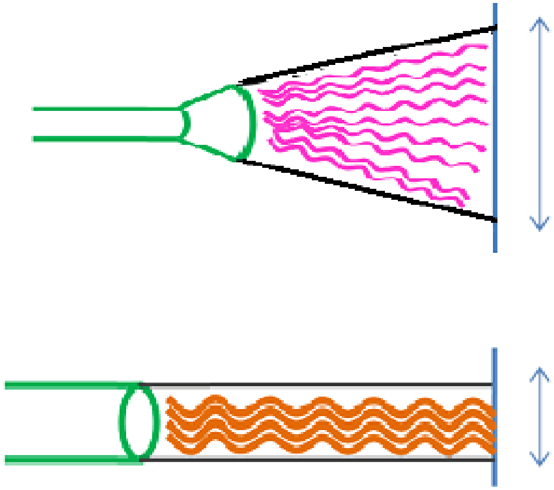


Since $\Delta\lambda$ is very small, coherence length is very high. Pulse width is narrow.

Highly Directional and Intense



$$Intensity\ I = \frac{E}{A \times t}$$



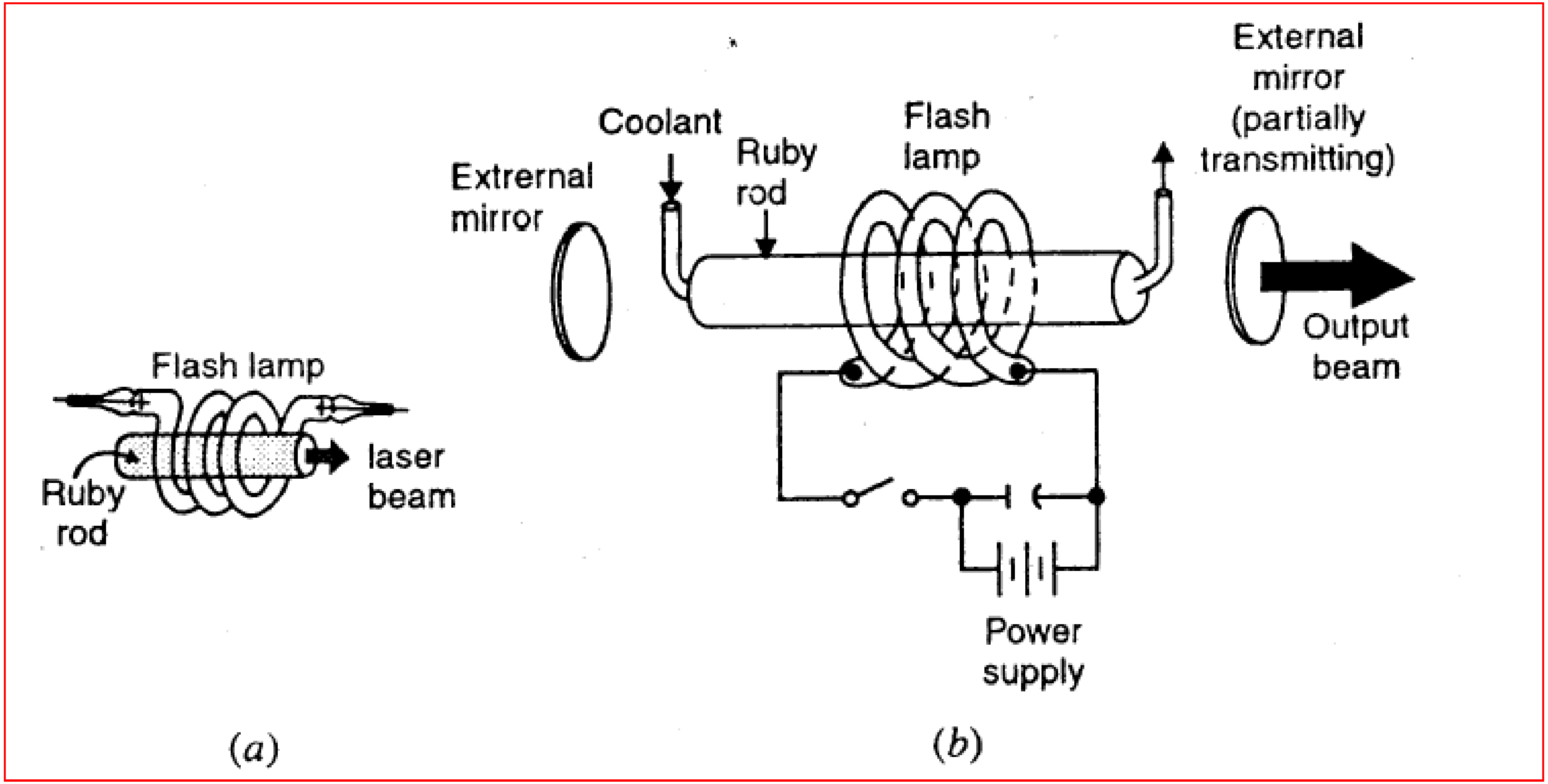
Ruby Laser

- First Laser developed in 1960 (TH Maiman)Ruby laser rod
- A synthetic pink Ruby crystal (Al_2O_3 doped with Cr^{3+}ions)
- Cr^{3+}ions concentration: 0.05%

- Al_2O_3(sapphire) host is hard, with high thermal conductivity, and transition metals can readily be incorporated substitution ally for the Al
- Active Centres(Cr^{3+}ions) have a set of three energy

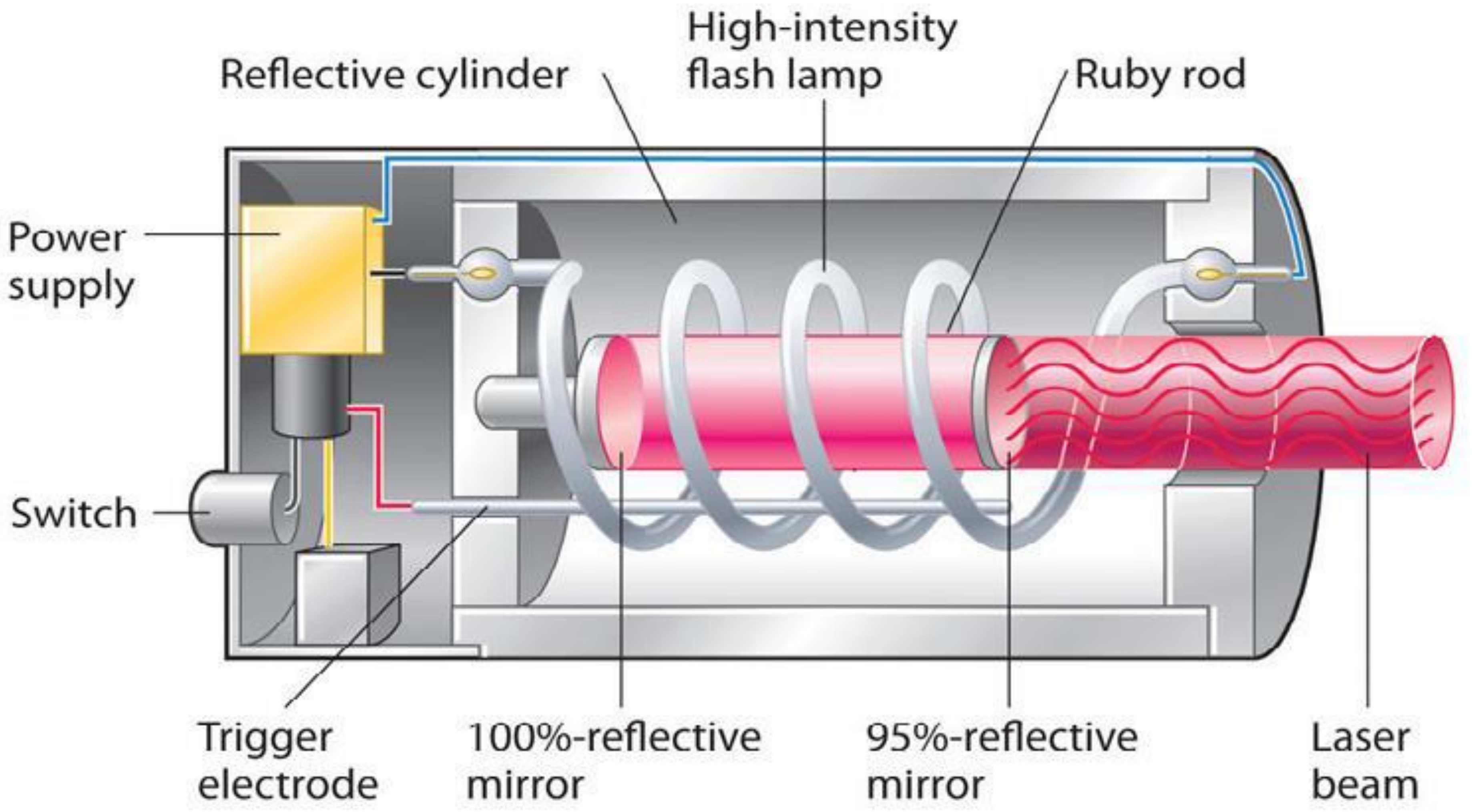
- Ruby crystal as cylindrical rod (4cm length 0.5 cm in diameter)
- Aluminum & Oxygen ions are inert
- Helical photographic flash lamp filled with Xenon

Construction

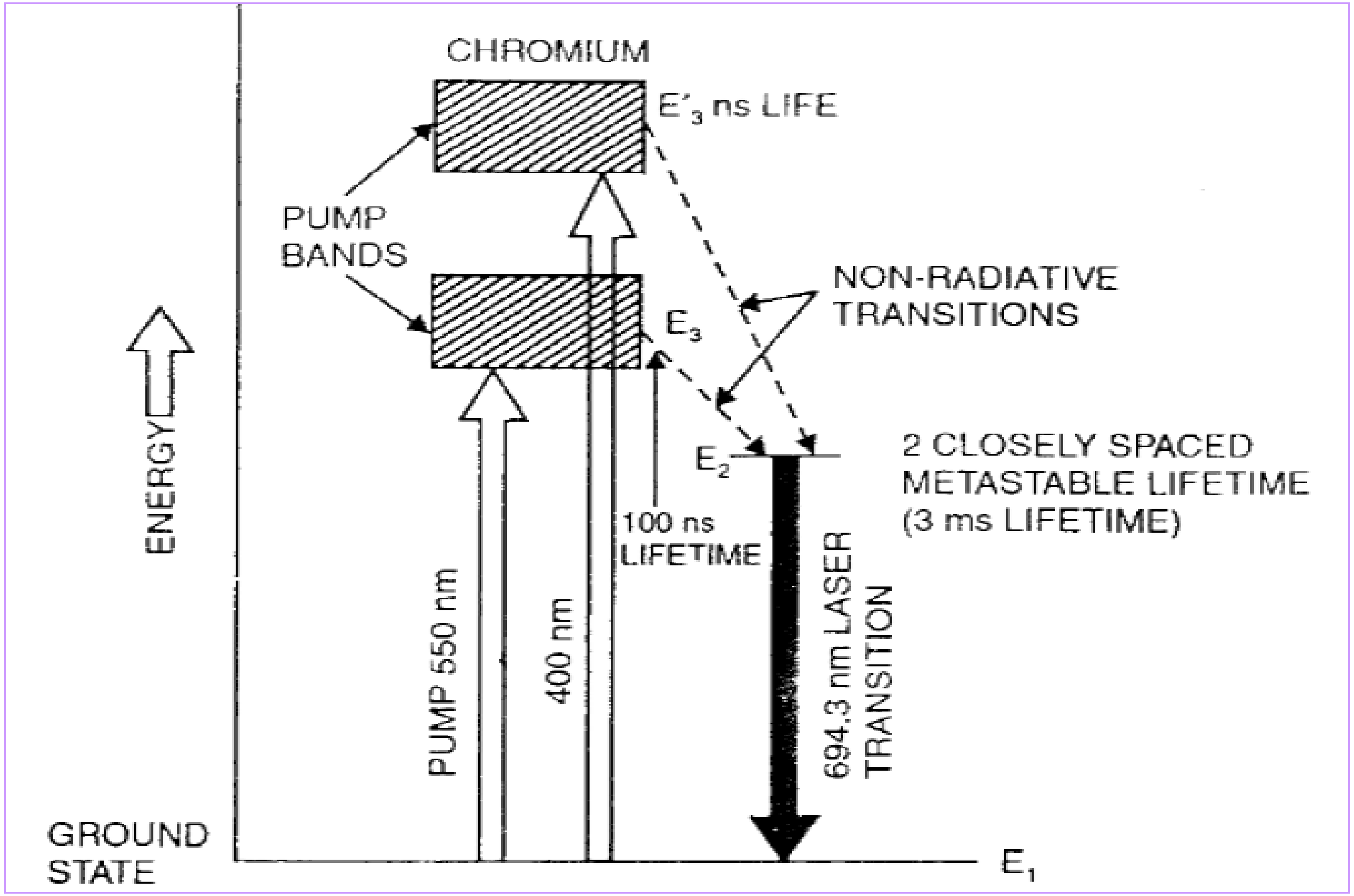


A typical Ruby laser (a) with internal mirrors (b) with external mirrors

Construction



Energy level of Cr Ions



Working

- A Three level laser system
- E2-metastable state (3ms)

- Ruby rod pumped with an intense Xenon flash lamp
- Ground state of Cr3+ions absorb light at pump bands
- 550nm and 400nm
- Non-radiative transitions to E2
- Population Inversion at E2

- Radiative transitions from E2to E1 Red wavelength at 694.3 nm
- Under intense excitation: Pumping > Critical threshold
- A spontaneous fluorescent photon (red) acts as input and trigger
- Stimulated emission; SYSTEM LASES

Beam Output

- Stimulated transitions faster than rate at which population inversion is maintained
- Once stimulated emission commence, the metastable state E2, depopulate very rapidly
- At the end of each pulse, population at E2 falls below the threshold value required for sustaining emission of light
- Lasing ceases & Laser becomes inactive

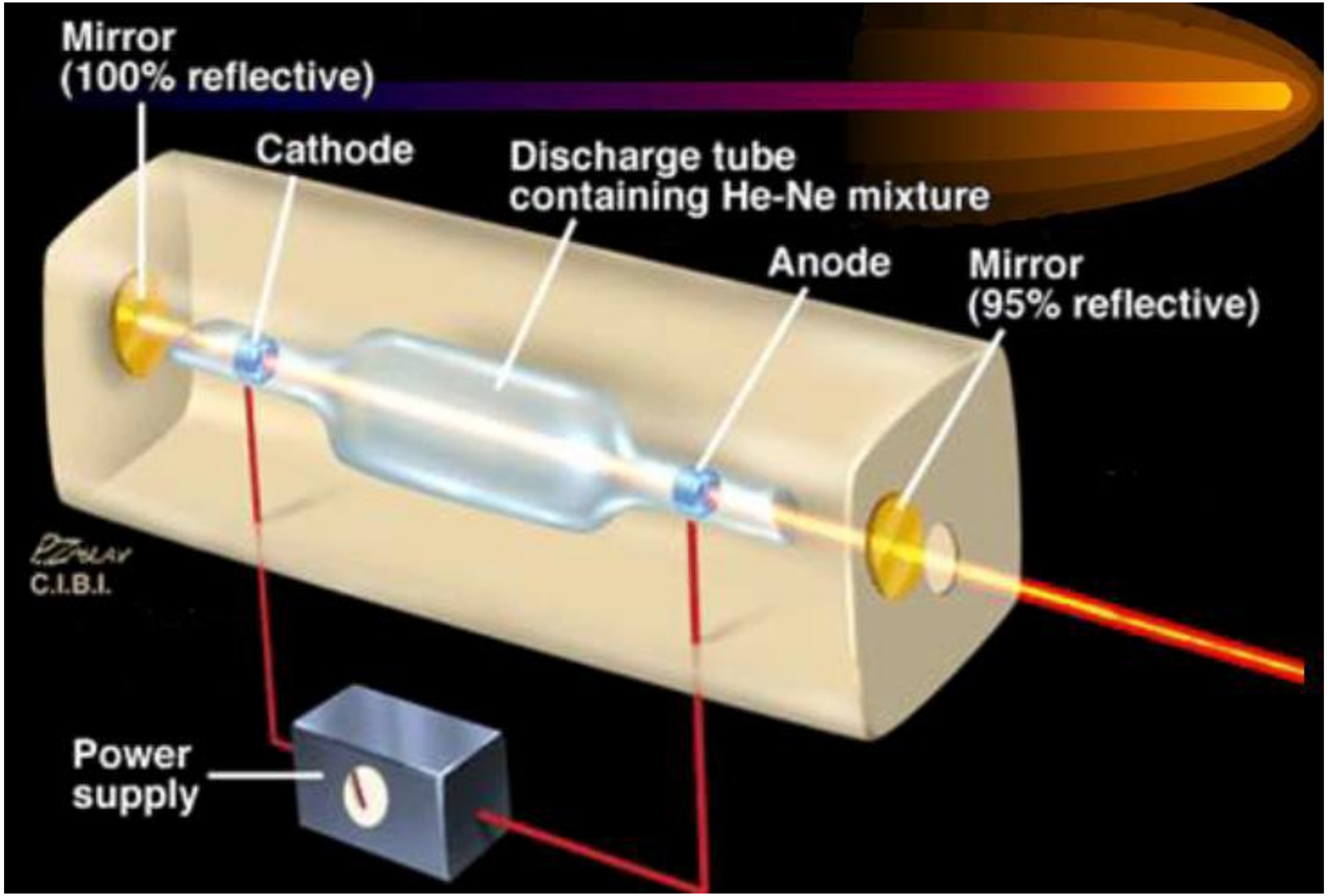
- **Next pulse will arrive only after P.I. is restored**

- High energy storage capability due to long upper laser level lifetime
- Pulse energy upto100J
- Relatively inefficient;0.1 to 1%
- Variety of applications: Plasma diagnostics; Holography

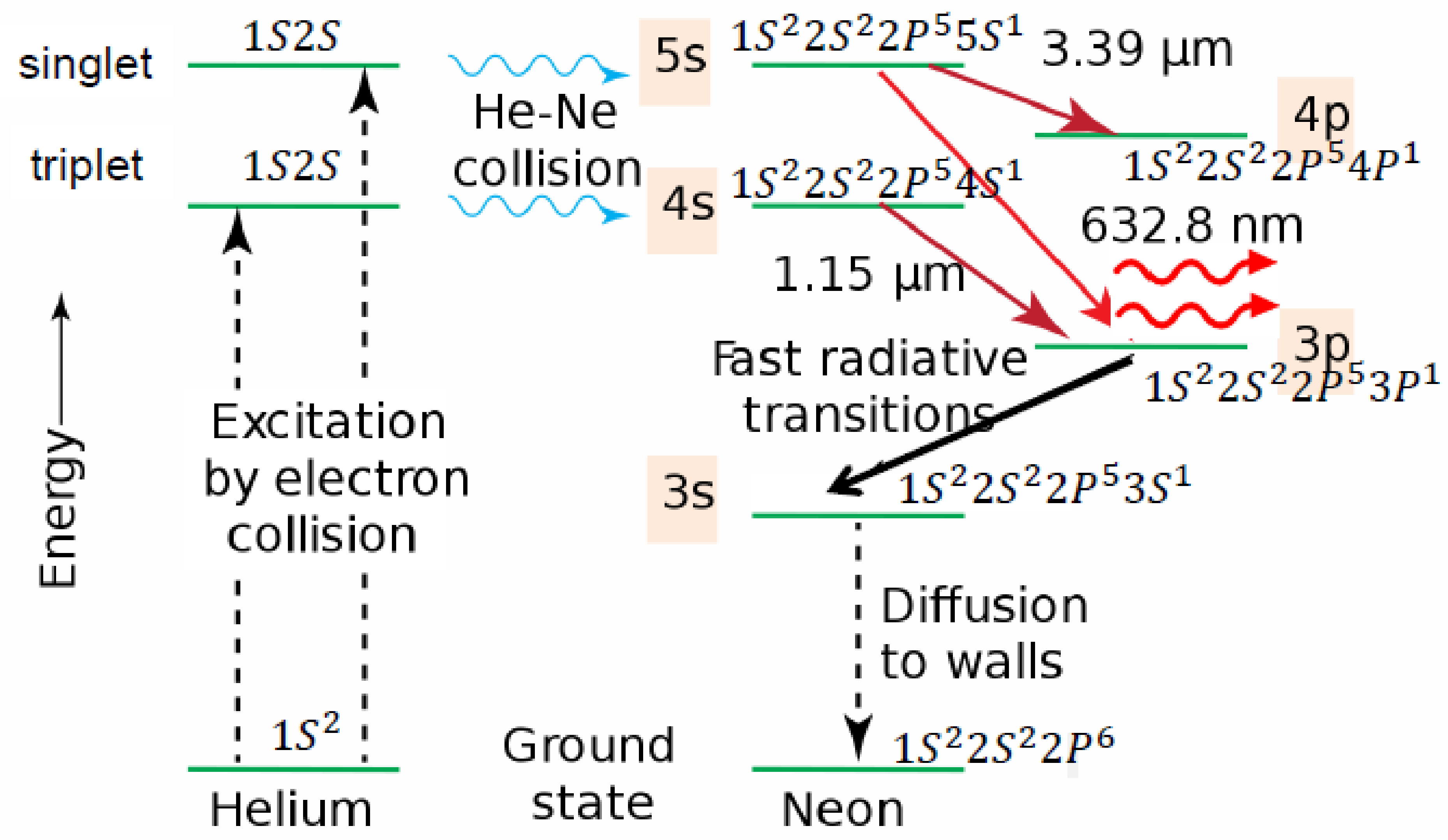
He-Ne Laser

- It is a gas laser, which consists of a narrow quartz tube filled with a mixture of helium and neon gases in the ratio 9:1 at low pressure (~0.1 mm of Hg).
- Ne atoms act as active centres and responsible for the laser action, while He atoms are used to help in the excitation process.
- The length of the quartz tube is about 50 cm and the diameter is about 1 cm.
- Two parallel mirrors are placed at the ends of the quartz tube; one of them is partly transparent while the other is fully reflecting. The spacing between the mirrors is adjusted such that it should be equal to the integral multiple of half-wavelengths of the laser light.
- The pumping is done through electrical discharge by using electrodes that are connected to a high voltage source

Construction



Energy Level Diagram



Working

- It is a four energy level laser system.
- The electrons produced from electric discharge collide with He and Ne atoms and excite them to the higher energy levels.
- He is excited to 20.61 eV and Ne is excited to 20.66 eV.

- These two states are metastable so the atoms may stay there for a longer time. Some of the He atoms get additional energy of 0.05 eV due to collisions with fast moving electrons so that their energy becomes 20.66 eV & they transfer their energy to ground-state Ne atoms through in-elastic collisions and excite them to the metastable energy level at 20.66 eV. Thus, He atoms help to achieve population inversion in Ne atoms.

Continue

- Now some of the Ne atoms will decay spontaneously to the lower state at 18.70 eV by emitting photons of wavelength 6328 Å.

- The photons that are moving parallel to the axis of the tube will reflect back and forth by the end mirrors and stimulate other excited Ne atoms to radiate another photon with the same phase. Thus, due to successive reflections of these photons at the ends of the tube, the number of photons multiplies.

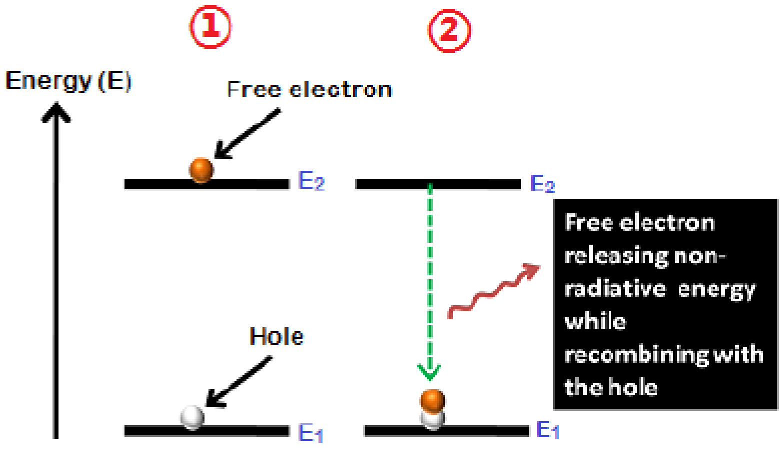
- After a few microseconds, a monochromatic, intense and collimated beam of red light of wavelength 6328 Å emerges through the partially silvered mirror.

Semiconductor Laser

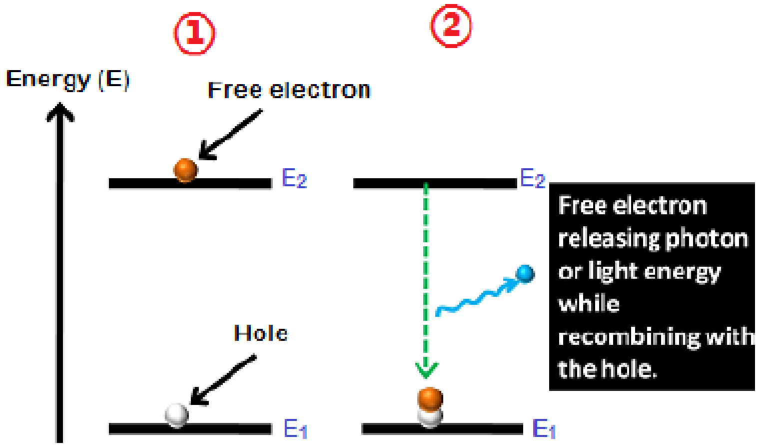
- Specially fabricated p-n junction device which emits coherent light when it is forward biased.
- R. N. Hall group: 1962 – First semiconductor laser made from Gallium arsenide (GaAs) operated at low temperatures and emitted light in the near IR region.
- Nowadays, p-n junction lasers are made to emit light almost anywhere in the spectrum from UV to IR.
- Diode lasers are remarkably small in size (0.1mm long).
- They have high efficiency of the order of 40%.
- Modulating the biasing current easily changes laser output.
- Operate at low powers & output power equivalent to that He-Ne Laser

Laser Diode

- An optoelectronic device converting electrical energy into light energy to produce high-intensity coherent light. The p-n junction of the semiconductor diode acts as the laser medium or active medium.
- The working of the laser diode is almost similar to the LED.
- Main difference: LED emits incoherent light. But, Laser diode emits coherent light.



Electron transition in ordinary diode



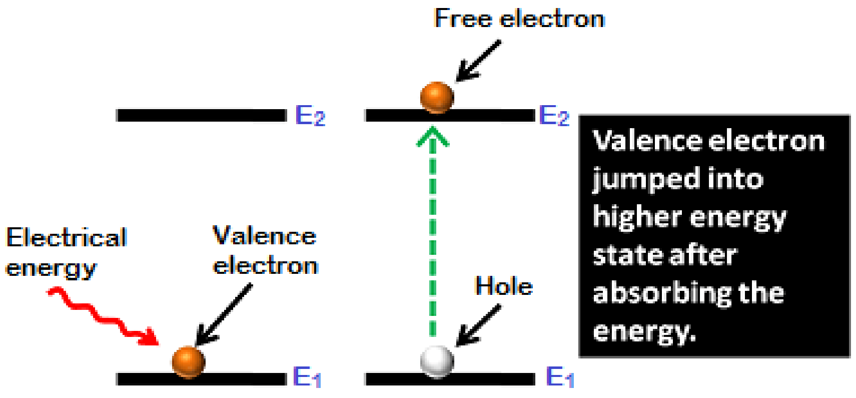
Electron transition in laser diode

Construction

- Made of two doped Gallium-Arsenide (GaAs) layers.
- One doped GaAs layer acts as n-type semiconductor!
- Second doped GaAs layer acts as p-type semiconductor.
- Doping agents: Selenium, Aluminum, and Silicon.
- A p-n junction (lasing/active medium) is formed by
- joining a p-type & n-type layers.
- GaAs diodes: Energy release in the form of light/photons.
- But, Si diodes energy release is not as light (mostly heat).
- Steps to produce a coherent beam of light:
- (i) Energy absorption
- (ii) Spontaneous emission
- (iii) Stimulated emission.

Working

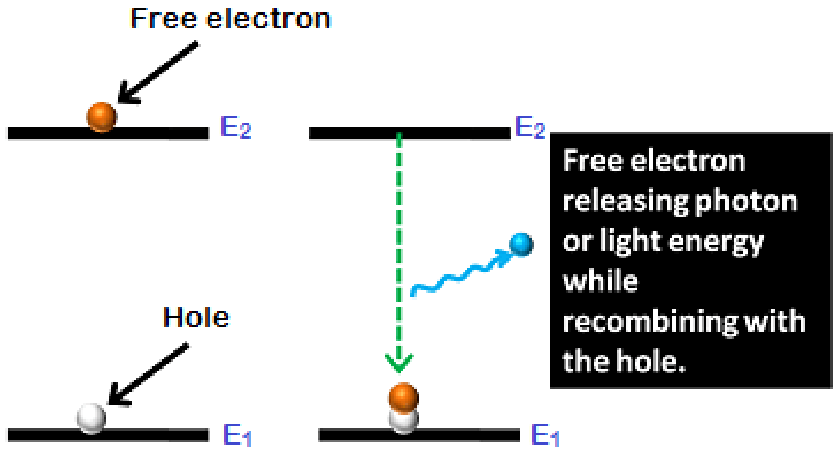
- Energy absorption from external sources. Electrical energy or DC voltage – external energy source.
- It supplies enough energy to the valence electrons in parent atom for jumping into the higher-energy (conduction) level.
- These conduction band electrons – free electrons.
- When the electron leaves the valence shell it creates an empty space (hole) at the point.
- Both free electron-hole pairs are generated due to absorption of energy from the external DC source.



Absorption

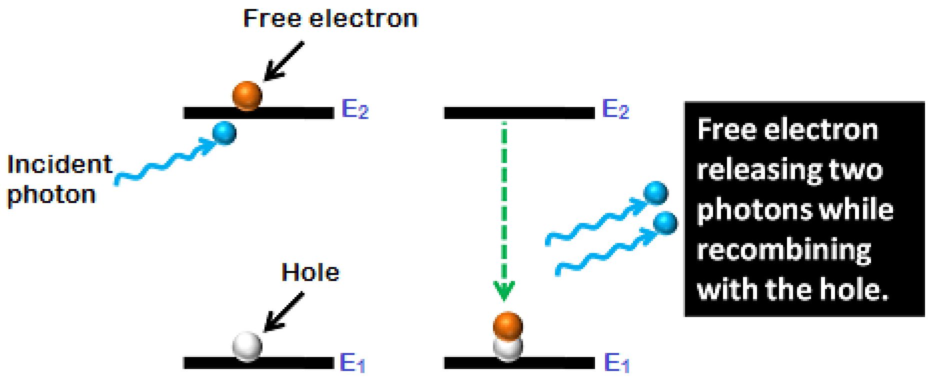
Continue

- Spontaneous emission due to natural fall of electrons to the lower energy state.
- Laser diodes: The valence band electrons (and so holes generated) are in the lower energy state.
- Conduction-band/free electrons are in the higher energy state. i.e. Free electrons have more energy than holes.
- The free electrons need to lose their extra energy by photons to recombine with the holes in the valence band.



Spontaneous emission

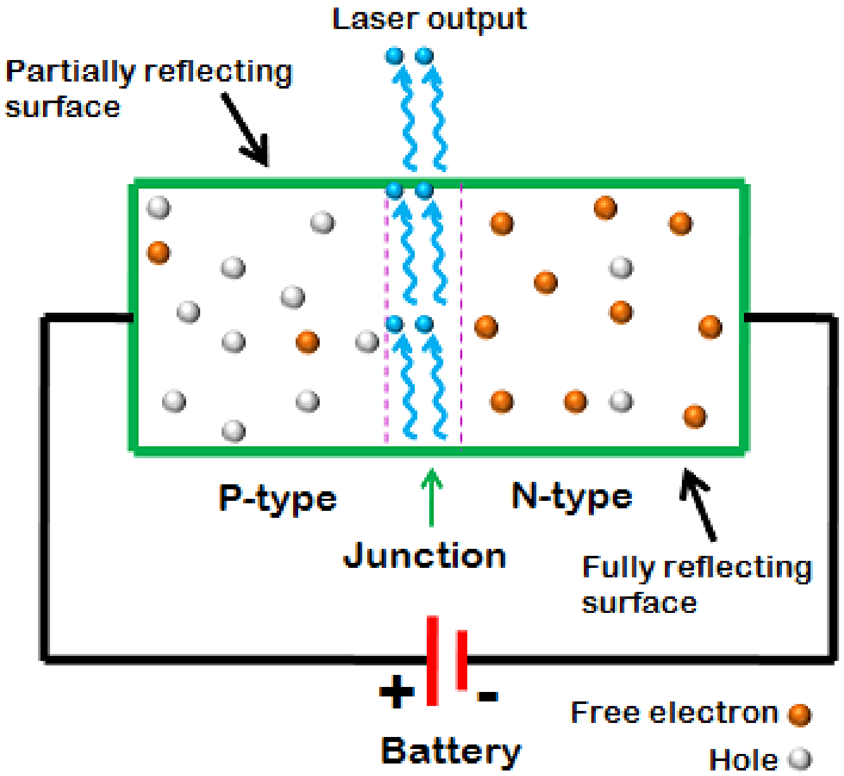
- Stimulated emission: Artificially inducing the free electrons by photon to fall into the lower energy state by releasing energy/photons.
- Free electrons need not wait for their whole lifetime.
- With external photons the free electrons are forced to recombine with holes releasing doubled-number of photons.
- All the stimulated photons travel in the same direction.
- Beam of high-intensity coherent light: diode-laser.



Stimulated emission

Continue

- Some electrons directly interact with the valence electrons.
- Some other electrons recombine with holes & releases photon.
- Photons generated due to stimulated emission moves parallel to the p-n junction.



Laser diode

Application of Laser

- Barcode Scanners

- Supermarket scanners He-Ne lasers: Laser beam scans the code, send a modulated beam to a light detector and then to a computer which has the product information stored.

- Semiconductor lasers can also be used for this purpose.

Continue

- Communication
- Fiber optic cables are a major mode of communication, because multiple signals can be sent with high quality and low loss by light propagating along the fibers.
- The light signals can be modulated with the information to be sent by either light emitting diodes or lasers. The lasers have significant advantages because they are more nearly monochromatic and this allows the pulse shape to be maintained better over long distances.
- If a better pulse shape can be maintained, then the communication can be done at higher rates without overlap of the pulses.
- Telephone fiber drivers are solid state lasers in the size of sand grain and consume a power of only half mW. Yet they can sent 50 million pulses per second into an attached fiber and encode over 600 simultaneous conversations.

Continue

- Welding and Cutting
- The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for welding and cutting.
- The automobile industry makes extensive use of CO_2 lasers with powers up to several kilowatts for computer controlled welding on auto assembly lines.
- CO_2 lasers to weld stainless steel handles on copper cooking pots.
- A nearly impossible task for conventional welding because of the great difference in thermal conductivities between stainless steel and copper, it is done so quickly by the laser that the thermal conductivities are irrelevant.

- Medical Uses of Lasers
- Highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for cutting and cauterizing instrument.
- Lasers are used for photocoagulation of the retina to halt retinal hemorrhaging and for the tacking of retinal tears.
- Higher power lasers are used after cataract surgery.
- A focused laser can act as an extremely sharp scalpel for delicate surgery, cauterizing as it cuts blood-rich tissue such as the liver.
- Lasers have been used to make incisions (cut/hole) half a micron wide, compared to about 80 microns for the diameter of a human hair.

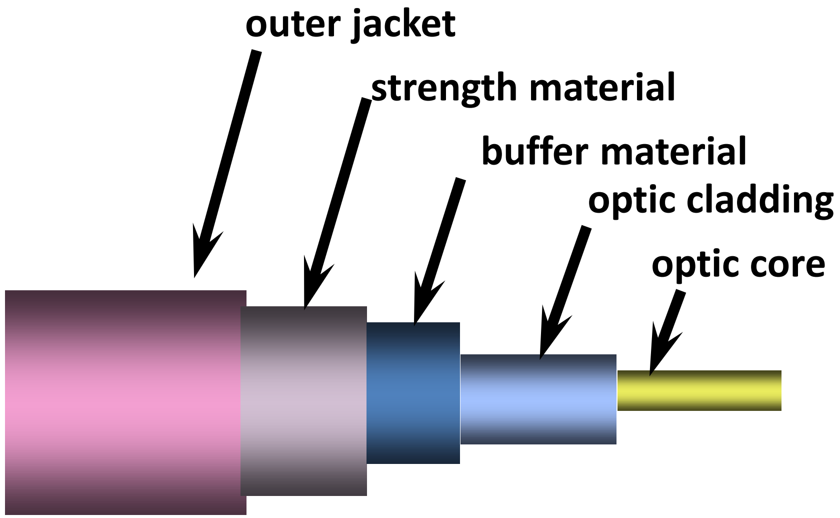
Continue

- Military: Lasers applications such as target designation and ranging, defensive countermeasures, communications and directed energy weapons.
- Directly as an energy weapon: Directed energy weapons are being developed, such as Boeing's Airborne Laser which was constructed inside a Boeing 747. Designated the YAL-1, it was intended to kill short- and intermediate-range ballistic missiles in their boost phase.
- Laser Guidance: A technique of guiding a missile or other projectile or vehicle to a target by means of a laser beam.
- Target designator: Another military use as a laser target designator. This is a low-power laser pointer used to

  indicate a target for a high precision-guided munition, typically launched from an aircraft.

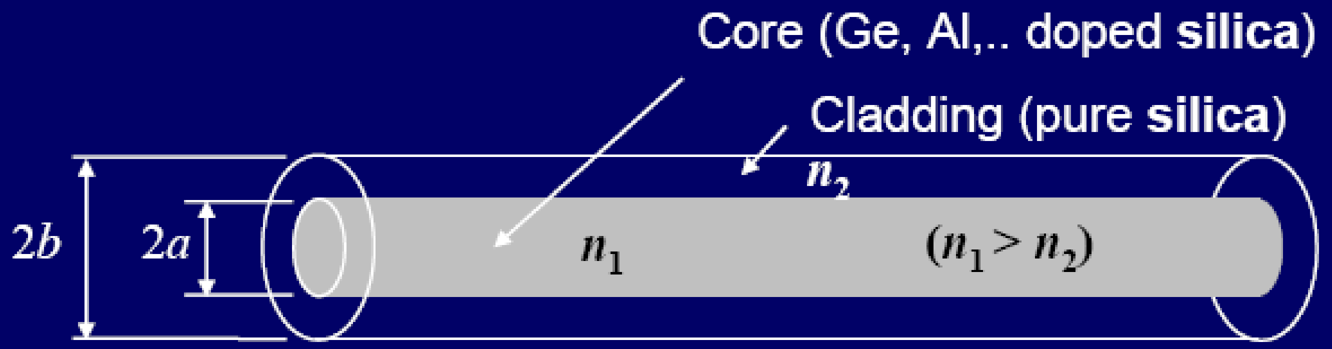
Optical Fiber

- The *optic core* is the light carrying element at the center of the optical fiber.
  - Commonly made from a combination of
  - silica and germanium.
- Surrounding the core is the *optic cladding*.
  - Made of pure silica.
  - The difference in materials between
- core and cladding is important ...



- *Buffer material* helps shield the core and cladding from damage.
- *Strength material* helps prevent stretch problems when the fiber cable is being pulled.
- *Outer jacket* protects against abrasion, solvents, and other contaminants

Optical fibers are cylindrical dielectric waveguides



Typical dimensions

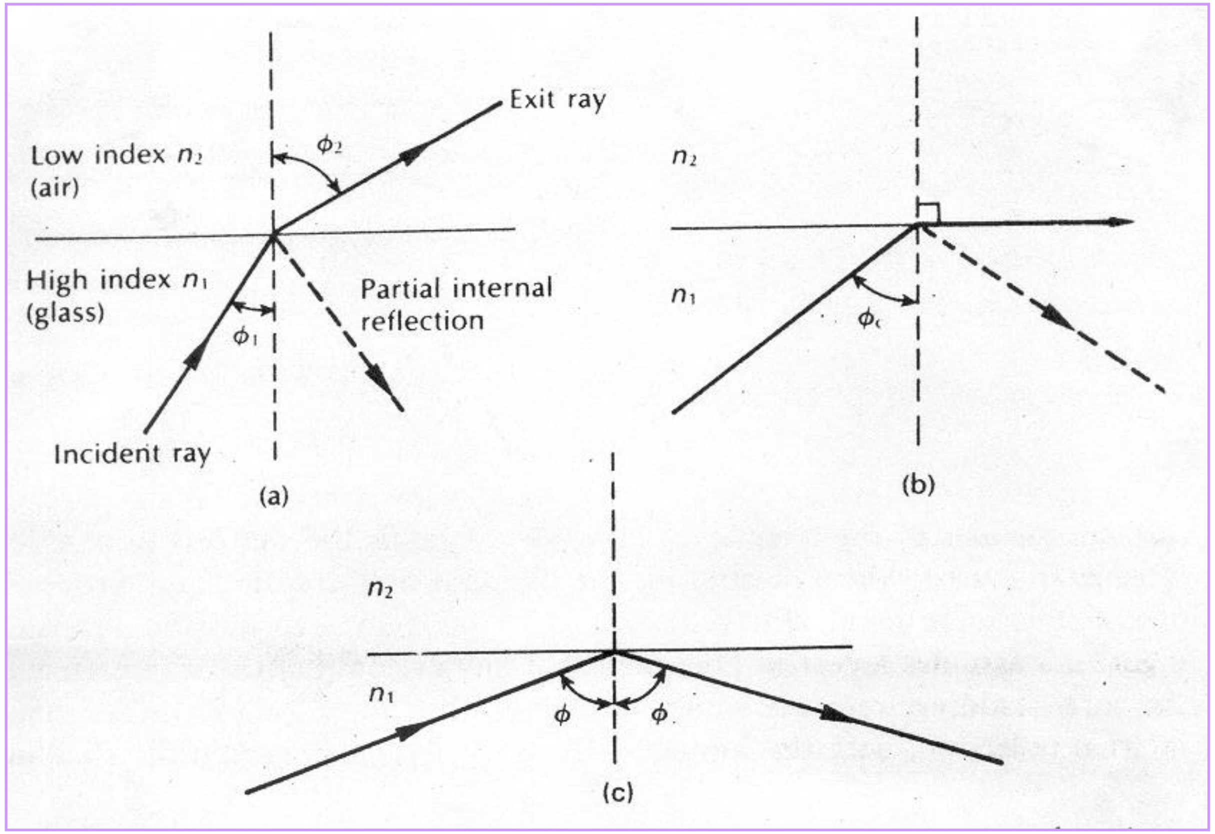
Core diameter	$2a = 9$ to $62.5\ \mu m$
Cladding diameter	$2b = 125\ \mu m$

Typical values of refractive indices

Core:	$n_1 = 1.461$
Cladding:	$n_2 = 1.460$

TIR

- Light entering from glass-air interface ($n_1 > n_2$) – **Refraction**
- At $\phi_2 = 90^o$, refracted ray moves parallel to interface between dielectrics and $\phi_1 < 90^o$ - **Limiting case of refraction**
- $\Rightarrow$ Angle of incidence, $\phi_1 \rightarrow \phi_C$; **critical angle**



Snell's Law:

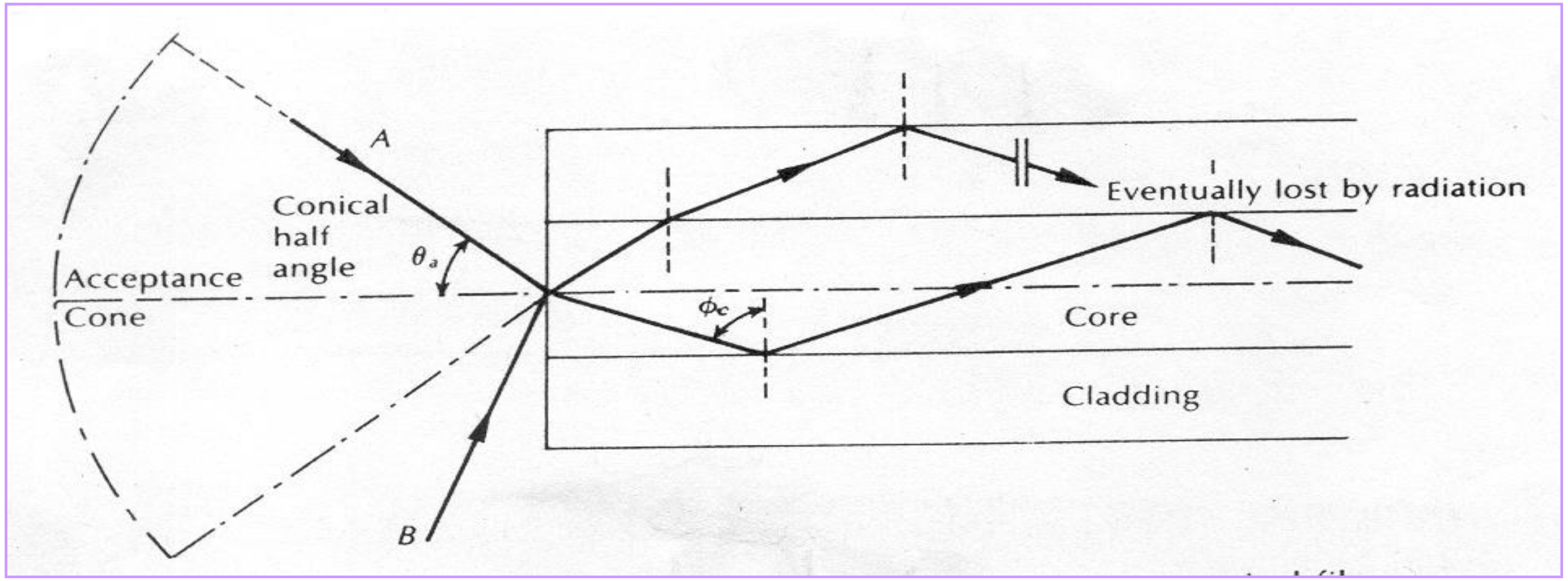
$n_1 \sin \phi_1 = n_2 \sin \phi_2$

or

$\Rightarrow \phi_2 > \phi_1$

Acceptance Angle

- Not all rays entering the fiber core will continue to be propagated down its length
- Only rays with sufficiently shallow grazing angle (i.e. angle to the normal > ϕ_C) at the core-cladding interface are transmitted by TIR.
- Any ray incident into fiber core at angle > θ_a will be transmitted to core-cladding interface at an angle < ϕ_C and will not follow TIR



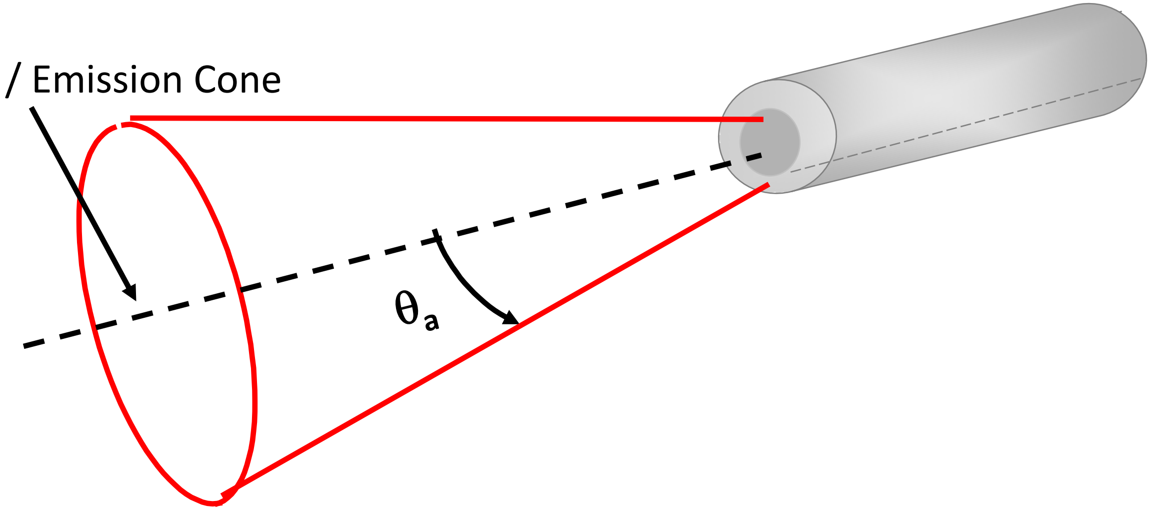
Acceptance angle θ_a when launching light into an optical fiber

Numerical Aperture (NA)

- **A Very useful parameter : measure of light collecting ability of fiber.**

  Larger the magnitude of NA, greater the amount of light accepted by the fiber from the external source

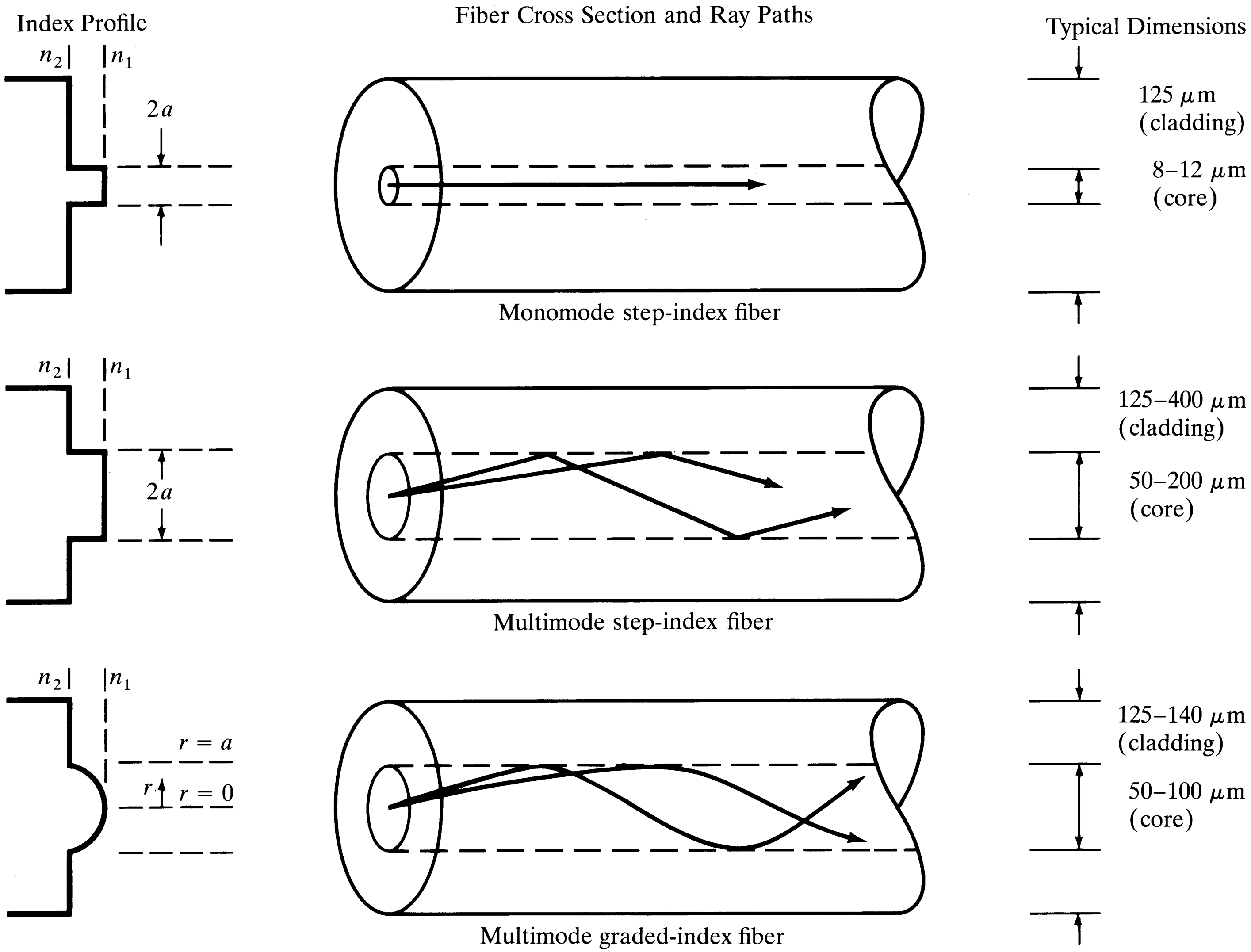
- For a lens or a fiber, the NA is commonly defined as the sine of half the maximum angle of acceptance. For multimode fibers, the equation shown calculates the NA using the index of refraction (n) of the core and cladding. The NA value is dependant on the fiber's core diameter, typical values for Step-Index fibers are 0.3 to 0.4.
- The equation is also a fair approximation for single-mode fibers, which have NAs in the order of 0.1.
- Conceptually, the NA of a fiber describes how easy it is to couple light into and out of the fiber, like in the case of a laser launching light into a fiber.



Numerical Aperture (NA) :

$$NA = \sin\theta_a = [(n_1)^2-(n_2)^2]^{1/2}$$

Classification of Fibre



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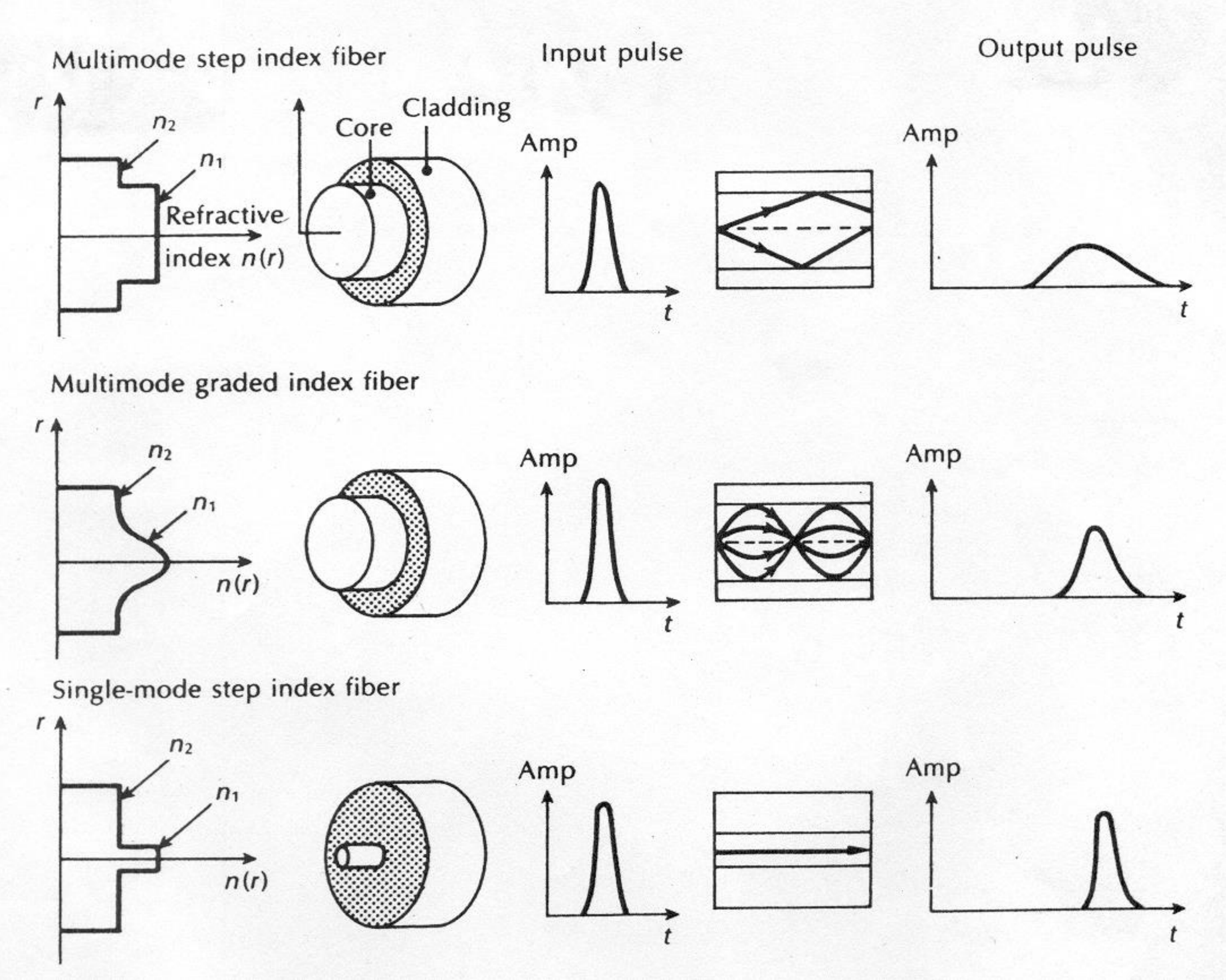


Multimode step index fiber
Input pulse
Output pulse
r
n_2
n_1
Core
Cladding
Refractive index $n(r)$
Amp
t
Multimode graded index fiber
$n(r)$
Single-mode step index fiber

Attenuation (or Transmission loss): determines the maximum ***repeater less separation*** between a transmitter and receiver.

Logarithmic relationship between the optical output power and the optical input power

- **Measure of the decay of signal strength or light power**

$$P(z) = P_o e^{(-\alpha z)}$$

where,

P(z) **:** Optical power at distance 'z' from input
P_o **:** Input optical power
α **:** Fiber attenuation coefficient, [dB/km]

- Applications – Temperature Sensing

Multi-Point Fire Detection Systems

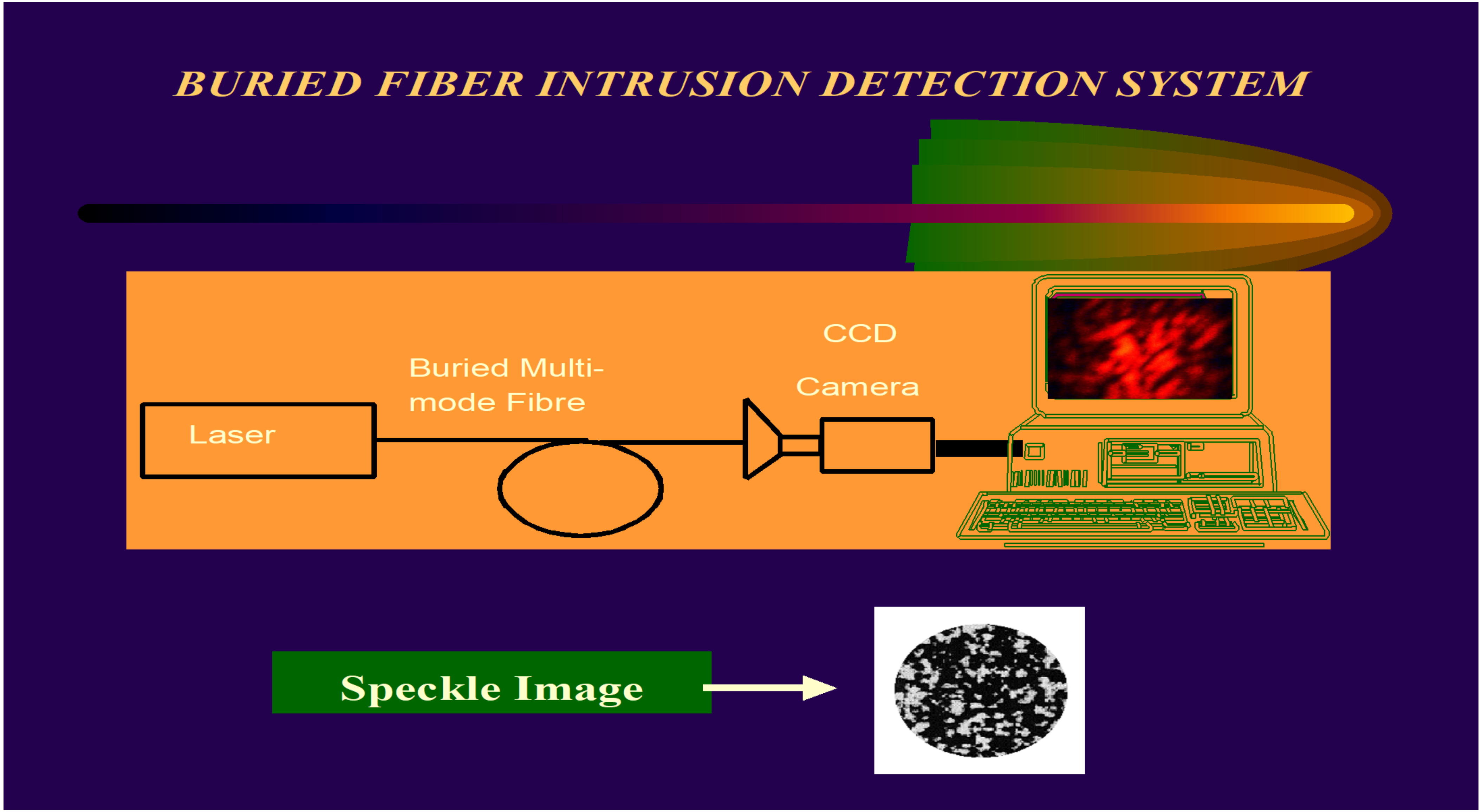
- ➢ Road and Rail Tunnels, Mineshafts
  Public Buildings, Car Parks

Leak Detection by Temperature Change

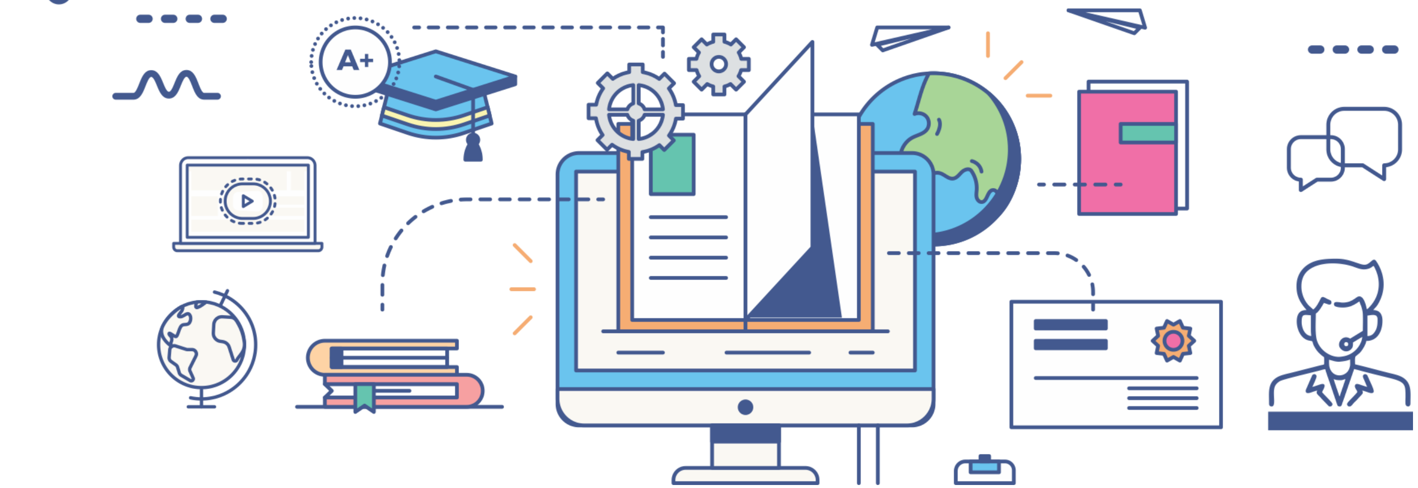
- ➢ Oil & Gas pipelines, LNG storage tanks

Health Monitoring

- ➢ Oil wells, power cables, petrochemical plants
  Cable stays


BURIED FIBER INTRUSION DETECTION SYSTEM
Buried Multi-
mode Fibre
CCD
Camera
Laser
Speckle Image

DIGITAL LEARNING CONTENT



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