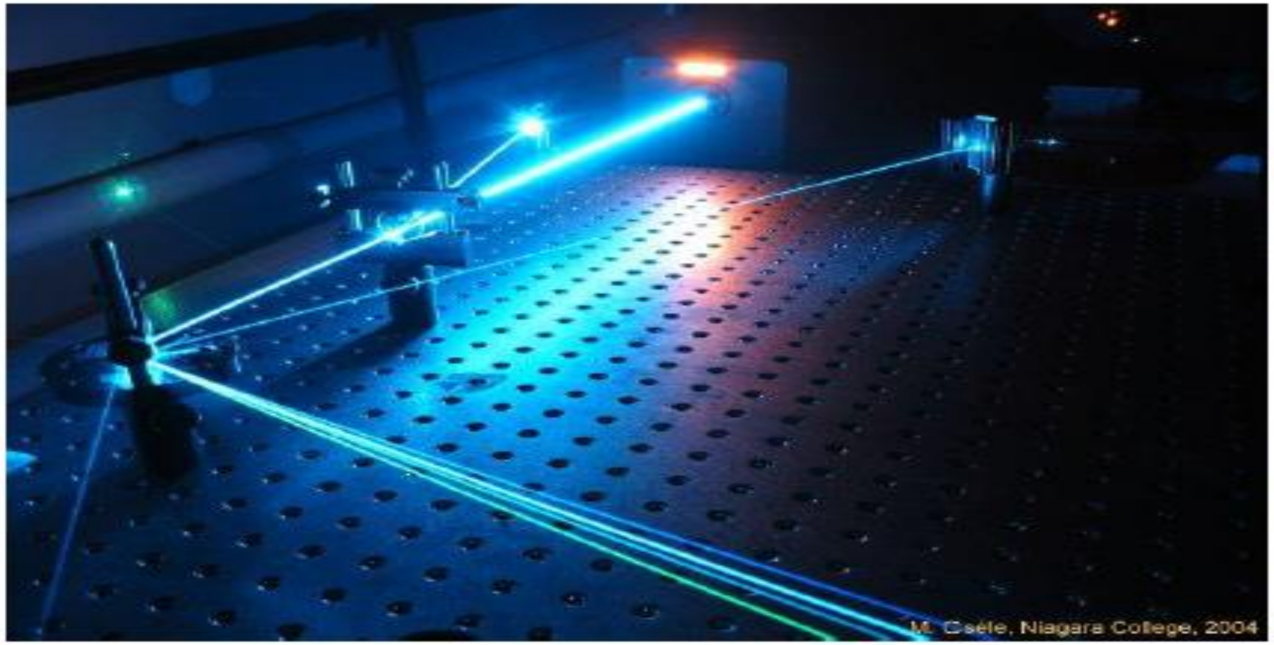
# CHAPTER 4

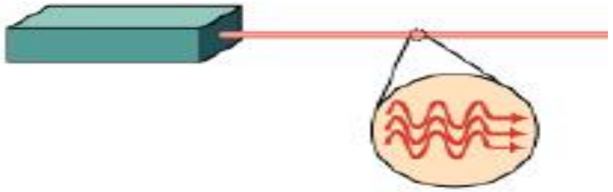
## Laser and Fibre Optics

# What is a laser ?

Light Amplification by Stimulated Emission of Radiation

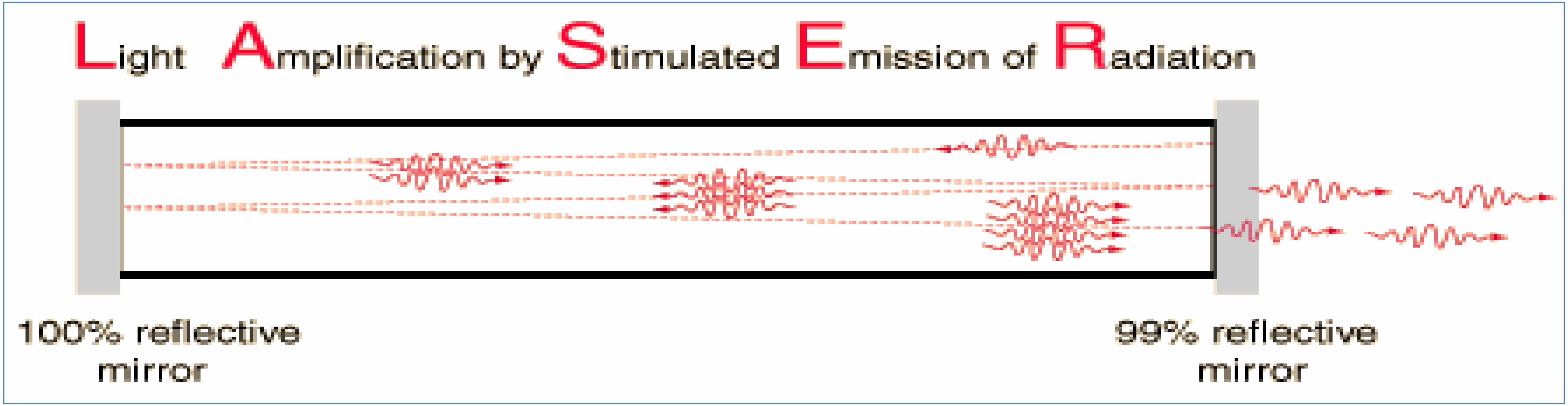



Spontaneous emission

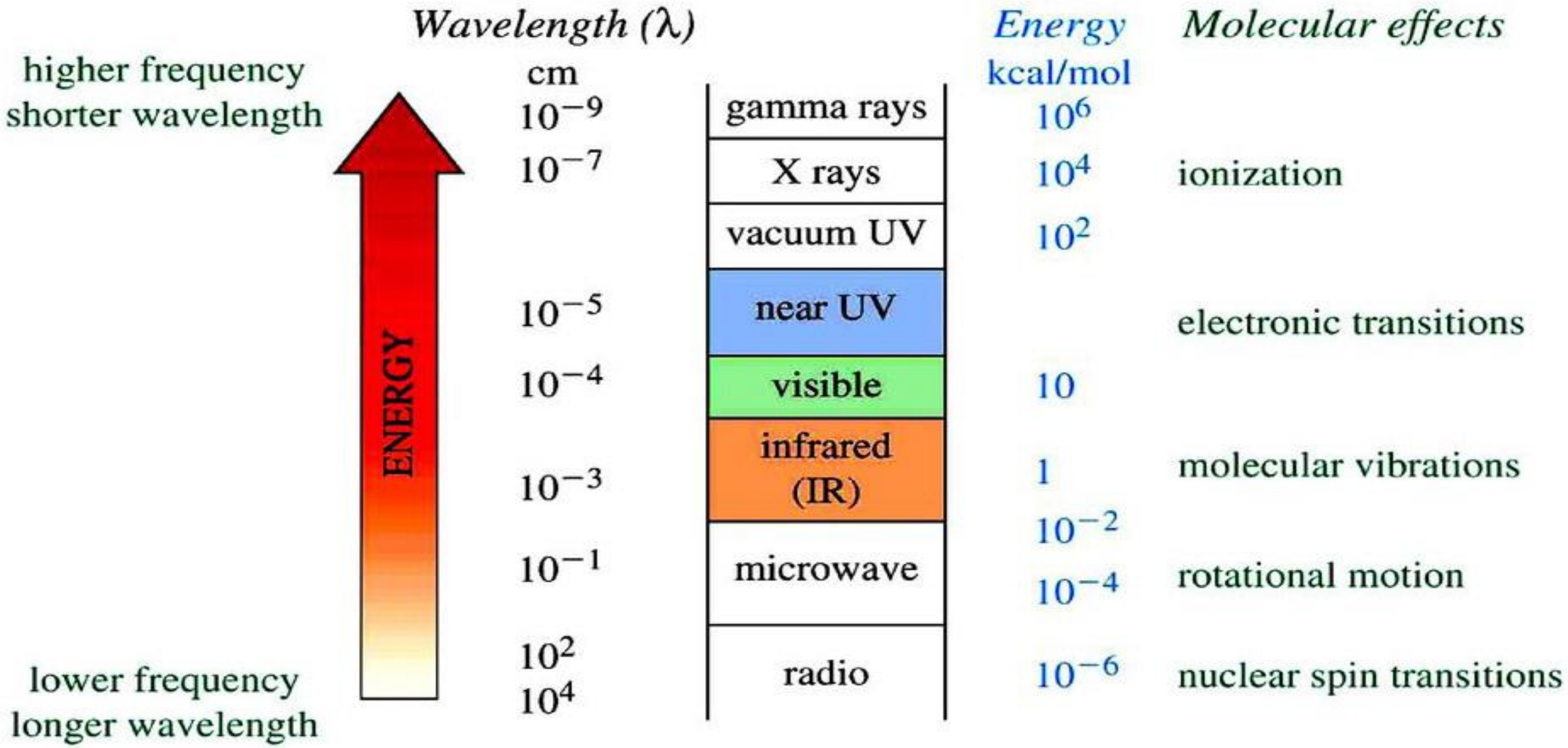


Stimulated emission

## What is the meaning of LASER?

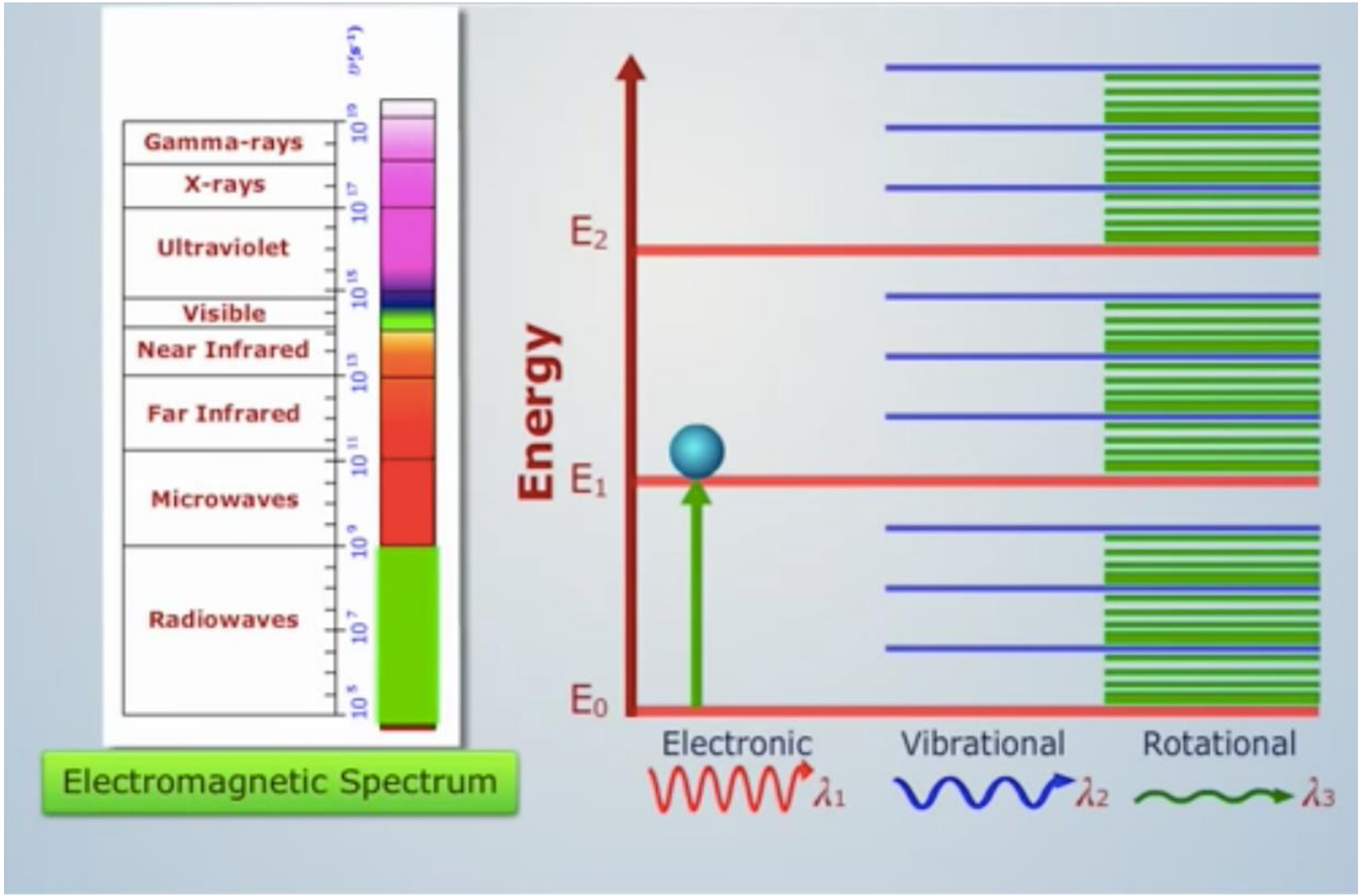


# • Interaction of radiation with matter

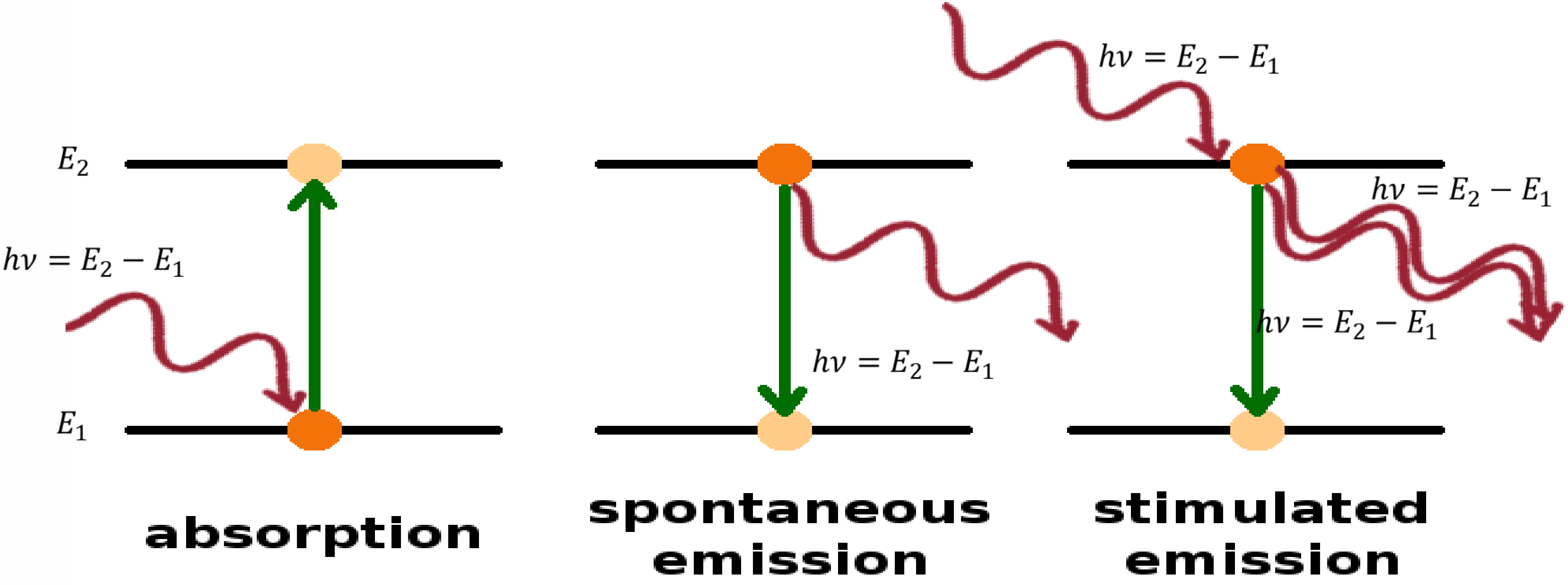



Graphics source: Wade, Jr., L.G. *Organic Chemistry*, 5th ed. Pearson Education Inc., 2003

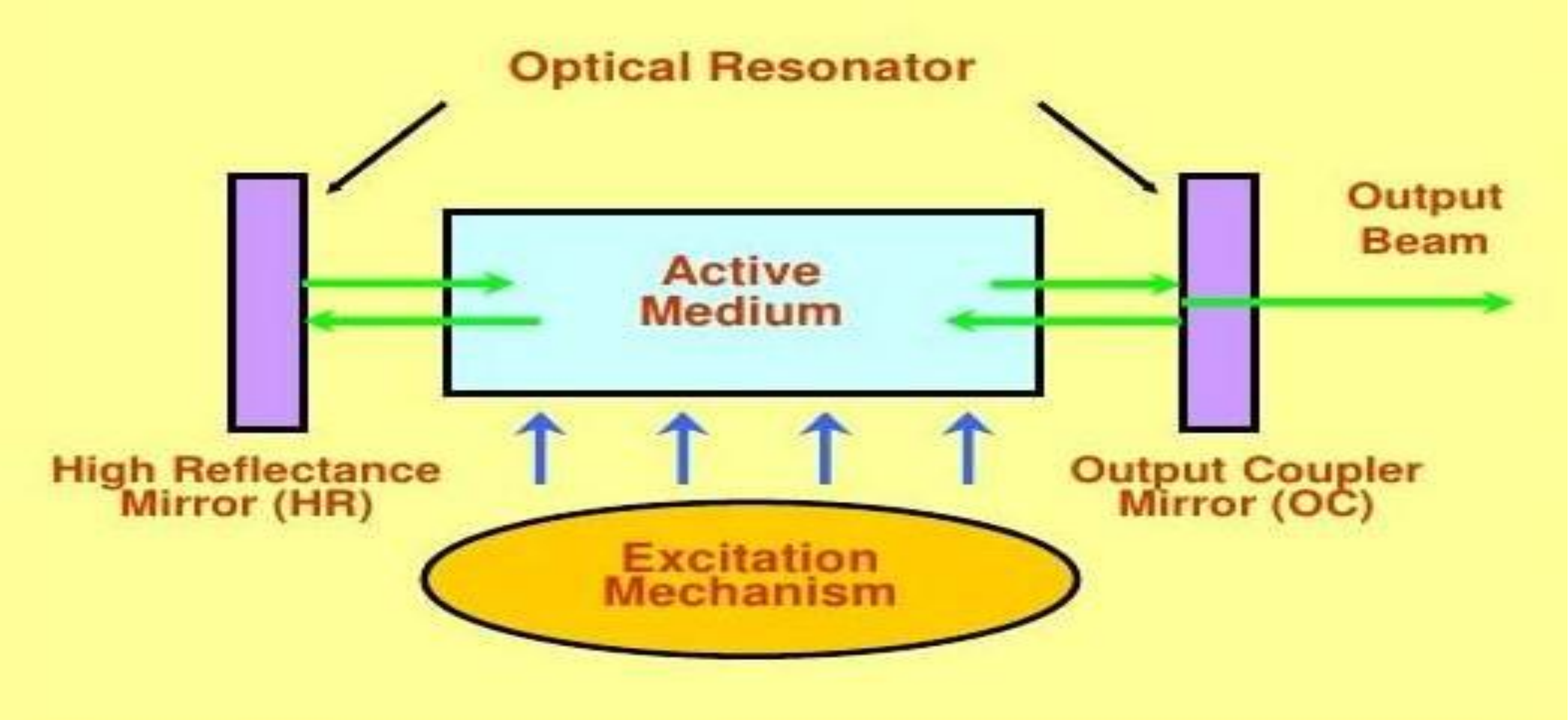
# • Three types of spectra in Molecular transitions



# Interaction of Radiation with Matter



# Essential components of a LASER system



# Essential components 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.

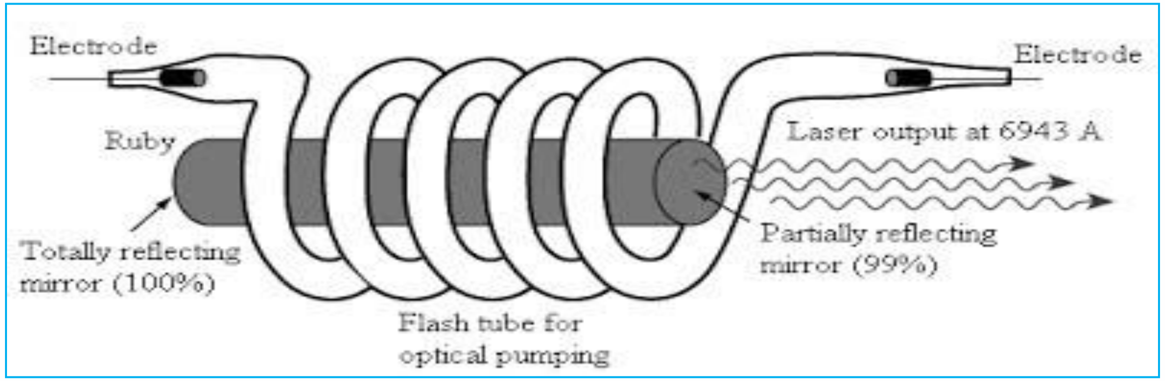
# Different Pumping Mechanisms

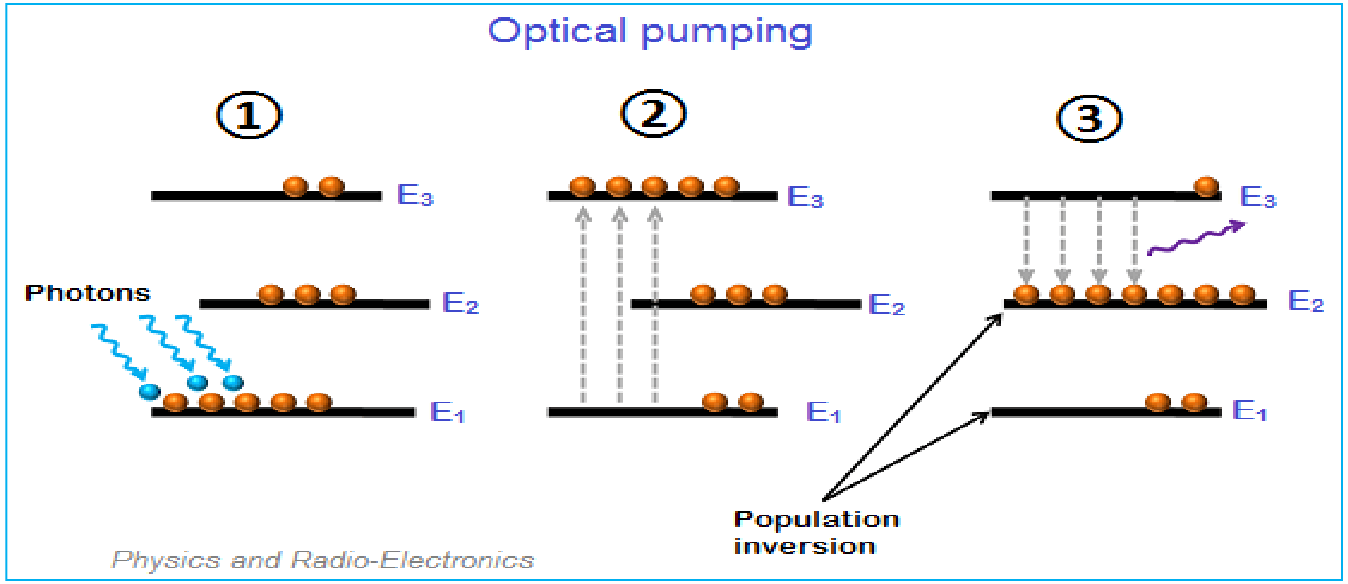
- ***Optical pumping*** **:** Exposure to electromagnetic radiation of frequency $\upsilon = (E_2\text{-}E_1)/h$ obtained from discharge flash tube  Suitable for solid state lasers

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

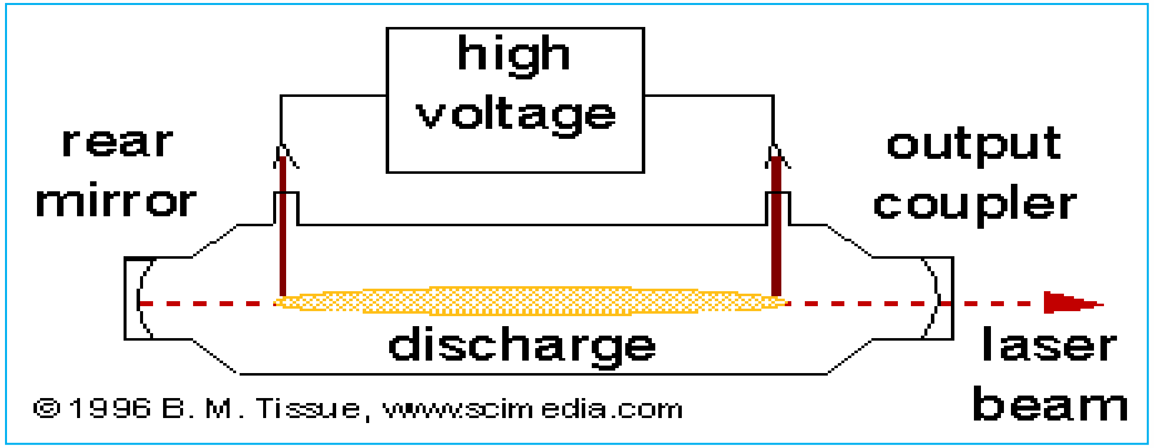
- ***Chemical pumping*** **:** By suitable chemical reaction in the active medium, population of excited state is made higher compared to that of ground state Suitable for liquid lasers

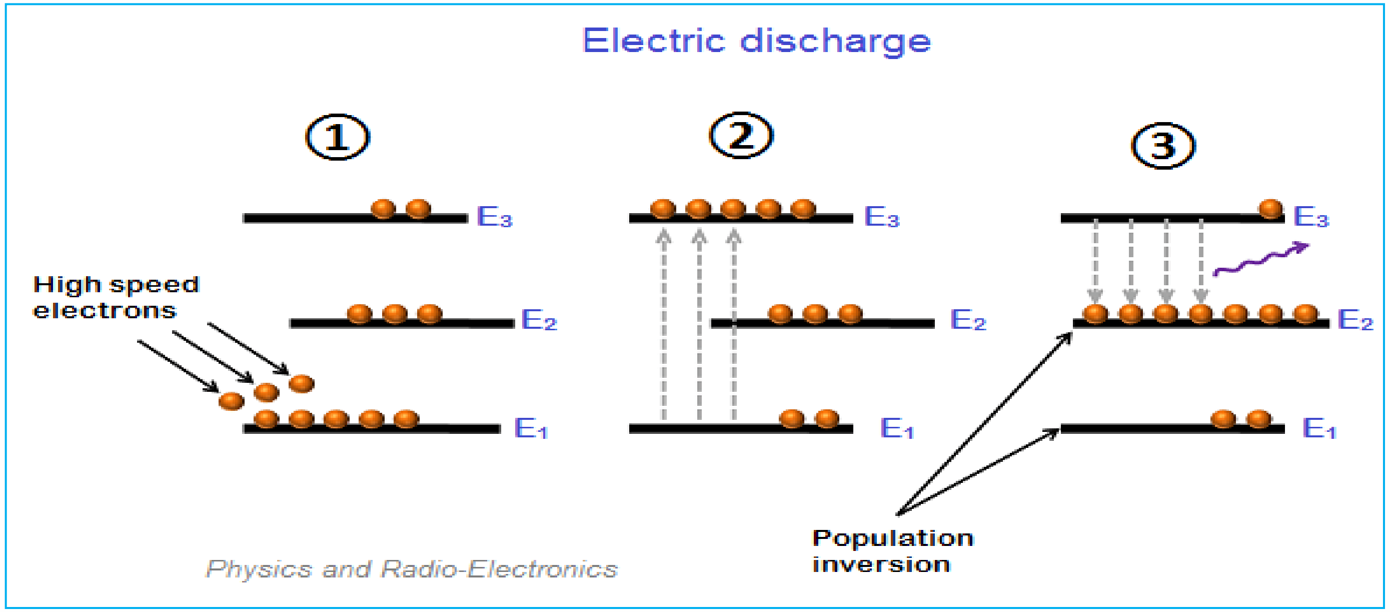
# Optical pumping



# Electrical pumping



# Chemical pumping

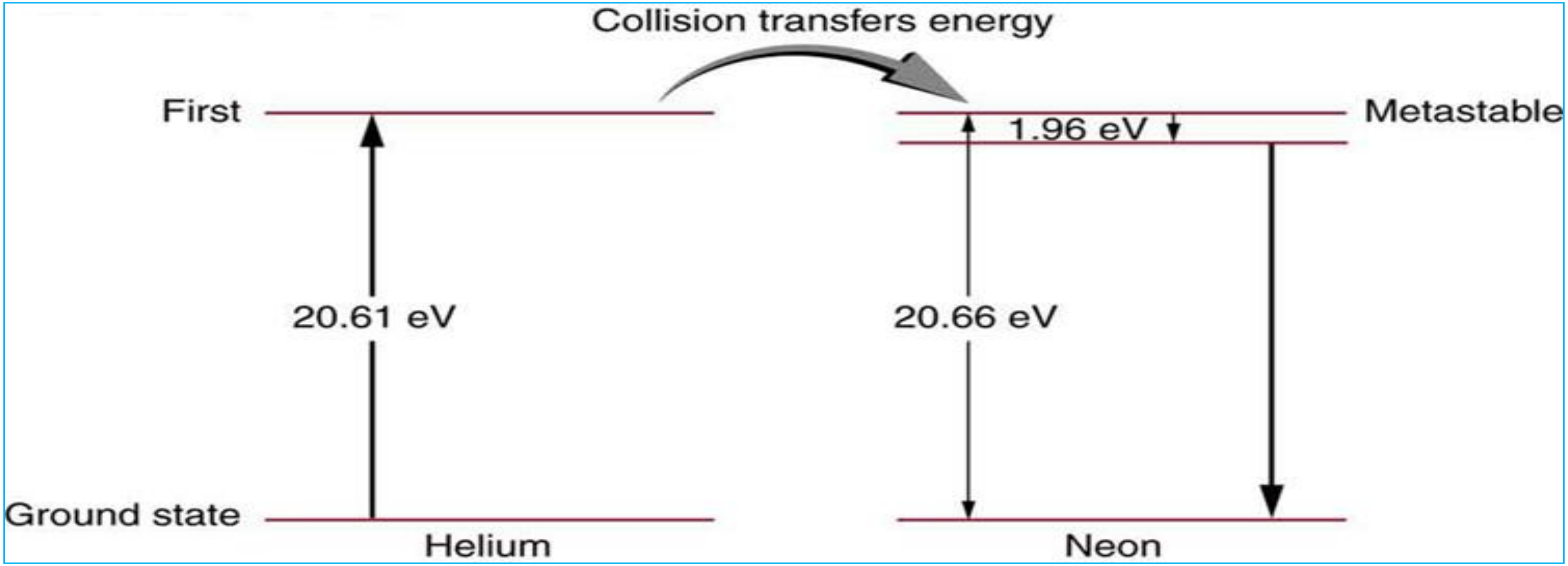
## Chemical Pumping

$$H_2 + F_2 \rightarrow 2HF$$

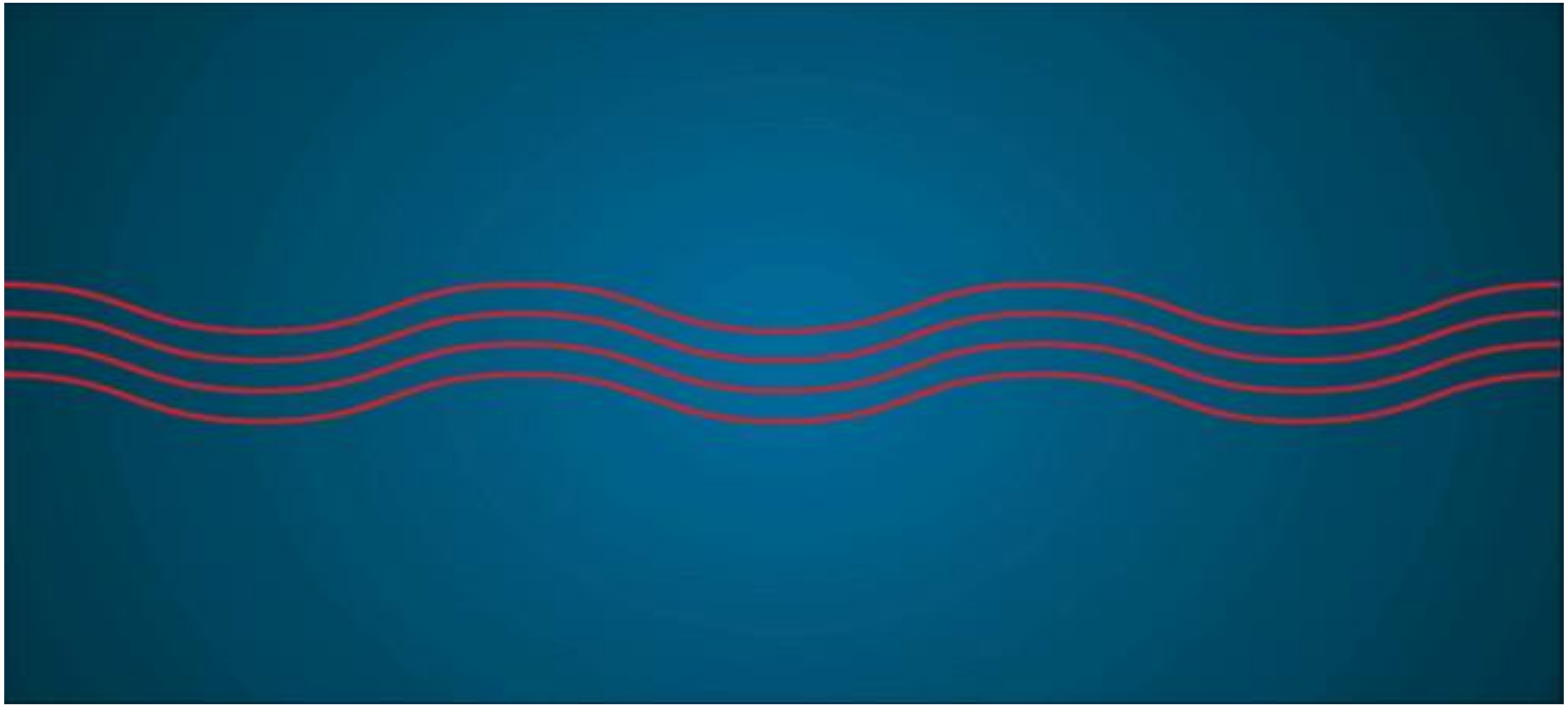
In this chemical reaction, hydrogen ($H_2$) and fluorine ($F_2$) molecules are chemically combined to produce hydrogen fluoride molecule (2HF) in an excited state.

If the number of produced excited atoms or molecules is greater than the number of normal state atoms or molecules, population inversion is achieved.

# Inelastic collision pumping



# Properties of Laser light (Highly coherent)



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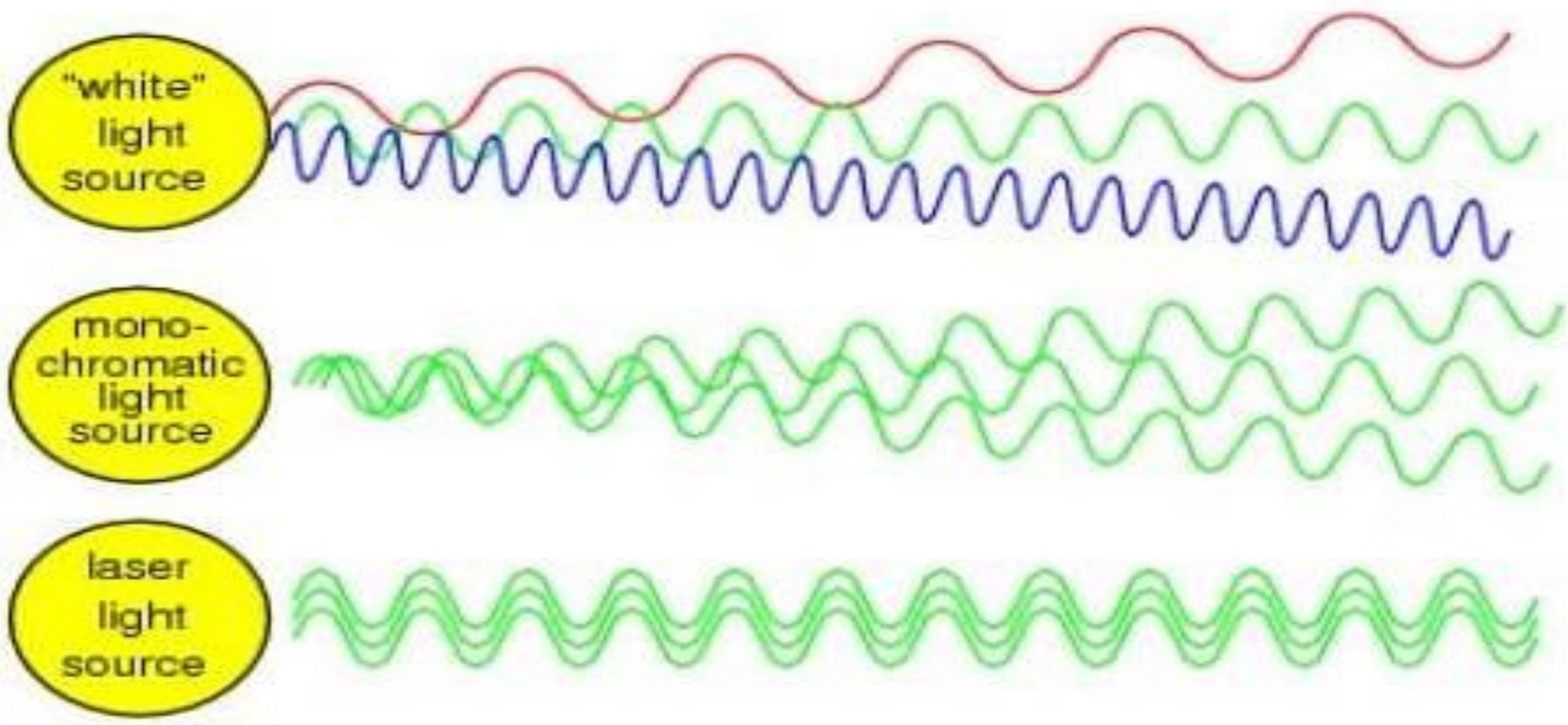
DIGITAL LEARNING CONTENT

# Properties of Laser light (Highly monochromatic)



# Pulse width is narrow

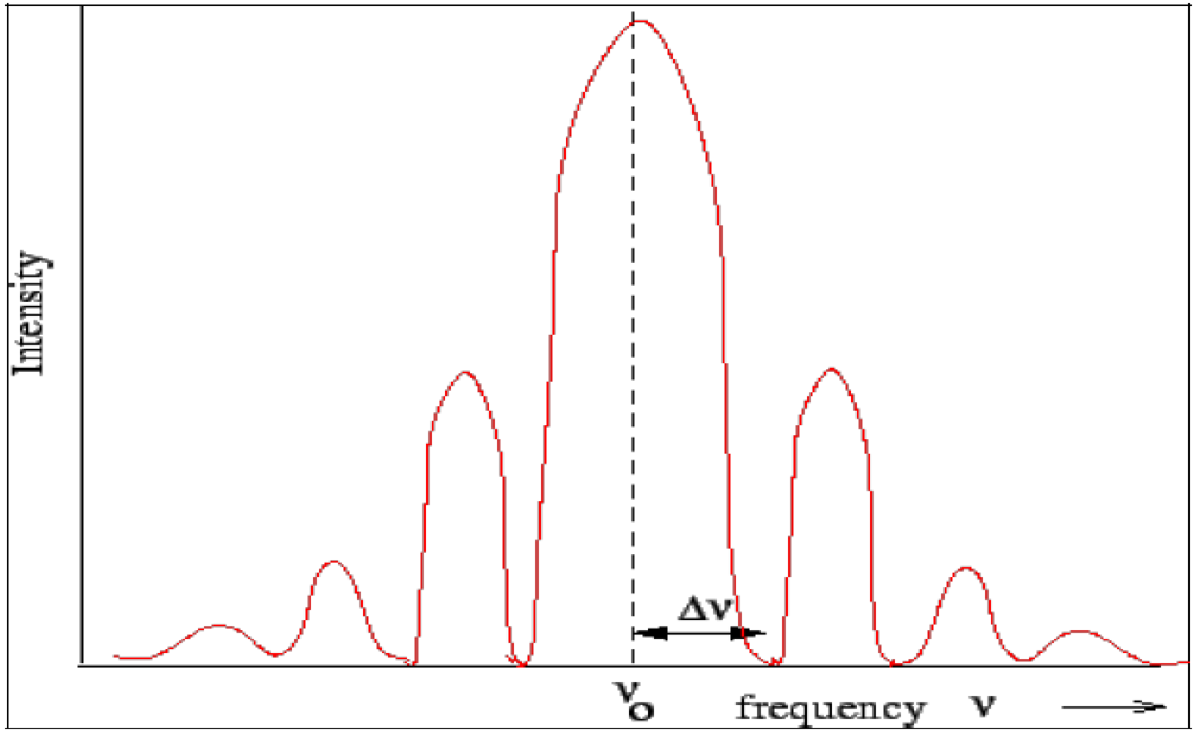
*COHERENCE LENGTH*

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

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

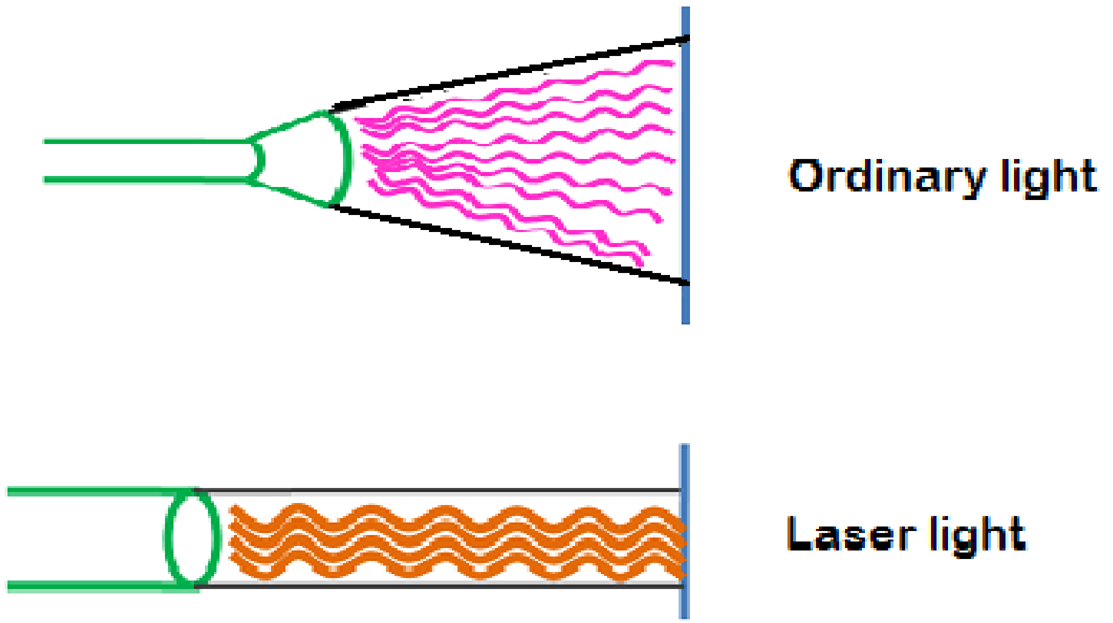
$$\therefore \Delta\nu = \frac{c}{\lambda^2}\Delta\lambda$$

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



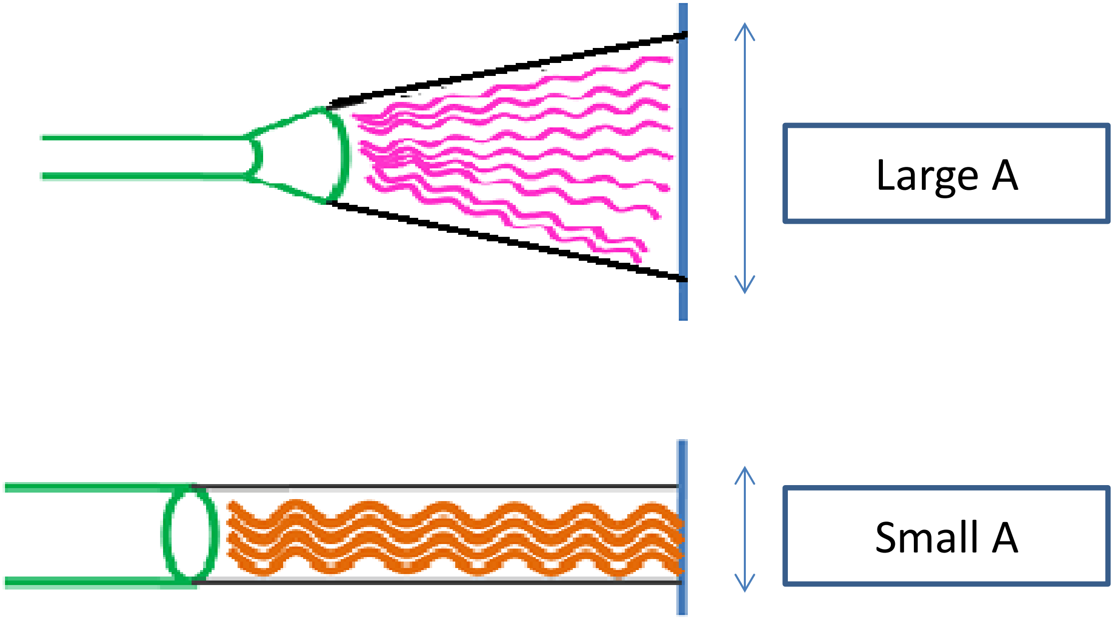

Since $\Delta\lambda$ is very small, coherence length is very high. Pulse width is narrow.

# Properties of Laser light (Highly directional)

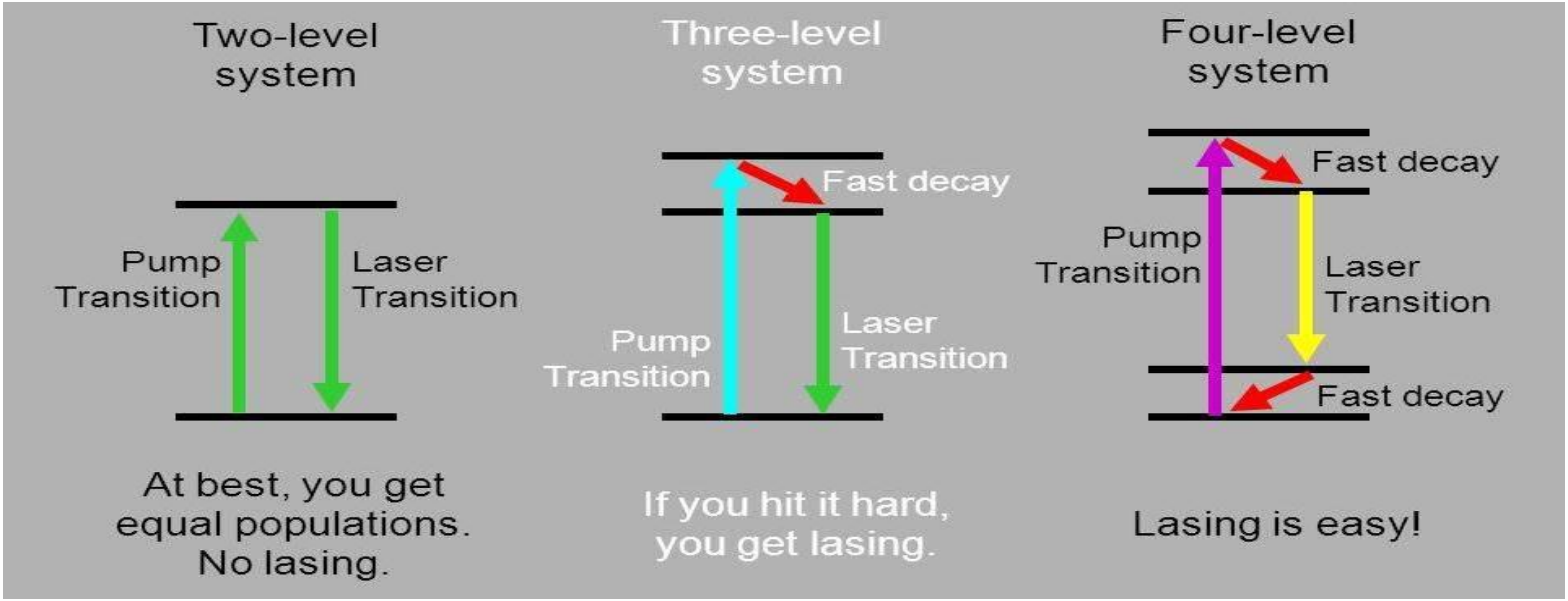


# Properties of Laser light (Highly intense)

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



# Lasers based on energy levels



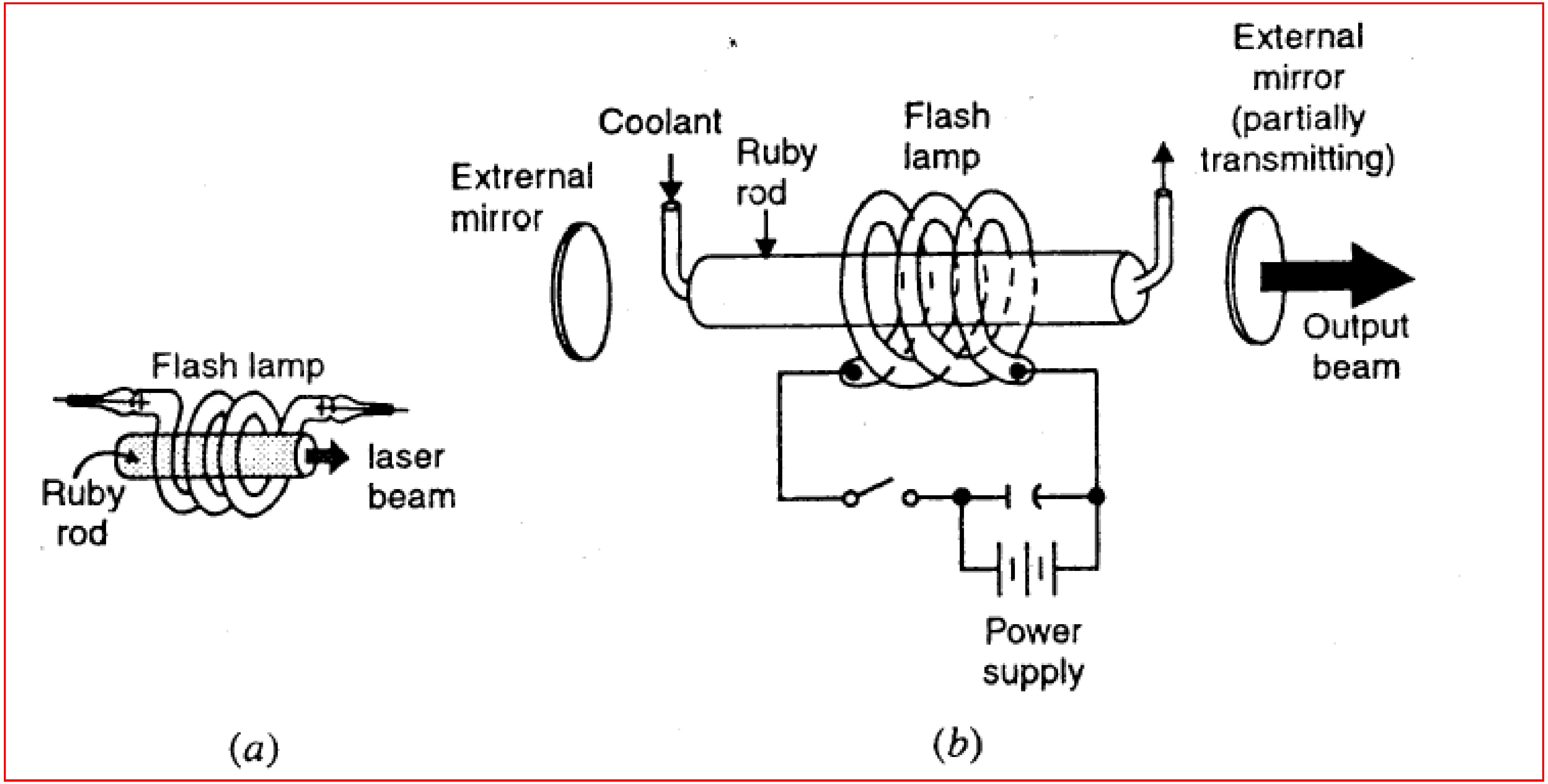
# Ruby Laser

- It is the first LASER developed in 1960 by Maiman.
- It is a Solid state laser whose active medium is pink ruby crystal
  $(Al_2O_3\ doped\ with\ Cr^{3+}\ ions\ with\ concentration\ 0.05\%)$
  $(Cr^{3+}\ ions\ act\ as\ active\ centres\ responsible\ for\ producing\ laser\ light)$
- Active medium is taken in the form of a rod with 4 cm length & 0.5 cm diameter.
- Helical flash lamp filled with Xenon gas is used for optical pumping.
- End faces of the rod are grounded & polished with silver to make front end 90% reflecting and back end 100% reflecting which form optical resonator.
- The whole arrangement is kept in a reflective cylinder.

# Ruby Laser

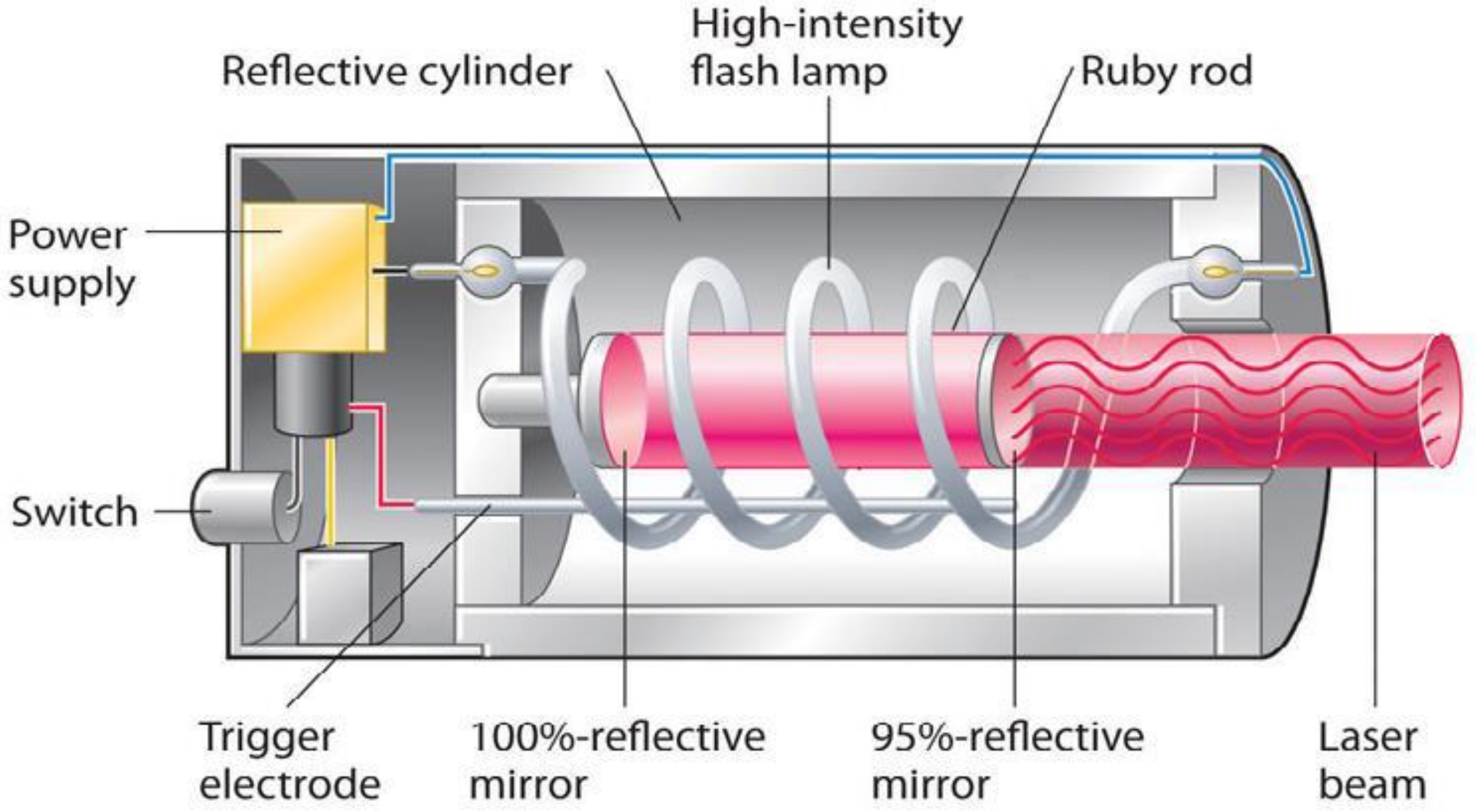
- $Al_2O_3$(sapphire) host is hard, with high thermal conductivity, and transition metals can readily be incorporated substitution ally for the Al
- Aluminum & Oxygen ions are inert

# Construction

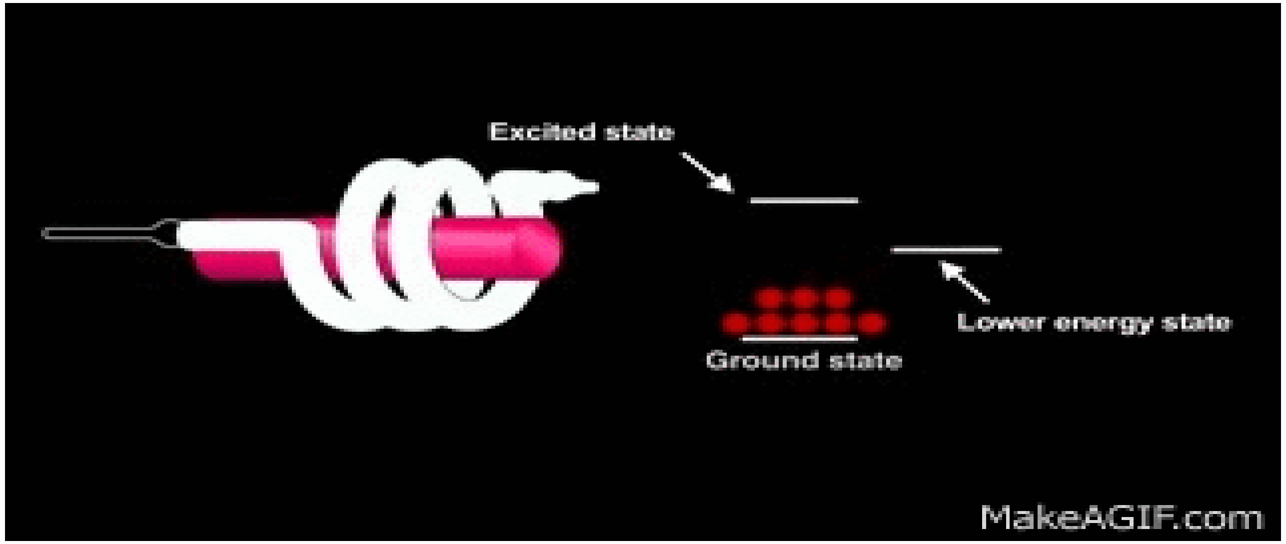


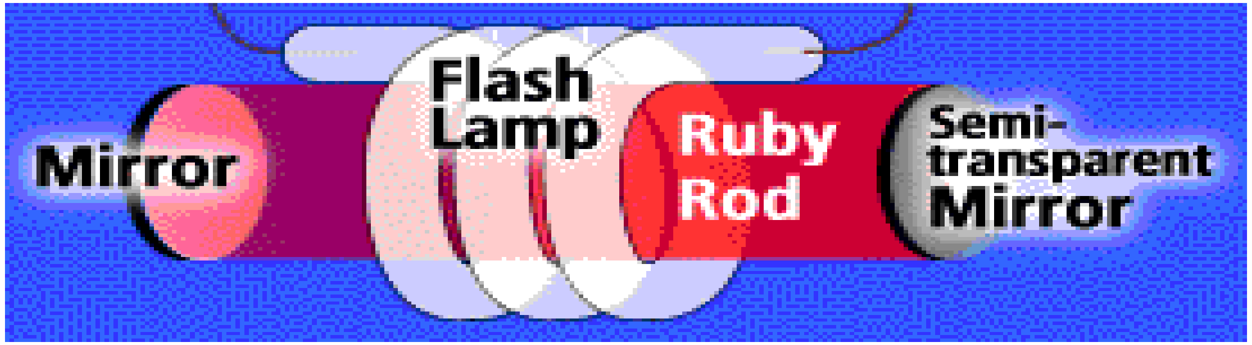

A typical Ruby laser (a) with internal mirrors (b) with external mirrors

# Construction

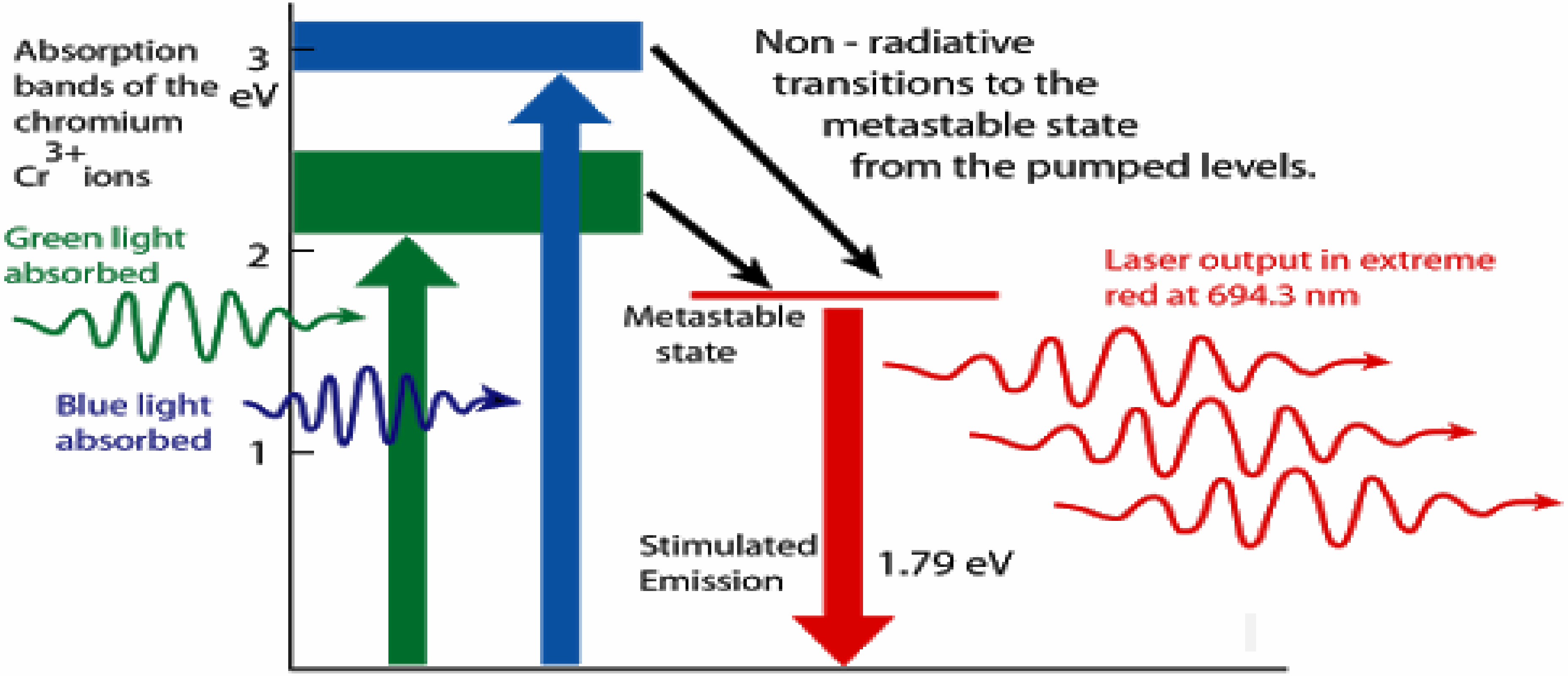


# Ruby Laser (working)

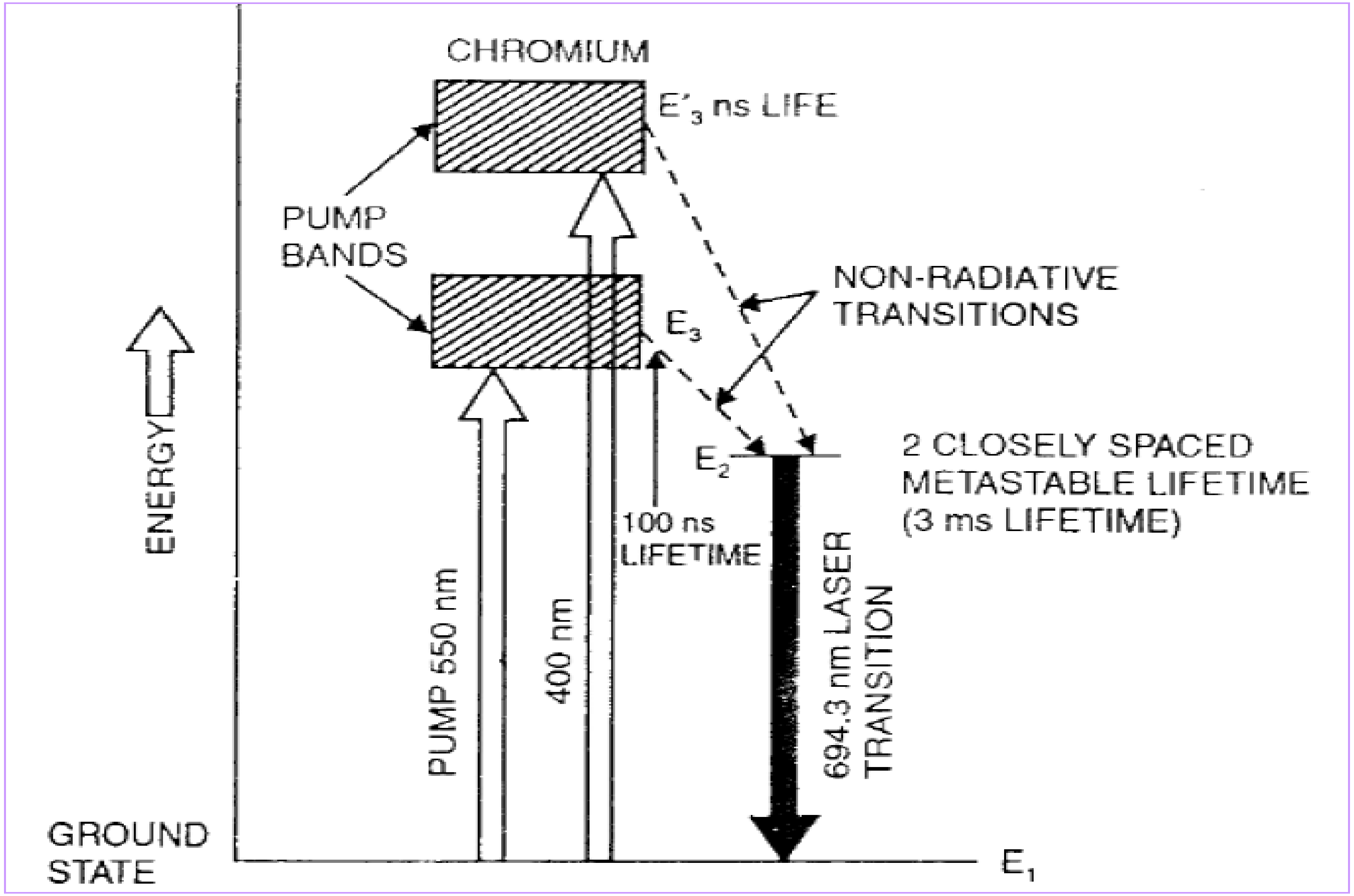


# Ruby Laser (working)



# 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 $Cr^{3+}$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.

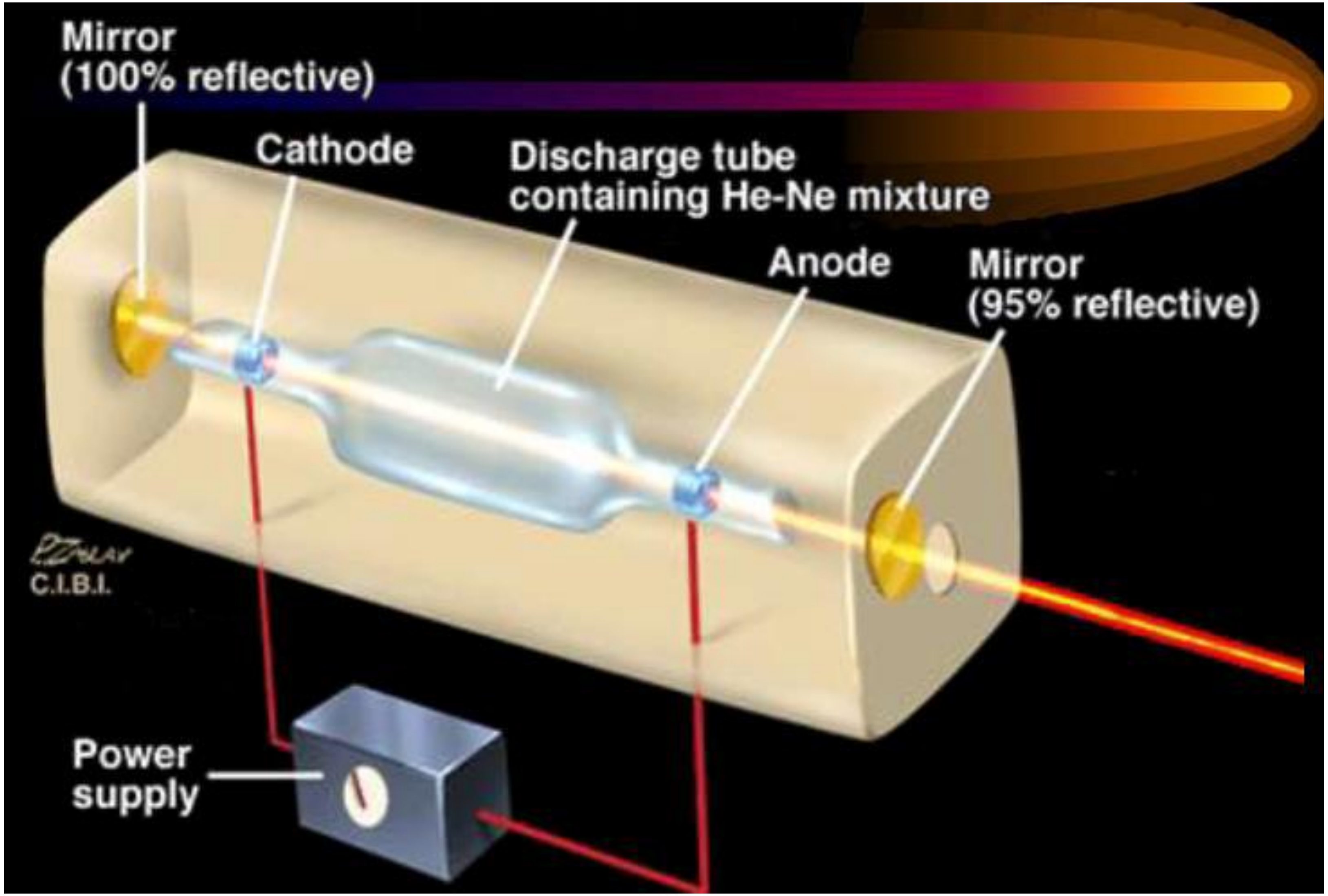
- Two parallel mirrors are placed at the ends of the quartz tube; one of them is partly transparent while the other is fully reflecting. The spacing between the mirrors is adjusted such that it should be equal to the integral multiple of half-wavelengths of the laser light.

# He-Ne Laser

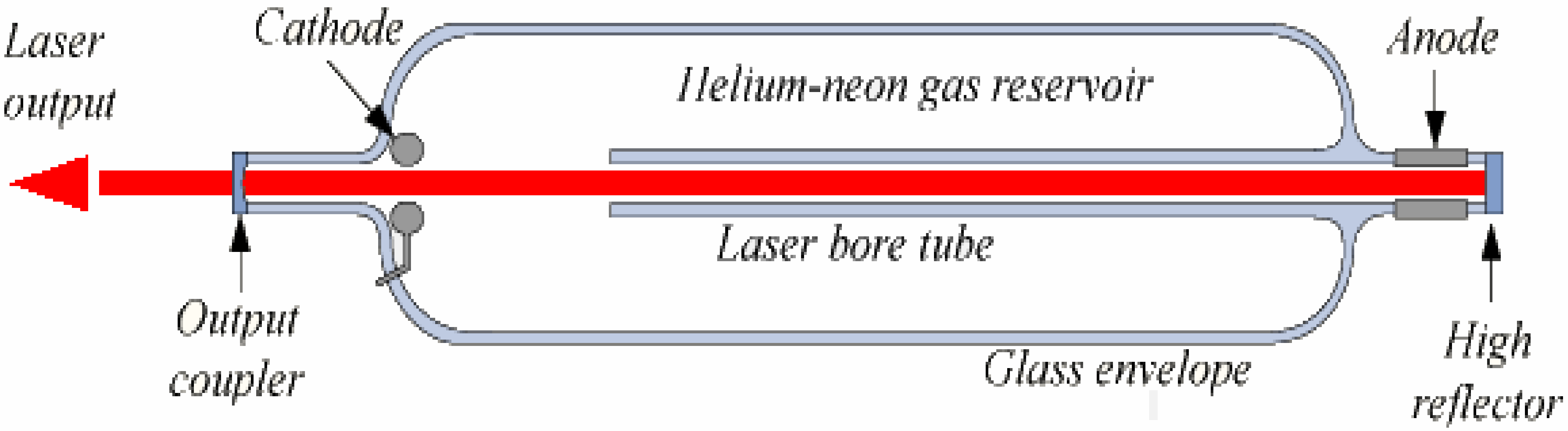
- The pumping is done through electrical discharge by using electrodes that are connected to a high voltage source.

- At the end of the quartz tube a glass plate is kept at around $55^0 - 56^0$ angle known as Brewster's window which polarises the light and reduces the interference losses. We can also use two Brewster's window at both the ends of a quartz tube with same orientation.

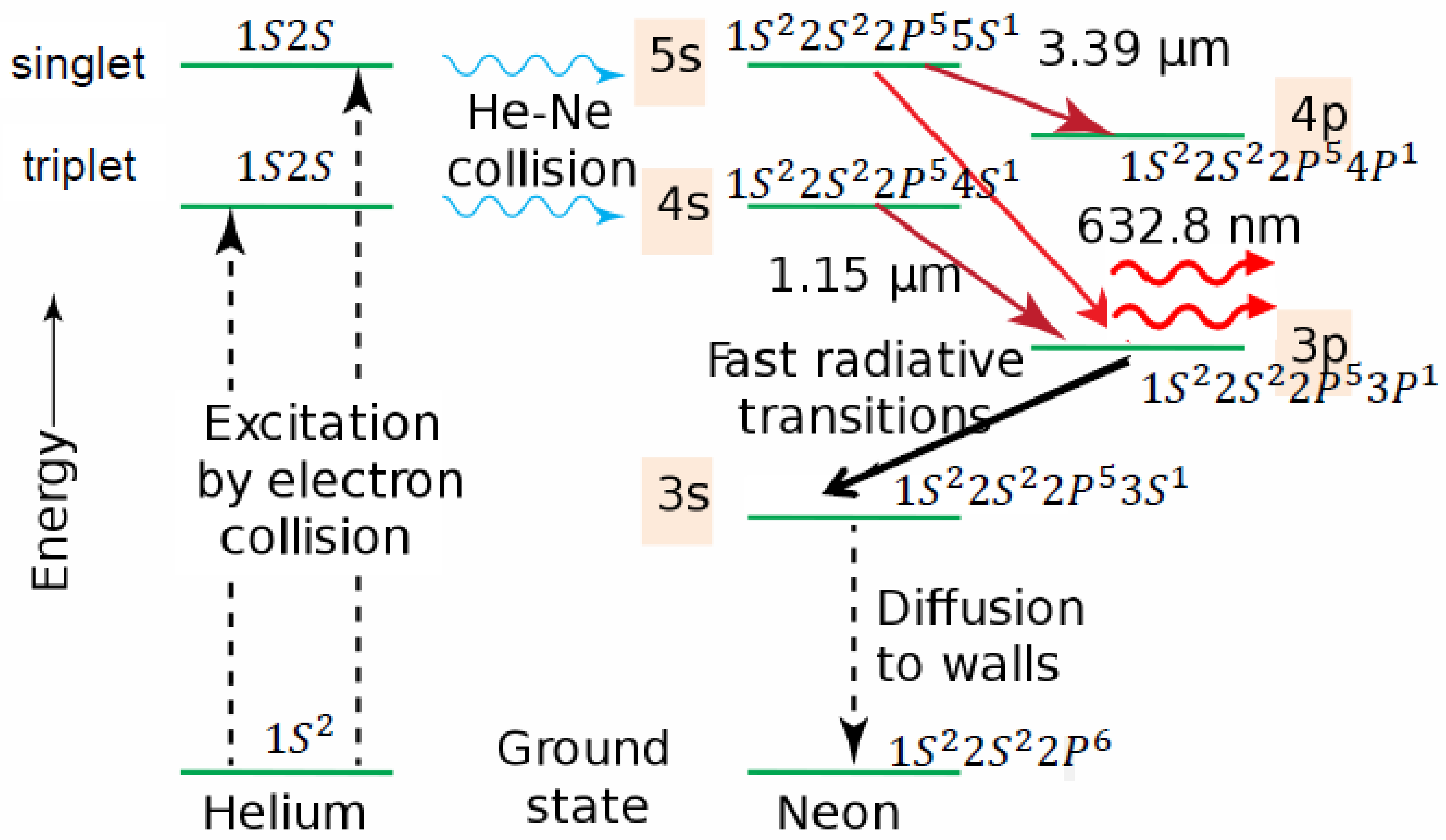
# Construction



# He:Ne Laser (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.

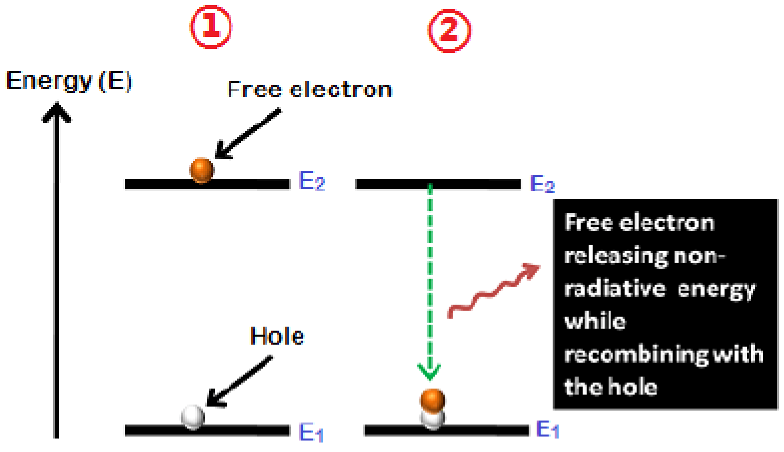
- After a few microseconds, a monochromatic, intense and collimated beam of red light of wavelength 6328 Å emerges through the partially silvered mirror.

# Semiconductor Laser

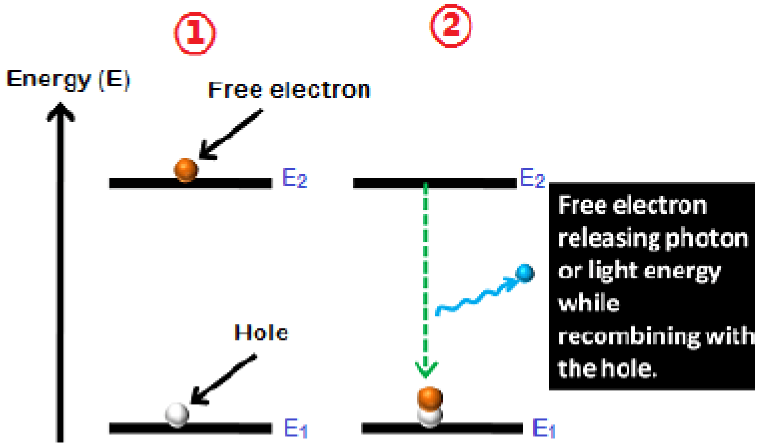
- Specially fabricated p-n junction device which emits coherent light when it is forward biased.
- R. N. Hall group: 1962 – First semiconductor laser made from Gallium arsenide (GaAs) operated at low temperatures and emitted light in the near IR region.
- Nowadays, p-n junction lasers are made to emit light 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



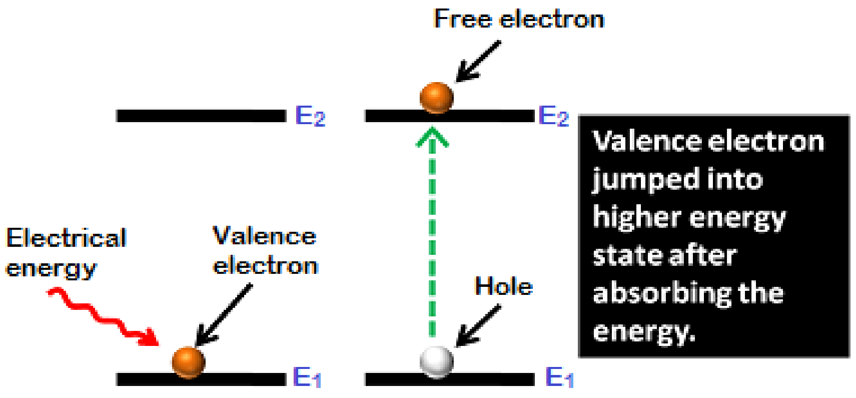

Electron transition in laser diode

# 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

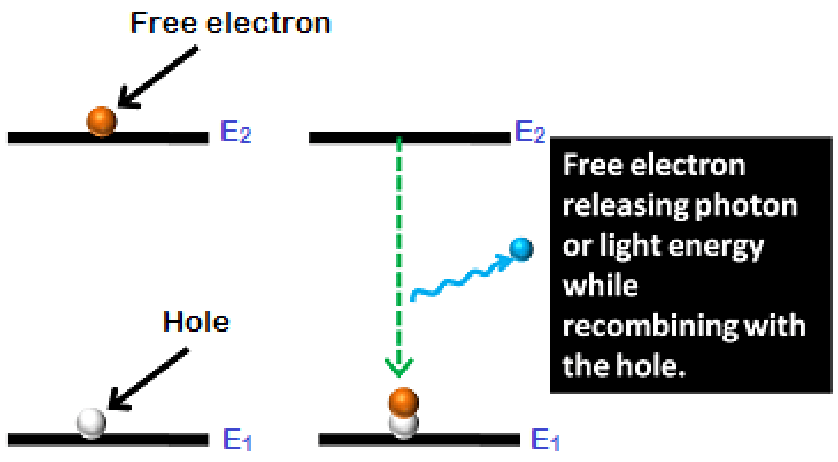
- Energy absorption from external sources. Electrical energy or DC voltage – external energy source.
- It supplies enough energy to the valence electrons in parent atom for jumping into the higher-energy (conduction) level.
- These conduction band electrons – free electrons.
- When the electron leaves 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

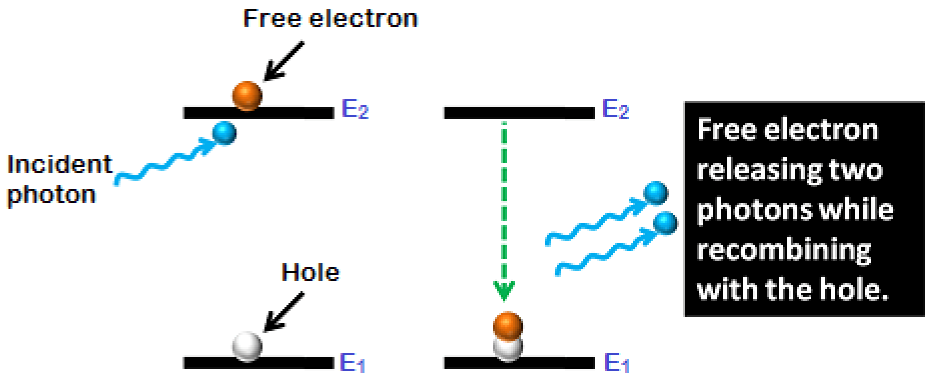
# Continue

- 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

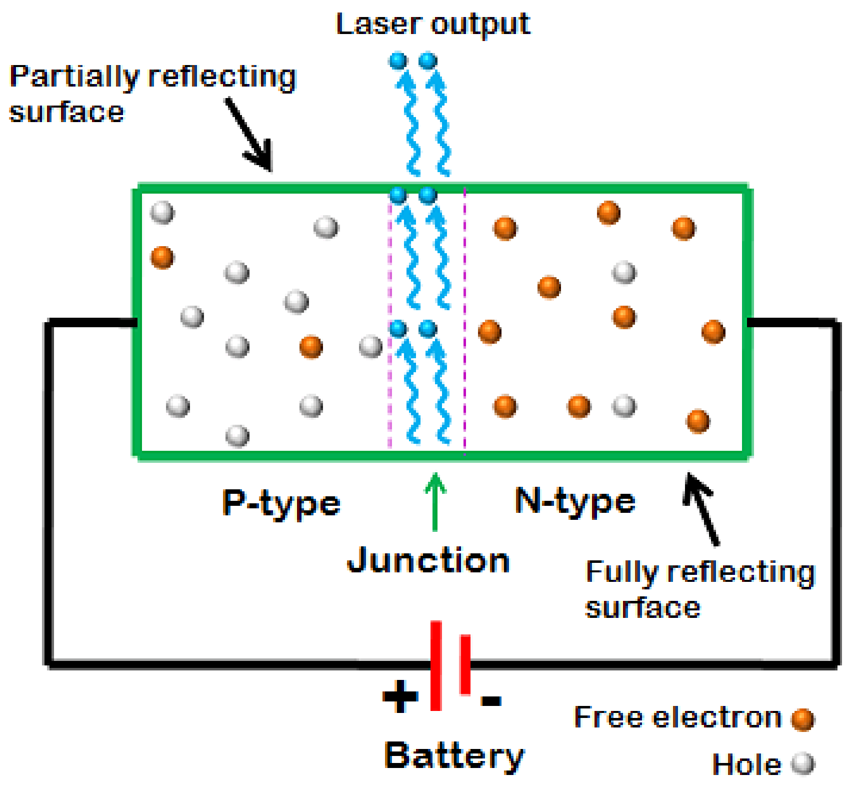
- Stimulated emission: Artificially inducing the free electrons by photon to fall into the lower energy state by releasing energy/photons.
- Free electrons need not wait for their whole lifetime.
- With external photons the free electrons are forced to recombine with holes releasing doubled-number of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




Stimulated emission

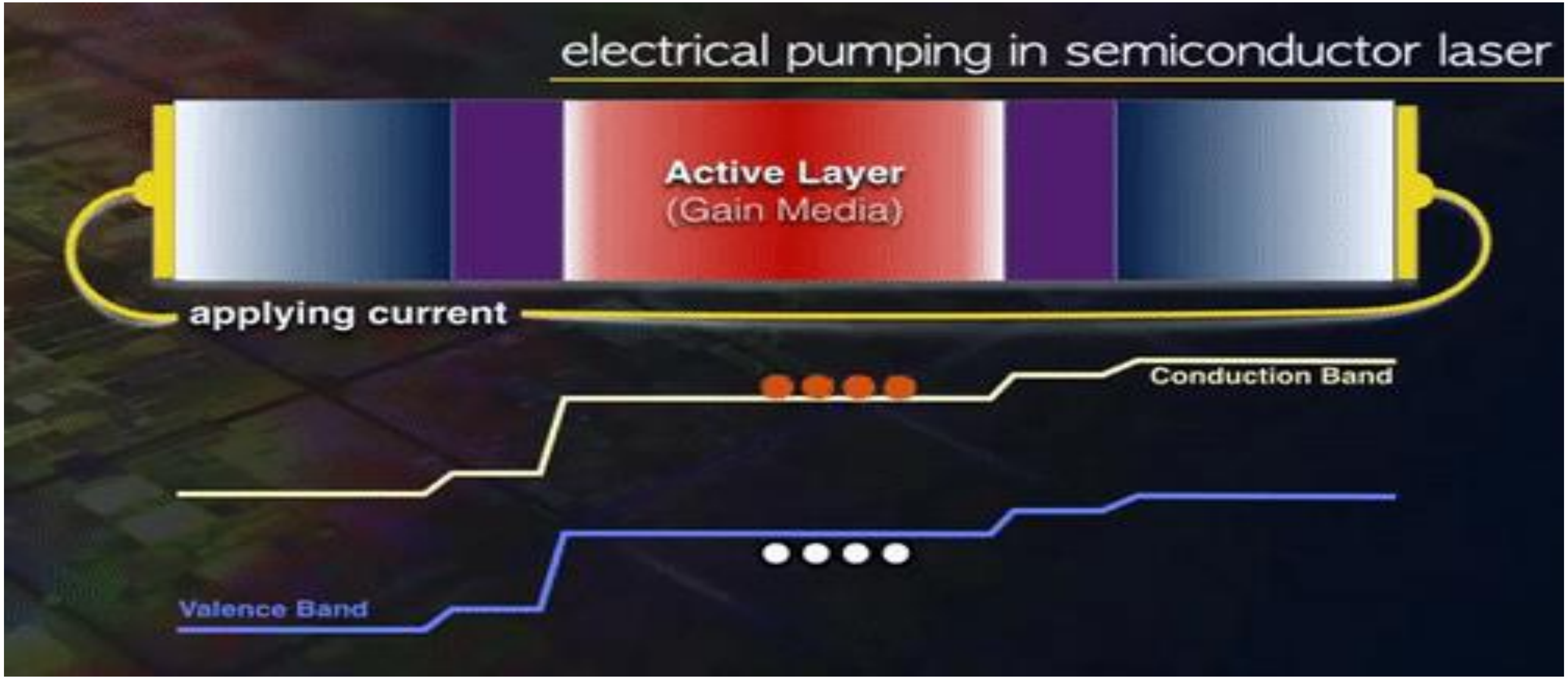
# Continue

- 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

# Pumping mechanism (Direct conversion of energy)



# Applications 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.

- 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.

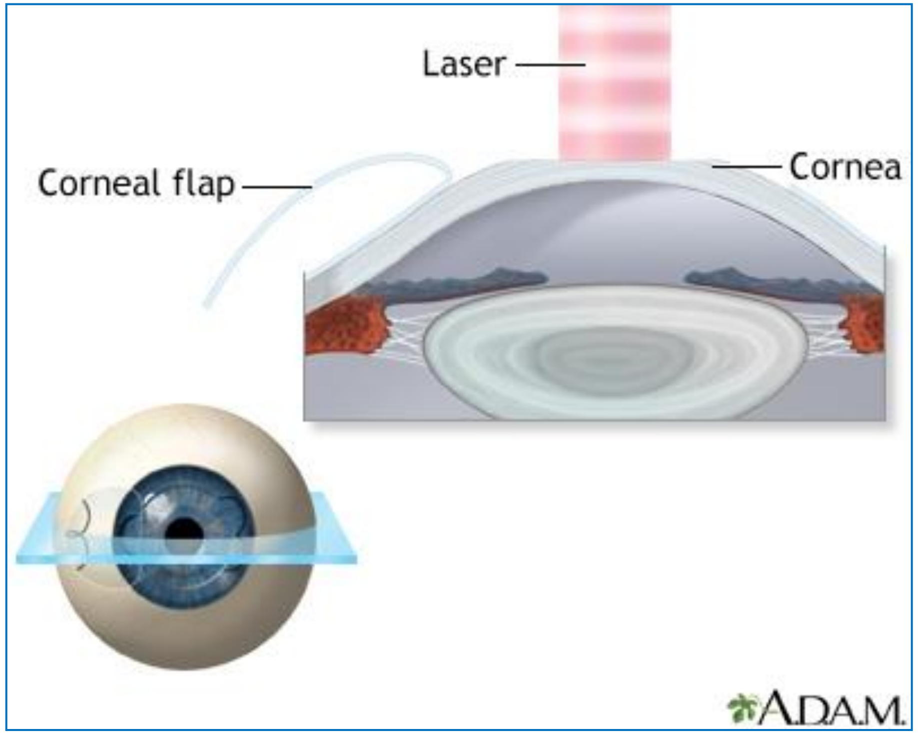
# Continue

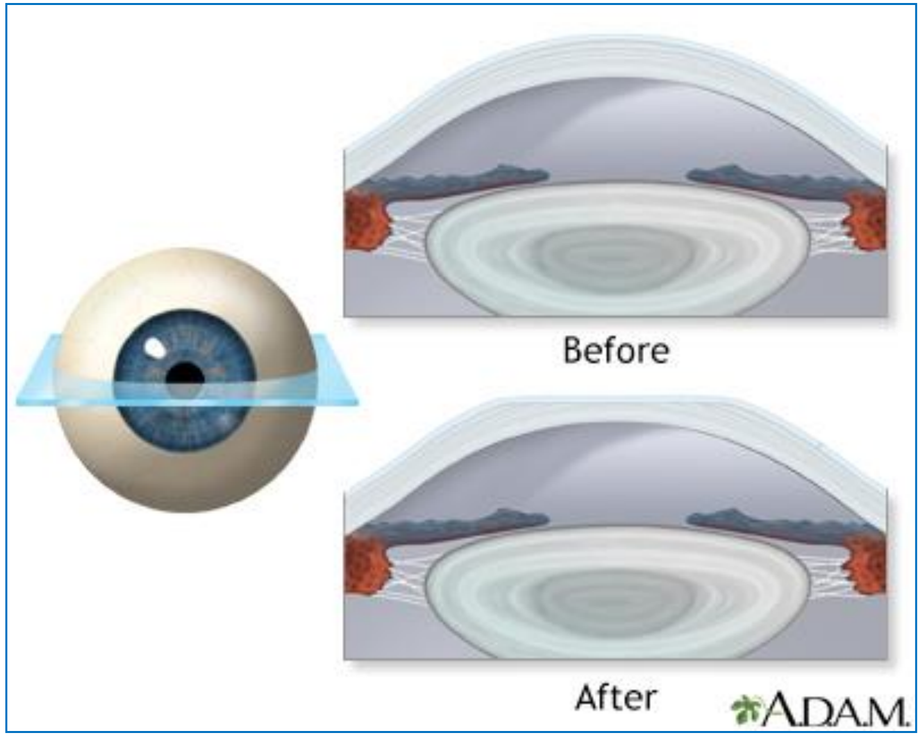
- Welding and Cutting
- The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for welding and cutting.
- The automobile industry makes extensive use of $CO_2$ lasers with powers up to several kilowatts for computer controlled welding on auto 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.

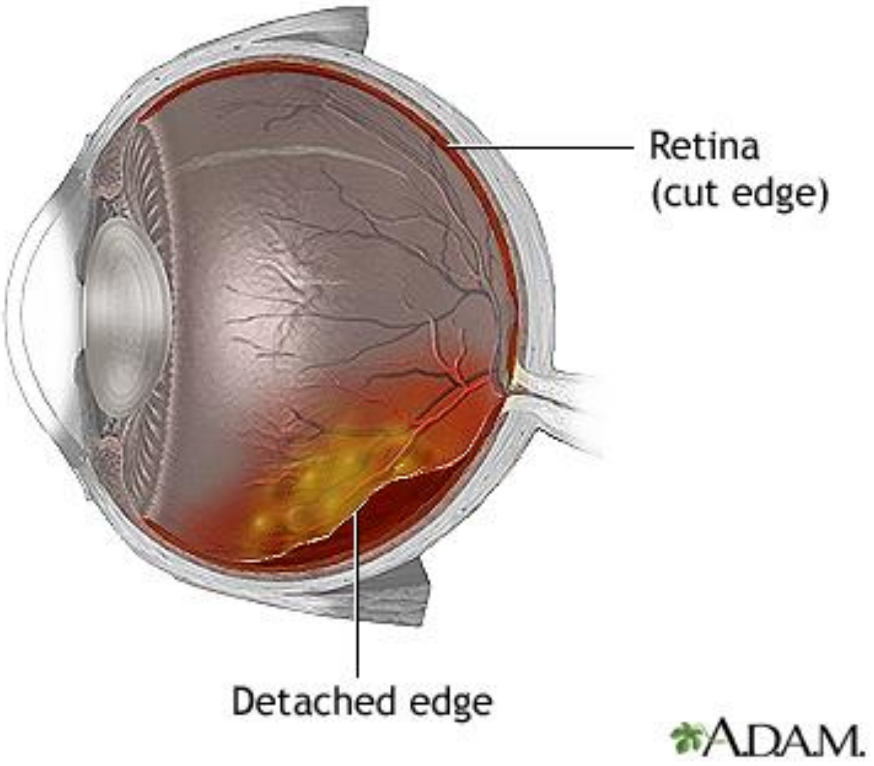
# Continue

- 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.

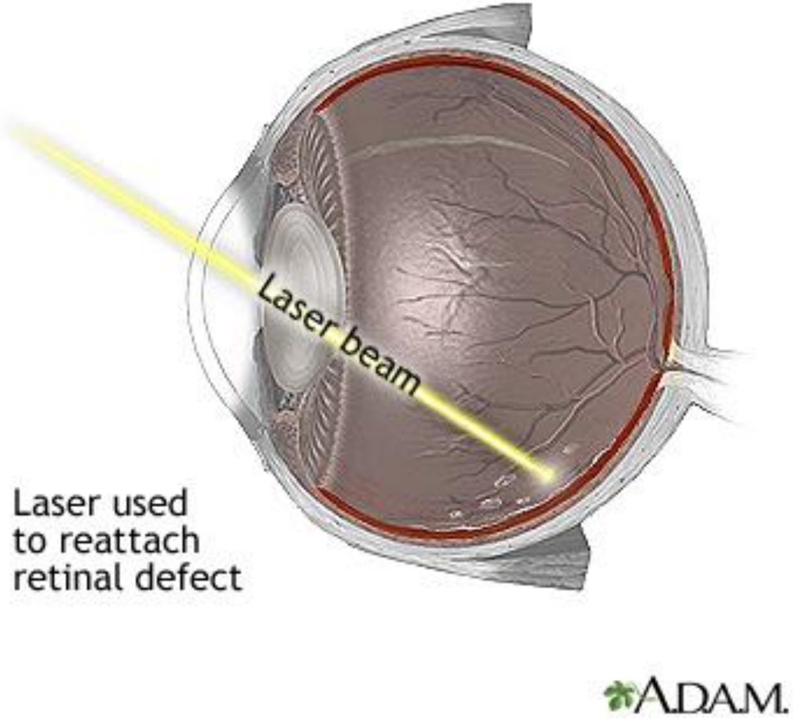
# LASIK – Laser Assisted in situ keratomileusis





Retina
(cut edge)
Detached edge
A.D.A.M.

Laser beam
Laser used
to reattach
retinal defect
A.D.A.M.

# 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

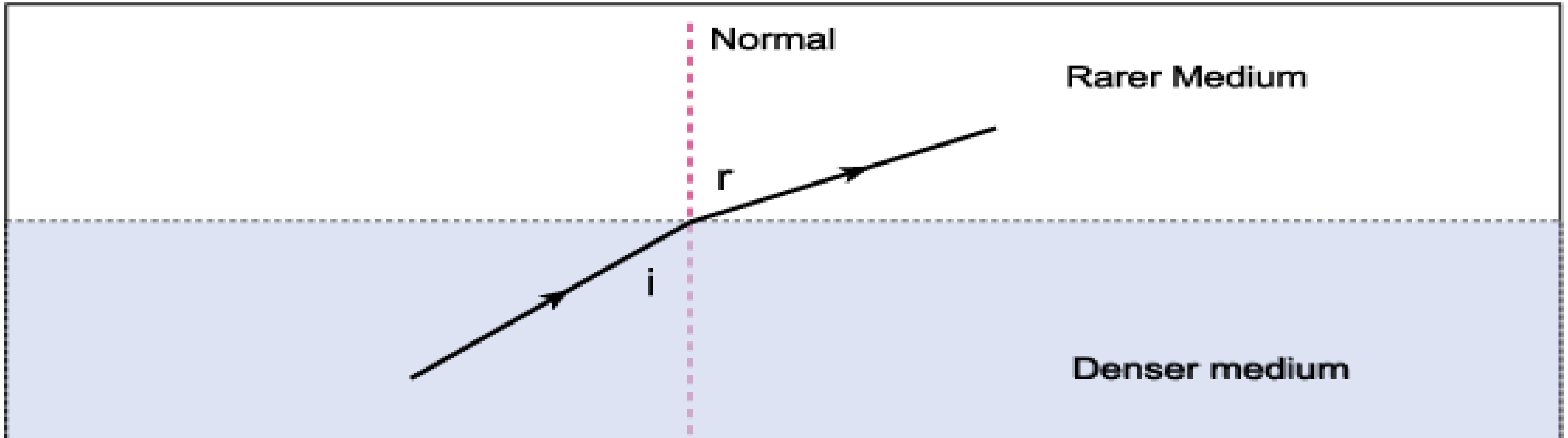
  indicate a target for a high precision-guided munition, typically launched from an aircraft.

# 30 kW Laser Weapon developed by US

# Russian Laser Weapon

# TOTAL INTERNAL REFLECTION

$$\sin \varnothing_c = \frac{n_2}{n1}$$




Total Internal Reflection process, Land Nepal

# Total Internal Reflection

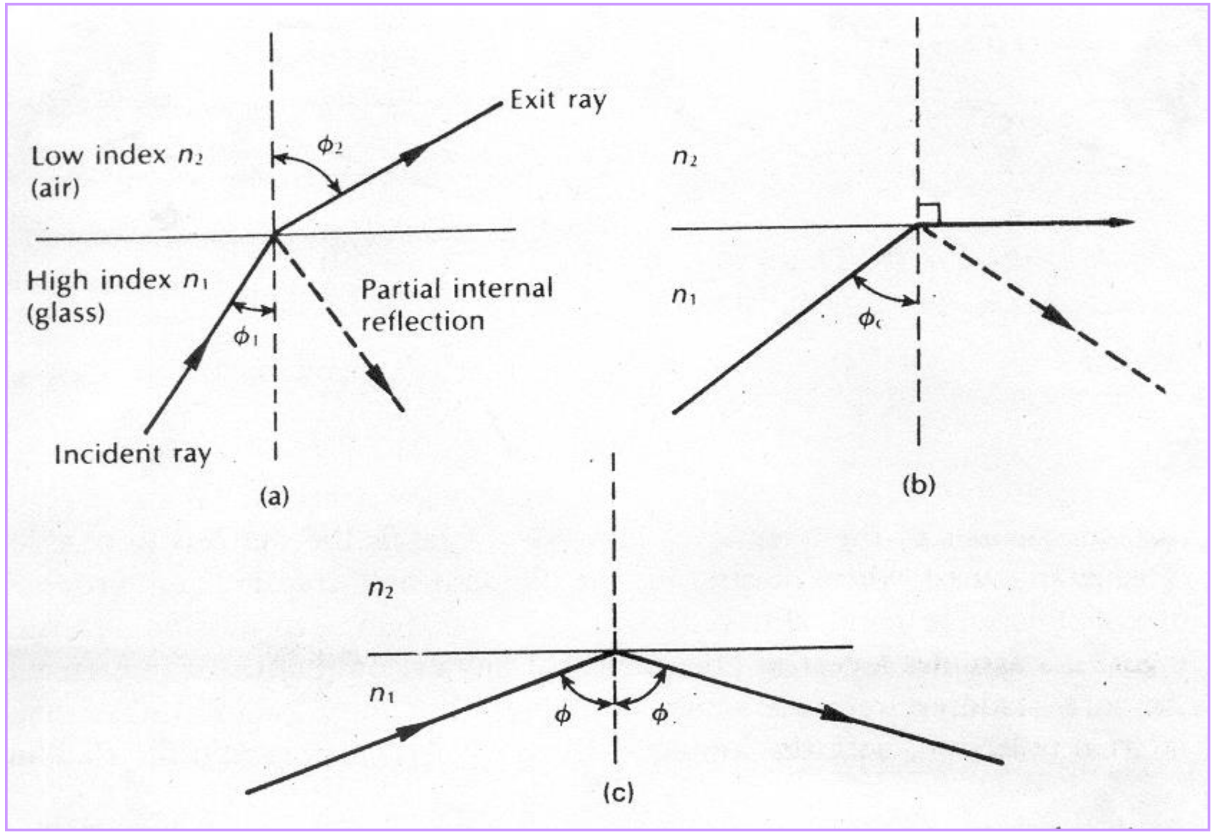
- Core has refractive index $n_1$
- Cladding has refractive index $n_2$ ($n_1 > n_2$)
- Light falling at core-cladding boundary undergoes **Refraction** up to certain value of incidence angle
- When Angle of incidence,

$\phi_1 = \phi_C$ ; **critical angle,**

refracted ray moves parallel to interface between core and cladding

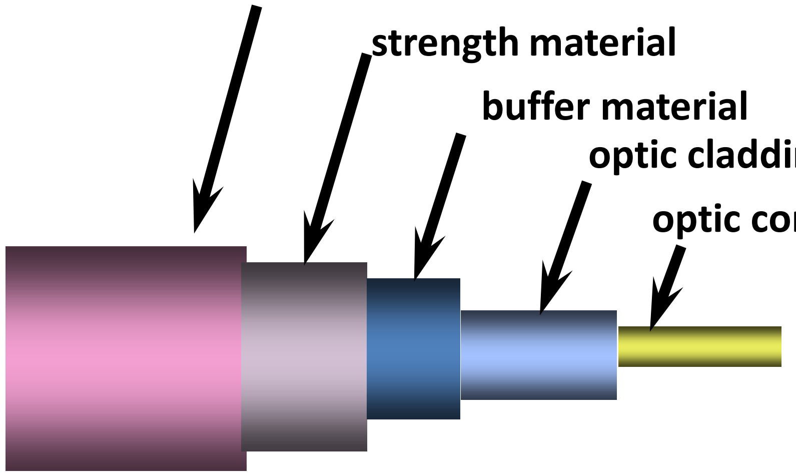
- When Angle of incidence,

$\phi_1 > \phi_C$ then Total internal reflection occurs



# Optical Fiber

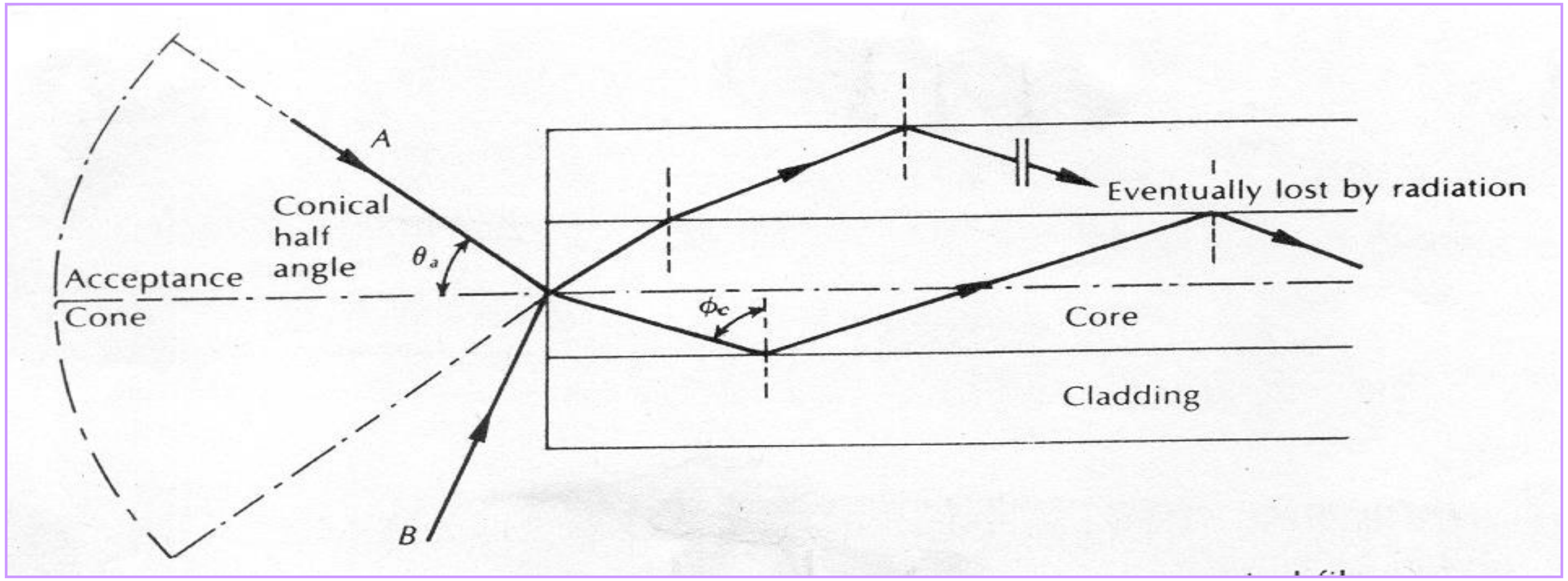
- The *optic core* is the light carrying element at the center of the optical fiber.
  - Commonly made from a combination of
  - silica and germanium.
- Surrounding the core is the *optic cladding*.
  - Made of pure silica.
  - The difference in materials between
- core and cladding is important ...




- *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

# 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 > $\phi_C$ ) at the core-cladding interface are transmitted by TIR.
- Any ray incident into fiber core at angle > $\theta_a$ will be transmitted to core-cladding interface at an angle < $\phi_C$ and will not follow TIR

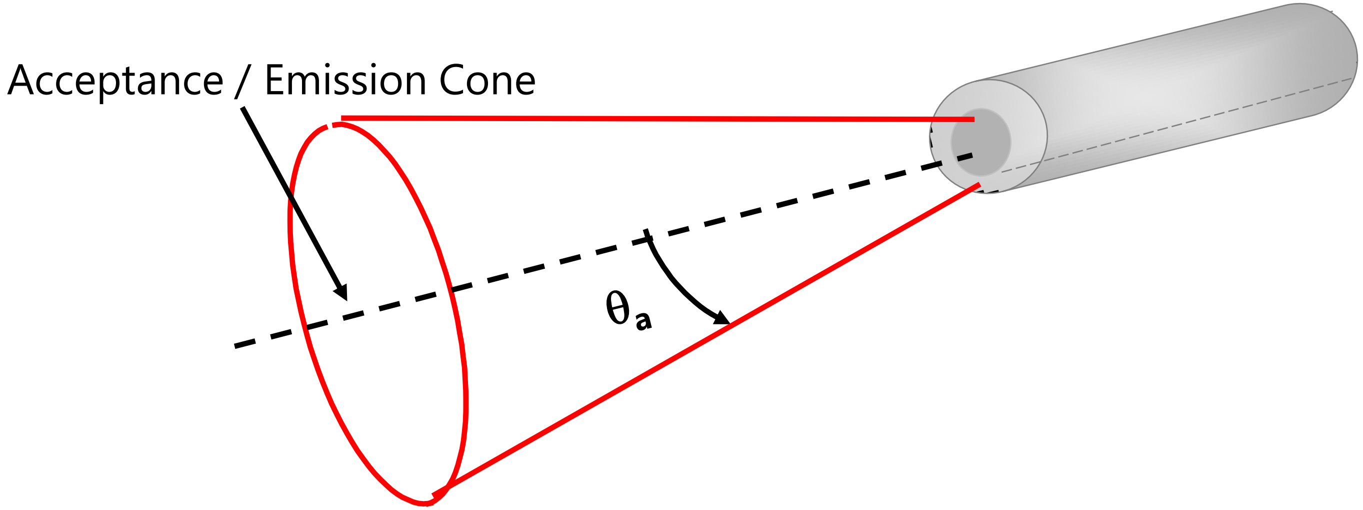



Acceptance angle $\theta_a$ when launching light into an optical fiber

# 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)** :

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

# TYPES OF OPTICAL FIBER

- Based on Materials
- Based on mode of propagation
- Based on refractive index profile

# CLASSIFICATION BASED ON MATERIALS

- Plastic core with plastic cladding (Also called PCP fibre, plastic -clad-silica).
- Glass core with plastic cladding (Also called PCS fibre, plastic -clad-silica).
- Glass core with glass cladding (Also called SCS fibre, silica-clad-silica).

# PCP (PLASTIC CLADDED PLASTIC) FIBERS

- **ADVANTAGES**
- EASY TO MANUFACTURE
- MORE DURABLE
- LESS EXPENSIVE
- LOW WEIGHT

- **DISADVANTAGES**
- HIGH ATTENUATION OF SIGNAL

- **EXAMPLES**
- A Polystyrene core and a poly methyl methacrylate cladding.
- A poly methyl methacrylate core and a cladding of it’s co-polymer.

- **USAGE**
- ONLY FOR SHORT RANGE COMMUNICATION

# PCS (PLASTIC CLADDED SILICA) FIBERS

- **ADVANTAGES**
- LIGHTER THAN SCS
- MORE DURABLE THAN SCS
- LESS AFFECTED BY RADIATION

- **DISADVANTAGES**
- LOW ATTENUATION AS COMPARED TO PCP BUT MORE THAN SCS

- **EXAMPLES**
- A glass core and a poly methyl methacrylate cladding.

- **USAGE**
- USEFUL FOR MILITARY APPLICATIONS

# SCS (SILICA CLADDED SILICA) FIBERS

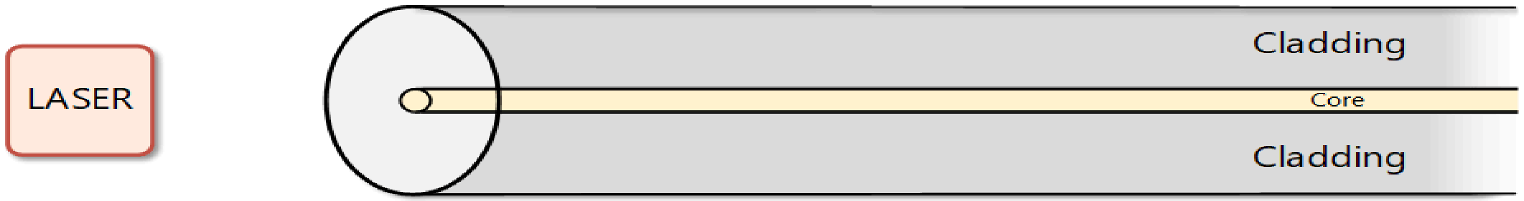
- **ADVANTAGES**
- LOWEST POSSIBLE ATTENUANTION

- **DISADVANTAGES**
- MORE DELICATE
- MORE EFFECT OF RADITION ON SIGNAL

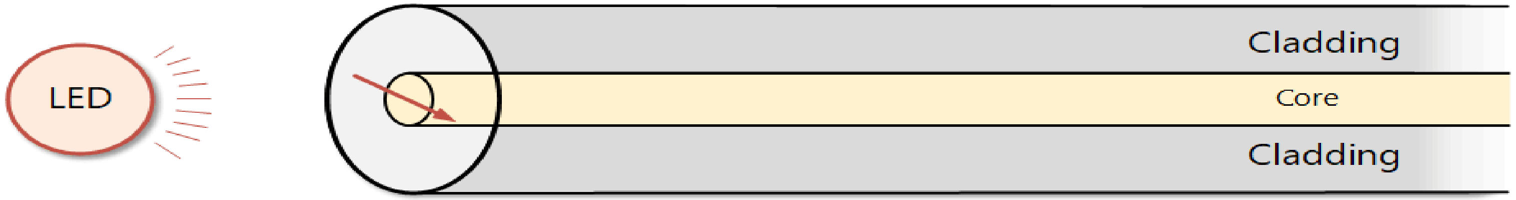
- **EXAMPLES**
- CORE (SILICA + INDEX RISING OXIDES LIKE $GeO_2, Al_2O_3, P_2O_5, B_2O_3$)
- CLADDING (SILICA + INDEX LOWERING FLUORIDES LIKE $CaF_2, MgF_2$)

- **USAGE**
- LONG RANGE COMMUNICATION

# CLASSIFICATION BASED ON MODE OF PROPAGATION

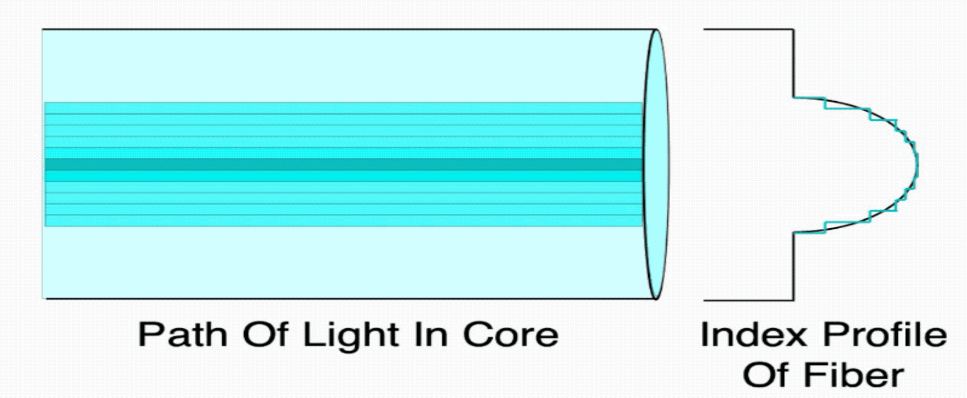



SINGLE MODE FIBER

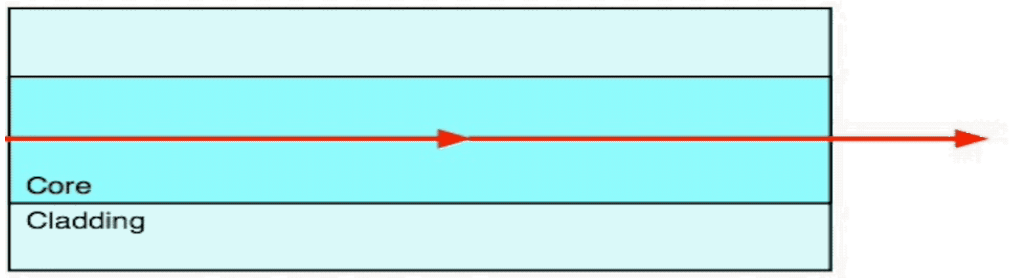



MULTI MODE FIBER

# CLASSIFICATION BASED ON REFRACTIVE INDEX PROFILE

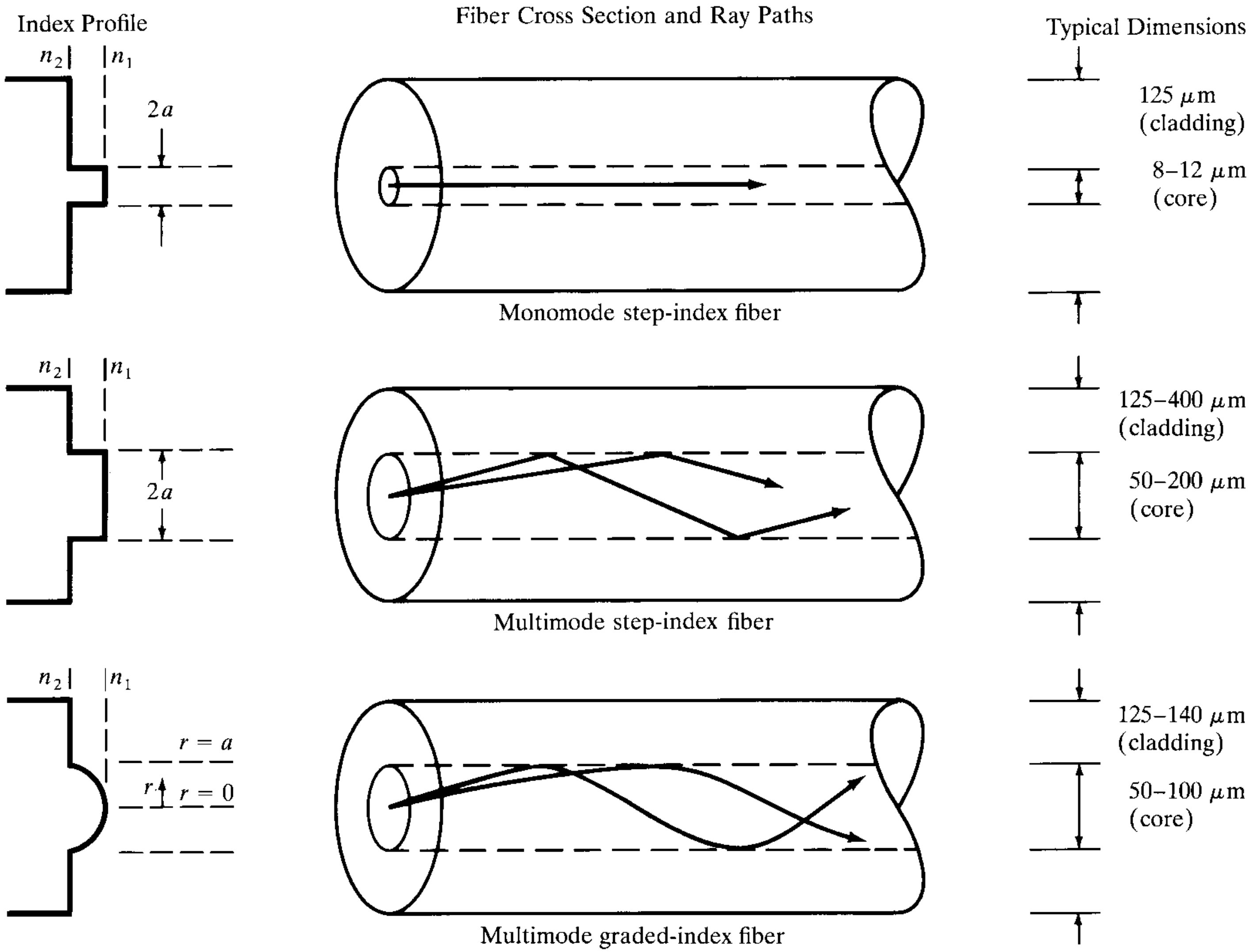



GRADED INDEX FIBER




STEP INDEX FIBER

# Classification of Fibre



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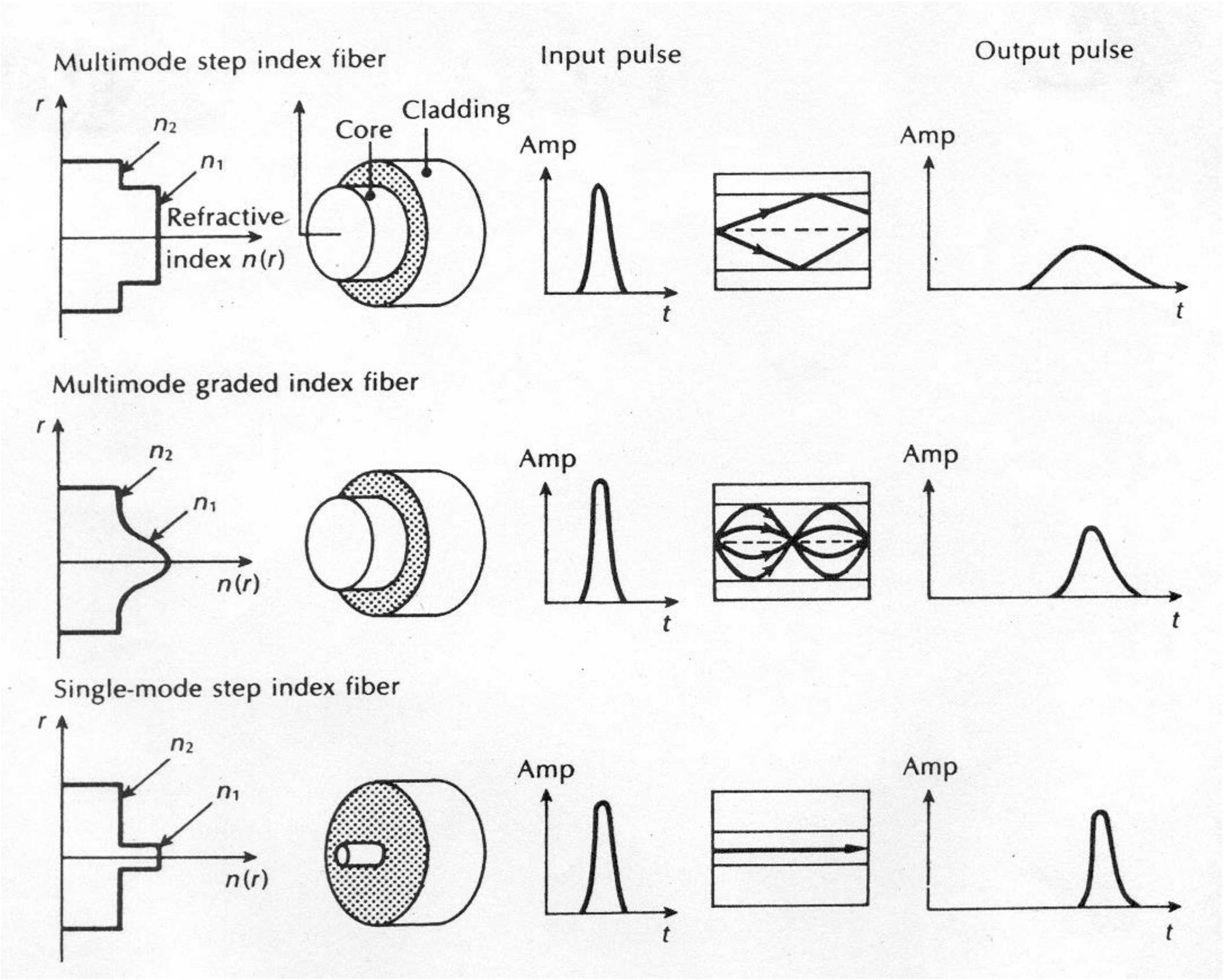


Multimode step index fiber
Input pulse
Output pulse
r
n2
n1
Core
Cladding
Refractive
index n(r)
Amp
Amp
t
t
Multimode graded index fiber
r
n2
n1
n(r)
Amp
Amp
t
t
Single-mode step index fiber
r
n2
n1
n(r)
Amp
Amp
t
t

**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
$\alpha$ **:** Fiber attenuation coefficient, [dB/km]

# ADVANTAGES OF OPTICAL FIBER

- LARGE BANDWIDTH (more than 100 GHz)
- IMMUNITY TO ELECTROSTATIC INTERFERENCE
- NO CROSSTALK (Electromagnetic Coupling) BETWEEN ADJACENT CABLES
- LIGHT WEIGHT AND SMALL SIZE
- ABUNDANT RAW MATERIAL
- DATA SECURITY
- SAFETY IN HAZARDOUS ENVIRONMENT
- CORROSION RESISTANT

# OPTICAL FIBERS IN COMMUNICATION

- INTERNET AND TELECOMMUNICATION
- LIGHT WEIGHT COMMUNICATION SYSTEM FOR MILITARY AND SPACE

# OPTICAL FIBERS IN ENDOSCOPY

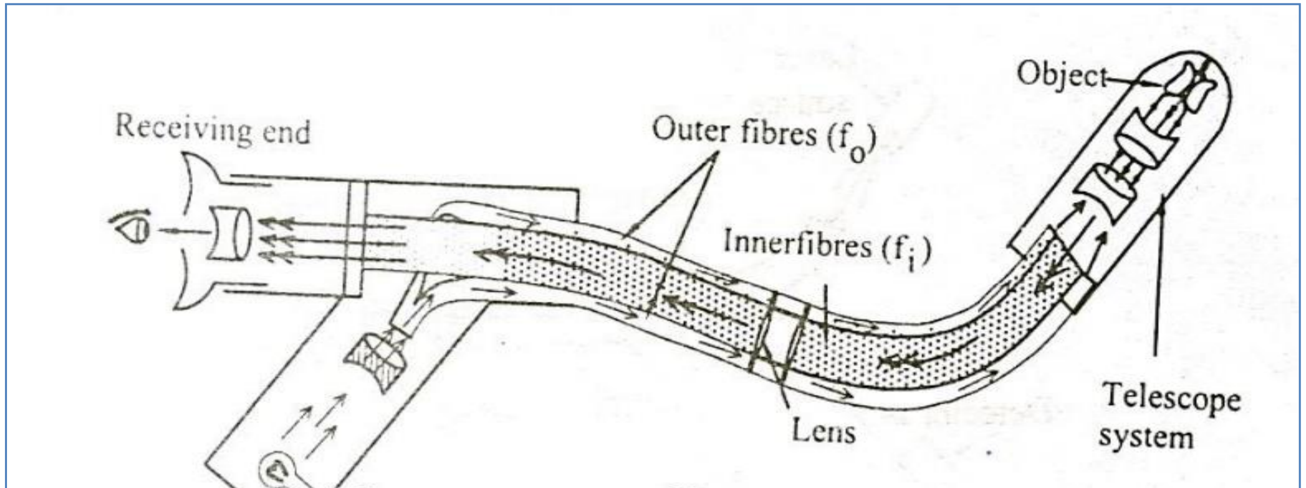
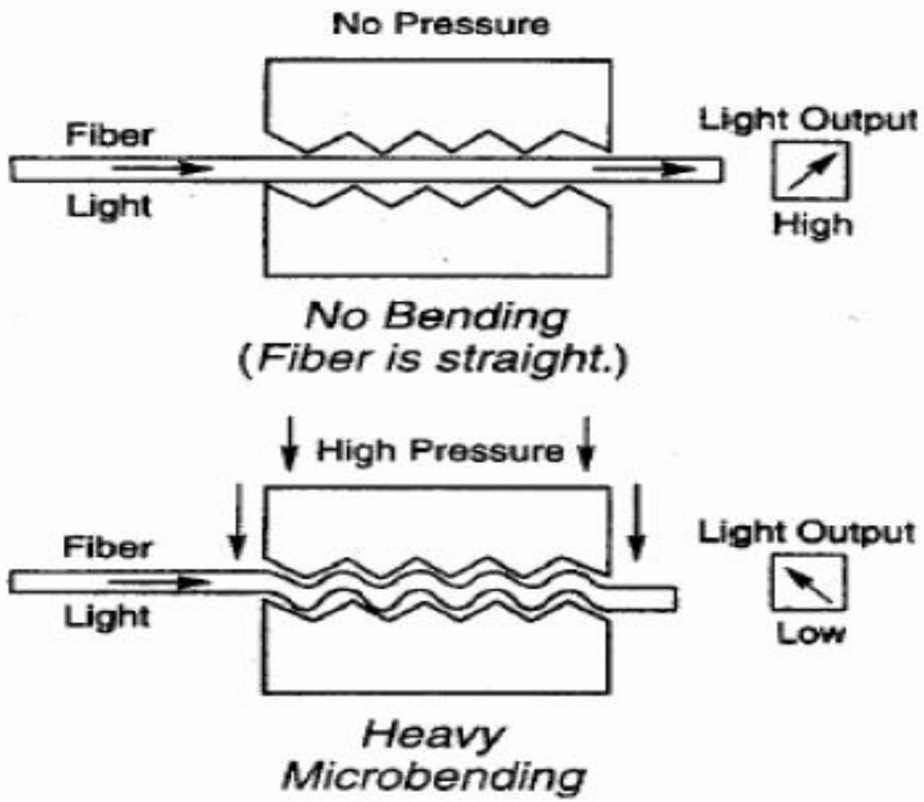



Fig 9.22

# OPTICAL FIBERS IN ENDOSCOPY

# OPTICAL FIBER BASED PRESSURE SENSOR

Microbending sensor



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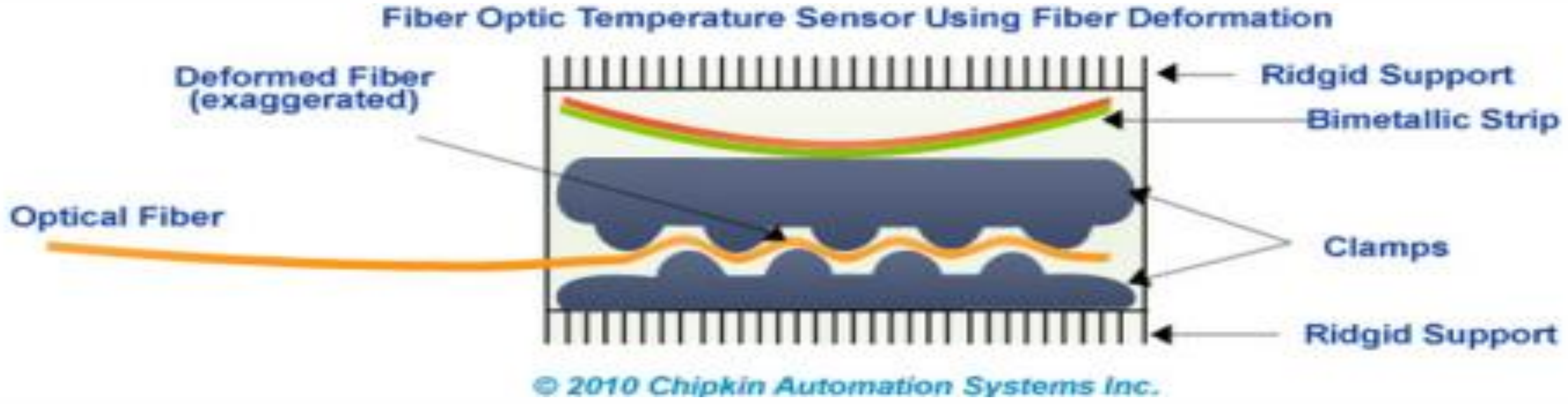
# OPTICAL FIBER BASED TEMPERATURE SENSOR



# Application

- Applications – Temperature Sensing

**Multi-Point Fire Detection Systems**

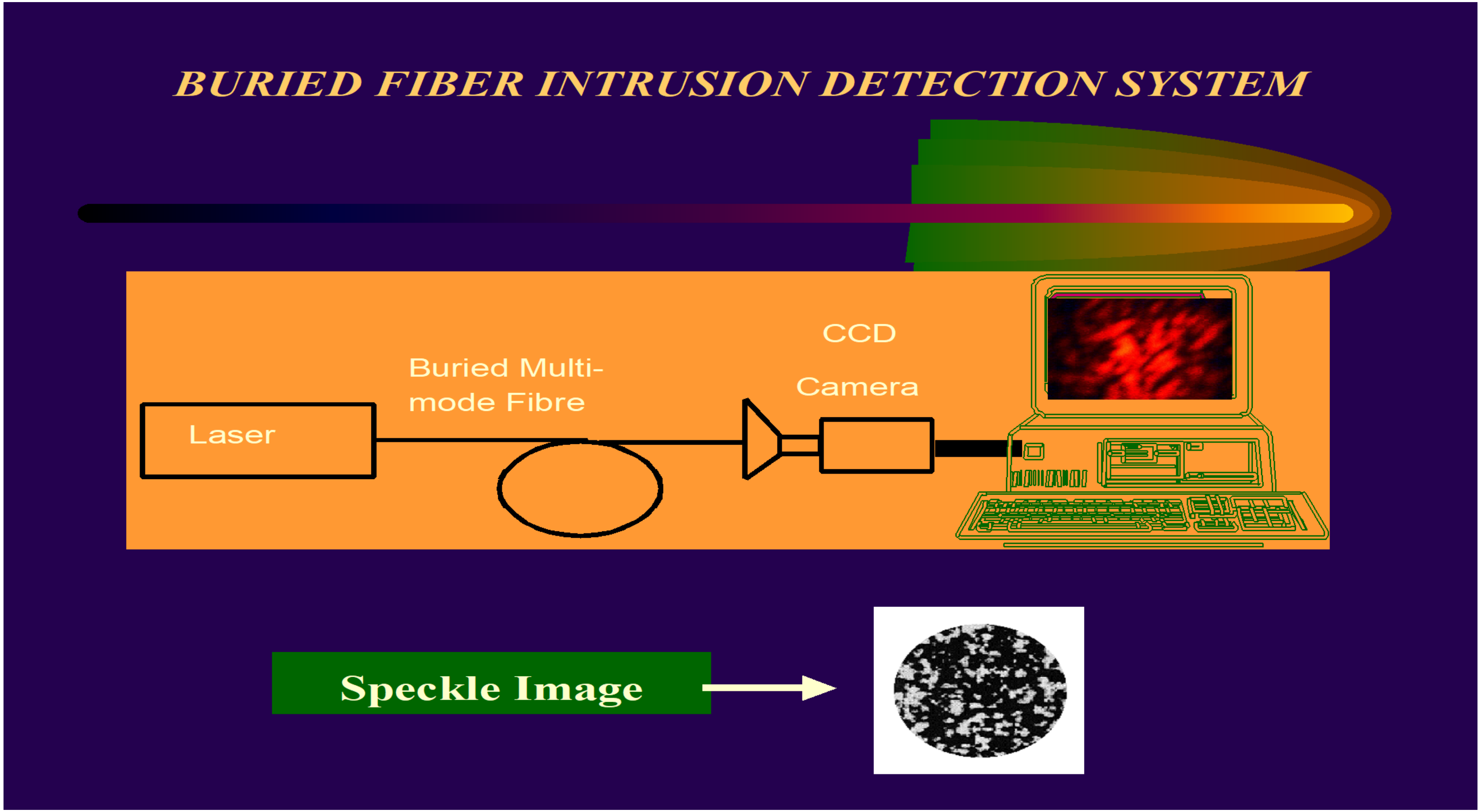
➢ Road and Rail Tunnels, Mineshafts
Public Buildings, Car Parks

**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
CCD
Camera
Buried Multi-
mode Fibre
Laser
Speckle Image

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