Laser Systems

CHAPTER 2

ESSENTIAL COMPONENTS OF A 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.

LASER TYPES

- According to the active material:

  solid-state, liquid, gas, excimer or semiconductor lasers, Dye Lasers, Gas Lasers, Chemical Lasers, Metal vapour Lasers.

- According to the wavelength:

  Visible Region, Infrared Region, Ultraviolet Region, Microwave Region, X-Ray Region etc.

- Based on its pumping action:

  Optically pumped laser, Electrically pumped laser,

- Basis of the operation mode

  Continuous wave Lasers, Pulsed Lasers

TYPE OF LASERS

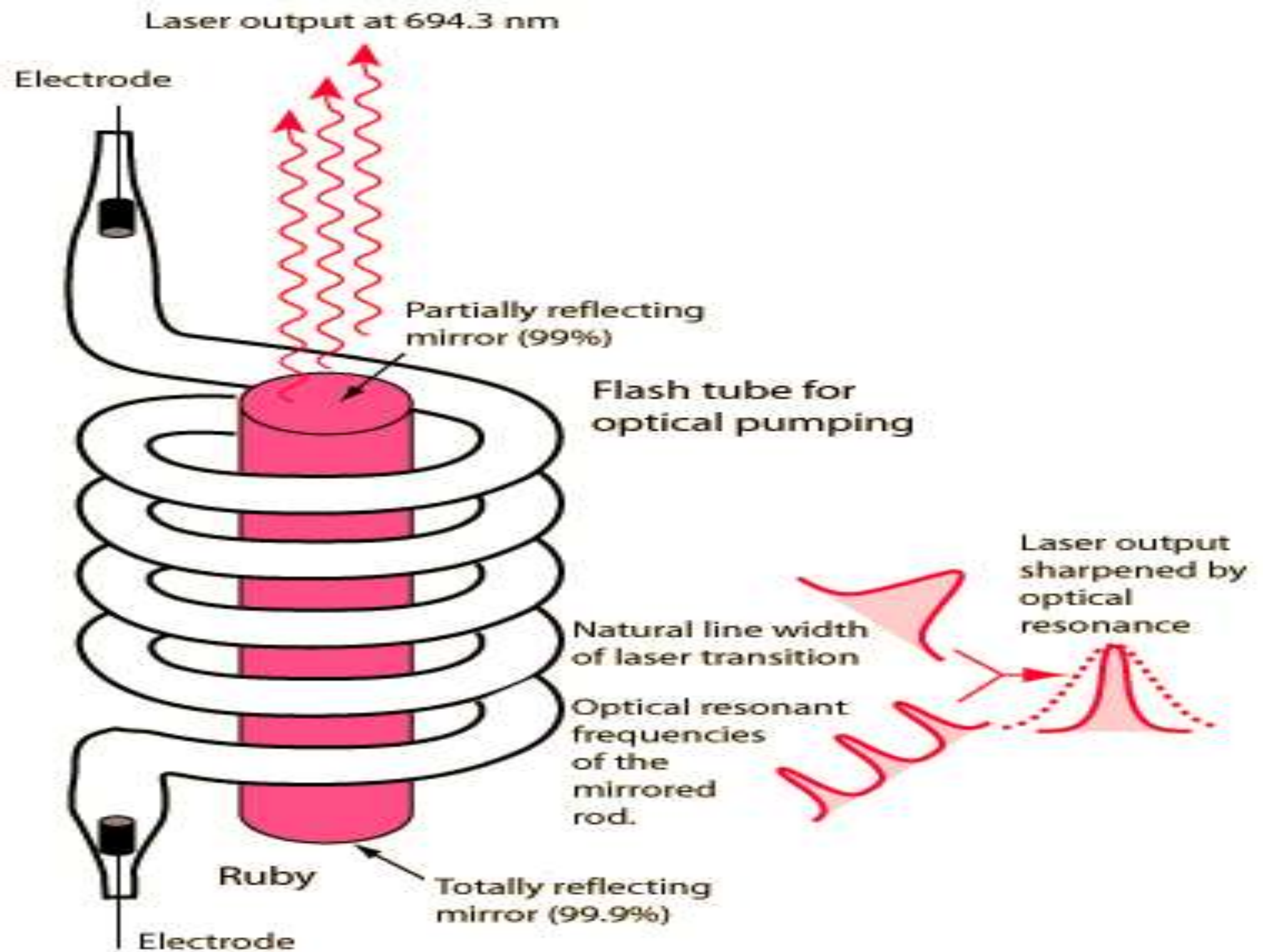
- Solid state lasers
- Gas Lasers
- Liquid or dye lasers
- Ion lasers
- Molecule lasers
- Semiconductor lasers
- Chemical lasers

INTRODUCTION

- A ruby laser is a solid-state laser that uses a synthetic ruby crystal as its gain medium.
- It was the first type of laser invented, and was first operated by Theodore H. "Ted" Maiman at Hughes Research Laboratories on 1960-05-16 .
- The ruby mineral (corundum) is aluminum oxide with a small amount(about 0.05%) of chromium which gives it its characteristic pink or red color by absorbing green and blue light. The ruby laser is The ruby laser is used as a pulsed laser, producing red light at 694.3 nm. After receiving a pumping flash from the flash tube, the laser light emerges for as long as the excited atoms persist in the ruby rod, which is typically about a millisecond.

HISTORICAL IMPORTANCE

- A pulsed ruby laser was used for the famous laser ranging experiment which was conducted with a corner reflector placed on the Moon by the Apollo astronauts. This determined the distance to the Moon with an accuracy of about 15 cm.


Laser output at 694.3 nm
Electrode
Partially reflecting mirror (99%)
Flash tube for optical pumping
Laser output sharpened by optical resonance
Natural line width of laser transition
Optical resonant frequencies of the mirrored rod.
Ruby
Totally reflecting mirror (99.9%)
Electrode

LASER CONSTRUCTION

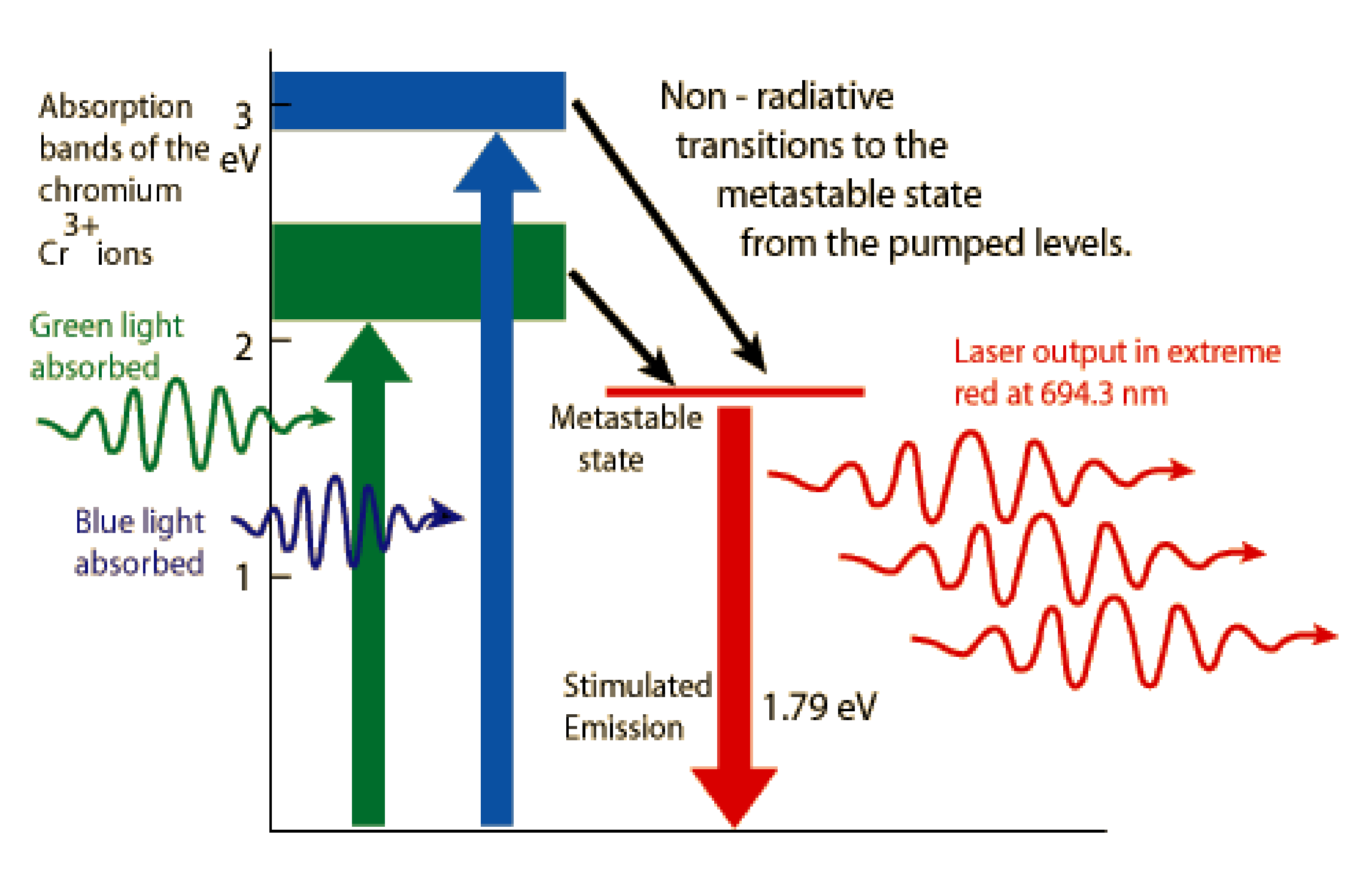
- The active laser medium (laser gain/amplification medium) is a synthetic ruby rod. Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with chromium atoms(0.05% by weight). Chromium gives ruby its characteristic red color and is responsible for the lasing behavior of the crystal. Chromium atoms absorb green and blue light and emit or reflect only red light. For a ruby laser, a crystal of ruby is formed into a cylinder.

- The rod's ends had to be polished with great precision, such that the ends of the rod were flat to within a quarter of a wavelength of the output light, and parallel to each other within a few seconds of arc. The finely polished ends of the rod were silvered: one end completely, the other only partially. The rod with its reflective ends then acts as a Fabry-Pérot etalon.

- A xenon lamp is rolled over ruby rod and is used for pumping ions to excited state.

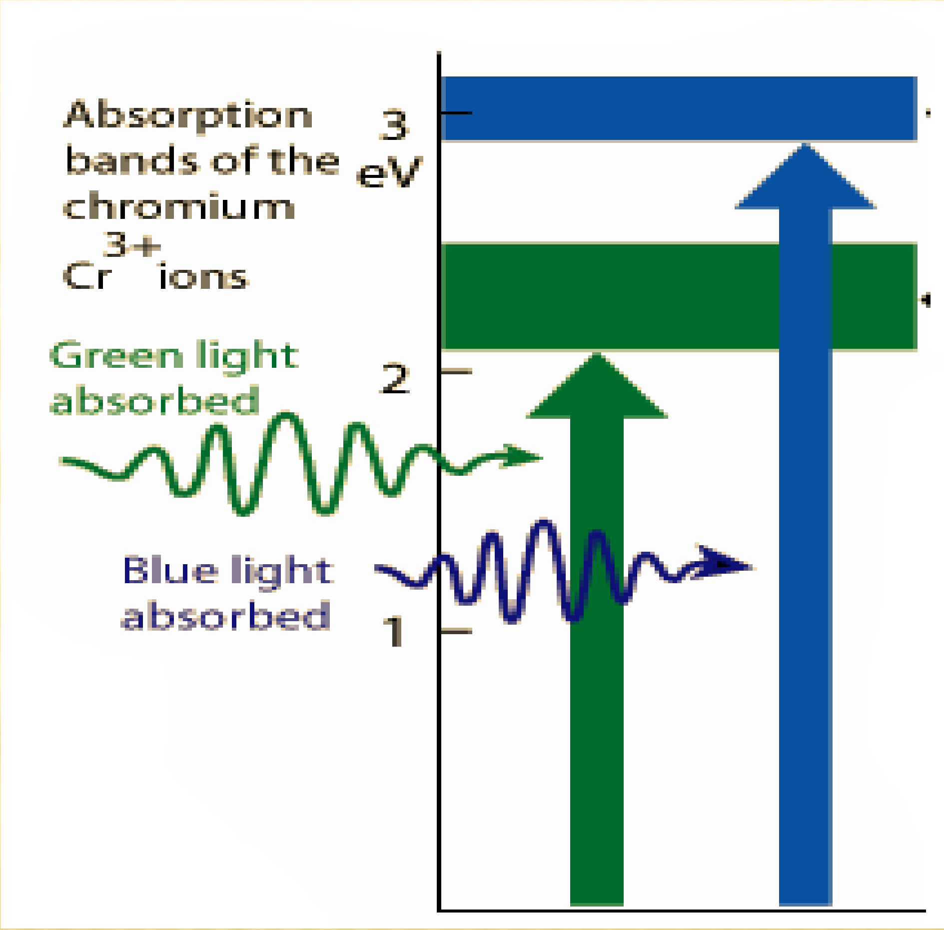
WORKING OF RUBY LASER

- Ruby laser is based on three energy levels. The upper energy level E3 I short-lived, E1 is ground state, E2 is metastable state with lifetime of 0.003 sec.

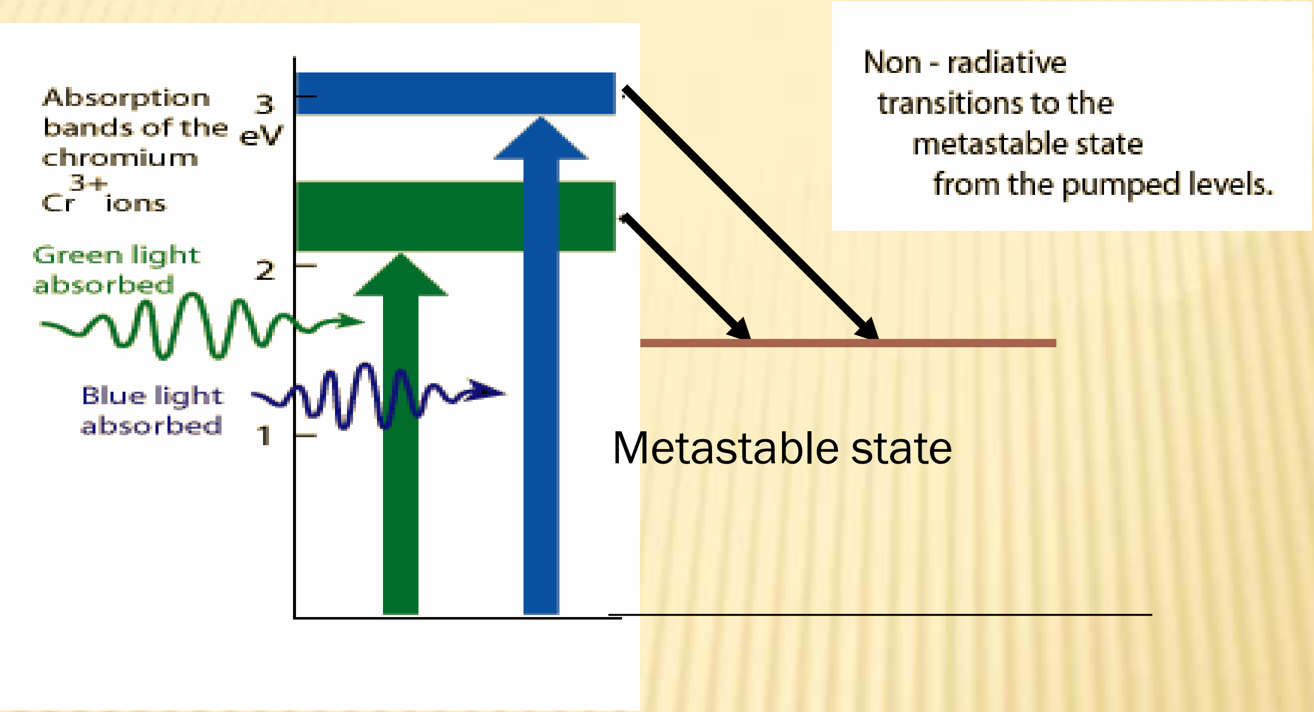


Energy levels of Cromium atom

When a flash of light falls on ruby rod, radiations of wavelength 5500 are absorbed by Cr^{3+} which are pumped to E3.

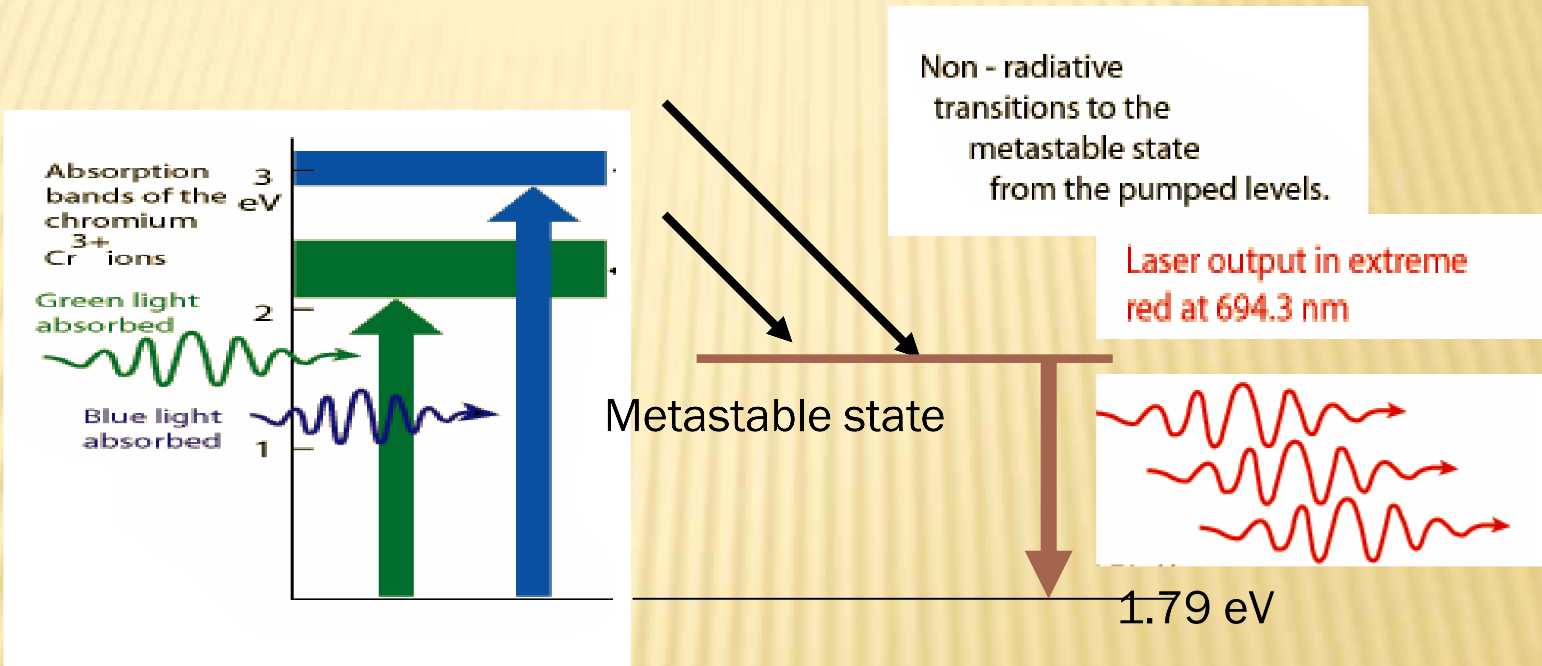


THE IONS AFTER GIVING A PART OF THEIR ENERGY TO CRYSTAL LATTICE DECAY TO E2 STATE UNDERGOING RADIATION LESS TRANSITION.



In metastable state , the concentration of ions increases while that of E1 decreases. Hence, population inversion is achieved.

A spontaneous emission photon by cr3+ ion at E2 level initiates the stimulated emission by other cr3+ ions in metastable state



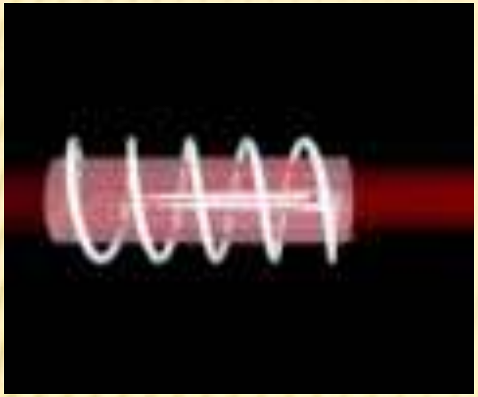
APPLICATION

- Ruby lasers have declined in use with the discovery of better lasing media. They are still used in a number of applications where short pulses of red light are required. Holographers around the world produce holographic portraits with ruby lasers, in sizes up to a metre squared.
- Many non-destructive testing labs use ruby lasers to create holograms of large objects such as aircraft tires to look for weaknesses in the lining.
- Ruby lasers were used extensively in tattoo and hair removal

DRAWBACKS OF RUBY LASER

- The laser requires high pumping power because the laser transition terminates at the ground state and more than half of ground state atoms must be pumped to higher state to achieve population inversion.
- The efficiency of ruby laser is very low because only green component of the pumping light is used while the rest of components are left unused.
- The laser output is not continuos but occurs in the form of pulses of microseconds duration.
- The defects due to crystalline inperfection are also present in this laser.

SOLID-STATE LASER

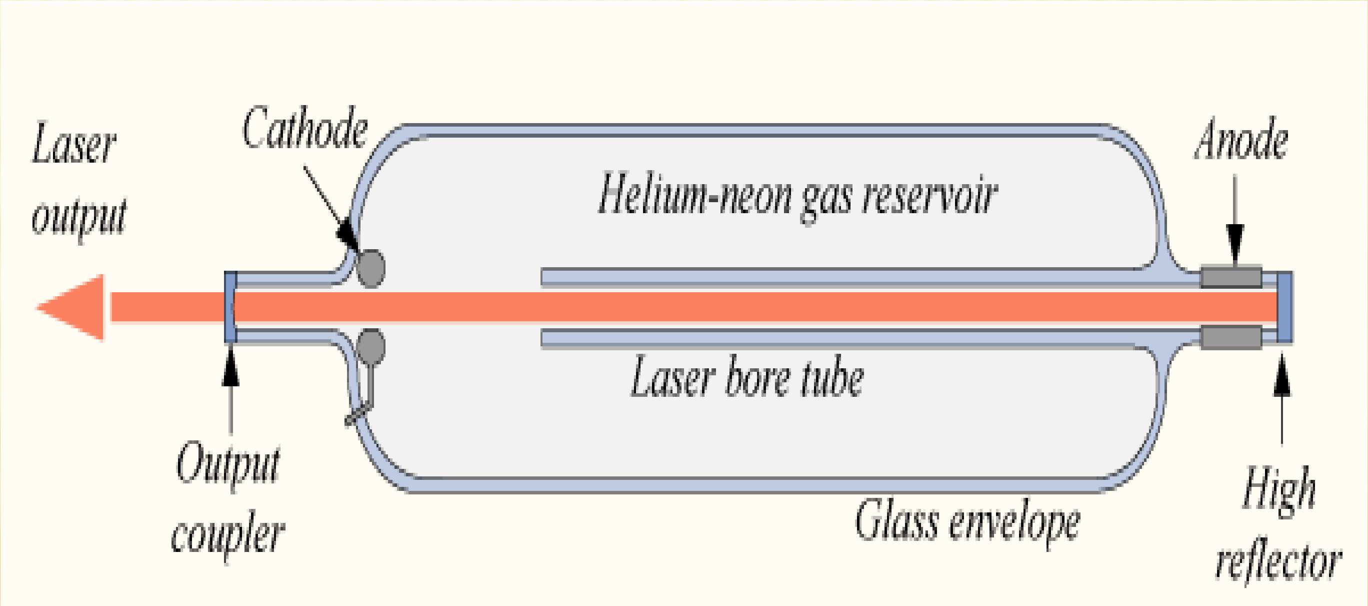


- Example: Ruby Laser
- Operation wavelength: 694.3 nm (IR)
- 3 level system: absorbs green/blue

- Gain Medium: crystal of aluminum oxide (Al_2O_3) with small part of atoms of aluminum is replaced with Cr^{3+} ions.
- Pump source: flash lamp
- The ends of ruby rod serve as laser mirrors.

GAS LASER

- Example: Helium-neon laser (He-Ne laser)
- Operation wavelength: 632.8 nm
- Pump source: electrical discharge
- Gain medium : ratio 5:1 mixture of helium and neon gases



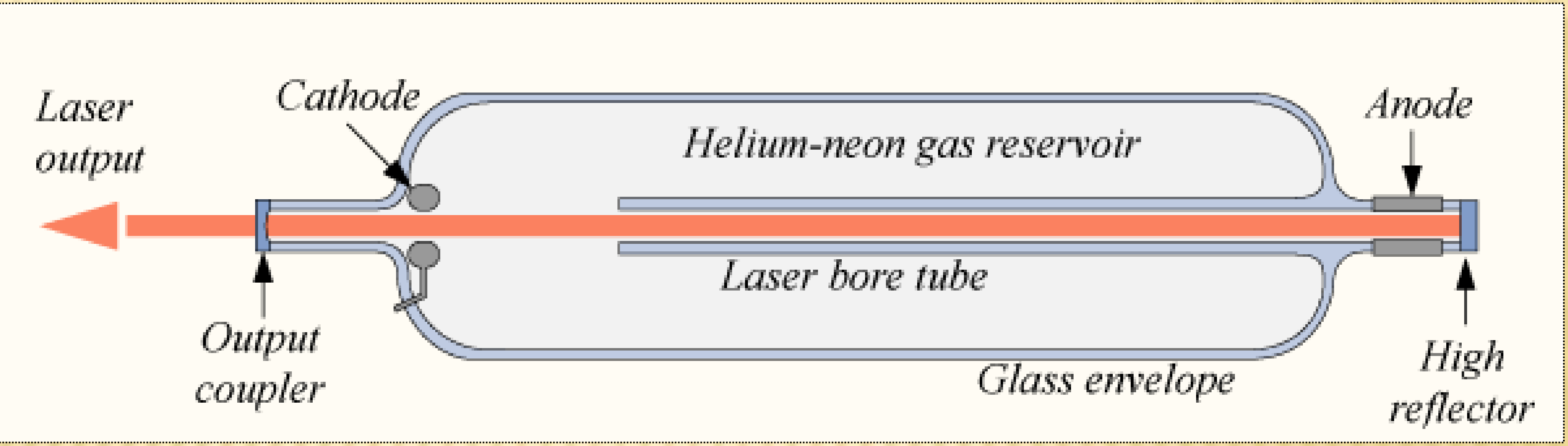
HE NE LASER

- A helium-neon laser, usually called a He-Ne laser, is a type of small gas laser. He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.
- He-Ne laser is a four-level laser.
- Its usual operation wavelength is 632.8 nm, in the red portion of the visible spectrum.
- It operates in Continuous Working (CW) mode.

CONSTRUCTION OF HE-NE LASER

- The setup consists of a long and narrow discharge tube of length 25-100 cm and diameter of 1.5-5 cm.
- The active medium of the laser, as suggested by its name, is a mixture of helium and neon gases, in a 10:1 ratio, contained at low pressure (an average 50 Pa per cm of cavity length).
- The energy or pump source of the laser is provided by an electrical discharge of around 1000 volts through an anode and cathode at each end of the glass tube. A current of 5 to 100 mA is typical for CW operation.
- The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end.
- He Ne lasers are normally small, with cavity lengths of around 15 cm up to 0.5 m, and optical output powers ranging from 1 mW to 100 mW.

CONSTRUCTION OF HE-NE LASER

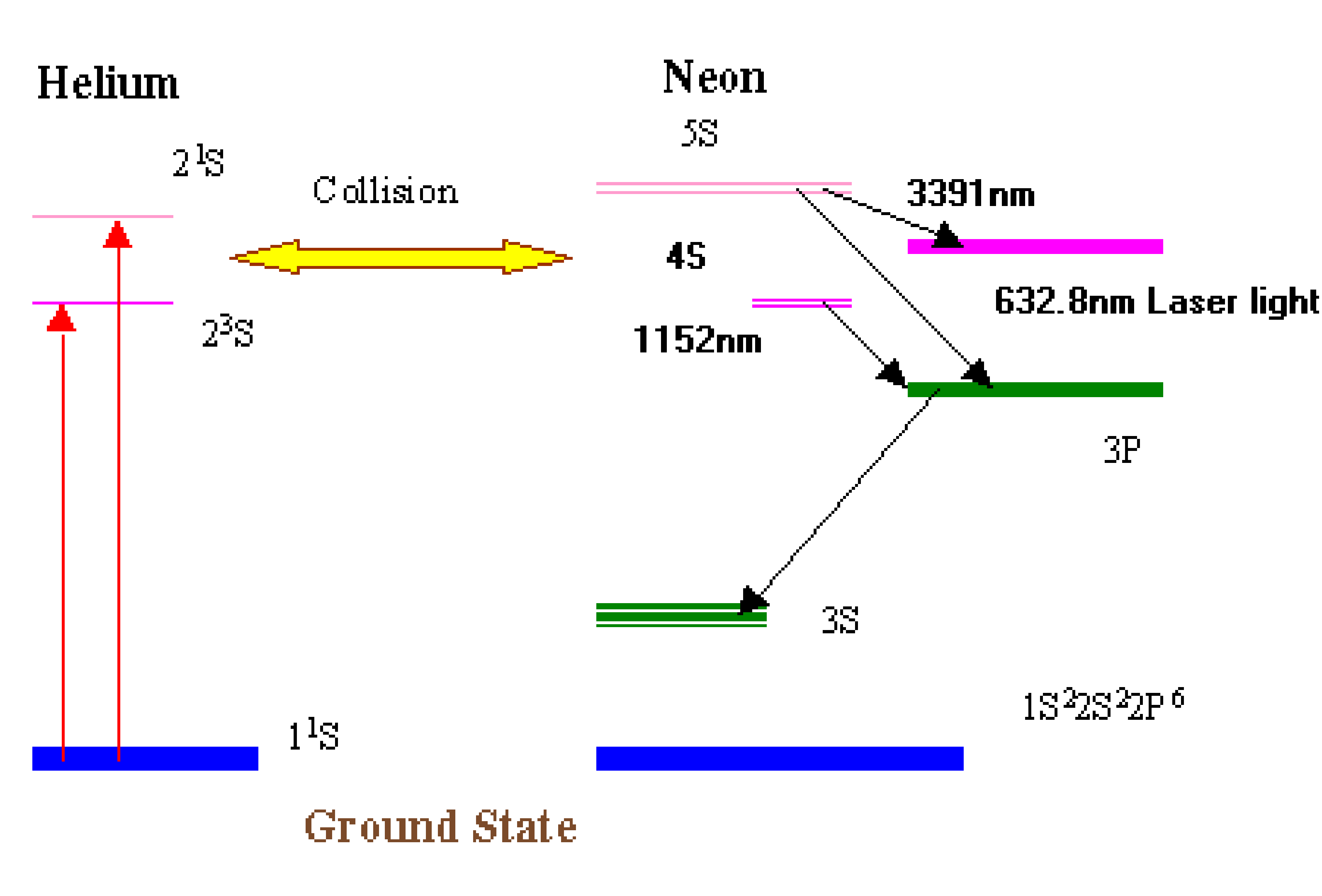


https://www.youtube.com/watch?v=RyY4PEpV2RQ

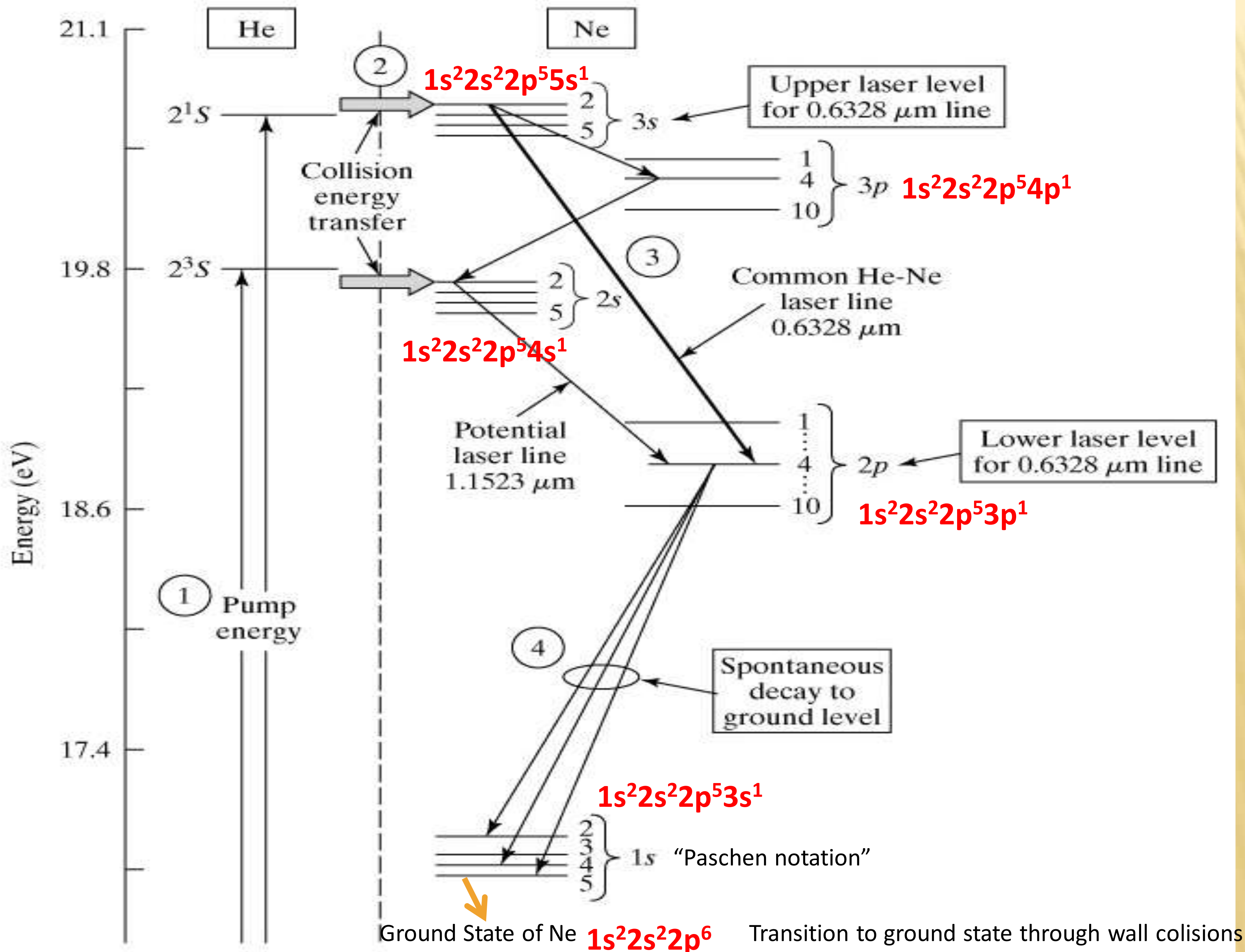
WORKING

- Neon atoms are the active centers and have the energy levels suitable for laser transitions. Helium atoms help for efficient excitation of neon atoms.
- He-Ne excitation process can be given in terms of the following four steps.
- (a)When the power is switched on, An energetic electron collisionally excites a He atom to the state labeled 2^1S . A He atom in this excited state is often written He*(2^1S), where the asterisk means that the He atom is in an excited state.
- (b) The excited He*(2^1S) atom collides with an unexcited Ne atom and the atoms exchange internal energy, with an unexcited He atom and excited Ne atom, written Ne*(3s), resulting. This energy exchange process occurs with high probability only because of the accidental near equality of the two excitation energies of the two levels in these atoms. Thus, the purpose of population inversion is fulfilled

He-Ne laser



$$\lambda_1 = 3.39\,\mu\text{m} \qquad \lambda_2 = 0.6328\,\mu\text{m} \qquad \lambda_3 = 1.15\,\mu\text{m}$$



21.1
19.8
18.6
17.4
Energy (eV)
He
Ne
2
1s22s22p55s1
2¹S
2³S
Collision energy transfer
Upper laser level for 0.6328 μm line
3s
1s22s22p54p1
3p
3
Common He-Ne laser line 0.6328 μm
2s
1s22s22p54s1
Potential laser line 1.1523 μm
Lower laser level for 0.6328 μm line
2p
1s22s22p53p1
1
Pump energy
4
Spontaneous decay to ground level
1s22s22p53s1
1s
"Paschen notation"
Ground State of Ne
1s22s22p6
Transition to ground state through wall colisions

DESCRIPTION OF ENERGY LEVEL DIAGRAM

- When the excited Ne atom passes from metastable state(5s) to lower level (3p), it emits photon of wavelength 632 nm.
- This photon travels through the gas mixture parallel to the axis of tube, it is reflected back and forth by the mirror ends until it stimulates an excited Ne atom and causes it to emit a photon of 632nm with the stimulating photon.
- The stimulated transition from (5s) level to (3p) level is laser transition.
- This process is continued and when a beam of coherent radiation becomes sufficiently strong, a portion of it escape through partially silvered end.
- The Ne atom passes to lower level 3s emitting spontaneous emission. and finally the Ne atom comes to ground state through collision with tube wall and undergoes radiation less transition.

APPLICATIONS

- The Narrow red beam of He-Ne laser is used in supermarkets to read bar codes.
- The He- Ne Laser is used in Holography in producing the 3D images of objects.
- He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.

CO_2 LASER

Introduction :

CO_2 lasers belong to the class of molecular gas lasers.

- In the case of atoms, electrons in molecules can be excited to higher energy levels, and the distribution of electrons in the levels define the electronic state of the molecule.

- Besides, these electronic levels, the molecules have other energy levels.

- C.K.N. Patel designed CO_2 laser in the year 1964.

Active medium :

It consists of a mixture of CO_2, N_2 and helium or water vapors. The active centers are CO_2 molecules lasing on the transition between the rotational levels of vibrational bands of the electronic ground state..

Optical resonators :

A pair of concave mirrors placed on either side of the discharge tube, one completely polished and the other partially polished.

Pumping :

- Population inversion is created by electric discharge of the mixture.

- When a discharge is passed in a tube containing CO_2, electron impacts excite the molecules to higher electronic and vibrational-rotational levels.

- This level is also populated by radiationless transition from upper excited levels.

- The resonant transfer of energy from other molecules, such as, N_2, added to the gas, increases the pumping efficiency.

Contd.

- Nitrogen here plays the role that He plays in He-Ne laser.

- A carbon dioxide (CO_2) laser can produce a continuous laser beam with a power output of several kilowatts while, at the same time, can maintain high degree of spectral purity and spatial coherence.

- In comparison with atoms and ions, the energy level structure of molecules is more complicated and originates from three sources: electronic motions, vibrational motions and rotational motions.

Fundamental Modes of vibration of CO_2 :

Three fundamental modes of vibration for CO_2

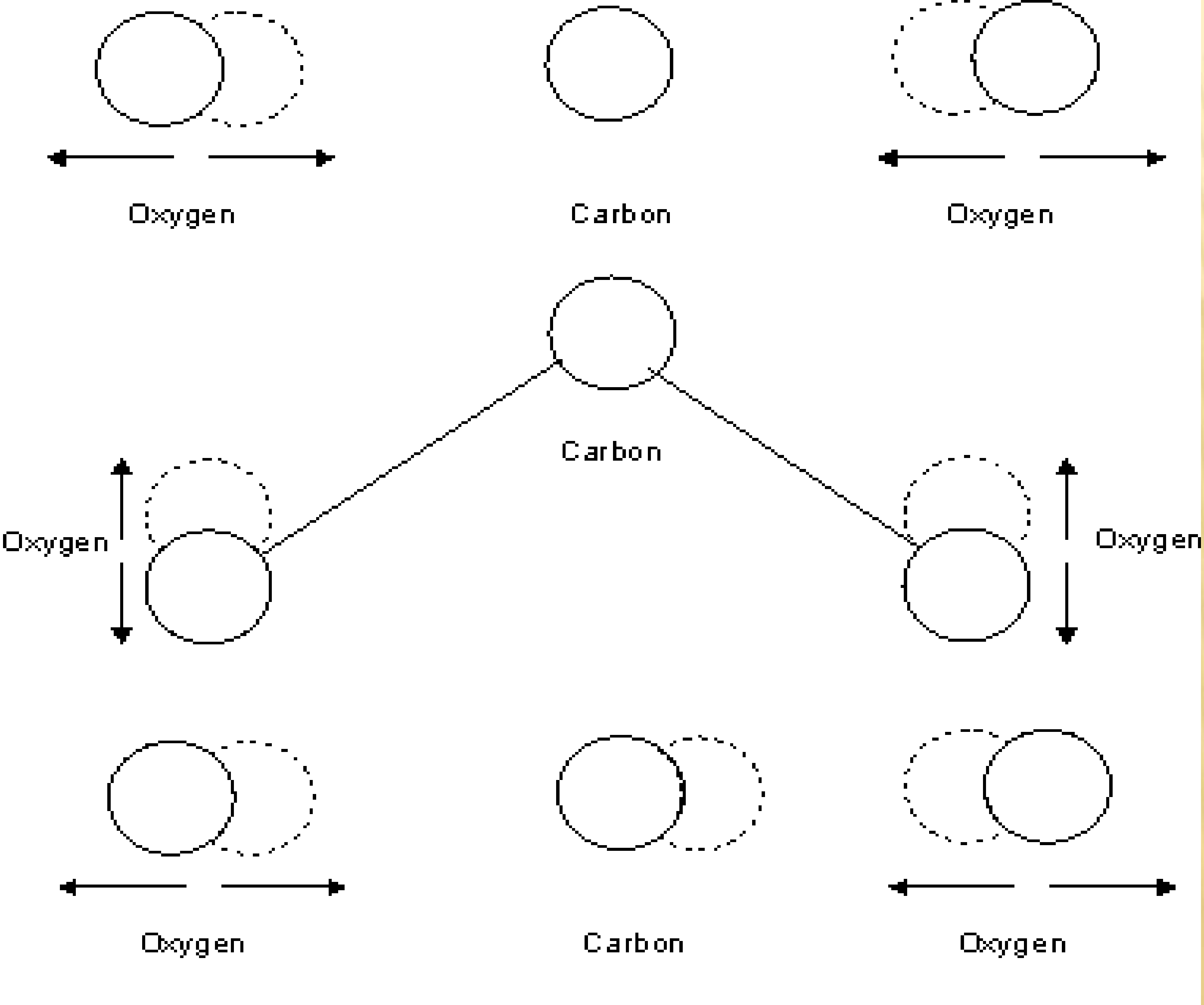
- Symmetric stretching mode (frequency ν_1),
- Bending mode (ν_2) and
- Asymmetric stretching mode (ν_3).

- In the symmetric stretching mode, the oxygen atoms oscillate along the axis of the molecule simultaneously departing or approaching the carbon atom, which is stationary.

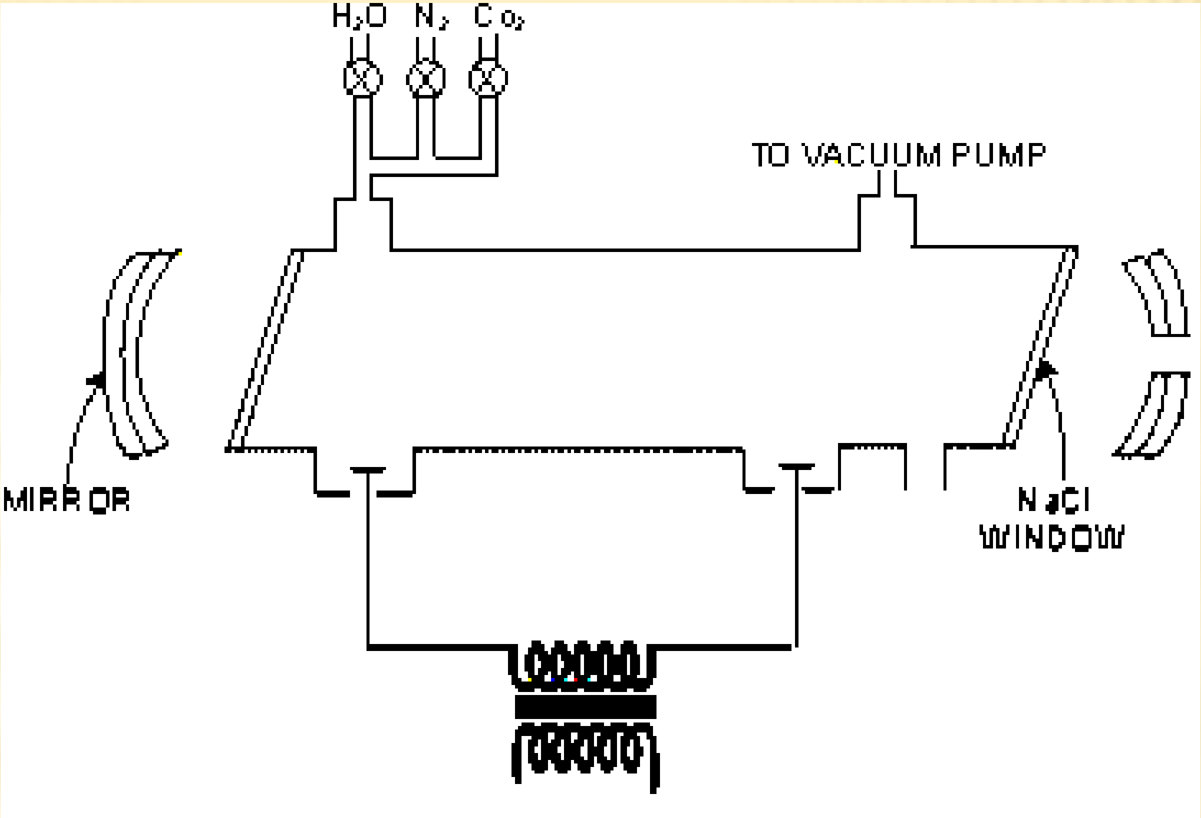
- In the ‘bending mode’, the molecule ceases to be exactly linear as the atoms move perpendicular to the molecular axis.

- In ‘asymmetric stretching’, all the three atoms oscillate: but while both oxygen atoms move in one direction, carbon atoms move in the opposite direction.

- The ‘internal vibrations’ of carbon dioxide molecule can be represented approximately by linear combination of these three normal modes.



INDEPENDENT MODES OF VIBRATION OF CO_2 MOLECULE



CO_2 LASER

- The energy level diagram of vibrational – rotational energy levels with which the main physical processes taking place in this laser.

- As the electric discharge is passed through the tube, which contains a mixture of carbon dioxide, nitrogen and helium gases, the electrons striking nitrogen molecules impart sufficient energy to raise them to their first excited vibrational-rotational energy level.

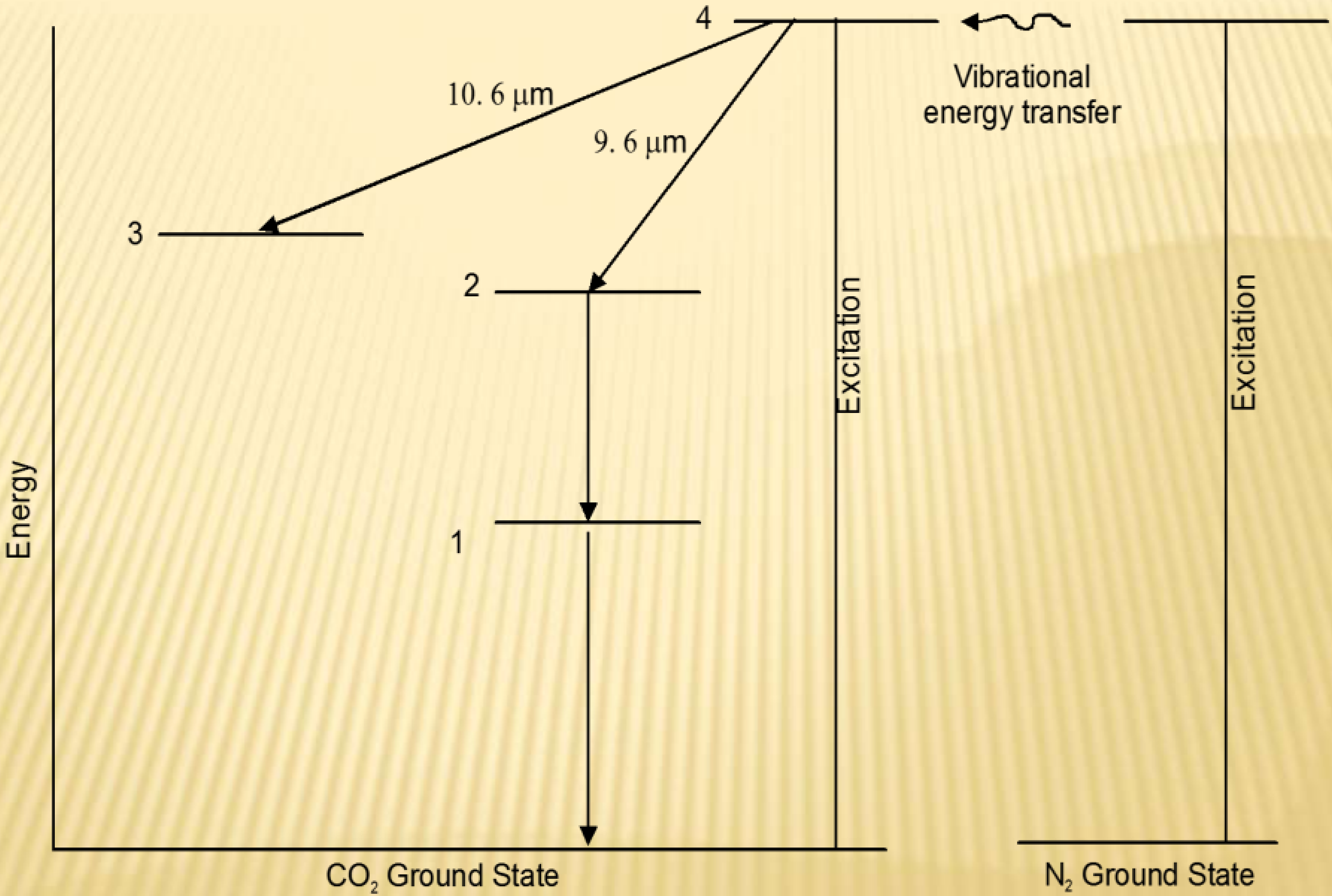
- This energy level corresponds to one of the vibrational - rotational level of CO_2 molecules, designated as level 4.

- collision with N_2 molecules, the CO_2 molecules are raised to level 4.

- The lifetime of CO_2 molecules in level 4 is quiet significant to serve practically as a metastable state.

- Hence, population inversion of CO_2 molecules is established between levels 4 and 3, and between levels 4 and 2.

- The transition of CO_2 molecules between levels 4 and 3 produce lasers of wavelength 10.6 microns and that between levels 4 and 2 produce lasers of wavelength 9.6 microns.



ENERGY LEVEL DIAGRAM

- The He molecules increase the population of level 4, and also help in emptying the lower laser levels.

- The molecules that arrive at the levels 3 and 2 decay to the ground state through radiative and collision induced transitions to the lower level 1, which in turn decays to the ground state.

- The power output of a CO_2 laser increases linearly with length. Low power (upto 50W) continuous wave CO_2 lasers are available in sealed tube configurations.

Contd.

- Some are available in sizes like torches for medical use, with 10-30 W power.
- All high power systems use fast gas-floe designs.
- Typical power per unit length is 200-600 W/m.
- Some of these lasers are large room sized metal working lasers with output power 10-20 kW.
- Recently CO_2 lasers with continuous wave power output exceeding 100 kW.
- The wavelength of radiation from these lasers is 10.6μm.

Nd: YAG Laser (Doped insulator laser)

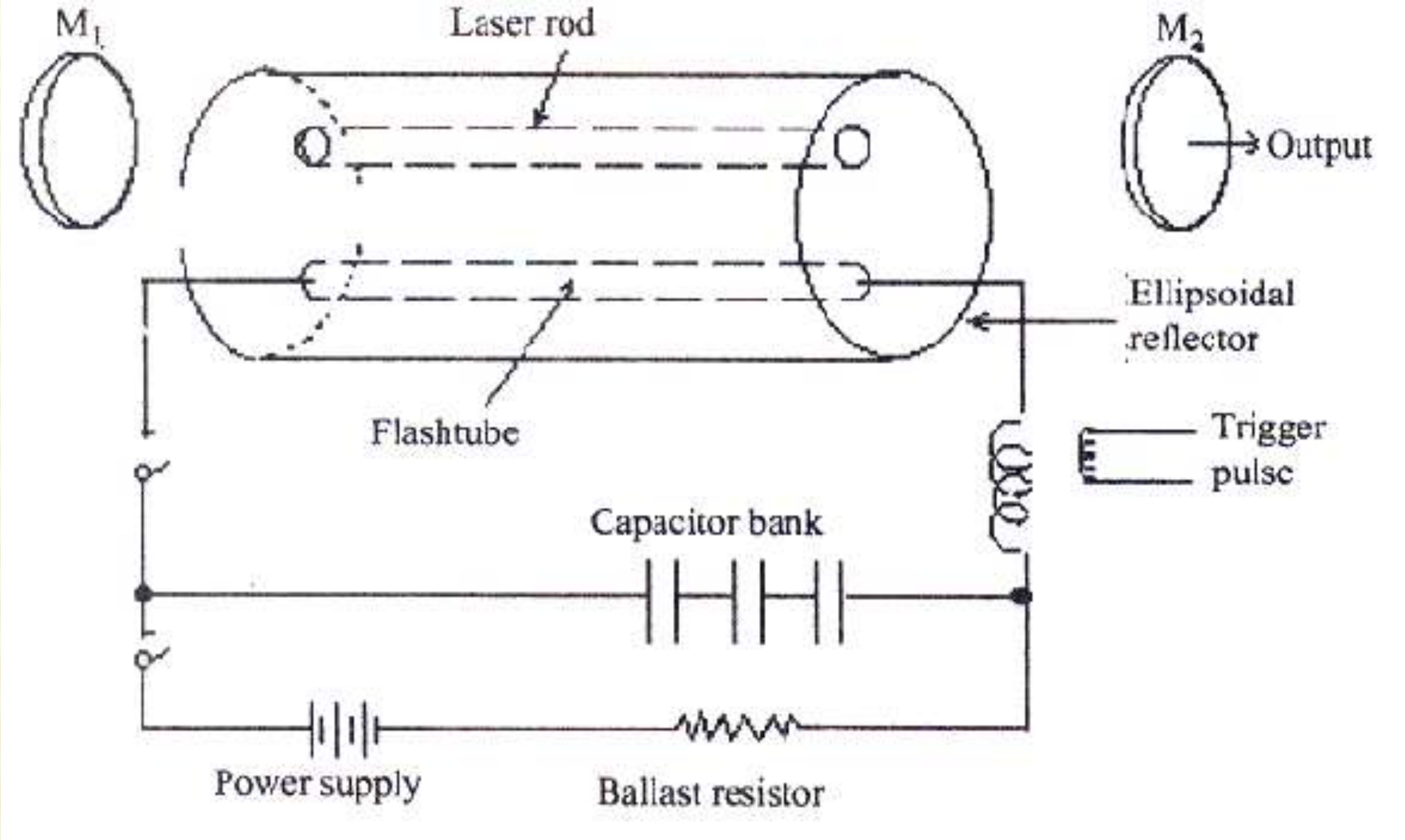
<u>**Lasing medium :**</u>

- The host medium for this laser is Yttrium Aluminium Garnet (YAG = $Y_3\ Al_5\ O_{12}$) with 1.5% trivalent neodymium ions (Nd^{3+}) present as impurities.

- The (Nd^{3+}) ions occupy the lattice sites of yttrium ions as substitutional impurities and provide the energy levels for both pumping and lasing transitions.

- When an (Nd^{3+}) ion is placed in a host crystal lattice it is subjected to the electrostatic field of the surrounding ions, the so called crystal field.

- The crystal field modifies the transition probabilities between the various energy levels of the Nd^{3+} ion so that some transitions, which are forbidden in the free ion, become allowed.



M_1
Laser rod
M_2
Output
Ellipsoidal reflector
Flashtube
Trigger pulse
Capacitor bank
Power supply
Ballast resistor

Nd: YAG laser

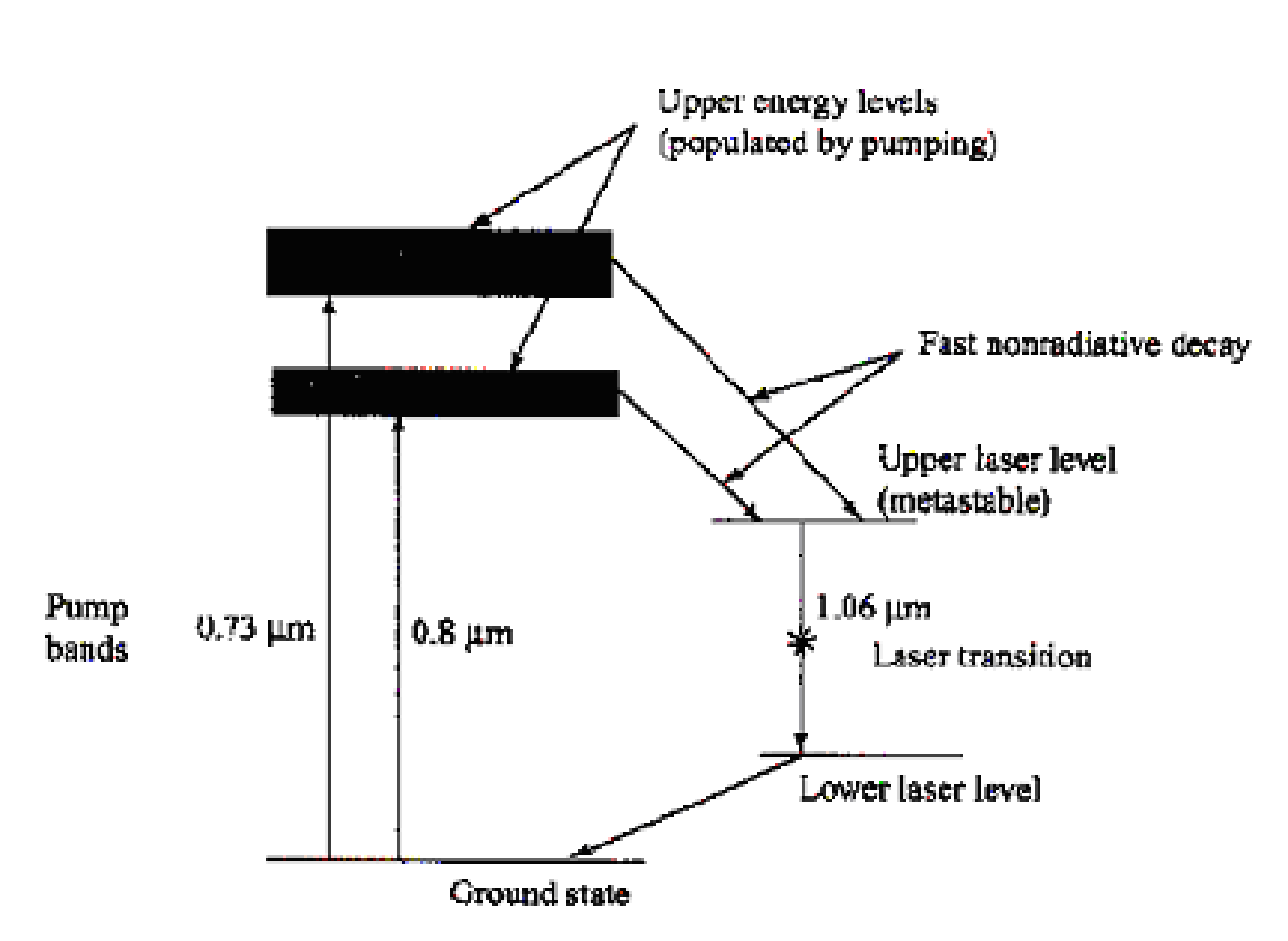
- The length of the Nd: YAG laser rod various from 5cm to 10cm depending on the power of the laser and its diameter is generally 6 to 9 mm.
- The laser rod and a linear flash lamp are housed in a elliptical reflector cavity
- Since the rod and the lamp are located at the foci of the ellipse, the light emitted by the lamp is effectively coupled to the rod.
- The ends of the rod are polished and made optically flat and parallel.

- The optical cavity is formed either by silvering the two ends of the rod or by using two external reflecting mirrors.

- One mirror is made hundred percent reflecting while the other mirror is left slightly transmitting to draw the output

- The system is cooled by either air or water circulation.

ENERGY LEVEL DIAGRAM



Simplified energy level diagram for the Nd-ion in YAG showing the principal laser transitions

- This laser system has two absorption bands (0.73 μm and 0.8 μm)
- Optical pumping mechanism is employed.
- Laser transition takes place between two laser levels at 1.06 mm.

OUTPUT CHARACTERISTICS :

- The laser output is in the form of pulses with higher repetition rate
- Xenon flash lamps are used for pulsed output.
- Nd: YAG laser can be operated in CW mode also using tungsten-halide incandescent lamp for optical pumping.
- Continuous output powers of over 1KW are obtained.

Nd: Glass laser

- Glass acts as an excellent host material for neodymium.

- As in YAG, within the glass also local electric fields modify the Nd^{3+} ion energy levels.

- Since the line width is much broader in glass than in YAG for Nd^{3+} ions, the threshold pump power required for laser action is higher.

- Nd: Glass lasers are operated in the pulsed mode at wavelength 1.06 μm

Nd:YAG/ Nd: Glass laser applications :

- These lasers are used in many scientific applications which involve generation of other wavelengths of light.

- The important industrial uses of YAG and glass lasers have been in materials processing such as welding, cutting, drilling.

- Since 1.06 μm wavelength radiation passes through optical fibre without absorption, fibre optic endoscopes with YAG lasers are used to treat gastrointestinal bleeding.

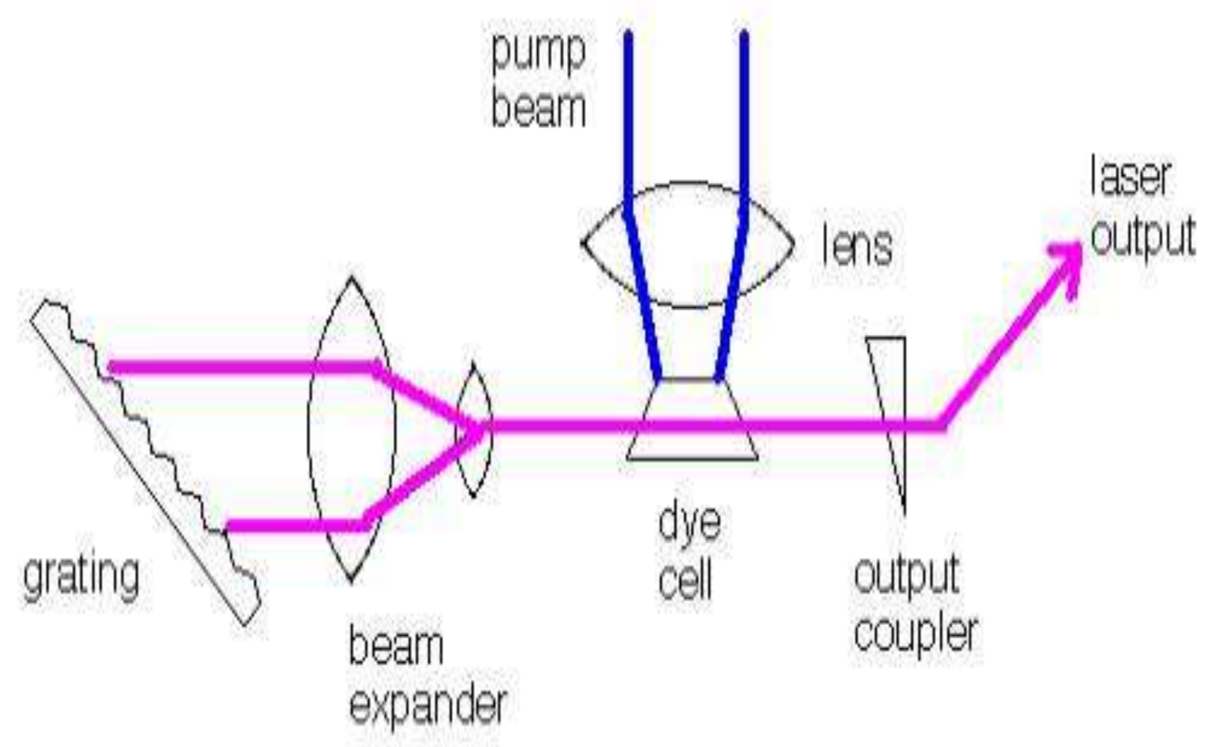
Contd.

- YAG beams penetrate the lens of the eye to perform intracular procedures.
- YAG lasers are used in military as range finders and target designators.

LIQUID LASER

- Example: dye laser
- Gain medium: complex organic dyes, such as rhodamine 6G, in liquid solution or suspension.
- Pump source: other lasers or flashlamp.
- Can be used for a wide range of wavelengths as the tuning range of the laser depends on the exact dye used.
- Suitable for tunable lasers.

dye laser

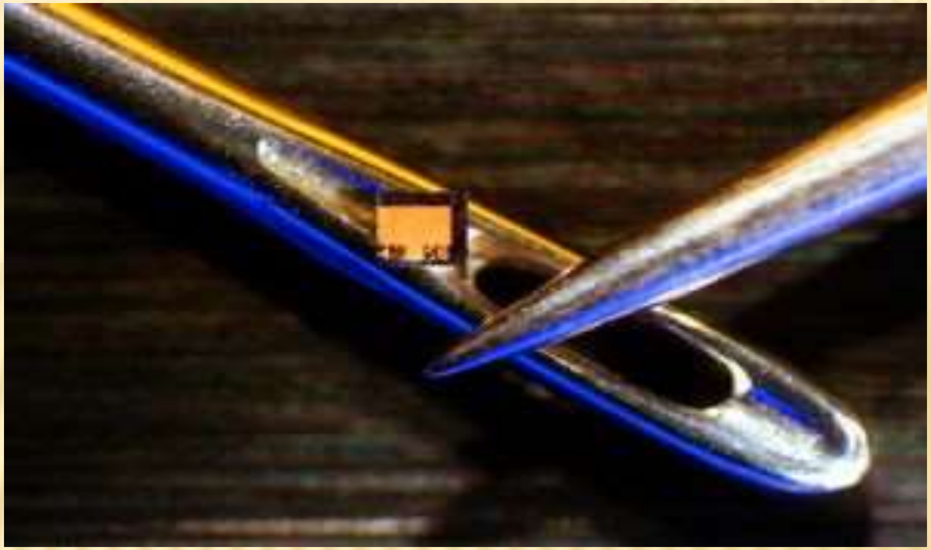


Schematic diagram of a dye laser

A dye laser can be considered to be basically a four-level system.
The energy absorbed by the dye creates a population inversion, moving the electrons into an excited state.

SEMICONDUCTOR LASER

Semiconductor laser is a laser in which semiconductor serves as photon source.



Semiconductors (typically direct band-gap semiconductors) can be used as small, highly efficient photon sources.

THE END