UNIT – V PHOTONICS AND FIBRE OPTICS
LASER

The term laser stands for "Light Amplification by Stimulated Emission of Radiation".

Characteristics of Lasers

- High intensity
- Highly directional
- Highly coherent
- Highly monochromatic

Einstein Coefficients for LASER action

In order to understand the basic laser operation, we must consider the important terms like absorption, stimulated emission, spontaneous emission, etc. The interaction of light with matter gives rise to three types of possible interactions between a system of atoms and light that are of interest:

Stimulated absorption

If light (photons) of frequency ν pass through the group of atoms, there is a possibility of the light being absorbed by atoms which are in the ground state, which will cause them to be excited to the higher energy state. The probability of absorption is proportional to the radiation intensity of the light, and also to the number of atoms currently in the ground state, N_1.

The rate of stimulated absorption $N_{ab} = B_{12}N_1Q$

Spontaneous emission

If a collection of atoms are in the excited state, spontaneous decay events to the ground state will occur at a rate proportional to N_2, the number of atoms in the excited state. The energy difference between the two states ΔE is emitted from the atom as a photon of frequency ν as given by the frequency-energy relation above.

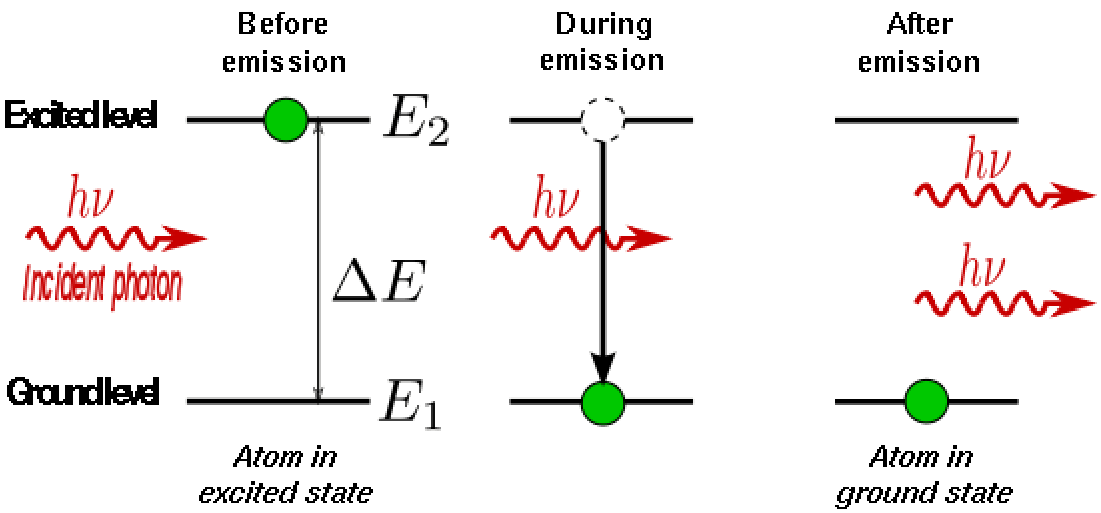
The photons are emitted stochastically, and there is no fixed phase relationship between photons emitted from a group of excited atoms; in other words, spontaneous emission is incoherent.

The rate of stimulated absorption $N_{ab} = A_{21}N_2$

Stimulated emission

If an atom is already in the excited state, it may be perturbed by the passage of a photon that has a frequency ν corresponding to the energy gap ΔE of the excited state to ground state transition. In this case, the excited atom relaxes to the ground state, and is induced to produce a second photon of frequency ν. The original photon is not absorbed by the atom, and so the result is two photons of the same frequency. This process is known as stimulated emission.

The rate of stimulated absorption $N_{ab} = B_{21}N_2Q$



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

At equilibrium,

Stimulated absorption = spontaneous emission + stimulated emission

$B_{12}N_1Q = A_{21}N_2 + B_{21}N_2Q$

$$Q = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$Q = \frac{A_{21}N_2}{B_{21}N_2\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]}$$

$$Q = \frac{A_{21}N_2}{B_{21}N_2}\frac{1}{\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]}$$

Using Maxwell – Boltzmann eqn.,

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

$$Q = \frac{A_{21}}{B_{21}}\frac{1}{\left[\frac{B_{12}}{B_{21}}e^{\frac{h\nu}{kT}} - 1\right]}$$

According Planck's theory of black body radiation the energy density,

$$Q = \frac{8\pi h\nu^3}{c^3}\frac{1}{\left[e^{\frac{h\nu}{kT}} - 1\right]}$$

Comparing these eqn. we get the result,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$
$$B_{12} = B_{21}$$

Results

- The ratio of the probability of spontaneous to stimulated light emission depends directly on the frequency of emission or inversely to the wavelength. Thus in the microwave region, stimulated emission is more probable than spontaneous, hence the early production of the maser. In the optical region, spontaneous emission is more likely than stimulated emission and this gets worse as we go into the UV and X-ray regions of the spectrum. Also the band gap is small enough to get laser action.
- The probability of stimulated emission and stimulated absorption are equal so the rate of stimulated emission is more only when the number of atoms in the excited state is more than the ground state, i.e., $N_2 > N_1$ so called population inversion.

Components of laser

- An active medium with a suitable set of energy levels to support laser action.
- An active center in which laser action takes place
- A source of pumping energy in order to establish a population inversion.
- An optical cavity or resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses.

Pumping methods

In order to achieve and maintain a population inversion we must excite electrons into the short lifetime levels above the upper LASER level. There are a number of ways this can be done.

Optical pumping – If use an intense flash of white light. Used in all solid state laser.

Electric discharge method – High energy electrons are used to excite in an electric discharge tube. Gas laser use this method.

Atom – Atom inelastic collision – Atoms in excited state is used to excite to higher energy levels. It is also used in gas lasers

Direct conversion – electrical energy directly converted to light energy.

Types and classes of laser

Nd:YAG LASER

Type: four level solid state laser

Active medium: Nd:YAG crystal (rod)

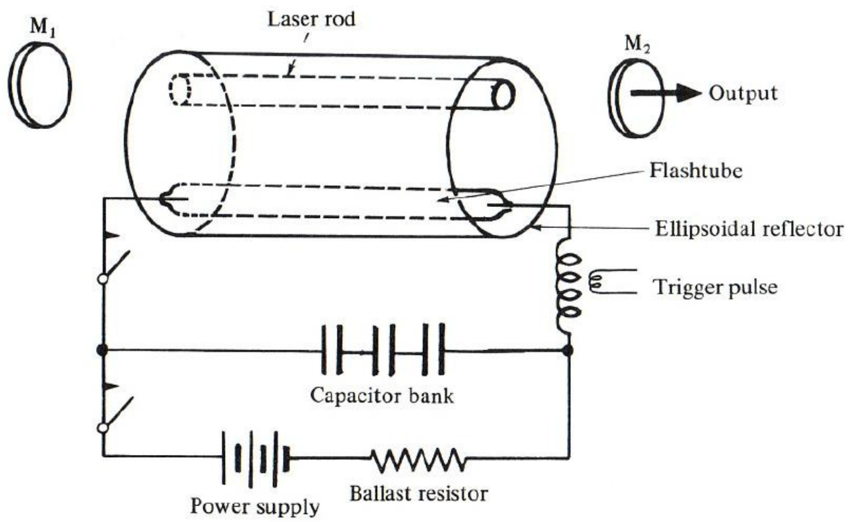
Active center: Nd^{3+} ions

Pumping method: optical pumping [Xenon or Krypton flash lamp used]

Power output: 70 watt

Nature of output: pulsed or continuous

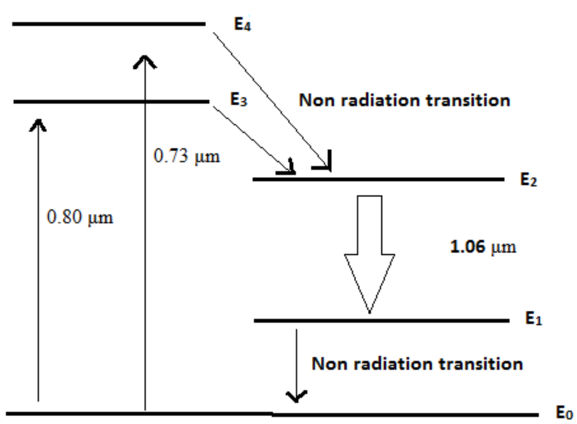
Wavelength: 1.06 μm [infra red region]



Construction

It consists of an elliptical cavity with Neodymium doped ythrium aluminium garnet ($Y_3Al_5O_{12}$) where neodymium Nd^{3+} impurity in ythrium sites. Pumping is by optical flash, using a Xenon flash light pulse of duration 1ms. Optical resonator is by two external mirrors one partially and another fully silvered mirror.

Working



When krypton flash lamp switched on the neodymium atoms get excited to E_3 and E_4 energy levels by absorbing light of wavelength 0.80 μm and 0.73 μm respectively. The neodymium atoms make a radiation less transition from these higher energy levels to a more stable state E_2 (metastable state) level. The transition from E_2 to E_1 gives out light of wavelength 1.06 μm. Initially a light photon is emitted spontaneously and the remaining transitions occur by stimulated emission with the help of optical resonators. Thus laser light emerged from the partially silvered mirror when it attains high intensity of laser source.

Advantages

- It has high energy output
- It has very high repetion rate
- It is easier to achieve population inversion

Disadvantages

- The efficiency is only about 0.1%. By contrast the related Nd:Glass laser produces 3 times the power of Nd:YAG but has a broader line width.
- The electron energy level structure of Nd^{3+} in YAG is complicated

Applications

- It has many applications in range finders and illuminators
- It find many application in medical field for bloodless operation

Carbon di oxide laser

Type: four level gas laser

Active medium: N_2, He & CO_2 gas mixture

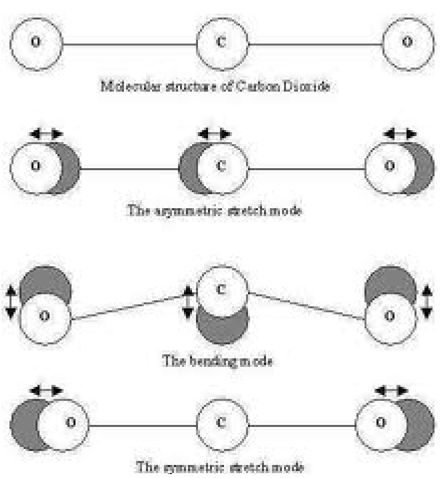
Active center: CO_2 gas molecule

Pumping method: Electric discharge method to excite N_2 & Atom-Atom inelastic collision to excite CO_2 molecule

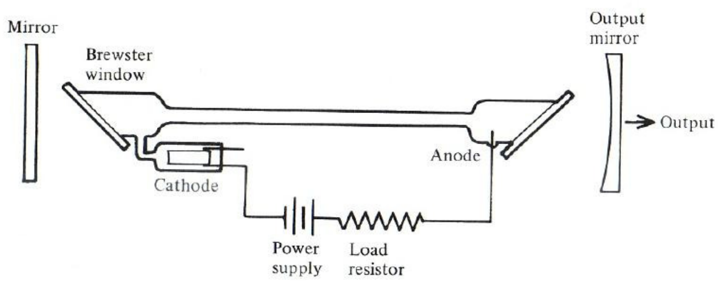
Power output: 10 kilowatt

Nature of output: pulsed or continuous

Wavelength: 10.6 μm & 9.6 μm [infra red region]

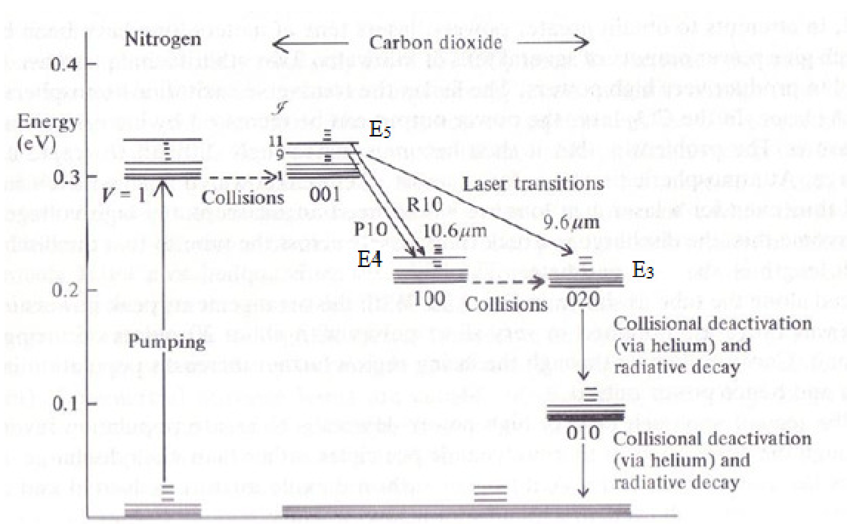


The carbon dioxide laser (CO_2 laser) was one of the earliest gas lasers to be developed (invented by Kumar Patel of Bell Labs in 1964), and is still one of the most useful. Carbon dioxide lasers are the highest-power continuous wave lasers that are currently available.



Construction

It consists of 5m long and 2.5 cm diameter electric discharge tube inside which the mixture of N_2, CO_2 and He gas mixture is taken in appropriate proportions. Two concave mirrors one partially and one fully silvered mirror act as optical resonator. The ends of the tube are kept at polarizing angle which is called as brewster's window. An optical filter is used so that any one wave length is obtained from the two possible wavelengths of 10.6 μm and 9.6 μm.



Working

The population inversion in the laser is achieved by the following sequence: Electron impact excites vibrational motion of the nitrogen. Because nitrogen is a homonuclear molecule, it cannot lose this energy by photon emission, and its excited vibrational levels are therefore metastable and live for a long time. Resonance energy transfer between the nitrogen and the carbon dioxide molecule causes vibrational excitation of the carbon dioxide, with sufficient efficiency to lead to the desired population inversion necessary for laser operation.

Two transitions are possible in CO_2 laser to give laser light. The transition from $E_5 - E_4$ gives out 10.6 μm and the transition from $E_5 - E_3$ gives out 9.6 μm. Stimulated transition can be triggered between $E_5 - E_4$ or $E_5 - E_3$ by choosing suitable optical filter. Laser light is emerged from partially silvered mirror.

Advantages

- High power laser
- It can be operated in continuous mode
- Power can be altered by altering the length of the tube

Disadvantages

- Very huge apparatus due to its length
- High power and invisible so careful handling required

Applications

- Used in material processing like cutting, welding, drilling and alloying
- Used for inertial fusion and nuclear bomb research

Semiconductor lasers

Semiconductor laser is made up of direct bandgap semiconducting material which emits light energy during recombination of electrons and holes. On the other hand indirect band gap semiconductor emits heat energy during recombination of electrons and holes.

Semiconductor laser is of two types

I) Homojunction semiconductor laser – p region and n region is made of same material. Example – GaAs semiconductor laser

II) Heterojunction semiconductor laser - p region and n region is made of different material. Example – p made of GaAs and n made of GaAlAs

Homojunction laser

They are basically a PN junction diode. In order to get LASER action there needs to be a region where BOTH excited electron states and holes (vacant electron states) are present. This is achieved using heavily doped n and p material and applying a forward bias to the junction.

Type: It is a solid state semiconductor laser

Active medium: A pn junction diode made of single crystal

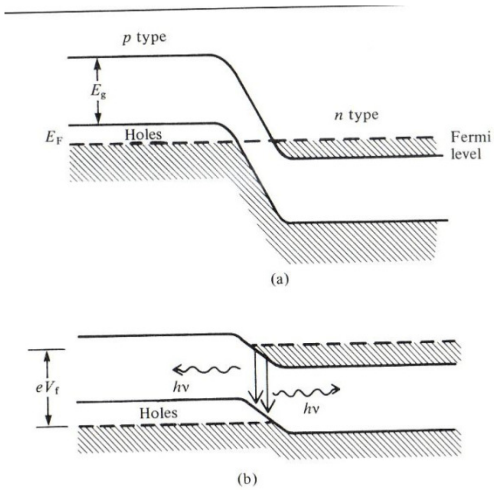
Active center: Recombination electron and holes at junction give rise to laser

Pumping method: Direct conversion

Power output: 1 mW

Nature of output: pulsed or continuous

Wavelength: 8400 A°



Construction

The active medium is a p-n junction diode made from a single crystal of gallium arsenide. This crystal cut in the form of a platelet having a thickness of 0.5 mm. The platelet consists of both p and n region depend on the impurity added. The ends of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

Working

The energy level diagram of semiconductor laser is shown above. When the pn junction is forward-biased, the electrons and holes are injected into junction region in considerable concentration. The electron and holes recombine with each other and these recombination produce radiation in the form of light. These light photons trigger stimulated emission to get laser light.

The wavelength of the emitted light is given by $\lambda = \frac{hc}{E_g}$

Where E_g – band gap energy in joule

It gives out wavelength 8400 A°.

Advantages

- It has high efficiency
- It is very small in dimension
- It requires very little auxiliary equipment

Disadvantages

- It is difficult to control the mode pattern and mode structure of laser
- The purity and monochromatic nature are poorer than other types of laser
- It has poor coherence and poor stability

Application

- It is widely used in fibre optic communication
- It is used as pain killer

Heterojunction laser

Type: It is a heterojunction semiconductor laser

Active medium: p and n region of this diode made of different crystal

Active center: Recombination electron and holes at junction give rise to laser

Pumping method: Direct conversion

Power output: 1 mW

Nature of output: pulsed or continuous

Wavelength: 8000 A°

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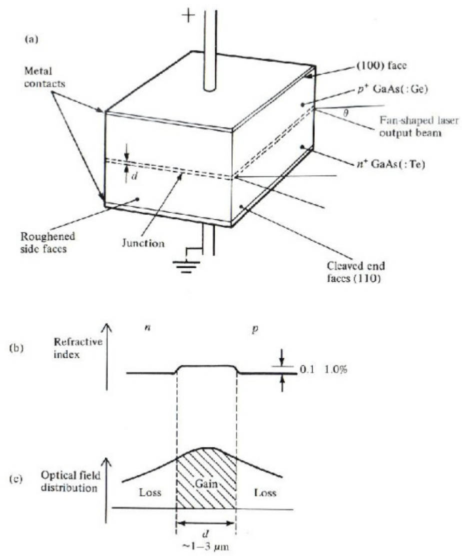


The pumping energy comes from the diode current. LASER action is induced above a certain threshold current density. The principle loss mechanism is scattering by optical in homogeneities in the active volume. Because the active region is thin the exit beam spreads due to diffraction.

Construction

The active medium is a p-n junction diode made of different materials for example gallium arsenide and gallium aluminium arsenide. This crystal cut in the form of a platelet having a thickness of 0.5 mm. The platelet consists of p and n region made of two different materials depend on the impurity added. The ends of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

Working

When the pn junction is forward-biased, the electrons and holes are injected into junction region in considerable concentration. The electron and holes recombine with each other and these recombination produce radiation in the form of light. These light photons trigger stimulated emission to get laser light of wavelength 8000 A°.

The wavelength of the emitted light is given by $\lambda = \frac{hc}{E_g}$

Advantages

- It has high efficiency
- It has more power output compared to homojunction laser

Disadvantages

- It is difficult to control the mode pattern and mode structure of laser
- The purity and monochromatic nature are poorer than other types of laser
- It has poor coherence and poor stability

Application

- It is widely used in fibre optic communication
- It is used as pain killer

Industrial application

Industrial application of laser uses a very high power laser like CO_2 laser, Nd:YAG laser etc. some of the industrial applications are as follows,

- **Laser cutting** – vaporization of the material at the point of focus of laser beam give rise to laser cutting

  Advantages

  1. laser cutting can be done at room temperature without any preheating
  2. Microstructure of surrounding layers not affected
  3. High cutting speed
  4. High rate of heating & cooling is achieved

- **Laser welding** – welding is joining of two or more metal pieces into a single unit

  Advantages

  1. Laser welding can be done very high rates
  2. Any dissimilar metals can be welded
  3. It can be done in very small places
  4. Heat affected zone is relatively small because of rapid cooling

- **Laser drilling** – holes in metal sheet can be made using laser at faster rate
- **Laser alloying –** laser alloying is more specific than conventional alloying since particular region alone made as alloy without disturbing the surrounding environment.

Medical applications

Medical applications of laser

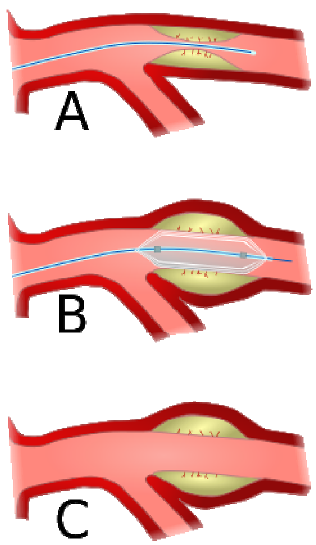
Laser medicine is the use of various types of lasers in medical diagnosis, treatment, or therapy. Types of lasers used in medicine include in principle any laser design, but especially:

- CO_2 lasers
- diode lasers
- dye lasers

- excimer lasers
- fiber lasers
- gas lasers
- free electron lasers

Angioplasty

Angioplasty is the technique of mechanically widening narrowed or obstructed arteries, the latter typically being a result of atherosclerosis. An empty and collapsed balloon on a guide wire, known as a balloon catheter, is passed into the narrowed locations and then inflated to a fixed size using water pressures some 75 to 500 times normal blood pressure (6 to 20 atmospheres). The balloon forces expansion of the inner white blood cell/clot plaque deposits and the surrounding muscular wall, opening up the blood vessel for improved flow, and the balloon is then deflated and withdrawn. A stent may or may not be inserted at the time of ballooning to ensure the vessel remains open.



Cancer treatment using laser (Photodynamic therapy)

Photodynamic therapy (PDT) is a form of phototherapy using nontoxic light-sensitive compounds that are exposed selectively to light, whereupon they become toxic to targeted malignant and other diseased cells. PDT has proven ability to kill microbial cells, including bacteria, fungi and viruses. PDT is popularly used in treating acne. It is used clinically to treat a wide range of medical conditions, including wet age-related macular degeneration and malignant cancers, and is recognised as a treatment strategy which is both minimally invasive and minimally toxic.

Most modern PDT applications involve three key components: a photosensitizer, a light source and tissue oxygen. The combination of these three components leads to the chemical destruction of any tissues which have either selectively taken up the photosensitizer or have been locally exposed to light. The wavelength of the light source needs to be appropriate for exciting the photosensitizer to produce reactive oxygen species. These reactive oxygen species generated through PDT are free radicals (Type I PDT) generated through electron abstraction or transfer from a substrate molecule and highly reactive state of oxygen known as singlet oxygen (Type II PDT). In understanding the mechanism of PDT it is important to distinguish it from other light-based and laser therapies such as laser wound healing and rejuvenation, or intense pulsed light hair removal, which do not require a photosensitizer.

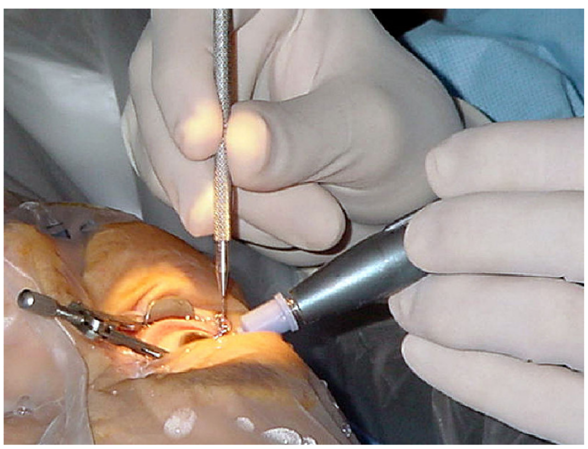
Ophthalmology (using laser photocoagulation)

Laser eye surgery

Although the terms laser eye surgery and refractive surgery are commonly used as if they were interchangeable, this is not the case. Lasers may be used to treat nonrefractive conditions (e.g. to seal a retinal tear), while radial keratotomy is an example of refractive surgery without the use of a laser. Laser eye surgery or laser corneal sculpting is a medical procedure that uses a laser to reshape the surface of the eye. This is done to improve or correct myopia (short-sightedness), hypermetropia (long sightedness) and astigmatism (uneven curvature of the eye's surface).

Cataract surgery

A cataract is an opacification or cloudiness of the eye's crystalline lens due to aging, disease, or trauma that typically prevents light from forming a clear image on the retina. If visual loss is significant, surgical removal of the lens may be warranted, with lost optical power usually replaced with a plastic intraocular lens (IOL). Owing to the high prevalence of cataracts, cataract extraction is the most common eye surgery. Rest after surgery is recommended.



Other Medical applications

- cosmetic applications such as laser hair removal and tattoo removal
- dermatology
- lithotripsy
- mammography
- medical imaging
- microscopy
- optical coherence tomography
- prostatectomy
- surgery

Other applications

In science, lasers are used in many ways, including:

- A wide variety of interferometric techniques
- Raman spectroscopy
- Laser induced breakdown spectroscopy
- Atmospheric remote sensing
- Investigating nonlinear optics phenomena
- Holographic techniques employing lasers also contribute to a number of measurement techniques.
- Laser based LIght Detection And Ranging (LIDAR) technology has application in geology, seismology, remote sensing and atmospheric physics.
- Lasers have been used aboard spacecraft such as in the Cassini-Huygens mission.
- In astronomy, lasers have been used to create artificial laser guide stars, used as reference objects for adaptive optics telescopes.

Lasers may also be indirectly used in spectroscopy as a micro-sampling system, a technique termed Laser ablation (LA), which is typically applied to ICP-MS apparatus resulting in the powerful LA-ICP-MS.