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RECENT LASER TECHNOLOGIES AND ITS APPLICATIONS

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ABSTRACT

A device that generates an intense beam of coherent monochromatic light (or other electromagnetic radiation) by stimulated emission of photons from excited atoms or molecules. Lasers are used in drilling and cutting, alignment and guidance and in surgery. The optical properties are exploited in holography, reading barcodes and in recording and playing compact discs. During the last decades laser technology has continuously developed. New types of lasers as ultra-short pulsed lasers in the femtosecond regime entered in medical applications in ophthalmology, diode lasers became more powerful and smaller with a broader range in wavelengths. In future new sources will also used in medicine, fibre lasers, LEDs and organic LEDs. Laser light is different from normal light in other ways as well. First, its light contains only one wavelength (one specific color). The particular wavelength of light is determined by the amount of energy released when the excited electron drops to a lower orbit. Second, laser light is directional. Whereas a laser generates a very tight beam, a flashlight produces light that is diffuse. Because laser light is coherent, it stays focused for vast distances, even to the moon and back.

Keywords: Pumping, Population Inversion, Stimulated Emission, Monochromatic Light, Photon

I. INTRODUCTION

Lasers are devices that produce intense beams of light which are monochromatic, coherent, and highly collimated. The wavelength (color) of laser light is extremely pure (monochromatic) when compared to other sources of light, and all of the photons (energy) that make up the laser beam have a fixed phase relationship (coherence) with respect to one another. Light from a laser typically has very low divergence. It can travel over great distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Because of these properties, lasers are used in a wide variety of applications in all walks of life. The basic operating principles of the laser were put forth by Charles Townes and Arthur Schalow from the Bell Telephone Laboratories in 1958, and the first actual laser, based on a pink ruby crystal, was demonstrated in 1960 by Theodor Maiman at Hughes Research Laboratories. Since that time, literally thousands of lasers have been invented (including the edible "Jello" laser), but only a much smaller number have found practical applications in scientific, industrial, commercial, and military applications. The helium neon laser (the first continuous-wave laser), the semiconductor diode laser, and air-cooled ion lasers have found broad OEM application. In recent years the use of diode-pumped solid-state (DPSS) lasers in OEM applications has been growing rapidly. The term "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. To understand the laser, one needs to understand the meaning of these terms. The term "light" is generally accepted to be electromagnetic radiation ranging from 1 nm to 1000 mm in wavelength. The visible spectrum ranges from approximately 400 to 700 nm. The wavelength range from 700 nm to 10 mm is considered the near infrared (NIR) and anything beyond that is the far infrared (FIR). Conversely, 200 to 400 nm is called ultraviolet (UV); below 200 nm is the deep ultraviolet (DUV)**[1,2]**. Figure 1 shows ordinary light source and LASER light source.

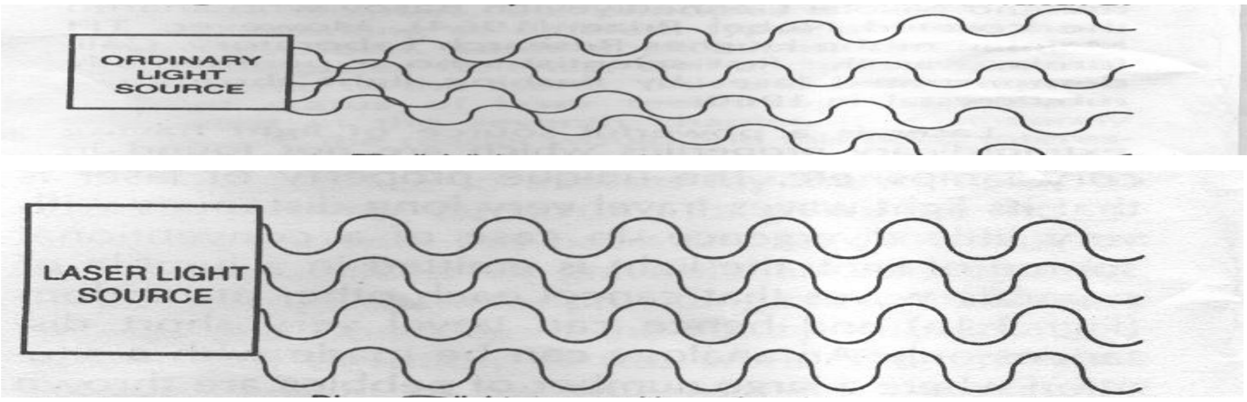

Figure 1. Ordinary and LASER light source

1.1 Energy Levels of atoms and Molecules

According to predication of quantum machines, the energy of an atom or a molecule can take only discrete values. Transitions from lower levels to higher are accompanied by absorption of radiation whereas from higher levels to lower are accompanied by emission of radiation. Energy states of atoms are defin below **[1]**.

(i) Ground State

It is the lowest possible energy state of atom which is the most stable state. Atom can remain in this state for unlimited time.

(ii) Excited State

These are the possible energy state of an atom which are higher than the ground state. Atoms remain in such energy states for a very short time called life time typically of the order of 10^{-8}s.

(iii) Mata stable states

These are excited states of an atom with relatively larger life times of the order of 10^{-3} s. As theses energy states are neither as stable as ground state nor as unstable as the other excited states, they are known as met stable states.

1.2 Absorption and Emission of Radiation by Matters

(i) Induced or Stimulated Absorption

If a photon is incident on an atom in its ground state E1, the atom absorbs the photon and is raised to its excited energy state E2 provided the photon energy is E2-E1. If the photon energy is not equal to the energy difference between the excited state and the ground state, the photon is not absorbed and the atom remains in its grounds state. This process of raising the atom to its excited state by a photon is known as induced or stimulated absorption and is shown in figure 2.

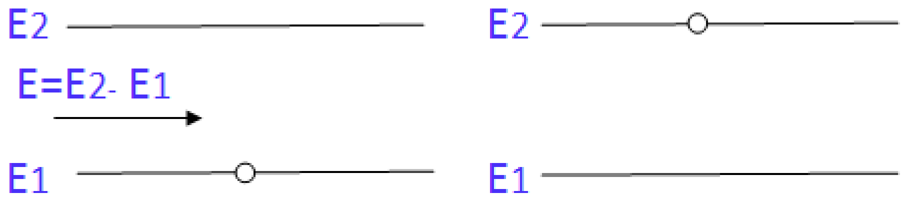

Figure 2: Induced or stimulated absorption

(ii) Emission of Radiation

If an atom is in the excited energy state E2, it makes a transition to its ground state by emitting a photon having energy E2-E1. The transition of atom from higher energy state E2 to lower energy state E1 can either take place spontaneously or the transition can be forced by stimulating the atom using a photon having energy E2-E1. These processes of emission of radiations are called spontaneous and stimulated emission respectively.

(iii) Spontaneous Emission of radiation

When an atom in its excited energy state E2 makes a transition to the ground state E1 on its own, without any external stimulus, it emits a photon of energy E2 – E1 as shown in figure 3. This is known as spontaneous emission of radiation.

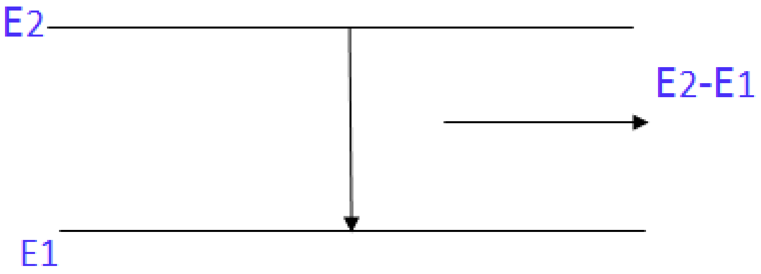

Figure 3: Spontaneous emission of radiation

Figure 4: Stimulated emission of radiation

Stimulated emission of radiation is possible from atoms in metastable states. Spontaneous emission of radiation takes place from excited states with very small life times**[1,2]**.

II. VARIOUS LEVELS OF LASER SYSTEMS

(i) Three Level Laser System

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In these systems three energy levels are involved in the laser action. The atoms are pumped from the ground state E1 to E3 out of the two transitions from E3 to E2 and from E2 to E1 one is a non-radioactive spontaneous transition and the other is the lasing transition as shown in fig 5 (a) and (b). The ruby laser is an example of three level laser system.

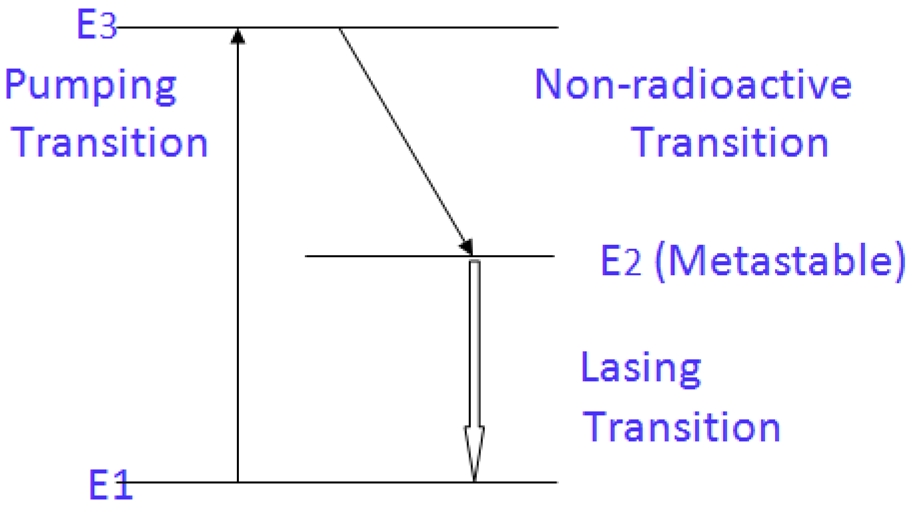

Figure 5(a) Various Transitions

The problem with the three level schemes shown in fig 5(a) is that the lower lasing level is the ground state and hence will be densely populated. It is difficult to produce population inversion in such case. It is easier to produce population inversion in the three level scheme shown in fig 5 (b). Here the lower lasing level E2 is an unstable state due to which it is depopulated very fast compared to the upper lasing level E3. For better utilization of pumping energy E3 should be a wide band and for better lasing action, it should be narrow band which are two contracting requirement**[1-3]**.

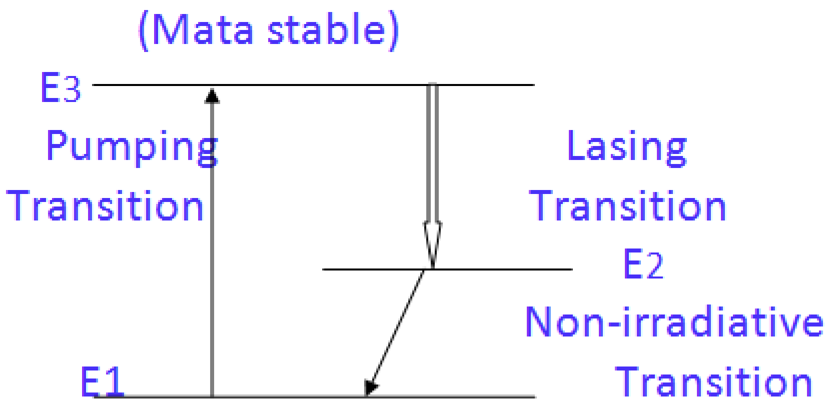

Figure 5 (b) Population Inversion

(ii) Four level laser system

Pumping transition takes the atoms from E1 to E4 from where there is a spontaneous transition to E3. The lasing transition is from E3 to E2 which is then followed by another spontaneous transition to E1 as shown in fig 6 Nd-YAG Laser in example of the four level laser system.

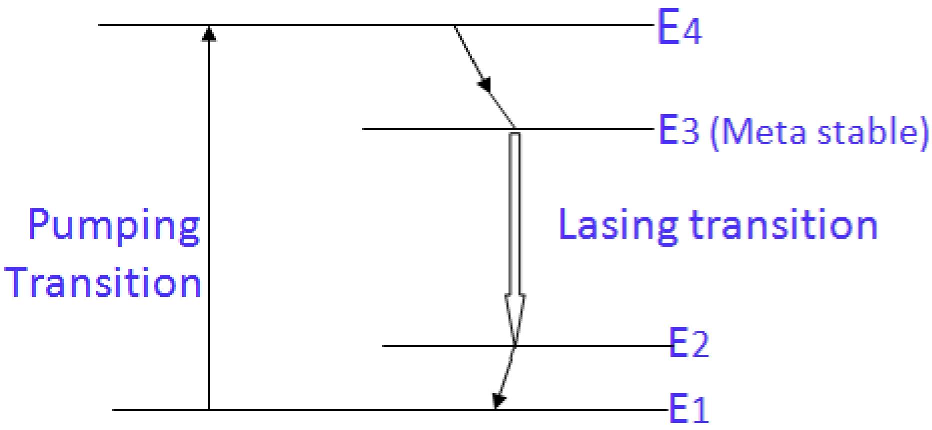

Figure 6 Four level laser system

Form the point of view of creating population inversion, the four level scheme is better than the three level scheme. Here E4 can be a wide band as required for better utilization of pumping energy and E3 can be narrow band as required for better Lasing action. The lower lasing level E2 is an unstable state and hence depopulated very last compared to E3 which maintains population inversion condition between the lasing levels E2 and E3**[1-3]**.

The only disadvantage of a four level scheme is that increase in number of transition leads to additional energy losses. In a two level scheme involving only the ground state (the lower lasing level) and a metastable state (the upper lasing level) to which atoms are excited by a pumping mechanism, the pumping radiation will not only excite the ground level atoms to excited state but also depopulate the metastable state by inducing stimulated emission. This makes it impossible to achieve population inversion with optical pumping. Hence two level scheme is not used.

III. LASER GAIN MEDIUM

Nearly all lasers are produced as a result of electrons jumping from an excited energy level within a radiating species to a lower-lying energy level and in the process, radiating light that contributes to the laser beam. Those radiating species can include **[3-5]**.

Atoms - such as in the red helium-neon (HeNe) laser, the visible and ultraviolet argon ion and helium-cadmium (HeCd) lasers, and the green and yellow copper vapor lasers (CVL).

Molecules - such as in the infrared carbon dioxide (CO_2) laser, the ultraviolet excimer lasers such as ArF and KrF, and the pulsed N_2 laser.

Liquids - such as those involving various organic dye molecules dilutely dissolved in various solvent solutions.

Dielectric Solids - such as those involving neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers.

Semiconductor materials such as gallium arsenide or indium phosphide crystals or various mixtures of purities blended with those and other semiconductor species. Figure-7: Absorption and Emission of Radiation by Matters.

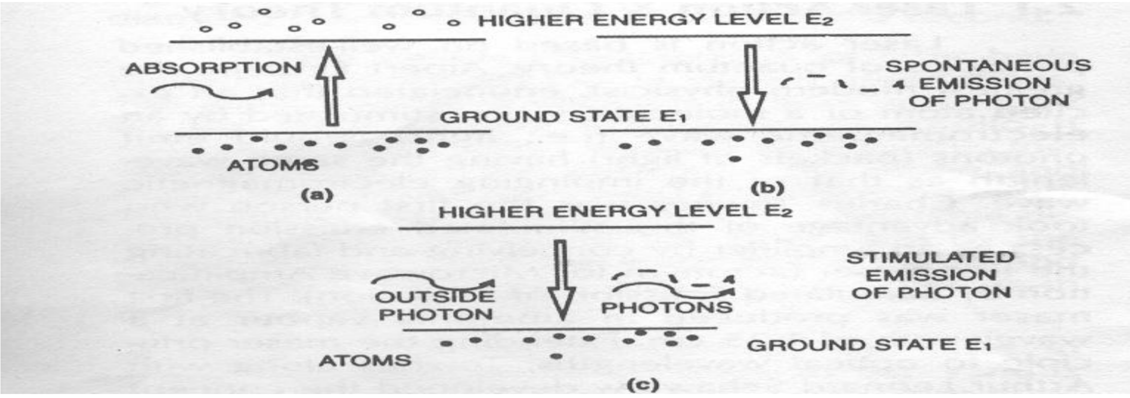

Figure 7: Absorption and Emission of Radiation by Matters

IV. RESEARCH AND DEVELOPMENT WORK OF LASER IN INDIA

The research and development work in the field of lasers started in our country 28 years back on a very small scale at a few research laboratories of the Defence Research & Development Organization, Bhabha Atomic Research Centre, National Physical Laboratory, IIT Kanpur and IISc Bangalore. Later, a number of research laboratories and teaching institutions also entered into this area. A Study Group on Lasers, constituted in 1971 by .DRDO and INSA Laser Committee constituted under the Chairmanship of Prof. P Venkateswarlu in 1976 (the author was a member of the two committees) made detailed studies to assess the status of R&D work on laser at both international and national levels and gave suitable recommendations for development of lasers and laser systems in the country. In 1988 Dr DD Bhawalkar, Director, Centre for Advanced Technology (CAT), Indore, gave a status report on lasers to the Science Advisory Council to the Prime Minister **[2]**. Very briefly the current status of the laser work in the country is outlined below [2,6-9].

(i) Ruby, Nd:YAG and Nd:Glass Lasers

Laser rods of ruby, Nd:glass, flash lamps and hard coated laser mirrors, have been developed indigenously at the Defence Science Centre (DSC), Delhi, and the solid sate lasers giving peak power output of a few megawatts have been developed for Defence applications. BARC has also developed these lasers with mainly imported components, Laser range finders with Nd:YAG or Nd:glass as the active element have been developed at Instruments Research Development Establishment(IRDE), Dehradun and DSC. CAT, is developing a high power Nd:glass laser for atomic energy application,

(ii) Helium-Neon Laser

Helium-Neon lasers of low power output (2- 5 mw) with lifetimes of a few thousand hours have been developed at IISc, NPL and Bharat Electronics Ltd., Bangalore. The technology has been transferred by NPL to M/s Laser Instruments, New Delhi and by BARC, Bombay to ECIL, Hyderabad. They started production of these lasers commercially about 20 years back but stopped production since their performance is far from satisfactory. BEL also made an attempt about 10 years back and stopped production due to lack of sufficient technology.

(iii) Carbon Dioxide Laser

Carbon dioxide lasers giving an output power in the range 10-100 W have been developed at BARC, IIT, Kanpur, IRDE and DSC, Central Electronics Ltd. (CEL) and Jyoti Ltd. have started commercial production of these lasers around 1975 but have stopped production by 1982. CAT has developed transverse carbon dioxide laser with 3.5 kW power.

(iv) Semiconductor Laser

BARC and Solid State Physics Laboratory (SPL), Delhi have developed low power gallium-arsenide lasers with a view to use them for applications in communication and ranging. BARC demonstrated communication over 20 Km distance using laser. Further work is necessary to develop these lasers with heterostructures and to improve their efficiency.

(v) Materials

Basic laser materials like ruby, Nd:phosphate glass and lithium niobate are being developed at DSC for Defence applications, Central Glass and Ceramics Research Institute, Calcutta(CGCRI), has also developed good quality Nd:silicate glass for commercial applications. The development of gallium-arsenide and Nd:YAG crystals is under process at SPL. Several establishments and institutes like DSC, IRDE, IISc, NPL, BARC, IIT, Kanpur and BEL have established optical workshops including coating facilities to fabricate laser components. Good experience has been gained to fabricate laser rods and hard coated laser morrors at DSC.

(vi) Fibre-Optic Communication

In 1980, a panel on Optical Fibre Communication System constituted by the Electronics Commission recommended the introduction of optical fibre communication in India. With this in view, CGCRI took up an R&D project on indigenous development of optical communication fibre. In1982, a System Appraisal Group for Optical Fibre and Cables comprising representatives of the Department of Electronics, Ministry of Defence, IIT, Delhi, Telecommunication Research Centre (TRC) and Hindustan Cables Ltd. recommended setting up of R&D and manufacturing facilities of optical fibres and cables at HCL through collaborative arrangement. It was decided to manufacture at HCL the multimode graded index fibre with' 3 to 5 db/km loss and bandwidth up to 100 MHz. Similarly, the production of optical fibre has been started at OPTEL, Bhopal with foreign collaboration. In 1983, a Committee on Optical Fibres and Cables (COFC) was Constituted by the Ministry of Communication to finalise the technical specifications for optical fibres and cables required not only for communications, but also for Defence and other sectors.

The Department of Communications has Successfully installed the optical fibre cable and an 8 Mb system to provide junctions between two exchanges in the Pune Telephone system. TRC has taken up a design of an indigenous 34 Mb .system to be installed between Thana and Powai in the Bombay Telephone system. Efforts are on1e way to introduce optical fibre communication several trunk routes in the country. Facilities for 93 characterization of optical fibres have been set up at HCL and IIT, Delhi.

V. APPLICATION OF LASER

Different applications need lasers with different output powers. Lasers that produce a continuous beam or a series of short pulses can be compared on the basis of their average power. Lasers that produce pulses can also be characterized based on the *peak* power of each pulse. The peak power of a pulsed laser is many orders of magnitude greater than its average power. The average output power is always less than the power consumed. Table 1: shows uses of LASER on the basis of power.

Table 1: The Continuous Or Average Power Required For Some Uses

Power	Uses
1-5 mW	Laser Pointers
5 mW	CD ROM Drive
5-10 mW	DVD Player
100 mW	High Speed CD-RW Burner
250 mW	Consumer 16x DVD-R Burner
400 mW	DVD 24 x dual layer recording
1 W	Green laser in current Holographic Versatile Disc Prototype development
1-20 W	Output of the majority of commercially available solid state lasers used for micro matching
30-100 W	Typical sealed CO2, surgical Lasers

(i)Welding

The two metal plates to be welded are held in contact at their edges and a high power laser is focused on the line of contact. The metal at the line of contact melts and solidifies on cooling which causes the two plates to, stick together. As the laser can be focused to a very sharp point, the heat affected area is very small. Hence laser welding does not cause distortion of the plates. Also, it is a contact less procedure. Hence there is no possibility of introducing impurities. Laser welding is commonly used in automobile, Ship building and aircraft manufacturing industries. CO2 and NdYAG lasers are used for this purpose.

(ii) Cutting

Cutting of metal sheets is achieved using high power lasers like NdYAG and CO2 lasers. The laser is focused on the metal sheet and a jet of oxygen is blown on the spot. A significant part of the energy required for cutting is supplied by burning of the metal in oxygen. The oxygen jet also blows away the vapourized metal and also cools the adjacent edges. Laser cutting produces higher quality of the cut edges.

(iii) Drilling

Holes can be drilled into materials using high power pulsed laser of 10^{-4} to 10^{-3} duration. The laser pulse evaporates the material which leaves a hole in its place. NdYAG laser is commonly used for this purpose. Laser drilling has a very high degree of precision and holes can be drilled in any direction. As the laser can be focused to a very fine spot, very small holes can be drilled having diameters of the order of a few microns. As there are no mechanical vibrations, holes can be drilled very close to the edges without damaging the metal plates.

(iv) Measurement of Atmospheric Pollution Levels

Pollution in the atmosphere is due to suspended particulate matter like dust, smoke, flash, aerosols etc. and non-particulate matter like carbon monoxide, sulphur dioxide etc. Conventional method for measurement of pollution levels require and does not give real time data. Using lasers, we can get real time data by transmitting the laser beam is atmosphere and then observing either the reflected or transmitted beam. LIDAR (Light detection and ranging) is used to measure concentration of suspended particulate matter in the atmosphere. A pulse of laser is transmitted into the atmosphere and the back scattered light is recorded using photodiodes. This gives information regarding concentration of suspended particulate matter. Absorption of certain wavelengths by some gases is used to study their presence in the atmosphere by transmitting a lasers beam through the atmosphere and recording the transmitted intensity.

The presence of different gaseous pollutants is best studied by means of Raman backscattering. The backscattered laser contains the transmitted wavelength as well as longer and shorter wavelengths than the transmitted wavelength. The change in wavelength from the original transmitted wavelength is known as Raman shift and is specific for particular gas. Hence these gases can be detected**[1]**.

(v) Seismography

In its seismographic application, i.e., detection of earthquakes and underground nuclear blasts, the instruments using lasers are ten times more accurate than the conventional devices. This laser application is based on the principle of Doppler shift in the frequency of the light scattered from a moving substance. The scattered beam is mixed with the part of the. incident beam in a detector and the beat frequency is determined, which gives the measure of the movement of the earth's crust**[3]**.

(vi) Nuclear Fusion

Thermonuclear fusion is the process by which huge energy is produced in the sun and stars. It is the process by which nuclei of light elements such as deuterium (an isotope of hydrogen) are fused (or joined) together to produce heavier elements like helium. In this reaction, a large quantity of energy and neutrons are released. For thermonuclear fusion to take place, a temperature of about one million degrees centigrade is required. Today, this is achieved by the implosion of the atoms of the material by a focused high energy laser beam. Thermonuclear re. action has several advantages over the fission process. Firstly, the immense energy comes from a very small quantity of material. Secondly, the supply of fusion fuel is virtually inexhaustible as deuterium can be extracted cheaply from the world's oceans. Thirdly, there is no problem of atmospheric pollution. It will be simpler and easier to make a hydrogen bomb which will be 'clean', i.e.,its explosion will be free from the lingering effects of radioactive Fallout**[3,8]**.

(vii) Fire Detection

Laser's application in fire detection is based on the principle that a laser beam is affected by hot gases emanating from a fire. A focused laser beam is directed across an open space near ceiling level from one side of the room to the other. It is reflected back to a photocell from a mirror fixed on the opposite wall. Any fire starting below this level will cause turbulent hot air to rise. The laser beam, normally steady, is refracted by the temperature gradients in the hot gases and is displaced from its usual position on a photocell. The deflection can be made to trigger an alarm. Results have indicated that the laser beam system is at least as fast as the most sensitive fire detection systems in use worldwide.

(viii) Intrusion Alarm

A gallium arsenide diode laser can be used to set up an invisible fence to protect an area. An infrared laser beam (in combination with an optical detector) can seal a path, an area or a volume against infiltrators. When the invisible beam is interrupted by an intruder trying to approach the protected area, it sets off a remote alarm. The laser alarm has many advantages over the conventional electric alarm. The infrared beam, being invisible, cannot be spotted by the intruder. The narrowness of the beam minimised false alarms by the passage of birds, small animals and objects floating in the air.

(ix) Medical Applications

Lasers are extensively used in medicine and surgery. The first practical application was in Eye surgery, where laser was used to weld detached retina and photocoagulate the blood vessels that grow into the region in front of the retina, thereby blocking vision. The laser beam easily passes through transparent portions of the eye, including Cornea and lens to the region of its intended use where its energy is absorbed for treatment. Retina is a sensitive membrane inside the eyeball. Its detachment from the surrounding choroid coat initiates due to a hole in the retina caused by an injury or degenerative changes during the old age. This makes the thick fluid vitreous humour seep and fill itself between the retina and chord oat. The pressure between the retina and choroid coating damages the retina which Soon gets detached from the optic nerve at the back of the to cause blindness.

Before the invention of laser, this delicate operation was done by irradiation of the eye with a xenon arc lamp or even by focusing the sunlight on to the choroid coat. This method involved exposure time to concentrate sufficient he the site of the detached retina. The process cumbersome, painful and relatively slow. Be the patient had to be anaesthesised to prevail eye from moving. Using a high energy pulsed laser, like Nd:YAG, the intense laser light focused as a tiny spot at the detached retina 'welding' it to the underlying choroid coat of the a short time (of the order of one-thousandth of a second). The operation is painless and doe affect the surrounding healthy tissues. Laser also be used to burn out small tumours on the surface of the eye and also those in the vessels of the eye. It is being used to treat coma, cataract, sealing of the retina and even viral diseases of the eye **[3,8-10]**.

The laser cane which is a boon for blind persoi1S operates on the principle of a radar. Two lasers within the cane provide pulses of infrared light which are reflected from points, a short distance in front of the cane. Each reflected beam returns to a photocell inside the cane. The two photocells activate pins in the handle. When the path is smooth, the two pins vibrate steadily. Any hole or other obstacle scatters the light from at- least one of the lasers and stops the vibrations, thus warning the user. The device operates on four small batteries which last up to ten hours. It allows a blind person to scan the area ahead of him and have an idea of the object's shape, distance and dimensions by variations in pitch and intensity of the tone it emits.

Lasers are increasingly being used for the treatment of many different types of cancer. A laser is less damaging than x-ray therapy and surgery and in many cases, it is quite effective. The use of lasers to remove certain forms of cancerous growth in the body has heralded an era of knifeless and bloodless surgery. It is very effective in curing the diseases of gynaecology, ear, nose, throat, tongue, palate and cheeks. It is curative in most early cancers, and in late cancers, it is useful in reducing the tumours to facilitate surgery **[3]**.

Photodynamic therapy (POT), a new exciting form of cancer treatment, combines laser with light-sensitive dye, hematoporphyrin derivative (HPD). This substance, derived from the cow's blood, travels throughout the body of the patient and settles in the malignant tissues. A red light from argon pumped dye laser, focused on the area activates HPD and the energized substance releases a highly reactive chemical that destroys the cancer cells. Reports indicate that POT is 80 to 90 per cent successful in causing total orneartotal regression of tumours, even after all other forms of therapy have failed. It is highly selective for a diseased tissue, leaving healthy cells relatively untouched.

At some medical centres in the US,searchers have used laser to treat colonic and other types of gastrointestinal cancer. Using endoscope, the laser energy is used to destroy neoplastic tissue while preserving bowel wall integrity. In some cases, rectal polyps were removed using the CW argon laser, delivered with a power of 4-5 W. With the development of optical fibres lasers are being used for heart surgery. A common problem with the arteries is the build up of plaque on their interior walls. The plaque, consisting fatty material, calcium, etc, blocks the coronary. arteries reducing the blood flow through the This results in Angina pectoris, a condition that afflicts millions of people worldwide. If the coronary artery is partially blocked, the situation can sometimes be improved by using a method called angioplasty. When substantial blockage of the coronary artery is observed, a laser beam se through the optical fibre could be used to vapourise the plaque, opening a clear channel for smooth flow of blood. This method is called laser angioplasty or vascular recanalisation. Usually argon-ion, Nd:YAG, and carbon dioxide lasers al used for this purpose **[3,8-10]**.

Another important use of the fibre-optic laser catheter is in the treatment of bleeding ulcers. The laser light can photocoagulate blood, thereby causing the cession of bleeding. For this purpose among the three important lasers(carbon dioxide, Nd:YAG and argonion), the Nd:YAG laser is preferred because it penetrates deep into the tissue and its effects are not localised at the surface. Using a laser endoscope, small tumours in the urinary bladder are destroyed. Similarly, Nd:YAG and dye lasers are also used to rapidly heat and shatter urinary stones in the kidney. Laser can also be used for dental treatment Laser beam is useful for charring tooth decay through a painless process called laser glazing. The beam from a high repetition pulsed laser can be focused on dark decayed areas of teeth cavities to destroy the infection in the affected areas in a fraction of a second.

VI. CONCLUSION

There are many types of lasers available for research, medical, industrial and commercial uses. Lasers are often described by the kind of lasing medium they use - solid state, gas, excimer, dye or semiconductor. **Solid state lasers** have lasing material distributed in a solid matrix, e.g., the ruby or neodymium-YAG (yttrium aluminum garnet) lasers. The neodymium-YAG laser emits infrared light at 1.064 micrometers. **Gas lasers** (helium and helium-neon, HeNe, are the most common gas lasers) have a primary output of a visible red light. CO2 lasers emit energy in the far-infrared, 10.6 micrometers, and are used for cutting hard materials. **Excimer lasers** (the name is derived from the terms excited and dimers) use reactive gases such as chlorine and fluorine mixed with inert gases such as argon, krypton, or xenon. When electrically stimulated, a pseudo molecule or dimer is produced and when lased, produces light in the ultraviolet range. **Dye lasers** use complex organic dyes like rhodamine 6G in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths. **Semiconductor lasers** sometimes called diode lasers are not solid-state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, e.g., the writing source in some laser printers or compact disk players.

The light beam produced by most lasers is pencil-sized and maintains its size and direction over very large distances, this sharply focused beam of coherent light is suitable for a wide variety of applications. Lasers have been used in industry for cutting and boring metals and other materials as well as welding and soldering and for inspecting optical equipment. In medicine, they have been used in surgical operations. CDs and DVDs read and written to using lasers and lasers also are employed in laser printers and bar-code scanners. They are used in communications both in fiber optics and in some space and open-air communications, in a manner similar to radio transmission, the transmitted light beam is modulated with a signal and is received and demodulated some distance away. The field of holography is based on the fact that actual wave-front patterns, captured in a photographic image of an object illuminated with laser light, can be reconstructed to produce a three-dimensional image of the object. Lasers have been used in a number of areas of scientific research and have opened a new field of scientific research, nonlinear optics, which is concerned with the study of such phenomena as the frequency doubling of coherent light by certain crystals. One important result of laser research is the development of lasers that can be tuned to emit light over a range of frequencies, instead of producing light of only a single frequency. Lasers also have been developed experimentally as weaponry.

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