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Review Paper

A Brief Introduction to Lasers and Applications: Scientific Approach

Rao M.C.
Department of Physics, Andhra Loyola College, Vijayawada, INDIA

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Abstract

Laser is a powerful source of light having extraordinary properties which are not found in the normal light sources like tungsten lamps and mercury lamps. The unique property of laser is that its light waves travel very long distances with a very little divergence. The two processes, namely, absorption and spontaneous emission, take place in a conventional light source, in case the atom, still in its turns to excited state, is struck by an outside photon having precisely the energy necessary for spontaneous emission, the outside photon is augmented by the one given up by the excited atom. Moreover, both the photons are released from the same excited state in the same phase, this process, called stimulated emission, is fundamental for laser action. Thus, the atom is stimulated or induced to give up its photon earlier than it would have done ordinarily under spontaneous emission. Different types of lasers are briefly explained. Laser radiation in various applications was made use of immediately after the first laser became operational. As a device, it is now used in medicine, astronomy, geodesy, metrology, chemistry, biology, spectroscopy, holography, power engineering, in various processes in engineering, as well as in communication technology, automation and remote control, in military technology, entertainment industry and art restorations. Industrial applications now include many new procedures, such as laser welding, drilling, cutting, annealing and sputtering. This paper deals with the study of fundamental aspects, properties and technological applications of lasers.

Keywords: Laser, lasing action, properties, types of lasers and applications.

Introduction

A laser is a device that emits electromagnetic radiation through a process of optical amplification based on the stimulated emission of photons. Lasers are devices that produce intense beams of light which are monochromatic, coherent and highly collimated. The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship 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. A basic understanding of a theory helps in understanding the laser device. Figure-1 shows that electromagnetic radiation is emitted whenever a charged particle such as an electron gives up energy. This happens every time an electron drops from a higher energy state, Q_1, to a lower energy state, Q_0, in an atom or ion as occurs in a fluorescent light. This also happens from changes in the vibrational or rotational state of molecules. The color of light is determined by its frequency or wavelength. The shorter wavelengths are the ultraviolet and the longer wavelengths are the infrared. The smallest particle of light energy is described by quantum mechanics as a photon[1].

Laser is a powerful source of light having extraordinary properties which are not found in the normal light sources like tungsten lamps, mercury lamps, etc. The unique property of laser is that its light waves travel very long distances with e very little divergence. In case of a conventional e source of light, the light is emitted in a jumble of e separate waves that cancel each other at random and hence can travel very short distances only.

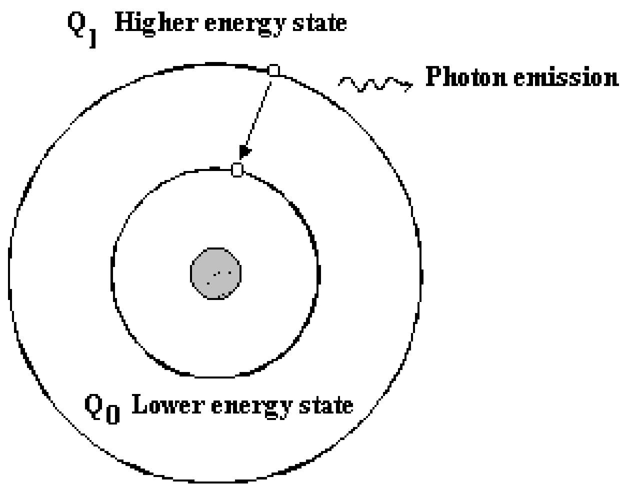

Figure-1
Emission of radiation from an atom by transition of an electron from a higher energy state to a lower energy state

An analogy can be made with a situation where a large number of pebbles are thrown it into a pool at the same time. Each pebble generates a wave of its own. Since the pebbles are thrown at random, the waves generated by all the pebbles cancel each other and as a result they travel a very short distance only. On the other hand, if the pebbles are thrown into a pool one by one at the same place and also at constant intervals of time, the waves thus generated strengthen each other and travel long distances. In this case, the waves are said to travel coherently. In laser, the light waves are exactly in step with each other and thus have a fixed phase relationship[2,3]. Figure-2 shows the schematic representation of laser.

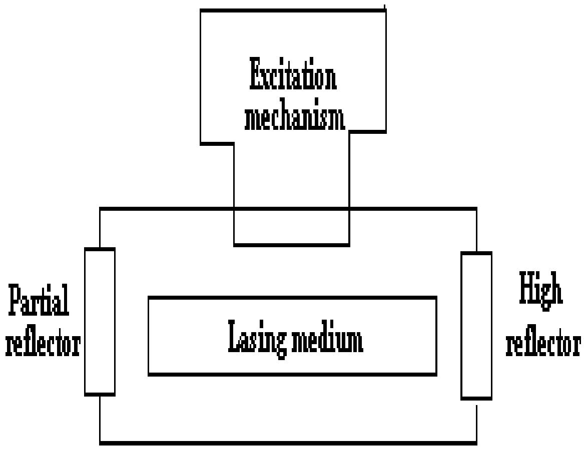

Figure-2
Schematic representation of laser

Spatial coherence is typically expressed through the output being a narrow beam which is diffraction-limited, often a so-called pencil beam. Laser beams can be focused to very tiny spots, achieving a very high irradiance or they can be launched into beams of very low divergence in order to concentrate their power at a large distance. Temporal coherence implies a polarized wave at a single frequency whose phase is correlated over a relatively large distance beam. A beam produced by a thermal or other incoherent light source has an instantaneous amplitude and phase which vary randomly with respect to time and position, and thus a very short coherence length. Most so-called single wavelength lasers actually produce radiation in several modes having slightly different frequencies, often not in a single polarization. And although temporal coherence implies monochromaticity, there are even lasers that emit a broad spectrum of light, or emit different wavelengths of light simultaneously. There are some lasers which are not single spatial mode and consequently their light beams diverge more than required by the diffraction limit. However all such devices are classified as lasers based on their method of producing that light, stimulated emission. Lasers are employed in applications where light of the required spatial or temporal coherence could not be produced using simpler technologies[4].

Principle of Lasing Action

Every atom, according to the quantum theory, can have energies only in certain discrete states or energy levels. Normally, the atoms are in the lowest energy state or ground state. When light from a powerful source like a flash lamp or a mercury arc falls on a substance, the atoms in the ground state can be excited to go to one of the higher levels. This process is called absorption. After staying in that level for a very short duration of the order of 10^{-8} second, the atom returns to its initial ground state, emitting a photon in the process, this process is called spontaneous emission. The two processes, namely, absorption and spontaneous emission, take place in a conventional light source, in case the atom, still in its turns to excited state, is struck by an outside photon having precisely the energy necessary for spontaneous emission, the outside photon is augmented by the one given up by the excited atom, Moreover, both the photons are released from the same excited state in the same phase, this process, called stimulated emission, is fundamental for laser action. Thus, the atom is stimulated or induced to give up its photon earlier than it would have done ordinarily under spontaneous emission. The laser is thus analogous to a spring that is wound up and cocked, it needs a key to release, in this process and the key is the photon having exactly the same wavelength as that of the light to be emitted. Figure-3 shows the basic energy level diagram of laser[5].

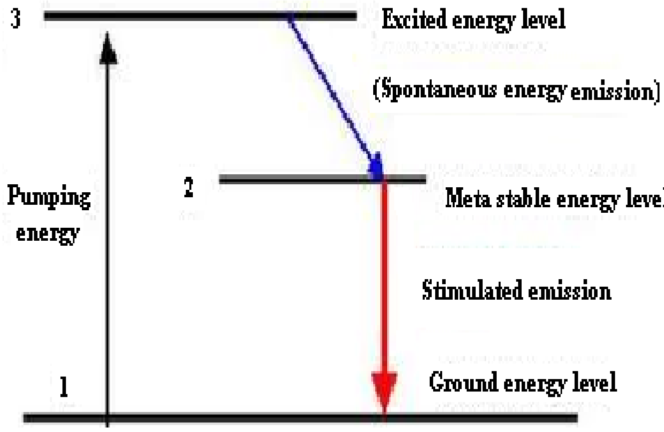

Figure-3
Energy level diagram of laser

Properties of lasers

Monochromaticity means "One color". To understand this term, examine "white light" which is the color interpreted in the mind when we see all colors together. When "white light" is transmitted through a prism, it is divided into the different colors which are in it and laser radiation does not have all those color, because it has only one same wavelength and phase. And Mono-chromaticity also means that laser has a high intensity of the light within the very small wavelength. So it can have a high energetic level in microscopic region. Actually, the temperature of the Laser radiation is higher than Sun. Radiation comes out of the laser in a certain direction and spreads at a defined divergence angle. This angular spreading of a laser beam is very small compared to other sources of electromagnetic radiation and described by a small divergence angle. Since, laser radiation divergence is of the order of milli-radians, which means almost negligible, the beam is almost parallel and can be sending over long distances. So, laser radiation is highly directional. Laser radiation is composed of waves at the same wavelength, which start at the same time and keep their relative phase as they advance. So, when two or more laser radiations can make regular interference each other. So, laser radiation has a coherency[6].

Types of lasers

Gas lasers: Helium-Neon (He-Ne) laser: He-Ne Laser is the most widely used noble gas laser. Lasing can be achieved at many wavelength 632.8 nm. Pumping is achieved by electrical discharge. The helium is excited by electron impact. The energy is then transferred to Neon by collisions. The first He-Ne laser operated at the 1.1523μm line[7]. He-Ne lasers are used in many applications such as interferometry, holography, spectroscopy, barcode scanning, alignment and optical demonstrations.

Argon and Krypton ion laser: Similar to the He-Ne laser the Argon ion gas laser is pumped by electric discharge and emits light at wavelength: 488.0nm, 514.5nm, 351nm, 465.8nm, 472.7nm, 528.7nm.It is used in applications ranging from retinal phototherapy for diabetes, lithography and pumping of other lasers. The Krypton ion gas laser is analogous to the Argon gas laser with wavelength: 416nm, 530.9nm, 568.2nm, 647.1nm, 676.4nm, 752.5nm, 799.3nm. Applications range from scientific research. When mixed with argon it can be used as "white-light" lasers for light shows.

Carbon dioxide laser: In the carbon dioxide (CO_2) gas laser the laser transitions are related to vibrational-rotational excitations. CO_2 lasers are highly efficient approaching 30%. The main emission wavelengths are 10.6μm and 9.4μm. They are pumped by transverse or longitudinal electrical discharge. It is heavily used in the material processing industry for cutting and welding of steel and in the medical area for surgery. Carbon monoxide (CO) gas laser are having wavelength range 2.6 - 4μm, 4.8 - 8.3μm and they are pumped by electrical discharge. They are used in material processing such as engraving, welding and in photo acoustic spectroscopy. Output powers as high as 100kW have been demonstrated.

Excimer lasers: Chemical lasers emitting in the UV: 193nm (ArF), 248nm (KrF), 308nm (XeCl), 353nm (XeF) excimer. These are molecules that exist only if one of the atoms is electronically excited. Without excitation the two atoms repell each other. Thus the electronic ground state is not stable and is therefore not populated, which is ideal for laser operation. These lasers are used for ultraviolet lithography in the semiconductor industry and laser surgery.

Dye lasers: The laser gain medium is organic dyes in solution of ethyl, methyl alcohol, glycerol or water. These dyes can be excited by optically with Argon lasers for example and emit at 390-435nm, 460-515nm, 570-640 nm and many others. These lasers have been widely used in research and spectroscopy because of their wide tuning ranges. Unfortunately, dyes are carcinogenic and as soon as tunable solid state laser media became available dye laser became extinct.

Solid state lasers: Ruby Laser: The first laser was indeed a solid- state laser is Ruby and it is emitting at 694.3nm[8]. Ruby consists of naturally formed crystal of aluminum oxide (Al_2O_3) called corundum. In that crystal some of Al^{3+} ions are replaced by Cr^{3+} ions. It's chromium ions that give Ruby the pinkish color, i.e. its fluorescence, which is related to the laser transitions. Today, for the manufacturing of ruby as a laser material, artificially grown crystals from molten material which crystallizes in the form of sapphire is used. The lifetime of the upper laser level is 3ms. Pumping is usually achieved with flash lamps.

Neodymium YAG laser: Neodymium YAG consists of Yttrium-Aluminum-Garnet (YAG) $Y_3A_{15}O_{12}$ in which some of the Y^{3+} ions are replaced by Nd^{3+} ions. Neodymium is a rare earth element, where the active electronic states are shielded inner 4f states. Nd: YAG is a four level laser. The main emission of Nd: YAG is at 1.064μm.

Ytterbium YAG laser: Ytterbium YAG is a quasi three level laser emitting at 1.030μm. The lower laser level is only 500-600cm^{-1} above the ground state and is therefore at room temperature heavily thermally populated. The laser is pumped at 941 or 968nm with laser diodes to provide the high brightness pumping needed to achieve gain[9].

Semiconductor lasers: An important class of solid-state lasers is semiconductor lasers. Depending on the semiconductor material used the emission wavelength can be further refined by using band structure engineering, 0.4 μm (GaN) or 0.63-1.55 μm (AlGaAs, InGaAs, InGaAsP) or 3-20 μm (lead salt). The AlGaAs based lasers in the wavelength range 670nm-780 nm are used in compact disc players and therefore are the most common and cheapest lasers in the world. In the semiconductor laser the electronic band structure is exploited, which arises from the periodic crystal potential[10].

Quantum cascade lasers: A new form of semiconductor lasers was predicted in the 70's by the two Russian physicists Kazarinov and Suris that is based only on one kind of electrical carriers. These are most often chosen to be electrons because of their higher mobility. This laser is therefore a unipolar device in contrast to the conventional semiconductor laser that uses both electrons and holes. The transitions are intraband transitions. Like semiconductor lasers these lasers are electrically pumped. The first laser of this type was realized in 1994 by Federico Capasso's group at Bell Laboratories[11], 23 years after the theoretical prediction. The reason for this is the difficult layer growth, that are only possible using advanced semiconductor growth capabilities such as molecular beam epitaxy (MBE) and more recently metal oxide chemical vapor deposition (MOCVD). Lasers have been demonstrated in the few THz range up to the 3.5μm region[12,13].

Applications of lasers

Laser radiation in various applications was made use of immediately after the first laser became operational. The ruby laser was designed and constructed by Teodor Maiman in 1960 and as early as 1961 its radiation was used to treat eye and skin diseases. Since it was designed thirty years ago, laser has found uses in many fields. As a device, it is now used in medicine, astronomy, geodesy, metrology, chemistry, biology, spectroscopy, holography, power engineering, in various processes in engineering, as well as in communication technology, automation and remote control, in military technology, entertainment industry, art restorations, etc.[14].

The ruby laser was verified in practice immediately after it had become operational, namely in ophthalmology and in dermatology. Medical doctors were attracted by its ability to concentrate the energy of optical radiation into a small area and the possibility of cutting and vaporizing tissues. It is due to these qualities that the laser has become so important in laser surgery, its advantage being the possibility of performing a non-contact sharp-contour tissue incision and removal of even tiny structures without any damage to the surrounding tissue and any possible infection of the cut. Laser surgery thus makes use of transformation of radiation into heat within the tissue, performing thus both the incision and coagulation. Monochromaticity and coherence, two properties of laser radiation, are utilized mainly in medical diagnostics. Due to further advances in laser physics and to new types of laser devices, the laser has gradually entered many new branches of medicine, namely ophthalmology, dermatology, general, plastic and cardiovascular surgery, neurosurgery, otolaryngology, urology, gynecology, dentistry, oncology, gastroenterology, orthopedics and others[15-18].

Industrial applications now include many new procedures, such as laser welding, drilling, cutting, annealing, sputtering and others. The main advantage of laser operations consists in machining the product without any mechanical contact, e.g., remote machining or machining in a protective atmosphere, in machining parts of the product difficult to access, as well as in technological treatment of materials that cannot be affected by classical methods. Laser welding makes use of optical radiation to melt the material to a desired depth, minimizing at the same time the surface vaporization. In practice, this process utilizes mostly the continuous lasers of the infrared CO_2 spectrum and the Nd: YAG lasers, of a wavelength of 10.6 nm and 1.06 nm, respectively. Welding, as against some other processes, uses a lower intensity optical beam and a longer laser pulse. The advantage of laser welding rests in the absence of physical contact with the electrode, in localized heating and cooling, in welding parts in a protective atmosphere or sealed into optically transparent material. Lasers can weld, e.g., air-tight shields of miniature relay, pacemakers, contacts in microelectronics, and metal sheets in car or aircraft industry[19-21].

Ground laser radars are used in ecology to measure air pollution. They are also used in meteorology. In this case it is both reflection and scattering that are made use of in measurements. Passing through the atmosphere, the laser pulse is scattered by the molecules and aerosols present there, causing Mie, Raleigh or Raman scattering. Part of the radiation scattered backwards is concentrated by a telescope, and passing through a filter detected by a photo detector. The received signal, whose amplitude at any moment is proportional to the intensity of the scattered radiation, is recorded as a function of time, due to which it is possible to obtain also the distance of the scattering body, while the filter width and the attached spectrometer determine the spectrum of the received signal. LIDAR serves to monitor the distribution and direction of smoke trails; to measure the bottom level and profile of clouds of atmospheric turbulence, distribution and areas of various imissions in the atmosphere, etc.[22].

Computer field of applications requires small-size lasers, so semiconductor or He-Ne low-power lasers seem to be the best. Thus the laser printer, used in a device that makes use of laser radiation to obtain the image of what is to be printed, i.e., transferred from the rotating drum to paper. The information to be printed, including the intended graphical layout, is encoded into the computer from which it is transferred to the modulator of optical radiation, which, according to the codes, interrupts the laser beam impinging upon the reflection part of the deflection disc. Every single segment on the deflection disc deflects the beam across the drum which is covered with a layer of photosensitive material of specific property, namely that after laser radiation has impinged upon it, its electric resistance at the irradiated dot will decrease by several orders. If this layer prior to receiving the relevant information carries a constant potential, then, upon the incidence of laser beam, in agreement with the code, it will produce an image composed of dots whose potential differs from the original one. The matrix thus created on the drum is then electro statically covered with a toning medium, whose adhesion to the cylinder is given by the potential of each dot. The image is then transferred to paper. The advantage of this type of printer is its high-quality recording, high resolution of characters and high printing speed computer science, has become standard equipment of computer centers. Figure-4 shows schematic representation of Laser printer[23-25].

Lasers appear also in various military applications, the most widely utilized being the so called laser range finders, an analogy to the ground laser radar that can measure with great accuracy the target's distance and thus obtain the optimal trajectory of a missile and higher reliability of the hit. For this purpose, the Nd: YAG lasers seem to be best. However, much less sophisticated are the laser markers used in, e.g., guns, to identify the target at a distance of up to 20 m. In this case small diode lasers are used. On the other hand, for intercontinental ballistic missiles to be destroyed, it is necessary to use a high-power laser, i.e., of the CO_2 or chemical type and mirrors placed in space. Due to minimal free-space path loss, the beam is transmitted without any loss to the next mirror focusing the beam and homing it to the target, e.g., a rocket to achieve best homing and hit, the mirrors can be moved round according to the rocket's parameters. The laser can be located at a ground station or on a trajectory[26].

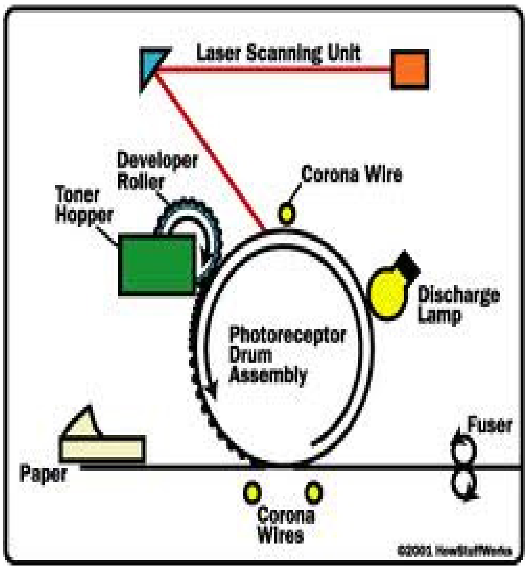

Figure-4
Schematic representation of Laser printer

Conclusion

A laser is a device that emits electromagnetic radiation through a process of optical amplification based on the stimulated emission of photons. The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. Laser is a powerful source of light having extraordinary properties which are not found in the normal light sources like tungsten lamps, mercury lamps, etc. The unique property of laser is that its light waves travel very long distances with e very little divergence. The laser is an analogous to a spring that is wound up and cocked, it needs a key to release, in this process and the key is the photon having exactly the same wavelength as that of the light to be emitted. As a device, lasers are used in medicine, astronomy, geodesy, metrology, chemistry, biology, spectroscopy, holography, power engineering, in various processes in engineering, as well as in communication technology, automation and remote control, in military technology, entertainment industry, art restorations, etc.

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