An Overview
Of
Lasers
and
Their Applications

A Senior Project

By

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I. Introduction

A Brief History

Since the dawn of modern science, the phenomena of light has carried a lot of significance, and our understanding of the physical nature of light has evolved since then. In the early 20th century, there existed two main theories for the behavior of light: one that stated light was a particle and one that stated light was a wave. In fact, light is actually both. This unique property of light what is referred to as *wave-particle duality*. If one designs an experiment to test the wave properties of light, then the result will be that light is a wave. Conversely, is one designs an experiment to test the particle properties of light, then the result will be that light is a particle.

Christian Huygens, a Dutch physicist contemporary with Newton, proposed the idea that light was a wave, spreading out from a light source in all directions and propagating through an elastic medium known as the *ether*. By adopting the wave theory, Huygens was able to derive the laws of reflection and refraction and to explain *double refraction* in calcite. Thomas Young performed his famous *double-slit experiment* in which an opaque screen with two small, closely spaced openings was illuminated by monochromatic light from a small source. This produced a fringe pattern made by wave interference and gave more support to the wave theory of light.

There were also notable experiments that successfully tested the particle nature of light. In 1900, Max Planck derived the blackbody radiation spectrum by making the assumption that light and its associated energy were dependent on its frequency. Albert Einstein published his paper on the photoelectric effect in 1905, where he postulated that light is quantized into discrete packets of energy called photons. Additionally, Arthur Holly Compton observed the phenomena known as *Compton scattering*, which describes the scattering of a photon by a charged particle, typically an electron. The experiment showed that photons carried momentum and can have collisions with other objects; both defining properties of particles. Wave theory remained the primary description of light until more evidence for particle theory surfaced in the twentieth century. Difficulties in the wave theory appeared in situations where light interacted with matter. The discourse that followed eventually led physicists to accept the theory of wave-particle duality.

Invention of the Laser

The laser is arguably the most important optical device to be developed in the past 60 years. Its transition from a theoretical idea to tangible applications has provided the means to make optics one of the fastest evolving fields in science and technology today. The word laser is an acronym that stands for **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation.

Albert Einstein laid the theoretical foundation for lasers in his 1917 paper regarding his theory of radiation [1]. Einstein theorized that there are three fundamental processes which explain interactions between atoms and light: *spontaneous emission, absorption, and stimulated emission*. He also predicted the possibility of creating a concentrated, coherent beam of light. However, his work went unexploited for several decades until C.H. Townes and Arthur Schawlow developed a *maser*, producing light in the microwave range of the electromagnetic spectrum [1]. To achieve this, they suggested positioning two parallel-facing mirrors along the optical axis of the cavity of a preliminary laser model. The mirrors were included in the cavity in order to reflect photons with desired frequencies back-and-forth through the medium of the laser. This process creates identical photons via stimulated emission at a rate which increases as the photons pass through the medium repeatedly. Townes and Schawlow published a paper regarding their idea of implementing parallel mirrors into a laser cavity in 1958 [1].
In 1960, Theodore Maiman, a Scientist from Stanford University, successfully constructed the first working laser using ruby as the gain medium using the ideas of Townes and Schawlow.

II. Theory

Light-Matter Interaction

After his publication in 1905, Einstein, using the work of Max Planck, gained recognition for his idea that light is quantized into discrete energy packets called photons. This was a profound scientific claim that challenged the widely accepted theories that light was solely wave-like in nature and that a medium known as “ether” was essential to the propagation of light. Through the careful review of these ideas, light is better understood today than it was at the time of the 1905 photoelectric effect publication. The notion of an invisible medium through which light propagates was replaced by the idea of a constant speed of light regardless of the reference frame. The wave-particle duality has been reconciled and accepted. It has also been discovered that photons are bosonic particles without internal structure or mass [2].

Along with our ability to better comprehend the elusive behavior of photons, is the ability to mathematically articulate the physical characteristics of light. It can be described by many properties such as polarization, color, wavelength, frequency, and so forth. A fundamental relationship between several of these properties of laser light and other forms of electromagnetic radiation can be shown in the equation

$$c = \lambda \upsilon, \qquad (1)$$

where c is the speed of light (300,000,000 m/s), λ is wavelength, and υ is frequency. In free space, all electromagnetic waves travel at the speed of light, c. An electromagnetic wave that propagates through space may be *monochromatic*, single frequency, or *polychromatic*, many frequencies. It can be seen from Eq. 1 that the frequency of light and the wavelength are directly proportional to the speed of light (c). It follows that because the speed of light is a constant, either wavelength and/or frequency must change. In other words, light of a higher frequency corresponds to shorter wavelengths, whereas light of a lower frequency has a longer wavelength. Higher frequency light also carries more energy per photon than lower frequency light. In terms of the generation of laser light, the energy of a photon is dependent upon the energy levels of the atom used to produce it via transitions. The energy of a photon can be found using the equation

$$E = h\upsilon, \qquad (2)$$

where E is the energy in Joules, h is Planck's constant ($6.626\text{x}10^{-34}$ Joule-seconds), and υ is frequency in Hertz.

The frequency of a photon can indicate both the photon energy and the type of electromagnetic radiation. The distribution of energy among the constituent waves forms the basis for the electromagnetic spectrum, which is dependent on wavelength. Figure 1 below shows the electromagnetic spectrum.

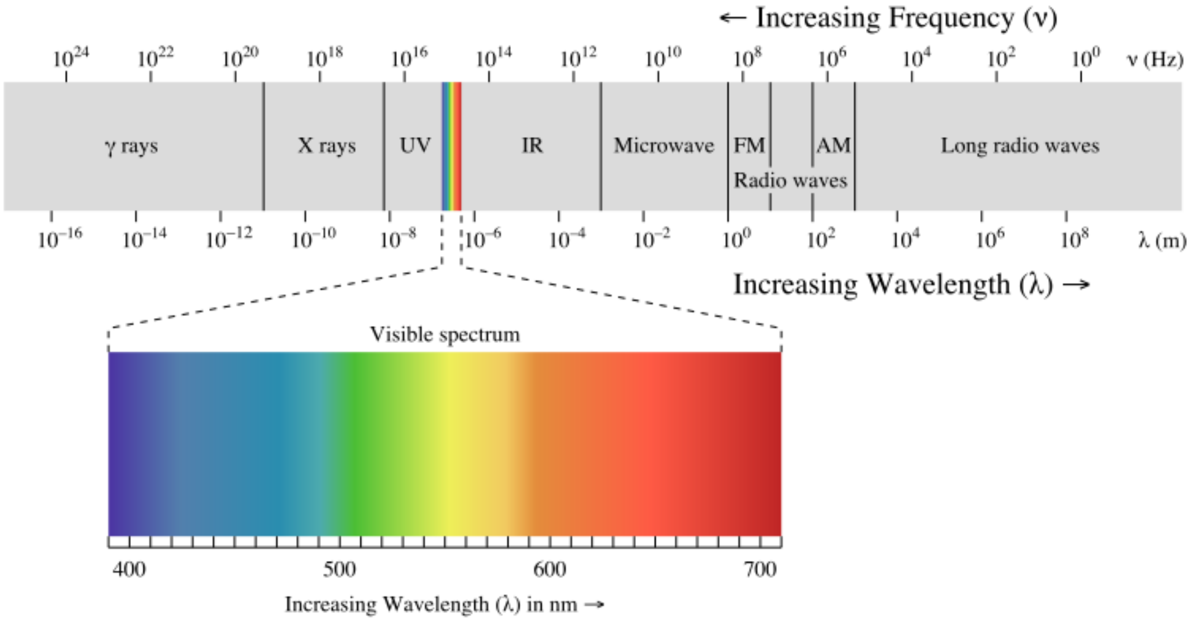

Figure 1: Electromagnetic Spectrum [3]

The various regions shown in figure 1 are known as radio waves, microwaves, infrared, visible light, ultraviolet, x-rays, and gamma rays. At one end of the spectrum lie high-frequency, high energy gamma rays and on the opposite, are low-energy, low-frequency radio waves. The visible range of EM radiation is roughly between 380nm to 770nm, and is referred to as visible because the human eye can detect these wavelengths. To understand the basic operation of lasers and their various applications, one must familiarize themselves with the electromagnetic spectrum. Many of the laser applications that will be explored in the forthcoming sections are in the infrared and the microwave part of the spectrum, with wavelengths ranging from 10^{-6} m to 1 m.

Energy Transfer between Electromagnetic Waves and Atoms

There are three primary mechanisms by which energy can be transferred between electromagnetic waves and atoms: spontaneous emission, stimulated absorption, and stimulated emission. *Spontaneous emission* results when an atom in an excited energy state drops down to lower energy state, releasing quantized energy in the form of a photon. There is no external motivating factor that inhibits this release of energy, hence the name spontaneous emission. *Stimulated absorption* occurs when a photon is absorbed by an atom, raising the energy of an electron by amount $E = h\nu$. If the energy absorbed is equivalent to the difference between two energy levels of an atom, the electron will populate the excited energy state.

The final and most important of these three mechanisms for energy transfer is *stimulated emission*. The process of stimulated emission occurs when a photon perturbs an atom in an excited state. If the incident photon has an energy equivalent to the energy gap between the electron's current state and lower state, it will release an identical photon and subsequently drop the electron down to a lower energy level. The new photon is exactly identical to the incident photon, which amplifies the energy of the passing electromagnetic wave twofold, and is responsible for the process of creating coherent laser light. The three processes by which energy is transferred from EM waves to matter are illustrated in figure 2.

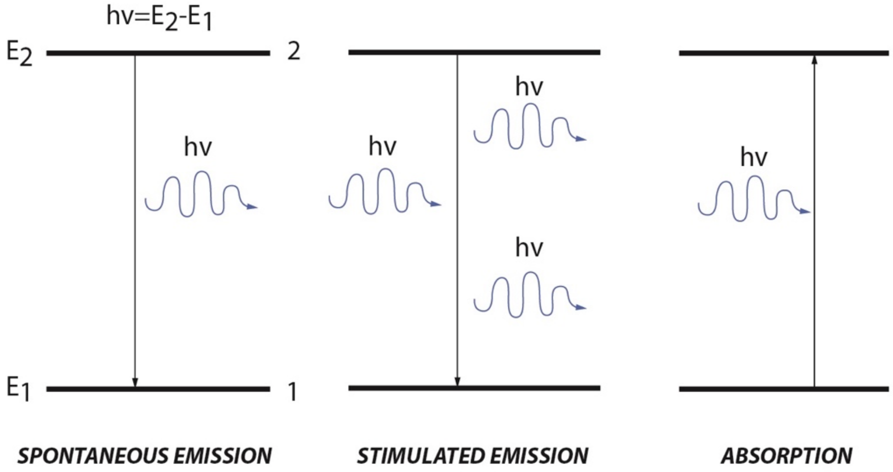

Figure 2: Primary mechanisms for energy transfer [4]

However, stimulated emission does not occur under normal conditions because of the tendency of atoms to decay to lower energy levels via spontaneous emission. At equilibrium, the distribution of atoms across individual energy levels decreases as energy increases. Since there are more atoms in lower energy levels, photon absorption is far more likely to be observed than stimulated emission [5]. To compensate for the low probability of stimulated emission at equilibrium, laser systems include an "optical pump" to introduce more energy to excite atoms into a specific excited state. If pumped with sufficient energy, the number of atoms in an excited state will be greater than the number of atoms in a lower energy state. This "bottleneck" behavior is referred to as *population inversion,* and it is critical to laser operation. Population inversion is shown in the figure 3 below.

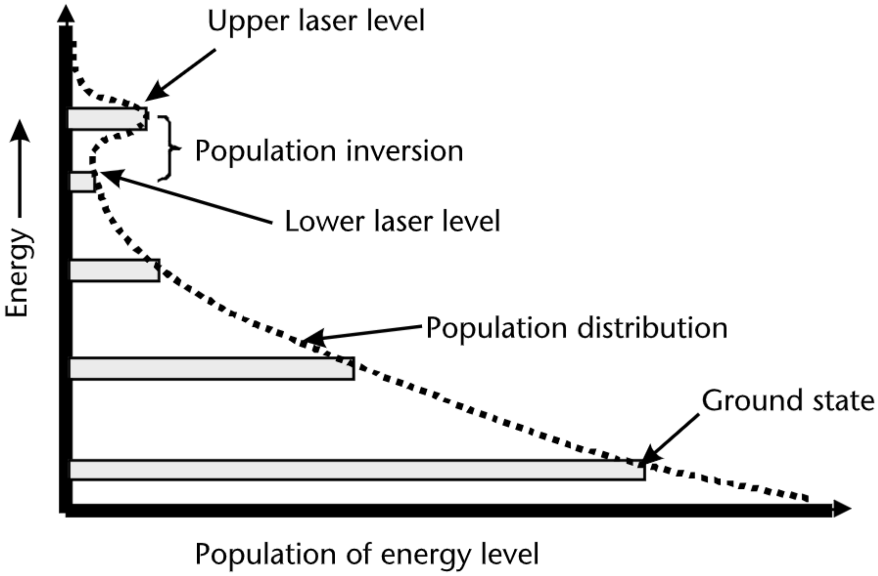

Figure 3: Population Inversion Distribution [6]

III. Laser Operation

Now that we understand the mechanisms of energy transfer that are involved in laser operation, it is appropriate to shift the focus to the components that make-up a laser. The main elements of a laser are the pump, the gain medium, and the resonator. Variations of the laser elements exist, each with different characteristics that are suited for many applications across multiple disciplines.

Laser Elements

In the previous section, we briefly discussed the function of a pump. Its purpose is to create the necessary conditions for population inversion to occur by exciting atoms to higher energy states. A fundamental requirement of laser action is that the gain achieved from stimulated emission must be greater than the losses that occur during the process. Only after population inversion is achieved can the amplification of the photon energy occur. Several mechanisms for pumping include: chemical reactions, atomic and molecular collisions, forward biasing of semiconductors, acceleration of electrons, absorption of photons from another source, such as a laser, and absorption of radio-frequency waves [5]. Ultimately, these different pumping techniques are accomplishing the same task of exciting the gain medium to create population inversion.

The gain medium is the matter inside the laser cavity that will be excited by the process known as pumping, to create the population inversion necessary for lasing to occur. The excitation can be applied to the gain medium through a variety of different methods. The gain medium can be solid, liquid, or gaseous, and usually determines what name is assigned to a particular laser system. For example, the carbon dioxide laser uses carbon dioxide as a gaseous medium. Because there is a different energy gap between the lasing levels of different gain media, each gain medium produces light of different wavelengths. Gain media are often selected to produce laser light in a specific region of the electromagnetic spectrum. In principle, a successful laser will utilize atomic transitions that are most likely to occur, although meta-stable states are sometimes used because the transitions are slower and can provide energy storage [6].

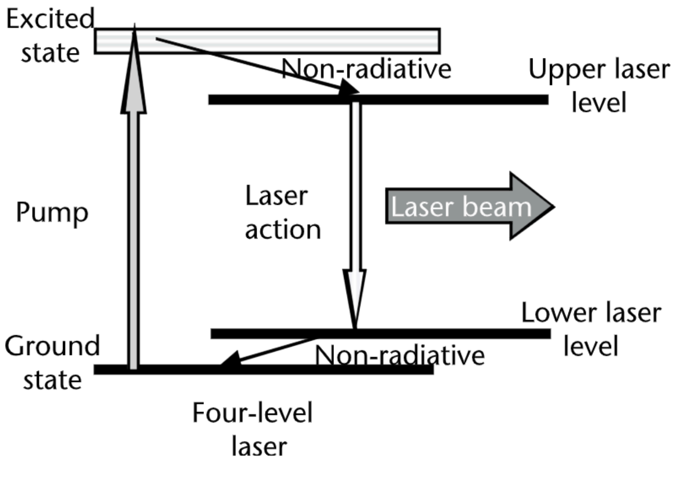

Figure 4: Schematic of a four-level laser [6]

An important property of varying gain media is the spontaneous lifetime of each atom’s upper energy level. There must be sufficient time between transitions from the higher level to the lower level. Additionally, the lower laser level must be depopulated faster than the upper level is excited resulting in a continual population inversion. Regardless if the gain medium is pumped rigorously or not, population inversion cannot occur if the excited atoms decay too rapidly. A schematic of a simple 4-level laser is shown in figure 4. Atoms in the gain medium are pumped and excited to the uppermost energy level, quickly transitioning back to a lower meta-stable state that defines the upper laser level. The atom transitions down to an even lower meta-stable state, which defines the lower laser level, before reaching the ground state again. Although 3-level lasers exist, they are not as efficient as 4-level lasers and struggle to maintain population inversion.

Another important component of the laser is the resonator. It is typically composed of two mirrors that can be planar or slightly curved, and are carefully oriented to allow photons created through stimulated emission to reverberate continuously through the same path in the laser cavity. Each mirror serves a slightly different purpose in the overall lasing action. One mirror, referred to as the hard or high reflector, is made to have a reflectivity of 100% and creates the boundary conditions for standing waves on one end of the cavity. The total reflectivity of the hard reflector allows for the amplification of photons with each pass through the gain medium. The second mirror, called the soft or output coupler, has a usual reflectivity of 98-99%. Its purpose is to allow for the transmission of a small fraction of the light that is created in the cavity, which becomes the laser beam. Figure 5 shows a simplified schematic of a laser.

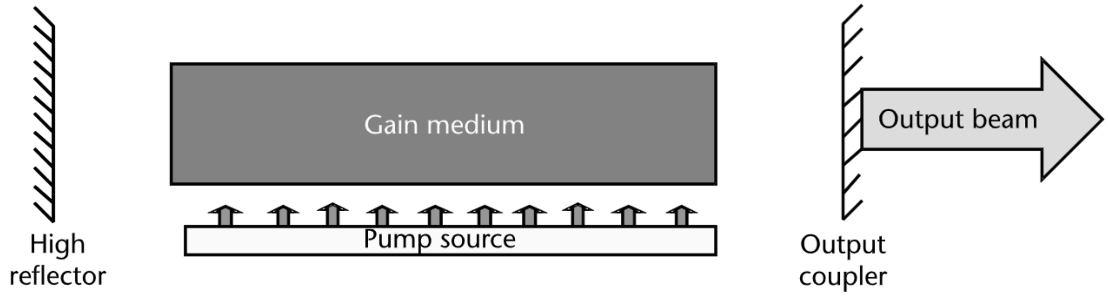

Figure 5: Basic Laser Schematic [6]

Overall, lasers are very inefficient in terms of the ratio of the optical power output to the total power input. The vast majority of energy into the laser ultimately ends up as thermal energy. Laser efficiency and operation is also significantly affected by the temperature at which the laser operates at. Unfortunately, many high-powered laser systems suffer from inefficiency caused by temperature fluctuations. Cooling systems have been developed to dissipate the excess thermal energy that is generated through the pumping process. Inability to regulate the thermal energy can be detrimental to the laser components. As with the gain medium, there are multiple techniques for cooling a laser. Lasers with solid gain media are often liquid cooled, such as Nd:YAG (neodymium-doped yttrium aluminum garnet) and Ti:sapphire (Titanium-Sapphire) lasers. A reservoir of liquid encases the gain medium and acts as a heat sink for the laser. Other methods of cooling laser systems can range from the simple use of fans to more complicated ways, as can be seen in carbon dioxide lasers when the medium itself is recycled and cooled down before returning to the cavity to be pumped again [5].

The properties of laser light are different than light from other sources, making them desirable to exploit. One unique property is the high degree of monochromaticity of laser light, meaning that the color of the laser light emitted is uniform. The linewidth, or range of possible frequencies of photons emitted by stimulated emission is broad, but only the photons with frequencies equivalent to the resonant frequency of the laser cavity can become amplified. This significantly narrows the linewidth and thus the uniformity of color is increased.

Another significant property of laser light is its coherence, both spatial and temporal. Coherence of laser light means that the spatial and temporal components of the electromagnetic wave emitted from the source have high degree of phase correlation. Spatial coherence is a measure of the uniformity of phase across the wave-front [5]. This means that for light to be spatially coherent, the phase of the wave describing it must be exactly synchronized with the phase of light from the same source, that is equidistant and traveling in another direction. The second type of coherence is temporal coherence. Temporal coherence refers to a measure of how uniform the frequency of laser light emitted from a source remains. It is the temporal coherence that defines the level of monochromaticity displayed in laser beams. The high degree of spatial and temporal coherence is another consequence of stimulated emission.

IV. Types of Lasers

Since the first iteration of the ruby laser in 1960, many laser variants have been produced. Laser systems are categorized by characteristics such as their gain medium, pump mechanism, emission wavelength, beam diameter, beam divergence, and power output.

There are two forms of laser power output known as *continuous wave* or *pulsed operation* lasers. In continuous wave (cw) lasers the laser system delivers a laser beam of constant irradiance, whereas a pulsed laser outputs bursts of radiation with very small durations (pulse widths) that can be as short as a few femtoseconds (10^{-15} s). Continuous wave lasers are typically used whenever sustained output is required, such as in an industrial setting or in a laboratory. Some examples of continuous wave laser systems include the carbon dioxide laser, the helium-neon laser, and semiconductor lasers. Pulsed lasers are sought after because of their high peak intensity. A plethora of applications rely on the use of pulsed laser outputs in materials-processing, time-of-flight distance measurements, and in tracking rapid changes in the properties of systems [5].

As previously discussed, another parameter commonly used to describe a laser system is its gain medium. Common types of gain media include gas molecular, excimer, liquid dye, solid state, and semiconductor laser systems. Gas atomic lasers are well known for their coherence properties. They typically emit laser light with frequencies on the visible to near infrared range, and are pumped by an electric discharge. Solid state lasers generate photons in a nonconducting solid material, that may be crystalline, ceramic, or glass. These solids are then doped with another material with a proper energy structure that allows light generation by stimulated emission [6]. Examples of solid state lasers are diode lasers and garnet doped lasers, such as the Nd:YAG mentioned earlier. Liquid dye lasers are among the most simple and versatile lasers. Figure 6 shows an Nd:YAG laser compared with a liquid dye laser.

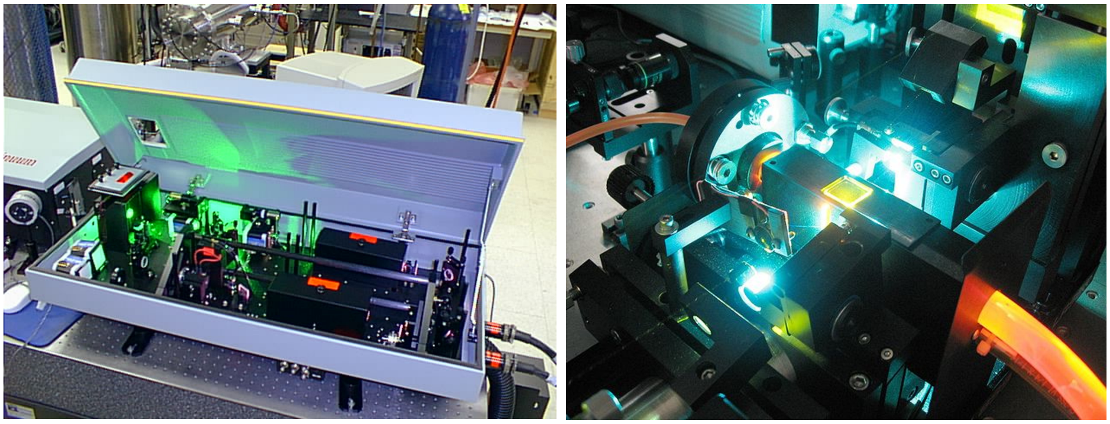

Figure 6: Left is an Nd:YAG laser operating near 532 nm. On the right is a CW Rhodamine dye laser operating at 590 nm. [7][8]

Dye lasers can operate in continuous wave and pulsed output mode and have a broad range of operating wavelengths because of the many different types of dyes that can be used. Common forms of dye in liquid-phase lasers are solvents like alcohol and ethylene glycol [6]. Figure 6 shows an Nd:YAG laser compared with a liquid dye laser.

V. Applications of lasers

Most laser applications can be categorized as being either interaction or information based. Lasers can interact with matter and cause either permanent or temporary changes depending on the purpose of the application. On the other hand, lasers can also be used to transmit, store, and process information at rapid and efficient rates. Some of the applications that will be discussed are medical use, remote sensing, laser-driven energy sources, communication, information processing, and military use.

Medical use

The use of lasers in medicine has become the standard for surgical precision within the past 50 years. Due to the versatile properties of laser light, it has been sought out in medicine for a myriad of reasons. The laser beam can be considered a scalpel of light, and can manipulate human tissue with extreme accuracy. Several different laser systems such as the carbon dioxide (CO_2) laser, the Nd:YAG laser, and the Argon-Ion laser are among the commonly used in the medical profession.

The CO_2 laser was among the first to be used among medical practitioners and surgeons. It emits radiation in the mid-infrared (IR) range at 10.6 micrometers and is strongly absorbed by water and hemoglobin, the main component of blood. This is of course a desirable wavelength because the human body is composed of 70-90% water, and the laser beam can easily make clean incisions and even vaporize malignant tissue. In addition to the efficiency of the CO_2 laser, surgery is essentially bloodless because a laser cauterizes and seals capillaries as it cuts [5]. Postoperative pain is also reduced because laser radiation can seal sensitive nerve endings. A drawback to the CO_2 laser is that it is not easily compatible with fiber optics, so the transmission of the beam to the target area is achieved by articulated optical arms. An example of a CO_2 medical laser is shown in figure 7.

Figure 7: A 40 watt CO_2 laser. Used in ENT, gynecology, podiatry, dermatology, and oral surgery. [9]

The Nd:YAG laser system has an operating wavelength of 1064 nanometers, and it is not easily absorbed by either hemoglobin or water. This allows it to penetrate through skin and tissue in an unfocused state, only cutting or coagulating tissue within the focal region of the laser beam. It is common to use a frequency-doubling crystal in order to shorten the wavelength to 532 nm, and it can then be absorbed by hemoglobin. “KTP-lasers” are mostly used to repair vascular lesions and in the vaporization of prostatic obstructions. These are used interchangeably with Ho:YAG lasers, which emit radiation at 2070 nm, to perform photoselective vaporization of obstructions, removal of kidney stones, and precisely shaving bone and cartilage [5].

Blue-green Argon-Ion lasers operate at 488 and 514 nm and are best absorbed by red and brown substances, such as hemoglobin and melanin pigment spots. This laser is commonly used in tattoo removal and in emergency retinal surgery, where it can stop retinal bleeding and weld detached retinas. Within the medical field, diode lasers are desirable because of the low cost, simplicity, compactness, and ease of use with fiber optics. They are primarily used for cosmetic procedures and hair removal, but will most likely find increasing application in medicine in the near future.

Remote Sensing

Advances in laser technology over the past decade and the availability of satellites orbiting the Earth provide the foundation for laser remote sensing. Remote sensing involves the detection of laser-scattered light from objects that are located remotely relative to the active laser system. The systems typically reside on space platforms, in order to detect objects far below such as the atmosphere, terrestrial vegetation, and the Earth's crust. Ground-based systems do exist as well, and are used in the detection of pollution and to monitor global winds.

Laser detection and ranging, or LIDAR, is a technique used for remote sensing. The ideal laser characteristics for a remote sensing system must include appropriate wavelength, tunability, output power, pulse repetition rate, and amplitude and frequency stability. In addition, it must also display high operating efficiency, be mechanically rigid, and possess a long operating lifetime. Current laser sources include carbon dioxide lasers, pulsed Nd:YAG and Nd-glass lasers, alexandrite lasers, Nd:YAG pumped dye lasers, excimer lasers, and a multitude of tunable solid-state lasers like the Ti:sapphire laser. The range of these wavelengths spans from 0.66 micrometers to 10.6 micrometers [5].

In principal, the targets must interact with the interrogating laser light and produce a measurable change that can be detected. The changes return to the detection system by the backscattered radiation in the forms of fluorescence, Raman-shifted wavelengths, and Doppler effects [5]. Each of these can provide important information on the species identity, concentration, or movement. Raman LIDAR and Doppler LIDAR, as well as differential absorption LIDAR are some highly specialized systems that are designed to detect the specific information content that is locked in the backscattered radiation.

The power of LIDAR is evident in the ability to take measurements of wind speed and shifts in the Earth's crust. Detailed movement and speed of tropospheric winds is of great interest in the study of global weather patterns. Because the source is satellite based, and therefore 250-800 km above the Earth, high initial laser power is required to detect weak backscattered radiation. Calculations for wind speed and direction can be made by considering Doppler frequency shifts in the backscattered radiation, usually with an accuracy of 1 m/s. The use of LIDAR's imaging from space has proven to be a reliable tool to geologists and geophysicists in extracting valuable information about Earth's crust, such as determining ground swell before volcanic activity and determining fault strains near earthquake hotspots.

Military

Lasers have inevitably found their way into the defense industry in a variety of sophisticated systems such as target imaging and ranging, defensive countermeasures, communications, and high powered weapons. It makes sense to connect our fascination with weaponizing lasers to a common example used in introductory physics classes: the Archimedes "death ray." Although this is just a legend, the possibility of setting ships ablaze using only the power of the sun, a mirror, and geometry seemed to resonate with physicists. Laser types commonly associated with military applications include the Nd:YAG and carbon dioxide lasers, due to their efficiency and infrared outputs.

Directed energy weapons are another controversial military laser application. They can range from low-power, non-lethal to lethal, high-power laser systems. Examples of low-power weapons include dazzlers, which temporarily disable a target's eyesight, to jammers. Infrared countermeasures (IRCM) are devices used to protect aircraft from heat seeking missiles by confusing the missiles' guidance system. They are based on a source of infrared radiation that has a higher intensity than the target, which overwhelms the missile's tracking abilities and causes it to deviate from the target. IRCM laser systems can be mounted on aircraft much like a turret, and only operate when cued by a missile warning system. These systems make use of the missile plume to accurately aim at the missile seeker. Once the missile deviates from its target, it is highly unlikely that it will reacquire another one [6]. The potential advantages of laser weapons are far and wide. A deep magazine capacity is attainable, in theory, given an adequate power supply. A high level of precision is also an advantage to laser weapons, and they operate well in conjunction with traditional kinetic weapons systems. Chemical or gas laser systems are typically used in weapon applications for their mid-infrared output, such as the oxygen-iodine laser, the deuterium fluoride laser, and the CO_2 laser. One of their weaknesses is the size of these large devices and the high rates of gas-flow needed to maintain steady laser operation. A comparison between two laser weapons can be shown in figure 8. A dazzler is used in conjunction with a heavy machine gun to provide a hybrid style of target elimination. An experimental weapon called the PHASR is a non-lethal dazzler used to temporarily blind and incapacitate targets. Just recently the US Navy revealed that they can shoot down an airplane-sized drone using a ship-based laser [10].

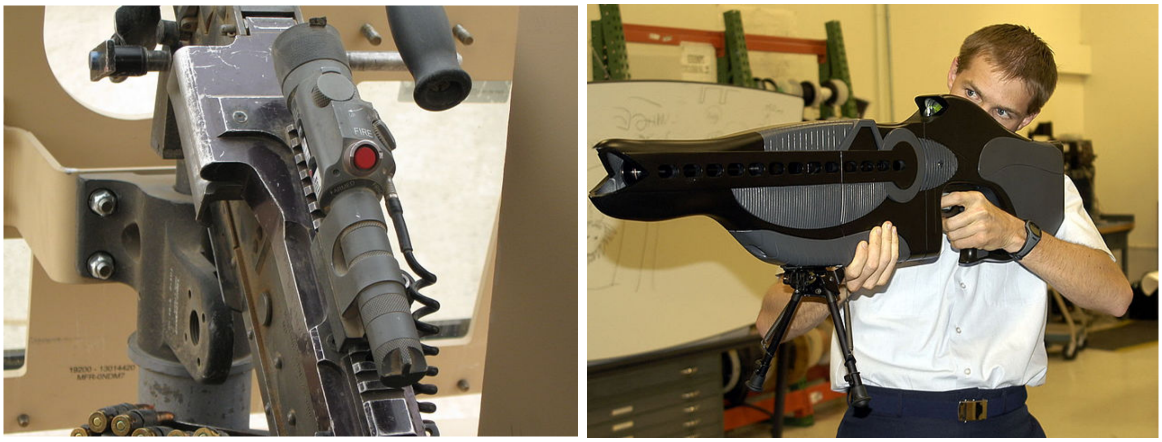

Figure 8: Left image is a dazzler attached to a heavy machine gun. Right image is a prototype weapon called the PHASR rifle. [11][12]

A controversial topic in the realm of military laser applications is the use of lasers to separate isotopes of radioactive elements. Uranium enrichment is the process of purifying the uranium for use in nuclear reactors. Traditionally, this requires a lot of energy and is quite costly to produce. It was predicted several decades ago that laser separation could be used to enrich the uranium, cutting the costs drastically. For many reasons, it was economically unfeasible to conduct more research on this enrichment method. In 1994 an advancement was made by Horst Struve and

Michael Goldsworthy in an Australian government facility. They called their method the separation of isotopes by laser excitation, or SILEX. In 2006 General Electric bought the rights to SILEX and continued conducting research for the American government [13]. One of the most controversial aspects of SILEX is that the enrichment process is nearly undetectable from space, leaving open the possibility of rogue states producing nuclear weapons.

VI. Areas of active research

Lasers can provide many useful methods for conducting research and experiments across many different scientific disciplines. As an extension of the applications of lasers, research applications are creative and sophisticated. In an effort to narrow the scope of material, I will discuss laser cooling and atom trapping, quantum computing, nuclear fusion, and experimental mineral physics.

Atom Trapping and Laser Cooling

An interesting property of laser radiation is that it can be used to reduce the speed of atoms in a gas. This is known as laser cooling. If we consider that the average kinetic energy of a gas is related to the temperature, then we can make use of the fact that photons carry momentum. As photons collide with atoms, they are absorbed through inelastic collisions and can reduce the momentum of atoms by precisely the photon's momentum. However, even slow moving atoms will tend to drift apart. Several different atom trapping apparatuses exist that can hold these wandering atoms in place. In a magneto-optical trap, magnetic coils surround the cooled atoms at the center of three pairs of counterpropagating laser beams [5]. Magnetic fields can affect the transition frequency of an atom, and it is possible to create a spatial magnetic field gradient in which the atoms become trapped. Trapped atoms exhibit peculiar behavior unlike naturally occurring atoms, leading to new understandings about the nature of matter. One such example, is a Bose-Einstein condensate. This is a unique state of matter in which all the super cooled atoms coexist together in the ground state of the trap system [5]. Of course, this state of matter is only permitted by Bosons as a result of bosonic statistics. Fermions, such as electrons, cannot exist in the same state as another fermion because of the Pauli exclusion principle. Liquid helium was studied extensively during the twentieth century for its ability to display superfluid characteristics at temperatures near 2.71 Kelvin.

Quantum Computing

Quantum computing takes the foundations of laser cooling and atom trapping one step further. Similar to the way that computers revolutionized the way information was created and transferred, quantum computers represent the next generation of information processing and may yield new applications beyond the scope of our current knowledge. At the center of this new technology is the ability to exploit the quantum mechanical nature of particles to store and transfer information. Traditional computers process data as binary digits (bits), which ultimately represent the patterns of high and low currents. Quantum computers are fundamentally different because they use the properties of superposition and entanglement to perform computation [14]. The spin states of an atom that are used to store and process information, are called quantum bits or "qubits." As a result of superposition, complex computations that would be otherwise unfeasible on classical computers are short work for quantum computers.

There is other motivation for researching the field of quantum computing and information. The United States Department of Energy is funding quantum information research at facilities such as IBM and Argonne National Laboratory, in hopes of establishing the foundation for a quantum internet. The 2021 United States Department of Energy budget for quantum information research is $237 million [14]. The creation of a quantum internet holds the key to a faster, more secure communication network. The capabilities of a quantum internet put the user organization at a distinct advantage over other sociopolitical organizations without this technology. An aspect of what drives this research is the application of quantum encryption. Quantum encryption and cryptography is the use of quantum computers to create or break cryptographic systems. In other words, quantum computers can be utilized defensively or offensively to secure the transfer of information. Investing in a more secure network defense means better defense against hackers and espionage. Overall, researchers are just beginning to scratch the surface of the applications of quantum computers. Once these devices are more readily available to other scientists, it is predicted that the number of applications will explode and a new era of technology will arrive.

Nuclear Fusion

As we progress into a new era of consumerism, the necessity for a renewable energy source is higher than ever, for we cannot rely on fossil fuels much longer. Efforts are made to transform nuclear fusion into a viable energy source. Harnessing the power of nuclear fusion would be akin to human ancestors mobilizing fire, the possibilities are limitless. The National Ignition Facility (NIF) at Lawrence Livermore National Lab (LLNL) is a facility dedicated to the pursuit of harnessing this power. NIF construction began in the late 1990s and was completed in 2001. The main goals of this facility are to study conditions for fusion and achieving the fusion ignition of hydrogen fuel. The temperatures, pressures, and energy required for this nuclear process to happen are immense, but ingenuity and persistence has carried scientists one step closer to the end goal.

Fusion experiments typically consist of blasting a small capsule of hydrogen fuel with over 1.9 mega Joules of direct energy from a short-pulse, high-power laser. One of the astounding features of this laser is the amplification of the original output beam. To reach such extreme energy levels required for fusion ignition, the initial laser beam is split into 192 different beams that travel through long amplification chambers before recombining just in time to reach the fuel capsule. Once the recombined laser beam strikes the fuel capsule, it generates x-rays that drive the implosion of the hydrogen fuel inside. When the implosion is at its apex, the deuterium and tritium atoms fuse and release energy on large scales [15]. Understanding and sustaining nuclear fusion of hydrogen fuel holds the key to unlocking knowledge about the cosmos. Millions of dollars and many bright minds contributed to the working success of the National Ignition Facility.

LIGO

Few applications of lasers have revealed such important confirmation of theoretical physics as LIGO has. Short for Laser Interferometer Gravitational Observatory, LIGO represents one of the greatest engineering feats in recent science. LIGO was designed to use large scale interferometry to measure small ripples in space-time, better known as gravitational waves. Gravitational waves originate from cataclysmic cosmic events such as colliding stars, black holes, or even by supernovae [16]. During its initial phase from 2002-2010, LIGO unsuccessfully measured gravitational waves but much was learned about. From 2010-2014 phase two commenced, named “Advanced LIGO,” and engineers used the knowledge from previous LIGO trials to incorporate more sophisticated detection technology. Within a few days of turning on the new and improved instruments, LIGO detected the first gravitational wave, created by a pair of colliding black holes roughly 1.3 billion light years away [16]. This is an incredible achievement that provides strong evidence in support of Einstein’s theory of relativity.

Although it is considered one observatory, LIGO is comprised of two interferometers in fairly isolated regions of the United States. One is located in Hanford, Washington and the second is in Livingston, Louisiana. These two facilities collect data simultaneously when running experiments, which is a fundamental feature to critical assessment of gravitational waves. As a gravitational wave passes through the 4 km long interferometer arm, it perturbs a hanging mirror just enough to change the length of the laser path. This displacement can be measured up to 1/10,000th the width of a proton [16]! Figure 9 shows two aerial images taken from the Livingston facility and the Hanford facility, demonstrating the massive scale of these interferometers.

Figure 9: Aerial images taken of both LIGO facilities. Pictured left is the LIGO Livingston. Pictured right is LIGO Hanford. [16]

Mineral Physics

A geophysical application of lasers is its use in the field of mineral physics research. There is a lot of information to learn about the Earth’s interior through the minerology of the deep layers of our terrestrial planet. The connection of surface geology to deep earth processes is rich with knowledge about the mechanisms of mineral evolution in the mantle. In order to study phase transformations of minerals in the Earth's mantle, an equation of state is needed. An equation of state is a relation that describes how density varies with temperature and pressure [17].

How is it possible to create pressures on the order of gigapascals and temperatures upwards of 1300 Celsius in the laboratory? Mineral physicists use the hardness of diamond to replicate the extreme pressure found in the mantle. Physicists have created a diamond anvil cell (DAC), shown in figure 10, which acts as a housing for a sample of mineral.

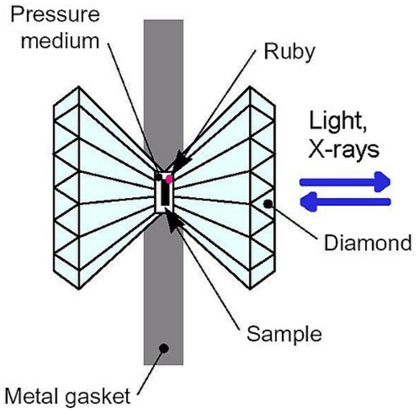

Figure 10: A diamond anvil cell (DAC), used to hold a mineral sample a few μm in size. [18]

The mineral sample is a grain only a few microns in size and fitting it into the cell can be troublesome. Once in the DAC, mineral physicists use x-ray diffraction to obtain data on the sample's volume temperature. Laser heating is used to achieve temperatures that emulate the deep layers of the Earth. For example, Nd:YAG and CO2 lasers are commonly used because of their infrared output. Most laboratories have particle accelerators that allow for the emission of x-rays into the DAC. To obtain data on the elastic modulus of the mineral sample, Brillouin scattering is performed. From this, one can deduce the mineral's behavior regarding seismic wave propagation and uncover more details about earth structure.

LHMEL I & II

The Laser Hardened Materials Evaluation Laboratory I and II, LHMEL I & II, are laboratories at Wright-Patterson Air Force Base, Ohio that test material responses to high laser energy for national defense programs and the aerospace industry [19]. The LHMEL I laser is a 15 kW, continuous wave CO_2 laser that operates at 10.6 μm. The LHMEL II laser is an even more powerful laser, producing 150 kW of CW power that also operates at 10.6 μm. Both lasers operate at the same frequency and are capable of delivering stable, full power irradiations for up to 80 s [19]. Materials testing at LHMEL is crucial to the development of new technologies with applications in defense, space simulation, automobiles, jet engines, etc. LHMEL can also perform a limited production run to laser cut thick sheets of metal for custom orders. In general, applications that require uniform irradiation of large surface areas to produce heat can be satisfied at LHMEL. LHMEL II can be shown in operation in figure 11.

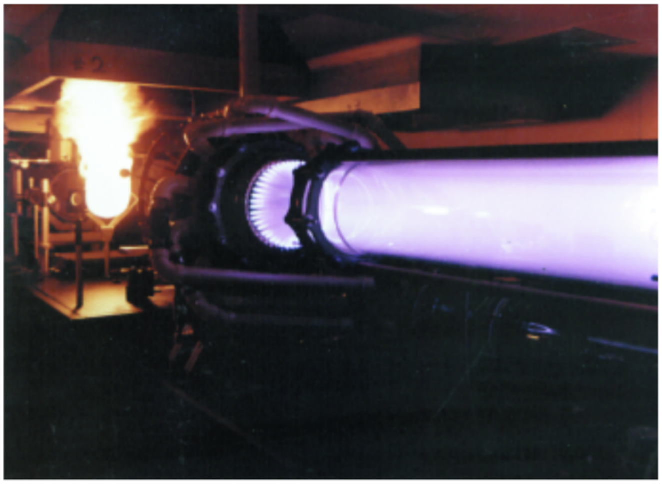

Figure 11: The LHMEL II high-energy CO_2 CW laser. [19]

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