Learning Unit 6, Principles of Lasers

Laser light is unique in that it is the most-pure light source known. It is monochromatic, or one color. Its photons are in phase or step with each other, which is called coherence. Laser light is very directional and doesn't diverge or spread out much as it travels. And many lasers are brighter than the sun. Lasers have been used in science, medicine, and industry since 1960!

Let's look at what the acronym laser stands for. Way back in the early 1960s when lasers were new and no longer science fiction, in the labs, techs would say, "Hey Theodore! Pass me the light amplification by stimulated emission of radiation thingy." That took entirely too much time and they just got tired of saying all of it, so one of the clever techs said, "Hey, let's take the first letter of each main word and call these wonderful light sources Lasers!" From then on all bright brilliant light sources that emit coherent light are referred to as lasers.

Let's look at how the laser actually works. To start, we need to review a few basic fundamentals of an atom. Every atom consists of a nucleus and an electron cloud surrounding the nucleus. Electrons orbiting the nucleus have the possibility of orbiting in many different levels around the nucleus. If the electrons are orbiting in their lowest level, that atom is considered to be at its atomic ground state. What this means is that it is resting at the lowest energy level for that particular atom. If some form of energy is applied to the atom, the atom may absorb the energy and cause one or more electrons to jump to a higher level. When this happens, the atom is now in what is called an excited atomic state. Atoms can only hold on at this state for a very short amount of time, like nanoseconds. Think of using energy to stretch a large spring out with your hands and hold it in that position. You can only hold it for a short period before you get tired and have to release the spring and let it go back to its resting state. All atoms have many different energy levels where the electrons jump back and forth. When an atom changes energy levels by accepting or releasing energy, that is called an atomic transition. Remember from science class the Law of conservation of energy! Simply stated, "energy cannot be created or destroyed, only transferred." So when an atom makes a transition upward in energy, it is accepting this energy from another source. When it makes a downward transition, it is releasing its energy in some form. The difference between energy levels where an atom makes a transition is the total energy of the transition. So if an atom jumps from its ground state to its 4^{th} energy level, the energy it absorbed is exactly the difference between those levels.

Now is a good time to define a photon. A photon is a quantum or packet of energy in the form of light. It acts like a particle and a wave. Every photon emitted has a distinct energy, frequency, wavelength, phase, and direction. The two items from this list that cannot be changed with the photon still remaining the same are energy and frequency. Another important thing to remember is color correlates to frequency.

What are the possible 'transitions' an atom can make? Atomic transitions could be radiative or non-radiative. If light is involved the transition is said to be radiative. Atoms can collide with one another and give and take energy by collision. Better yet, once at a higher energy level, an atom can drop levels and squirt out a photon that has an energy equal to the energy level difference. This is called emission of a

photon. This can also work the other direction. An atom at a lower energy level may absorb a photon as it passes. The photon would disappear when it gives its energy to the atom. This is called absorption of a photon. Now the atom is sitting at a higher energy level, equal exactly to the energy of the photon. Photons can be absorbed by an atom if the energy levels match perfectly. The atom has to have a possible energy level difference the same as the photon's energy for them to be compatible. Photons will pass right by atoms that do not have the correct energy level difference, like visible light coming through a window. The glass atoms do not have energy levels that match visible photon energies. However, infrared light consisting of photons around 10 micrometers in wavelength is fully absorbed by the glass.

Max Carl Ernst Ludwig Planck was the mastermind behind determining how much energy each photon has. Since photon energy is directly proportional to its frequency, the higher the frequency the more energy per photon there is. Wavelength and photon energy are inversely proportional. Lower wavelengths are higher energy. The energy in each photon must match an energy level difference of an atom or molecule in order for that atom or molecule to absorb or emit the photon.

Transitions that involve light, radiative transitions, can be absorption or emission of a photon. Here two types of emission are possible. Spontaneous emission occurs when an atom at a high energy level drops on its own and emits a photon. Spontaneous emission is random in all photon characteristics, including direction. The other transition is one Einstein proposed almost 100 years ago. Stimulated emission is a process where an excited atom is grazed by a photon, the atom drops to a lower energy level and two identical photons emerge! These photons have the same energy, direction, phase, frequency, wavelength, and well they are identical. Just take my word for it.

Stimulated emission is great, however, it is not the only atomic effect necessary for lasing to occur. When a lasing material like the first laser ruby is at rest, most or all of its atoms, or the population of atoms, are at their lowest "ground" state of energy. When an outside source excites the atoms they start jumping up to an upper lasing level. If this level is a "metastable" state, the atoms can remain there longer than most upper energy states. As more of the atoms become excited and reach this metastable state, it begins to become more "populated." The point where there are more atoms in the upper lasing level than in the lower, the material is said to be in Population Inversion. When population inversion occurs, there is more of a chance that stimulated emission will occur, rather than absorption. It is necessary to have a gain of 1 or higher for lasing to begin. Population inversion allows for a higher gain.

If someone asks you how a laser works, now you can explain it to them. Here it is in a nutshell. It begins with a material, solid, liquid, or gas, called an active medium, whose atoms are excitable by some outside source. This outside source or excitation mechanism is the pump for the active medium. Excitation mechanisms can be electrical, optical, or some chemical reaction that causes atoms in the active medium to become excited or are raised to an upper lasing level. Once at an upper energy level, atoms can only stay there for a certain amount of time before they drop down and release a photon spontaneously. Ah! We are almost there. The spontaneous emission is only the beginning. Now the spontaneous photons are traveling in all directions. The photons that travel along the laser axis, or

toward the end mirrors are the photons that we are concerned about. Photons traveling “off axis” will eventually leave the side of the laser.

As the “on-axis” photons travel they collide with other excited atoms and two photons are released. That is stimulated emission. The “S.E.” in laser. This stimulated emission happens trillions of times a second. The mirrors on the end of the laser reflect the light back into the laser. Each pass of the reflected light picks up an exponential amount of new photons. This continues until there is a significant buildup of photons, and some of the light leaves the laser out of a partially reflective mirror or the output coupler. HeNe lasers are common gas lasers. The neon is the lasing gas and the helium is the buffer, or it helps the lasing process. A high voltage excites the gas to pump the neon up to its upper lasing levels.

There are four elements of a laser. They are the Active or amplifying medium – the material that is able to emit light efficiently; Excitation mechanism – the pump, it delivers energy to the active medium to pump up the atoms to excited upper lasing levels; Feedback mechanism – mirrors that reflect the correct light back into the active medium for further amplification; and Output coupler, or OC as techs call it – one mirror of the feedback mechanism that is coated to be less reflective than the HR, or High Reflector, and allows some of the light to exit the laser as a Laser Beam.

There are many types of mirror configurations. Which one is best? That depends on the laser type and its application. There are advantages and disadvantages to each like divergence, lasing mode, irradiance and volume the photons take up in the laser cavity. Alignment of the laser cavity end mirrors is not an easy task. The mirrors are usually on adjustable mirror mounts and must be aligned to reflect the light right back into the active medium. This sometimes means aligning to less that tenths of a degree. There are many alignment techniques, you will learn several later in the laser program.

Now, a little on what happens to the photons in the laser cavity. Once generated in the right direction, a photon will travel along the laser axis and as it is traveling it will cause stimulated emission and pick up a few friends along the way. By the time the initial photon reaches the other side of the active medium it will have a few million twins. This is the GAIN in the laser. Each reflection will send the photons back into the active medium and they will continue to pick up more and more each trip. When light is first generated there is a short time frame where the gain has to go beyond one. Once it does, lasing begins. However the loop gain continues to rise well above one, then relaxes down to 1 for continuous lasing and the laser power stabilizes. The “relaxed” gain is called Saturated Gain. Pulsed lasers take advantage of the high loop gain to capture the most efficient part of the lasing process.

Lasers operate in different modes across the mirrors or laser cavity. Each one of these modes, called longitudinal modes, consist of frequencies that generate waves with nodes on each end. When the waves reflect back and forth through the cavity they appear to be standing still. These are standing waves. When standing waves are present in an oscillating cavity, the amplitude is much greater. The photons are in phase and interfering constructively. When we look at these standing waves or longitudinal modes on a screen or a beam analyzer, we see what is called the Transverse Electromagnetic Mode or TEM. A single mode beam appears to be a circle. Most of the time this is the

most desired mode. Any time adjacent modes are allowed to lase they create another separate beam beside the initial. A multimode beam may have higher average power, but the single mode beam will generate far better images. A term called M^2 is a measure of the mode quality of a laser beam and will be discussed and demonstrated in future optics classes. This is the Spatial Coherence of a laser or what the laser beam looks like across the beam.

The most common types of laser pumping sources are electrical and optical. Electrical pumping is where current flow excites the atoms or molecules and usually involves a high voltage with gas lasers and a very low voltage with diode lasers. Optical pumping is where photons from one source are absorbed by the active medium of the laser. Common optical pumps are flash lamps, diode lasers, and other lasers. So one laser can be used as the excitation mechanism of another laser.

We say lasers are single wavelength, they are closer than any other source. But no source is perfect. Because of atomic movement and vibrations, some of the wavelengths are shifted a little depending on the direction of vibration or rotation during stimulated emission. Collision, thermal, and doppler broadening are the three factors in wavelength shifting. The smaller the bandwidth of a laser the better the Temporal coherence of the laser or the closer it becomes to a single wavelength.

A few laser beam characteristics are important to understand when working with lasers.

First is laser beam divergence. Divergence is the spreading of the beam as it travels out across space. Lasers as sources have very low divergence. The beams do not spread out like flashlights or car headlamps. Technicians measure beam divergence of a laser to make sure it meets specifications of customers. Irradiance of a laser beam is a very important parameter. Irradiance is the power per unit area of the laser beam and will determine if the beam is intense enough to perform the application or if it is too intense and will burn optics or detectors. Most laser beams are circular or nearly so. In order to find the irradiance you must know the power of the laser and the area of the beam. Area of a circle is pi times the square of the radius. Or you can use pi times the square of the diameter divided by four. The units of irradiance are typically watts per centimeter squared. A circular beam is measured many different ways. However, one universal measurement is the beam diameter. The beam itself is a Gaussian shape or bell shape profile with the maximum intensity in the center and lowest intensity on the edges. We cannot see this with the naked eye, so we need beam analyzers to show us contours and profiles of the beam. The beam diameter is ALWAYS measured at what is called the one-over-e-squared position. Or the 13.5% of max points across the beam. This is considered the usable portion of the beam.

When a laser beam is focused, the positive lens generates an image of the beam waist of the laser. The light, because of diffraction, has a limit to the diameter it can be focused down to. The focused spot diameter can be estimated just by multiplying the focal length of the laser by the beam divergence before the lens. When working with pulsed lasers, energy per pulse is an important parameter. The typical laser pulse is shaped like a triangle. Area under the pulse is the laser energy. So we use geometry to find the energy of the laser pulse. Find the area of a triangle by multiplying half the base by the height. With a laser pulse, half of the base is called the pulse width (t) and the peak power is the height of our triangle. So to find the energy of a single pulse you multiply the peak power by the pulse width.

When a laser beam is pulsed it is turned on and off several times a second. The time between pulses is the pulse repetition time or PRT. Because the beam is off between pulses the average power is the peak power times the duty cycle or the ratio of on time to total time. When a power meter is used to measure a pulsed laser, the readout will be average power. Average power is generally several times lower than peak power. The Frequency or Pulse Repetition Rate is the number of times per second the beam is turned on. PRR and PRT are inversely related.

Now we will look at different types of laser systems. First is an Ion laser, or in this case an Argon Ion laser. Argon gas fills a ceramic tube and a high voltage Ionizes the gas and current begins to flow. This excites the argon. Argon lasers can emit light from UV to IR. Common wavelengths are 488nm and 514.5nm. Many argon lasers are tunable with a prism. Argon lasers are used in forensic science, research, medicine, and entertainment industries. An argon laser is used in rapid prototyping where the beam hits a photopolymer and hardens it along a surface creating layers of a three dimensional part.

Neodimium doped Yttrium Aluminum Garnet, or YAG lasers, are common workhorses of our industry. The crystal active medium is optically pumped with a flashlamp or diode laser. The fundamental output is in the IR 1064nm. Nd:YAG lasers are used in every industry where we send technicians. Small YAG lasers are used to save lives in hostile countries.

Dye lasers are liquid lasers. They have a special dye that when illuminated with an argon laser the dye emits light. Dye lasers are highly tunable over a wide range of wavelengths making them very valuable in research.

Diode or semiconductor lasers are the most common laser in the laser field. They are small compact electronic devices that emit an elliptical beam. The ever popular laser pointer is a diode laser. CD and DVD players use diode lasers. So they are pretty much everywhere. Diode lasers operate off of only a few volts and not much current. The current flow across a pn junction excites atoms in the junction to emit light. The size of the entire laser is about the same size as a single grain of sand. The output facet is only 1 micron high by about ten microns wide. Many diode lasers are assembled under microscopes.