LU06: Principles of Lasers

1. Distinguish between spontaneous and stimulated radiation.
   1.1. Spontaneous: Electron-jumps from higher to lower energy levels during emission generally occur randomly, and the photons emitted in this process do not have a fixed phase relation between each other. Such a collection of emitted photons is called *spontaneous emission*. This is the same type of emission as that given off by ordinary light sources.
      1.1.1. In general, *spontaneous emission* is characterized as follows:
         1.1.1.1. A number of wavelengths—involving photons coming from transitions between many different energy levels—are simultaneously produced and hence the light is *non-monochromatic* radiation.
         1.1.1.2. The energy of the radiation is distributed among all of the wavelengths and hence the energy per wavelength is very small.
         1.1.1.3. The photons produced go off in random directions and do not have any phase correlation between them. This type of emitted light is called *incoherent light*.
         1.1.1.4. The spontaneously emitted light cannot be focused to a very small spot.
   1.2. Summarizing, absorption comes about when photons of a definite energy move the atom from one allowable energy state to another. *Emission,* a reverse process, occurs when photons are given up randomly as the atom drops to a lower energy state. We have called this *spontaneous* emission because it occurs *spontaneously* and *randomly* within certain *lifetime intervals* of the upper energy state.
   1.3. Stimulated: This type of emission occurs only when photons of a specific energy, are absorbed by an atom and move to an upper energy state. This energy is not sustainable, dropping back to the original, lower state causing an energy release (to *stimulate*) in the form of a photon. This photon has the direction, phase, and wavelength *identical* to the one that caused the stimulated emission in the first place. It is this stimulated emission—as opposed to spontaneous emission—that lies at the heart of the amplification of light by laser action. And that is why the "laser" acronym refers to "**light amplification by *stimulated emission* of radiation**." As a summary, Figure 6-4 recaps the radiative processes.

2. Define the basics of energy level diagrams.
   2.1.1. First, the classical *Bohr model* of the atom is chosen to describe orbits around a positive nucleus where electrons with different energies move. Second, though billions of atoms with billions of electrons are involved in a real situation, here we consider only a single atom with its cloud of electrons. Further, it is assumed that this atom is stationary and not disturbed by oscillations, rotations, or translations. These assumptions are not valid in a real situation, but they do allow us to describe simply the process involved.
   2.1.2. Basically when an atom is energized, an electron moves into a higher energy level but is unable to sustain that energy and moves back to its lower energy level. When that occurs, the energy is released as a photon. See Figure 6.2 a & b.
   2.1.3. Take a look at this: https://micro.magnet.fsu.edu/primer/java/fluorescence/exciteemit/index.html

3. Explain how coherent light is generated.
   3.1. In the process of stimulated emission, one incident photon colliding with an atom produces two photons of exactly the same wavelength and phase, and they both move in the same direction. This process, as we have said, is an amplification process.
   3.2. This situation is called a population inversion. If the atoms in energy level E3 are stimulated by an external mechanism such as incident photons of energy (E3 – E1), these atoms will return to the ground state E1 simultaneously, producing photons of the same energy, wavelength, and phase. These photons thus are "monochromatic" and in phase with each other. These coherent photons result from the important stimulated emission process.

4. List the conditions required for gain in a laser.
   4.1. The laser process depends on the following:
      4.1.1. A **population inversion** between two appropriate energy levels in the laser medium. This is achieved by the pumping process and the existence of a metastable state.
      4.1.2. **Seed photons** of proper energy and direction, coming from the ever-present spontaneous emission process between the upper and lower laser energy levels. These initiate the stimulated emission process.
      4.1.3. An **optical cavity** that confines and directs the growing number of resonant energy photons back and forth through the laser medium, continually exploiting the population inversion to create more and more stimulated emissions, thereby creating more and more photons directed back and forth between the mirrors, and so on.
      4.1.4. Coupling a certain fraction of the laser light (the cavity photon population) out of the cavity through an **output coupler mirror** to form the external laser beam.

4.2. As stimulated emission occurs more and more photons are added via being reflected back and forth in the laser cavity. This exponentially increases the number of photons because of sequential stimulated emission. Understanding that there will be cavity losses, once the gain is greater than the losses a laser beam will be propagated out of the laser. This is commonly referred to a gain of 1. Figure 6-7.

5. Describe the function of each component of a laser.
   5.1. Figure 6-10:
      5.1.1. Excitation Mechanism: the component that creates the energy absorbed by the Active Medium
      5.1.2. Active Medium: the component that absorbs the necessary energy to create stimulated emission of photons.
      5.1.3. Highly Reflective mirror: reflects the photons back through the active medium. Allows only a nominal amount of photons to exit. Usually has a reflectance of ~99.9%.
      5.1.4. Output Coupler mirror: reflects the photons back into the active medium. When the gain is =/> 1, allows the laser beam to exit the cavity. Usually has a reflectance of 96 - 98%.
      5.1.5. Note the various types of cavity configurations in Figure 6-11.

6. Explain TEM modes and their significance.
   6.1. The electromagnetic wave that makes up the laser beam has both electric and magnetic fields, as we know. If we examine in detail the variation in intensity—due to electric field—**across the beam**, we find many different intensity patterns that are possible, made up of patterns of bright and dark regions. These patterns of dark and bright in a plane perpendicular to the beam itself are called **transverse modes**. Different cavity geometries give rise to pure modes such as the TEM00 mode or a combination of many modes. Some of the transverse mode patterns one finds are shown in Figure 6-20.
   6.2. In practice, several TEM modes exist at the same time and overlap each other as shown in Figure 6-21. In order to operate the laser in a **pure TEM00** (~perfectly round) mode, for example, an aperture has to be placed in the beam such that the higher order modes are blocked

7. List the types of losses in a laser cavity.
   7.1. Diffraction losses, mirror misalignment

8. Define:
   8.1. Monochromaticity
      8.1.1. one pure color containing a very narrow range of wavelengths
   8.2. Line width
      8.2.1. All of the stimulated photons produced during the transition would have exactly the same wavelength and phase. In a real laser, this is far from the truth. First, the atoms in any laser medium are at a temperature higher than absolute zero and are in motion. Depending on the nature of the medium, the atoms and molecules collide with each other, vibrate, rotate, and translate. All of these motions and their combinations broaden the lasing medium's energy levels.
      8.2.2. So the resulting photons will have slightly different wavelengths and slightly different phases which leads to a broadening of the laser's wavelength or in **linewidth**.
   8.3. Far-field divergence and Near-field divergence
      8.3.1. An ideal laser would have no beam divergence (or spread) as it moves forward. A real laser does have a beam divergence. In fact, beam divergence is indirectly a measure of the coherence of the beam. Figure 6-26. Equation 6-14. By measuring the beam diameters at two different places along the beam, the beam divergence can be determined. Figure 6-27.
      8.3.2. The position where the beam converges to a minimum diameter before diverging is called the **beam waist**. In order to correctly measure the beam divergence, the beam diameters have to be measured at a sufficiently long distance from the beam waist.
      8.3.3. Two regions for beam divergence are specified. The near-field divergence region extends a distance $\boldsymbol{l}_{NF}$ from the beam waist, where $\boldsymbol{l}_{NF}$ is given by Equation 6-15.
      8.3.4. Here λ is the wavelength of the beam, d is the diameter of the beam waist, and $\boldsymbol{l}_{NF}$ is the limiting distance of the near-field region from the beam waist.
      8.3.5. By contrast, the far-field divergence is given by Equation 6-16. Where $\boldsymbol{l}_{FF}$ is any distance from the laser greater than 100 times d^2 divided by λ.
      8.3.6. So, one should perform measurements of beam diameters at distances $\boldsymbol{l}$ greater than $\boldsymbol{l}_{FF}$ to obtain the actual beam divergence.
   8.4. Beam power transmission through an aperture
      8.4.1. The relationship between the diameter of the beam and the diameter of an aperture in the path of the beam has a significant effect on how much power is transmitted through the aperture.

8.4.2. The beam power transmitted through a circular aperture of radius $r = a$, compared to the total power incident on the aperture, is given by Equation 6-21.

8.4.3. One must choose the aperture size relative to the beam size carefully when trying to get power through an aperture. To obtain a pure TEM00 output from a laser, a small aperture is used in the laser cavity. A small aperture blocks the higher-order modes, such as those shown earlier in Figure 6-21, and passes only the TEM00 mode. However, such a small aperture inevitably reduces the TEM00 beam power and increases the diffraction losses.

8.5. Irradiance

8.5.1. Intensity of laser light given by Equation 6-18. Radiant power per unit area upon the surface with a symbol E expressed in watts per centimeter squared

8.6. Coherence

8.6.1. Temporal: lasers can have coherence lengths of many meters. This type of coherence is called temporal coherence since it depends on a coherence time. Temporal coherence is maximum for highly monochromatic radiation and such radiation will have long coherence lengths

8.6.2. Spatial: This type of coherence concerns the phase relationship of different parts of the laser beam across the width of the laser beam. The larger the width of the emitting light source, the smaller will be the spatial coherence width of the emitted light.

8.6.3. Smaller beam divergences are indications of better coherence and longer coherence lengths.

8.7. Focus Ability

8.7.1. Spontaneously emitted light cannot be focused to a very small spot.

8.7.2. Laser beams can be focused to a very small spot size. The shorter the wavelength, the smaller the spot size given the same focal length lens. Ability to focus the beam depends on the quality of the beam and the lens. Equation 6-22. If you study Figure 6-31 close enough you may see that a spot size in 3 - dimensional.

9. Name the principal types/categories of lasers.

9.1. Neutral Atom: neon & cadmium

9.2. Ion: argon & krypton

9.3. Molecular: CO_2 and nitrogen

9.4. Excimer: xenon chloride and floride

9.5. Solid State: Nd:YAG and Ruby

9.6. Dye: Rhodamine 6G and B

9.7. Diode: GaAs and AlGaAs

10. Explain how spontaneous and stimulated emissions are produced noting their differences.

10.1. See #1.

11. Describe the use of mirrors with high reflectivity in a laser.

11.1. See #5.

12. Why is a CW laser less efficient than a pulsed laser?

12.1. At ignition, the gain is less than 1 since there are not enough stimulated photons in the cavity and time to output increases. The loop gain is not allowed to reach its maximum value due to this process.

13. What are the criteria by which the efficiency of a laser cavity configuration is decided?

13.1. Mode Volume

13.2. Ease of alignment

13.3. Diffraction losses

13.4. Cost of manufacturing the mirrors

14. Why is it important to align the mirrors in a laser cavity?

14.1. It is necessary to adjust/position the cavity mirrors and the amplifying medium so that they are in perfect alignment along the optic axis of the cavity. This will ensure an output of maximum power from the laser.

15. Explain how a gas laser cavity can be aligned using a low-powered HeNe laser.

15.1. The end mirrors of the laser are usually mounted on mirror mounts with adjusting screws to move the mirrors along two perpendicular axes. These mirror mounts are described in Module 1-2, Optical Handling and Positioning. Using the two screws, it is possible to adjust the mirrors to align the laser. However, before doing this, the laser tube has to be made coaxial with the reflecting beam. In order to do this, a low-powered HeNe laser is placed on a 3-point table and the laser plasma tube is mounted on an optical bench as shown in Figure 6-12.

16. How do longitudinal modes occur in a laser beam?
    16.1. A laser beam consists of a number of longitudinal modes that are characteristic of different lasers. These modes are based on standing waves created between the two reflecting mirrors on either end of the cavity. The stimulated photons in the cavity do not all have exactly the same wavelength. Hence, the photons take slightly different times to travel between the mirrors. This results in a slight difference in the relative phase of the photons.

17. Do all the longitudinal modes share the same gain?
    17.1. No they do not. Only those with an amplification greater than the threshold gain will be sustained.
    17.2. Is it better to have a larger or a smaller number of modes? Explain.
        17.2.1. Smaller as each mode competes for amplification (larger # of photons) which results in a de-amplification of the central mode.

18. A laser has an effective output aperture diameter of 1.6 mm at 488 nm. Find the beam divergence.
    18.1. $\theta_{\min=1.27\lambda/d}$ 0.39mrads. See Example 8.

19. A laser has a beam divergence of 4.2 mrads. The beam is focused by a lens of focal length 2.05 cm. Find the diameter of the focused spot.
        19.1.1. $d = f\theta$ 86μm. See Example 11.

20. Explain the terms pulse width, PRT, and PRR.
    20.1. When the laser output consists of a series of pulses, it is called a pulse train. The characteristics of such a pulse train are as follows. The time from the beginning of a pulse to the beginning of the next pulse is called the pulse repetition time (PRT). The energy of the pulse, which is equal to the area of the triangle, is also the same as the rectangle whose width is PRT and whose height is Pavg (the average power of the pulse). See Figure 6-33.

21. Explain the terms Full Width at Half Maximum and duty cycle.
    21.1. Figure 6-32: The peak of the triangle at A is Pmax (the peak power of the pulse). The pulsewidth $\Delta t_{1/2}$, distance BC, is the width of the pulse at half the height of the pulse, and is given in seconds. The pulsewidth is referred to as the full width at half maximum (FWHM).
    21.2. The ratio of pulse width $\Delta t_{1/2}$ and pulse repetition time PRT is called the duty cycle (DC). Rewriting Equation 6-24 in terms of the ratio of Pavg and Pmax, we get an expression for the duty cycle DC.

22. What role does Helium play in a HeNe laser?
    22.1. In the H_eN_e laser, Helium atoms, which are light and can be easily excited, collide with and transfer energy to the excited state of Neon through non-radiative collision transfers. The stimulated photons are produced when electrons jump from the metastable energy level to the lower laser energy level.