How Lasers Work:

Laser stands for Light Amplification by Stimulated Emission of Radiation, this article will hopefully make clear what all of that means. A scientific description of a laser beam would be something similar to this: lasers are monochromatic, they only consist of one[1] wavelength of light, coherent, all the light waves are in phase and they are collimated, meaning it produces a narrow beam of light. The three main components that are required for a laser are a pump source, an active gain medium and an optical cavity, what each do will be explained later.

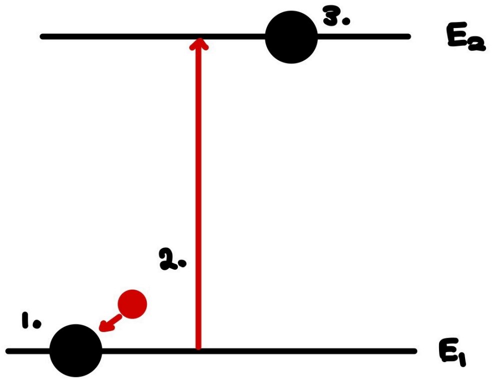
The Relevant Interactions Between Light (Photons) and Electrons:

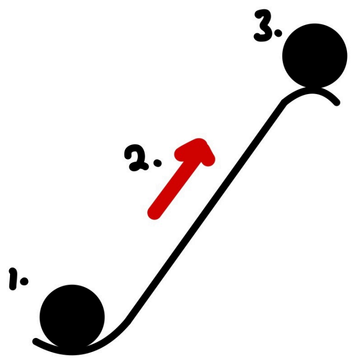
The theory behind lasers can get quite complicated to account for all the nuances in what properties a lasers can display and how it can be operated[2]. However to keep things accessible, we can consider a simplified version of the old quantum theory proposed by Einstein.

Electrons inside an atom for our purposes can be considered to exist around the nucleus at specific energy levels. Movement between different energy levels requires the electron to gain or lose the exact energy difference between the involved energy levels. The following interactions occur inside the material inside the laser, which is called the active gain medium, different materials will emit different wavelengths of light.

Stimulated Absorption:

Using the diagram as a guide, a ground state electron encounters a photon with the right energy that matches the difference between energy levels ie. $h\nu = E_2 - E_1$, where ν is the frequency of the photon and h is Planck's constant. The ground state electron absorbs this photon and moves to a higher energy level. This is similar to how a ball if given the exact rise energy will rise up to a higher potential energy, without rolling back down.



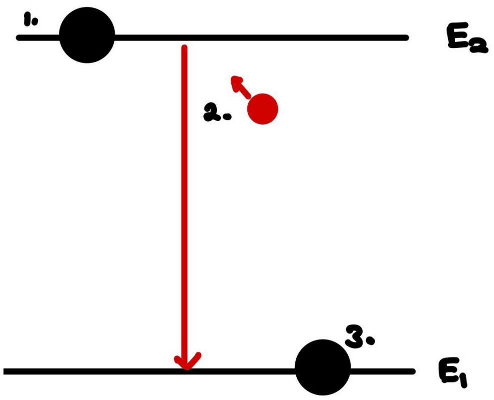


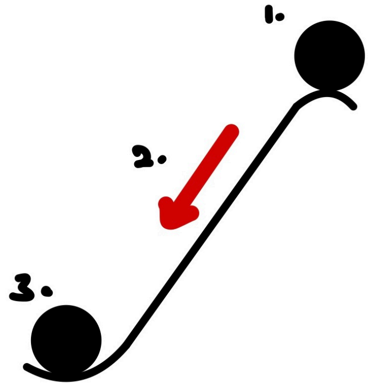
[1] A frequency-amplitude graph of a laser's output, would only have a vertical straight line at an exact frequency, however due to imperfections in mirrors the curve would be wider but still relatively narrow, implying a small range of light frequencies the laser is outputting.

[2] There are numerous different types of lasers, that involve modifying the materials and configurations of the gain medium or optical cavity. Furthermore, due to the wide variety of quantum phenomena that produce a photon lasers can be created utilising different physics from the ones discussed in this article.

Spontaneous Emission:

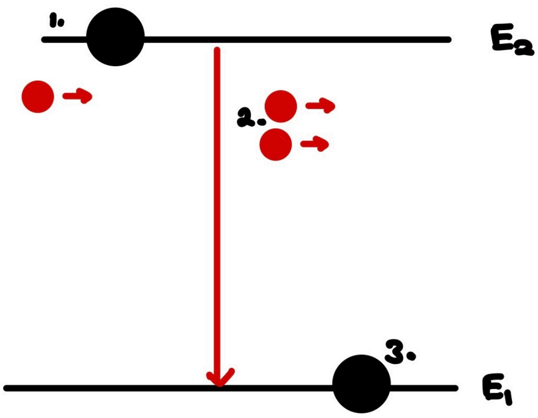
This involves a stimulated electron, one already in a higher state, emitting a photon and returning to the ground state. The emitted photon will be of the same energy as the energy levels, however it will be in a random direction with a random phase. Thus, an observer would see monochromatic light but it would be incoherent and not collimated, this is what occurs with the lighting of neon signs for example. Using the ball analogy again, the ball is at a local maximum, with a sharp node, meaning that any little force will make it lose its potential energy and fall back down.





Stimulated Emission:

It is possible that if another photon of the right energy interacts with an already stimulated electron, the electron with not absorb the photon but will drop back to the ground state and just like spontaneous emission release a photon. Unlike spontaneous emission, this photon will be in the same direction, phase and energy of the initial photon. Leaving us with double the photons we started with. As you can see this is a vital property for lasers, as this gives us a coherent light beam.

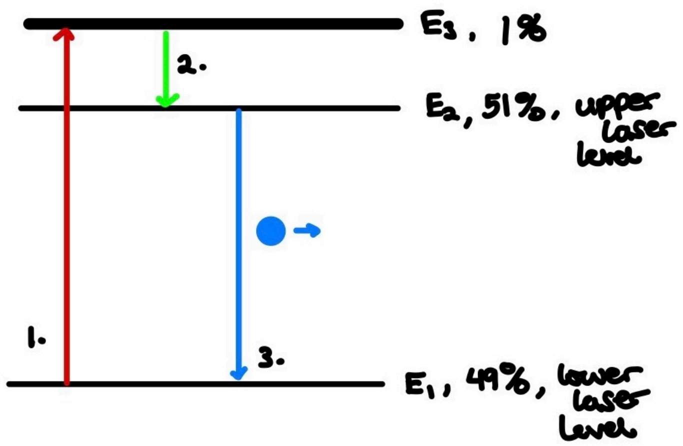


Population Inversion:

Population inversion is when there is a higher population of members in a system's excited state than in the ground state. The energy difference between the ground level and the excited level means that the photon required to pump the electron is also the same type of photon needed for stimulated emission. Then, whether we get gain (more stimulated emission) or attenuation (more stimulated absorption) is dependant on how many electrons are in an excited state compared to the electrons at the ground state, in other words there are at least 50% of all electrons in the excited state. A population inversion is created through a pumping source, which just continuous excites electrons from the ground state to the excited state (stimulated absorption), this can be done electronically, chemically or even with another laser.

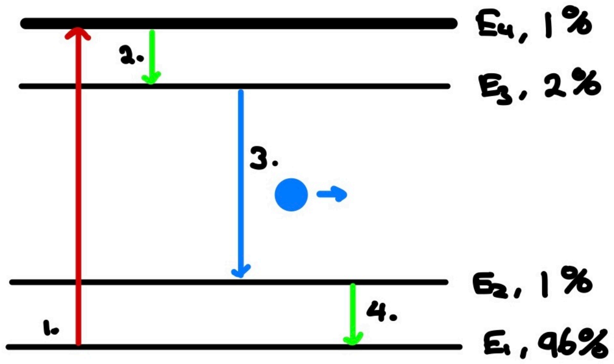
Three Level Lasers:

This model has three energy levels that the electron can occupy and the important thing about this is that the middle or upper laser level is metastable, meaning that the time it takes for an electron to decay to the lower laser level is orders of magnitude longer[3], allowing for more stimulated emission to take place. It is also important to note that there is a difference between the energies required to pump the electron from the lower laser level to the upper laser level and the energy of the emitted photon. Three level lasers are not commonly used because of the considerable amount of energy required to get 50% of the population of electrons to the third energy level[4].



Four Level Lasers:

The main advantage of four level lasers is their efficiency compared to three levels, this is achieved through a relative population inversion between the upper and lower laser level. First a small percentage of the ground state electrons are pumped to the highest energy level, the electron then makes a fast and radiationless decay to the metastable state, the upper laser level. Afterwards, stimulated emission can occur and if there are more electrons in the upper laser level then gain will be possible.

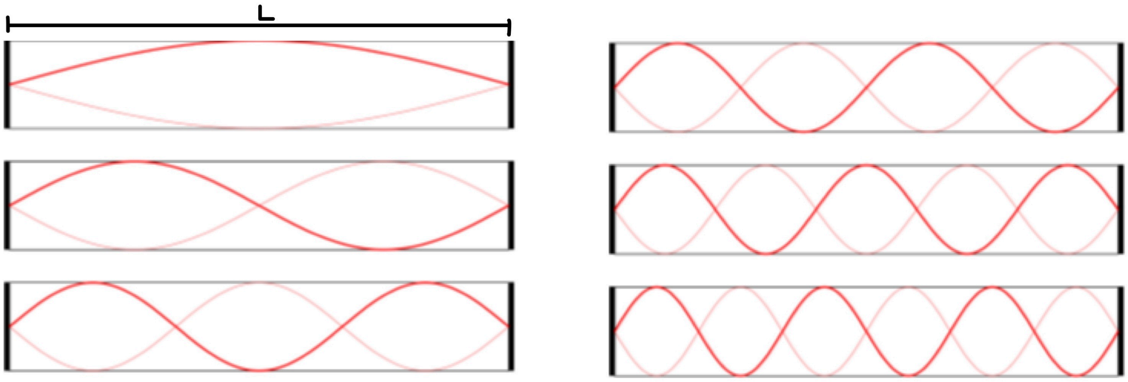


[3] Atoms with a metastable state can have electrons decay on timeframes of a millisecond, whilst spontaneous emission with an atom without a metastable state will occur at timeframes around a few nanoseconds

[4] It is not practically possible to create a two level laser, the main issue would be the inability to create a population inversion. Once an electron had been pumped, it would quickly drop back to the ground level, leaving a higher proportion of electrons in the ground state than excited state.

Optical Cavity:

The final component to a laser is the optical cavity that establishes a feedback for the emitted photons and can be even designed in a way to prevent photons from escaping the cavity. The feedback is because the emitted photons will be reflected back (by choosing a material with the conditions for total internal reflection) into the gain medium to cause more stimulated emission. Considering the photons as a wave, they are reflected into the gain medium with their phase changed by π, creating the opportunities for constructive and destructive interference, which will be a standing wave. Depending on the length of the gap between the mirrors, only certain frequencies of standing wave would be permitted inside the cavity[5]. To actually let light escape the optical cavity as a beam, one of the mirrors is made partially reflected.



The pump source, active gain medium and the optical cavity, work together to create a monochromatic, coherent and collimated beam. Slightly different theoretical foundations for a laser can result in the construction of a different laser. For example, if instead an electron in the bound band of a semiconductor was excited to a valence band of a semiconductor, then photons can be created from a semiconductor, which has led to the proliferation of cheap and accessible lasers. Another more exotic version, utilises the fact that a particle accelerator can accelerate an electron at different values and in doing so create radiation (Bremsstrahlung), which then uses magnets to direct the radiation. There are numerous possibilities with lasers.

[5] The equation for the frequency of the standing waves is, $\nu = n\dfrac{c}{2L}$, with the n for the frequency of the laser light found by: $\dfrac{\text{the frequency of emitted light}}{\text{the minimal frequency allowed}}$.

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