Light Matter Interactions & Lasers

Overview

- In this lecture you will learn,
- Light matter interactions: absorption, emission, stimulated emission
- Lasers and some laser applications
- Keywords: stimulated emission, lasers, laser applications

Induced Dipoles

- Light as we know is an EM wave and they way it interacts with matter is by ‘polarizing’ the molecules making up matter. Polarization in this context means slight disturbance in the symmetry of the electron cloud to create a dipole moment. Some molecules, like water, have a permanent dipole moment. Other molecules, are induced due to the oscillating electric field of light. In linear optics the induced dipole moment vector $\mathbf{p} = \alpha\mathbf{E}$, where α is called the polarizability of the medium.
- For isotropic materials α is a scalar but for anisotropic materials α will be a tensor and the direction of p and E may not coincide.

Induced Dipoles

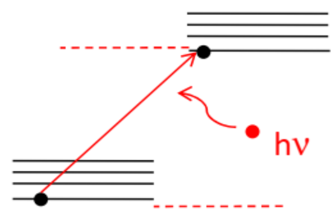
- The interaction of light with materials can be understood in terms of the scattering of light by the induced dipoles. There are two types of scattering processes, elastic and ineleastic. In elastic scattering there is no exchange of energies, i.e. photons with frequencies different from the incident photon are not produced, e.g. scattering of light by gas molecules in the atmosphere. In inelastic scattering photons of different frequencies are produced, e.g. Raman scattering.

Light Absorption

- As we saw before, electrons are situated in various energy levels in a molecule. It is possible for a photon, which is a quantum of EM radiation, to interact with an electron by causing its state to change, i.e. causing it to occupy a different energy level. When an electron absorbs a photon to move to a higher energy state that is available, it is called absorption. This is shown in the diagram below. Einstein described the rate of this transition by $W_{abs} = B_{if}N_i\rho$. Here B_{if} is the probability of transition from the initial state, i to the final state f, N is the number of electrons in i state incident per second and ρ is the density of photons.

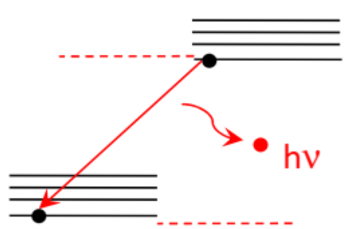
Light Absorption

- The diagram shows the schematic of the absorption process where the electron absorbs a photon of energy hν and moves to a higher energy state. The difference in energies of the final and initial state is equal to the photon energy. The closely spaced lines are the vibrational energy levels.



Spontaneous Emission

- An electron in a higher energy state can come down to a lower energy state by emitting a photon with an energy equal to the difference between the two states. In this case, the rate of this process is given by $W_{em} = A_{if}N_i$. Here A_{if} is the transition probability from state i to state f and N_i is the number of electrons in the initial state. This rate is independent of the photons density.
- The adjoining figure depicts the spontaneous emission process. Notice that it is exactly similar to the absorption process except that the directions are reversed.

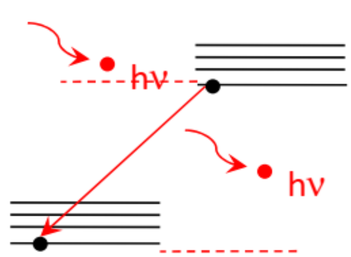


Stimulated Emission

- It is also possible to have a different emission mechanism called stimulated emission. In stimulated emission, an electron in a higher energy state is stimulated to move down to a lower energy state with energy difference hν by an incident photon of the same energy. The incident and emitted photons share all attributes such as direction, phase and polarization. In other words stimulated emission produces coherent photons.

Stimulated Emission

- The adjoining picture depicts the process of stimulated emission by an incident photon. The rate of this process is given by $W_{st.em} = B_{if}N_i\rho$. The coefficient B_{if} is the same as the absorption transition probability, N_i is the number of electrons in the excited state and ρ is the density of incident photons



Rate Balance and Population Inversion

- Using Einstein's relations for the rate of the absorption and emission processes, the rate balance for net emission can be written as, $W_{net} = N_f(A_{if} + B_{if}\rho) – B_{if}N_i\rho$

- When stimulated emission is present, it dominates over spontaneous emission so the expression is simply $B_{if}\rho(N_f – N_i)$.

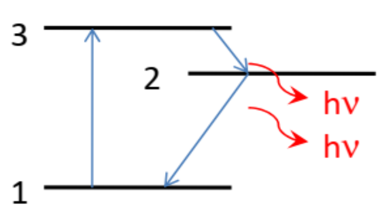
- The state f, being higher in energy compared to state i, has a lower probability of being occupied than state i. So N_f will normally be much lesser than N_i and emission rate will be negligible.

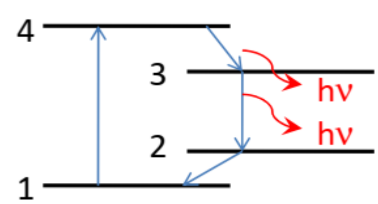
Population Inversion

- If somehow it is possible to create and maintain a 'population inversion', i.e. $N_f \gg N_i$, then using stimulated emission, we can amplify photons, i.e. an incident photon will created one stimulated photon which will create another stimulated photon and so on. In this manner we can create a light amplifier using stimulated emission. A device which does this is called a laser (Light Amplification by Stimulated Emission of Radiation)

Creating Population Inversion

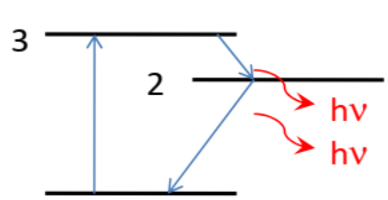
- Population inversion can be created by using multi-level systems as shown in the diagrams below. Consider a three level system as shown in the bottom left figure. If the decay from state 3 to 2 is fast but the decay from state 2 to 1 is slow, by pumping the electrons from 1 to 3, we end up in a situation where the population of state 2 is higher than 1, creating the required population inversion.

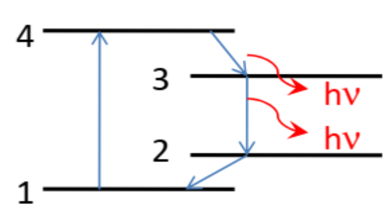




Creating Population Inversion

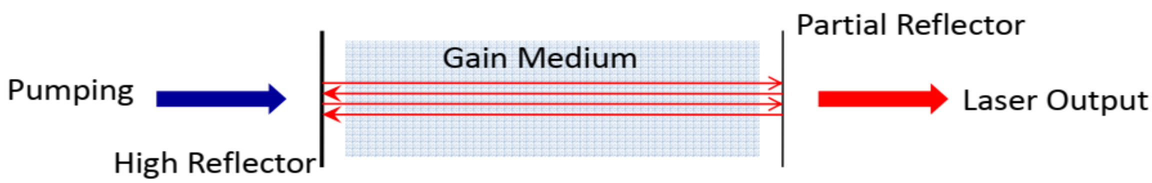
- A spontaneously emitted photon can then cause the stimulated emission of photons from electrons in the excited state. Similarly a 4 level system with the lifetime of 3 → 2 transition lifetime much slower than 4 → 3 and transition 2 → 1 transition. Electrons are pumped from state 1 to 4 and end up accumulating in level 3 creating an inverted population with respect to state 2.





Laser Resonator

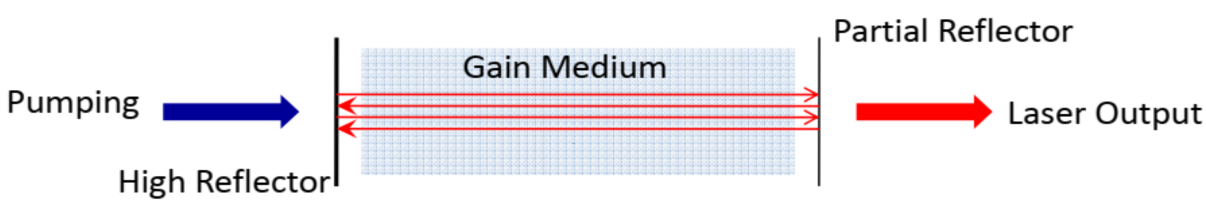
- The schematic below describes the construction of a laser resonator. Two mirrors create a open resonating structure, where one of the mirrors is only partially polished to allow some light to leak through. The other mirror has very high reflectance. The medium where population inversion can be created, called the gain medium, is kept between the mirrors.



Schematic of a laser resonator

Laser Resonator

- Some gain media exist in solid form, others can be gas mixtures and still others can be in the liquid form. Light in the cavity gets reflected multiple times each time amplifying the output. Electrons from the lower level are constantly pumped to the higher levels electrically or optically using flash lamps for instance. Laser output can be pulsed or continuous as described later.



Schematic of a laser resonator