3. Theory of Laser

3.1 Emission of common light sources-stimulated absorption and spontaneous emission

The emission process of a common light source such as electric bulb, flame, or sun is due to the interaction between the medium of the light source and external energy (optical, electric, or thermal energy). Electrons within the atoms are excited from lower energy state to upper energy state by absorbing the external energy, also called excitation of atoms. This is a process of stimulated absorption. Due to the short life time (10^{-8} to 10^{-9} s) of electrons at upper energy state, electrons at upper state are spontaneously released to lower energy state, giving off photons. The process is called spontaneous emission with the energy of photon radiated as

$$h\nu = E_2 - E_1 \tag{1}$$

where h is the Planck constant, E_2 and E_1 are the energies of upper and lower states, respectively. The spontaneous emission of atoms is totally random, as these atoms are independent of each other without correlation. As a result, the phases or polarizations of these radiative photons bear no fixed relationship so that the photons are radiated randomly in all directions. Because of the energy width at upper state, the frequencies of the radiative photons are not single but fall within a range. Under thermal equilibrium, the density of atoms at upper state is much lower than that at lower state, as described by the Boltzmann distribution law

$$N \propto e^{-\frac{E}{kT}} \tag{2}$$

Where N is the density of atoms at energy level E, k is the Boltzmann constant, and T is absolute temperature in Kelvin. Thus, the ratio between the densities of atoms at upper and lower states is

$$\frac{N_2}{N_1} \propto e^{-\frac{E_2-E_1}{kT}} \tag{3}$$

Since $E_2>E_1$, $N_2<N_1$. For example, the energy of Hydrogen atoms at the ground state is known as E_1=-13.6 eV, while the energy of Hydrogen atoms at the first excited state is E_2=-3.4 eV. At 20 °C, $kT\cong0.025$ eV and hence $N_2/N_1 \propto e^{-400} \cong 0$. This means almost all the Hydrogen atoms stay at the ground state at 20 °C. To realize light emission, external energy must be provided to excite these atoms from ground state to upper state. Generally speaking, common light emission involves two processes, stimulated absorption and spontaneous emission. Normally, the intensity of spontaneous emission is not strong and the optical energy is divergent in all directions.

3.2 Stimulated emission and light amplification

Based on the quantum theory, each energy level corresponds to an energy state of electrons. The energy of electrons is determined by the principal quantum number, n (n=1,2,..). Apart from energy E, other quantum parameters such as the orbital angular momentum L and spin angular momentum S are also used to describe the motion status of electrons in atoms. According to the quantum theory, the transition of electrons from upper state to lower state has to follow a selection rule, which demands the azimuthal quantum numbers between two transition states to differ by ±1. The probability of electron transition between energy states that do not satisfy the selection rule is extremely small. However, there exist specific energy states in atoms that do not meet the selection rule with respect to the ground state. Due to the violation of the selection rule, when electrons are excited to these states, they do not jump back to a lower state spontaneously but instead stay at these upper states with a long lifetime. These specific energy states are called the metastable states. When stimulated by external light, however, electrons at a metastable state are released to a lower state, giving off photons. This is the stimulated emission process, proposed by Albert Einstein in 1917, laying the foundation of laser invention.

The process of stimulated emission is as follows, when an atom at upper state E_2 is stimulated by an external photon with energy $h\nu$ ($h\nu = E_2 - E_1$), it is released from upper state E_2 to lower state E_1 giving off a new photon that bears the same energy, phase, polarization, and directivity as the stimulated photon. Hence, two identical photons are released with one photon incidence, and so light amplification is achieved. Such stimulated emission and light amplification is laser.

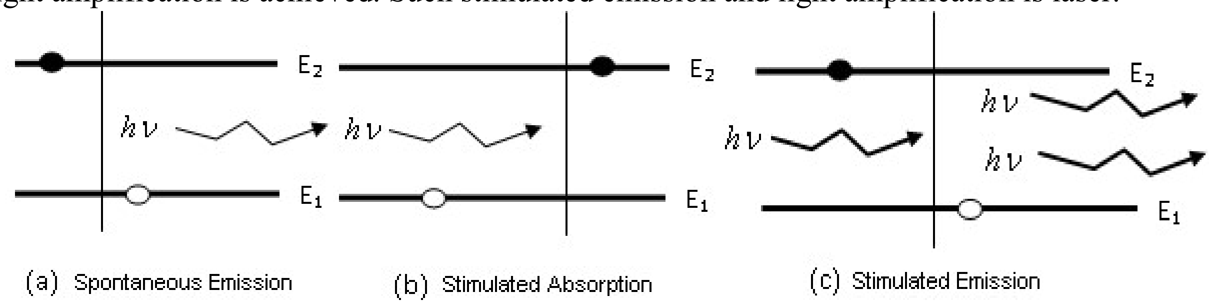

Figure 1 Schematic of three transitions of atoms in a two-energy system

3.3 Population inversion

A stimulated photon can trigger stimulated emission, but on the other hand, it is also subject to stimulated absorption. Hence, stimulated emission cannot exceed stimulated absorption unless the population of atoms at an upper state is larger than that at a lower state. This condition is called population inversion. Normally, in thermal equilibrium, almost all the atoms stay at the lower state (ground energy state). For this reason, the realization of population inversion is a necessary condition for the creation of laser light.

4. Basic Structure of Laser

Generally speaking, a laser is composed of three components.

4.1 Laser gain medium

A suitable gain medium, gas, liquid, solid, or semiconductor, is required for the creation of a laser. In the gain medium, population inversion of atoms or molecules is the necessary condition for lasing. Obviously, the existence of a metastable state benefits the realization of population inversion. So far, there are nearly a thousand gain media that can be used for laser creation from ultraviolet to far-infrared wavelength range.

4.2 Excitation source

To realize population inversion of atoms or molecules in a gain medium, the atoms or molecules in lower state must be excited to increase the population of atoms or molecules of upper states. A gas discharge lamp can be used to excite the atoms in a gain medium with the kinetic energy of electrons, called electric excitation; or a pulsed light source can be used to illuminate the gain medium, call optical excitation. Alternatively, there are thermal and chemical excitations. In general, all the excitation methods can be expresses by a technical term called “pumping”. To obtain a steady laser output, atoms must be continuously pumped from lower state to upper state to maintain a population inversion.

4.3 Resonant cavity

Upon the realization of population inversion of atoms in a gain medium, stimulated emission of light occurs. However, the intensity of such stimulated emission is weak without an optical amplifier-a resonant cavity. A resonant cavity is normally composed of two mirrors with high reflectivity, attached to either end of a gain medium. One mirror is totally reflective while the other mirror is highly reflective (slightly transmissive) so laser light can be transmitted through the second mirror. Stimulated emission is circulated within the cavity as reflected by the cavity mirrors, further amplifying the stimulated emission, and hence the realization of laser light.