Laser & Optoelectronics Techniques Engineering

Al-Farahidi University

Laser Principles

First year

Dr. Fayroz Arif Sabah

Lecture 7

- **Stimulated Emission**

Stimulated emission is the process by which an incoming photon of a specific frequency can interact with an excited atomic electron, causing it to drop to a lower energy level. The liberated energy transfers to the electromagnetic field, creating a new photon with a frequency, polarization, and direction of travel that are all identical to the photons of the incident wave (Figure (1)). This is in contrast to **spontaneous emission**, which occurs at a characteristic rate for each of the atoms/oscillators in the upper energy state regardless of the external electromagnetic field.

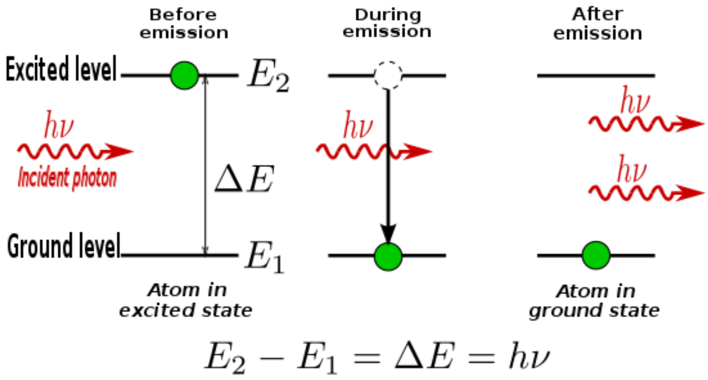

Figure (1). Energy states of stimulated emission

When an electron absorbs energy either from light (photons) or heat (phonons), it receives that incident quantum of energy. But transitions are only allowed between discrete energy levels such as the two shown in the figure above.

When an electron is excited from a lower to a higher energy level, it is unlikely for it to stay that way forever. An electron in an excited state may decay to a lower energy state which is not occupied, according to a particular time constant characterizing that transition. When such an electron decays without external influence, emitting a photon, that is called "spontaneous emission". The phase and direction associated with the photon that is emitted is random. A material with many atoms in such an excited state may thus result in radiation which has a narrow spectrum (centered around one wavelength of light), but the individual

photons would have no common phase relationship and would also emanate in random directions. This is the mechanism of fluorescence and thermal emission. Stimulated emission, in laser action as shown in Figure (2), the release of energy from an excited atom by artificial means. According to Albert Einstein, when more atoms occupy a higher energy state than a lower one under normal temperature equilibrium, it is possible to force atoms to return to an unexcited state by stimulating them with the same energy as would be emitted naturally.
In stimulated emission the emitted light wave will be coherent (i.e., in phase; see coherence) with the incoming wave.

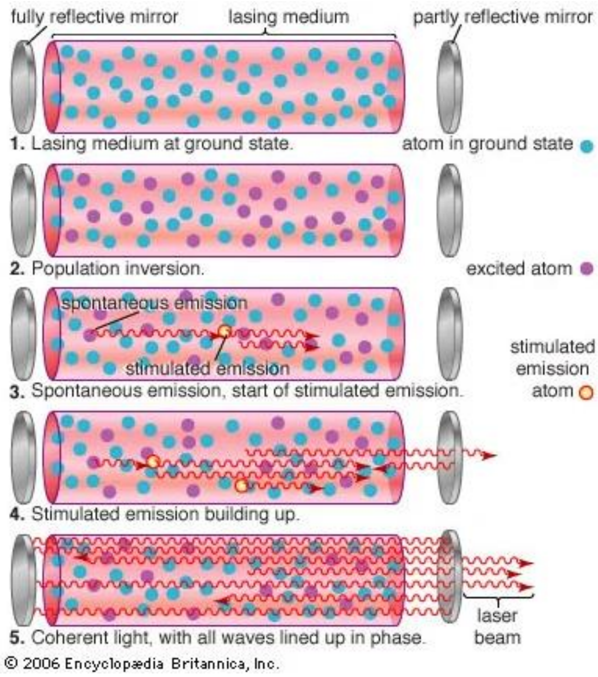

Figure (2). The process of stimulated emission

According to the American Physical Society, the first person to correctly predict the phenomenon of stimulated emission was Albert Einstein in a series of papers starting in 1916, culminating in what is now called the Einstein B Coefficient. Einstein's work became the theoretical foundation of the maser and the laser. The process is identical in form to atomic absorption in which the energy of an absorbed photon causes an identical but opposite atomic transition: from the lower level to a higher energy level. In normal media at thermal equilibrium, absorption exceeds stimulated emission because there are more electrons in the lower energy states than in the higher energy states. However, when a population inversion is present, the rate of stimulated emission exceeds that of absorption, and a net optical amplification can be achieved (Figure (2)). Such a gain medium, along with an optical resonator, is at the heart of a laser or maser. Lacking a feedback mechanism, laser amplifiers and superluminescent sources also function on the basis of stimulated emission.

- **Rate Equations and Criteria for Lasing**

The general criteria for a net photon gain to occur (i.e., a laser gain) is that the rate of stimulated emission must exceed that of spontaneous emission plus that of all the losses. We begin by determining, mathematically, the parameters involved. The rate of absorption of photons depends on the number of atoms in the lower state (i.e., the number of atoms available to absorb photons) as well as the energy density of incident photons. The second parameter should be obvious: More photons to absorb leads to a higher rate of absorption. Mathematically, the rate of absorption may be stated as:

$$r_{\text{absorption}} = B_{12}N_1\rho \qquad (1)$$

where B_{12} is a proportionality constant (Einstein's coefficient)

N_1 the number of atoms at the lower-energy state

ρ the energy density

The energy density in this case is specific: It represents the number of photons that have the exact energy for the transition between energy levels E_1 and E_2. Similarly, the rate of stimulated emission depends on the number of atoms at the upper state and can be written as:

$$r_{\text{stimulated}} = B_{21}N_2\rho \qquad (2)$$

where B_{21} is Einstein's coefficient

N_2 the number of atoms at the upper energy state

ρ the energy density

Finally, we must calculate the rate of spontaneous emission. This rate does not depend on incident energy density atoms emit photons spontaneously regardless of external conditions but solely on the number of atoms at the upper energy state available to emit a photon:

$$r_{spontaneous} = A_{21}N_2 \qquad (3)$$

where A_{21} is Einstein's coefficient for spontaneous emission

N_2 is the number of atoms at the upper energy state

It might be noted that the A coefficient for absorption is related to the spontaneous lifetime as:

$$A_{21} = \frac{1}{\tau} \qquad (4)$$

where τ is the spontaneous radiative lifetime of the upper state

Simply put, equation (3) states that the rate of spontaneous emission is equal to the number of atoms available in the upper state divided by the spontaneous lifetime (in seconds). It is calculated in units of s^{-1} (the rates are in terms of number of atoms per second).

Consider the ratio of stimulated to spontaneous emission. As previously mentioned, the rate of stimulated emission must exceed that of spontaneous emission for laser action to occur (in order to have amplification occur):

$$\frac{r_{\text{stimulated}}}{r_{\text{spontaneous}}} = \frac{B_{21}N_2\rho}{A_{21}N_2} \qquad (5)$$

The last concern is the rate of absorption of photons. We must ensure that photons emitted are not absorbed within the medium itself. If the medium absorbs more photons than were emitted by stimulated emission, the laser cannot work. This ratio is calculated directly from equations (1) and (2) as:

$$\frac{r_{\text{stimulated}}}{r_{\text{absorption}}} = \frac{N_2}{N_1} \qquad (6)$$

This relation proves the necessity of population inversion for laser action.

This is a simple introduction to the rate equations.

- **Laser Gain**

In laser physics, gain or amplification is a process where the medium transfers part of its energy to the emitted electromagnetic radiation, resulting in an increase in optical power. This is the basic principle of all lasers. Quantitatively, gain is a measure of the ability of a laser medium to increase optical power. However, overall a laser consumes energy.

The **laser gain** is a measure of how well a medium amplifies photons by stimulated emission. A photon generated in the laser cavity may interact with another atom in an excited state, stimulating the excited atom to emit a photon of the same frequency and phase. This is the laser 'gain'.

Calculating Laser Gain:

In the simplest case, we only have ions (or atoms) in the upper laser level with a number density N_2. We then obtain a gain coefficient of:

$$g(\lambda)=N_2\sigma_{em}(\lambda) \qquad (7)$$

where σ_{em} is the emission cross-section (in cm^2)

This translates into a power amplification factor of:

$$G=\exp(g)=\exp[N_2\sigma_{em}(\lambda)] \qquad (8)$$

for the incident light.

If there is also absorption from the lower laser level with a population density N_1, for example, we must take this into account and obtain:

$$g(\lambda)= N_2\sigma_{em}(\lambda)-N_1\sigma_{abs}(\lambda) \qquad (9)$$

where σ_{abs} is the absorption cross-section (in cm^2)

The last equation can be written in another way:

$$g(\lambda) = \sigma_{em}(N_2 - N_1) \qquad (10)$$

Ex.

Calculate the laser gain for a particular laser medium, having the following parameters:

Emission cross-section, $\sigma_{em} = 2.5 \times 10^{-19}\ cm^2$

Population density of the excited state, $N_2 = 5 \times 10^{17}\ cm^{-3}$

Population density of the ground state, $N_1 = 1 \times 10^{17}\ cm^{-3}$

Sol.

$g(\lambda) = \sigma_{em}(N_2 - N_1)$

$g(\lambda) = (2.5 \times 10^{-19}\ cm^2) \times (5 \times 10^{17}\ cm^{-3} - 1 \times 10^{17}\ cm^{-3})$

$g(\lambda) = (2.5 \times 10^{-19}\ cm^2) \times (4 \times 10^{17}\ cm^{-3})$

$g(\lambda) = 1 \times 10^{-1}\ cm^{-1}$

Factors Influencing Laser Gain

Several factors can impact the laser gain, which in turn affects the overall performance and efficiency of a laser system. Some of these factors are:

1- Pump Power: The amount of energy used to excite the laser medium directly affects the population densities of the excited and ground states, and hence, the laser gain.

2- Laser Medium: Different laser media have different emission cross-sections, which influences the gain coefficient.

3- Temperature: The temperature of the laser medium can affect the population densities of the excited and ground states, leading to variations in laser gain.

4- Cavity Design: The design and quality of the laser cavity can impact the overall gain by affecting the amount of feedback and the distribution of the pump energy within the medium.

- **Line Width**

The linewidth (or line width) of a laser, e.g. a single-frequency laser, is the width (typically the full width at half-maximum, FWHM) of its optical spectrum

(Figure (3)). More precisely, it is the width of the power spectral density of the emitted electric field in terms of frequency, wavenumber or wavelength.

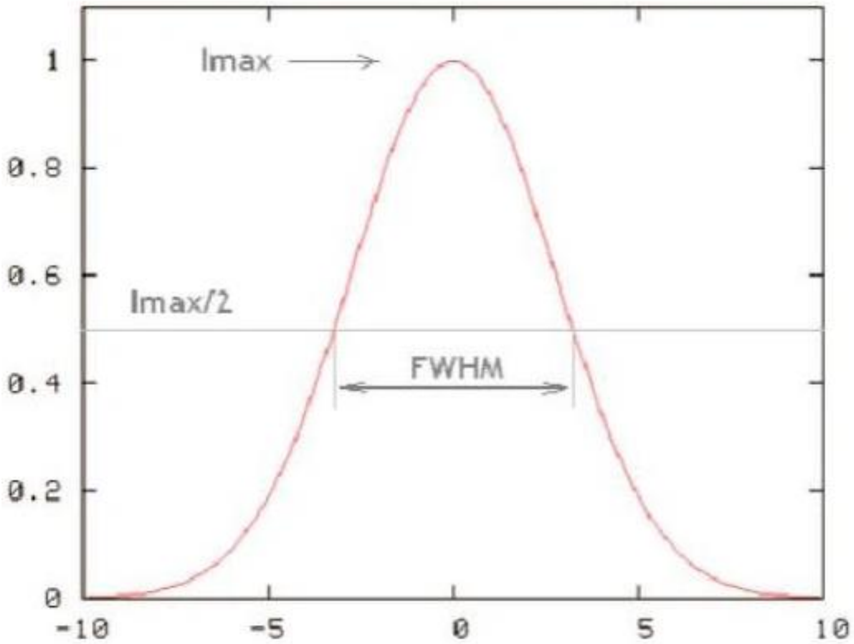

Figure (3). Laser linewidth

The line width is determined by the quality factor of the resonant cavity. The higher the quality factor of the cavity, the narrower the laser linewidth. It is a physical quantity related to space and time.

The **main reason for the linewidth generation** is the phase fluctuation caused by spontaneous radiation and the noise induced by mechanical and temperature factors. Therefore, the laser linewidth reflects the physical and frequency stability of the laser.

A simple way to define the linewidth would be to use the root-mean-square (r.m.s.) value of the instantaneous optical frequency:

$$\Delta\nu_{\mathrm{r.m.s.}} = \sqrt{\int_{f_1}^{f_2} S_{\Delta\nu}(f)\,\mathrm{d}f} \qquad (11)$$

where $S_{\Delta\nu}(f)$ is the power spectral density of the instantaneous frequency

It is more common to define the linewidth as the width of the optical spectrum, but the relation between the r.m.s. linewidth and the width of the optical spectrum is not trivial and depends on the shape of the frequency noise spectrum.

Lasers with very narrow linewidth (high degree of monochromaticity) are required for various applications, e.g. as light sources for various kinds of fiber-optic sensors, for laser spectroscopy (e.g. LIDAR ("light detection and ranging" or "laser imaging, detection and ranging")), in coherent optical fiber communications, and for test and measurement purposes.