LASER LINE- SHAPE

Analysis of a Single Pulse from a Solid State Laser

The width of the spectral line of the laser beam generated from a solid-state laser is more than 30 kHz (3×10^{10} Hz). Each spectral line contains hundreds of frequencies of longitudinal modes. For each of these modes, the operation illustrated in Figure 7.8 applies.

Natural Line Width

The first source of broaden of the spectral line, is the so-called "natural line broadening". which is the result of the uncertainty principle in determining or define the energy of the levels involved in the transition process. This source of broadening spectrum may be important in some nuclear spectra, but it is less important in the spectral analysis for atomic emission. From a physical point of view, any atom or molecule that exists alone, when doing transition between energy levels, it will emit a single photon with precisely defined energy and frequency. However, the shape of real spectral lines, is not infinitely narrow. The spectral line width ($\Delta\nu$) has already been defined as the full width of the spectral line at the half maxim of the intensity. The broaden of the spectral line of the laser beam is produced by the thickness of the energy levels involved in the emission process. As we know, the energy levels of a number of atoms cannot be represented by a sharp line but have a specific thickness. So the photons emitted from these levels do not have a specific energy or wavelength specified in Figure7.14

To find out how the spectral lines have a specific width, we would assume an excited level, which has an amount of E energy above the ground energy level. The electrons remain at the excited energy level of the average duration (Δt) before moving to the ground energy level. As we know that energy levels of a number of atoms, they cannot be considered to be quite specific energy where $\Delta E=0$ for each. This is a contradiction with the uncertainty principle of Hyzinberk. where the linewidth of the laser beam Is the result of uncertainty in determining the amount of energy of the energy levels involved in the light emission process as shown in Figure ().

uncertainty Principle: The amount of energy of any level not specified by ΔE and given by the relationship:

$$\Delta E\ \Delta t = h/2\pi$$

We already know that:

$$E=h\,\nu \quad \Rightarrow \quad \Delta E=h\,\Delta\nu$$

$$\therefore \Delta\nu=1/2\pi\Delta t$$

broadening of the spectral line as a result of this effect is called natural broadening of the spectral line.

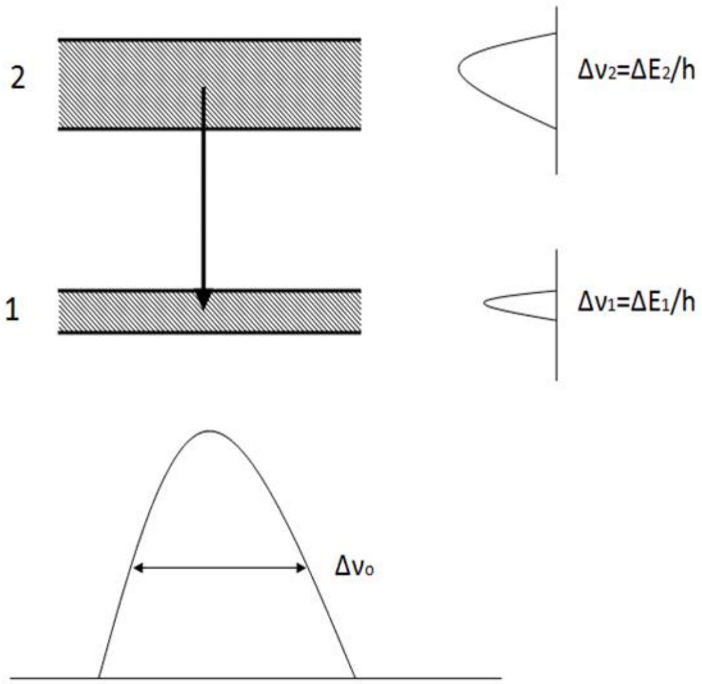

Fig. (7.14): Shows the principle of inaccuracy in determining the energy of the atomic energy levels

The excited atom at level E_2 must remain an infinite time to be accurate in determining The amount of energy equals zero. We know that the time in which the atom remains in the excited state is not definitively determined. If an atom is raised to an energy level, it will remain in a specified period of time, then return to the ground level and release photons.

$$\Delta E\,\Delta t = \hbar \quad \ldots$$

$$\Delta E = \hbar/\Delta t = h/2\pi\Delta t \quad \ldots$$

$$\Delta E = h\,\Delta\nu$$

$$\Delta\nu = \Delta E/h \quad \ldots$$

With compensation we get**:**

$$\Delta\nu = 1/2\pi\ \Delta t \ldots\ldots$$

From this equation, the long lifetime of the transition to the specified energy level, the narrower the spectral line width will be.

Numerical Example:

$$\Delta t = 10^{-8}\ s \quad ==> \quad \Delta\nu = 10^{8}\ Hz$$

$$\Delta t = 10^{-4}\ s \quad ==> \quad \Delta\nu = 10^{4}\ Hz$$

Thus, the natural broadening of the spectral line (ν_{o}), which is the result of the transition between two levels of energy E1 & E2 according to the relationship**:**

$$\Delta\nu_o = \Delta\nu_1 + \Delta\nu_2$$

$$\Delta\nu_o = 1/\ (2\pi\tau_1\ ) + 1/\ (2\pi\tau_2\ )$$

$$\Delta\nu_o = 1/\ \tau_1 + 1/\ \tau_2 \quad \ldots\ldots\ldots$$

We must realize that the emission line generated by the transition between two narrow-energy levels is an "ideal case"**.**

To understand this discrepancy between the principle of uncertainty and the limited lifetime of The existence of the excited atoms, Assume that energy levels have an broaden in energy and not a specified value , and that atoms emit as much radiation as possible at the ν_o frequency, as shown in Figure (), so the probability of emission at ν is less than the probability of emission at frequency, ν0 because the probability of distribution of the atoms is as large as possible at the middle of the energy level.

EXAMPLE 3.12:

The typical life time of an atom's energy level is about 10^{-8} seconds, while the normal line width is about 6.6 x 10^{-8} eV

Example 3.13:

an atom at excited energy level, its energy is 4.9 ev, when a photon is emitted, the atom returns to the ground energy level. the life time of the excited level is 1.2 x 10^{-13} seconds. What is the spectral line width (in wavelength) of the photon?

Let's start as follows:

$$\Delta E\ \Delta t = h/2\pi$$

But:

$$E = \hbar\ \nu$$

So:

$$1 / (4\pi\Delta t) = \Delta\ \nu \qquad \text{the answer is} \qquad 66.348 \times 10^{10}\ \ \text{Hz}$$

But if we take $\Delta\ \nu$ and turn it into a wavelength using

$$\Delta\lambda\ \Delta\nu = c$$

using

$$\Delta t\ = 1.2 \times 10^{-13}$$

$$c / \Delta\nu = \ \Delta\lambda$$

The answer is 452 µm

By taking the average life time τ for the energy level as a measure of the inaccuracy of time Δt. The broaden of the spectral line, as a result of the natural broadening of the energy level i, can be estimated by the following equation:

$$\Delta\nu_i = 1/(2\pi\,\tau_i)$$

Since the energy difference in the ground condition is zero ($\Delta\nu_i = 0$) As well as the life time, have a permanent $\tau_i = \infty$. the life time of the upper energy level, which is within 10^{-6}-10^{-10} seconds. In the case the energy levels that participate in transition have a wide range of energy, the line width of the emission, is given by the following relationship:

$$\Delta\nu_{21} = \Delta\nu_1 + \Delta\nu_2$$

The life time of the excited state, equal to the inverted probability of spontaneous emission (A_{21})

$$\tau = 1/A12$$

in general case:

$$\tau = 1 / \Sigma A_{12}$$

broaden of the spectral line Due to the natural cases of the emission of atoms, is given by the shape function of The spectral line. Where $\Delta\nu_o$ represents the full line width at a half maximum (FWHM). The shape of the function that describes the shape of the spectral line, resulting from this broadening, is the Lorentz function, and the Lorentzian distribution. As shown it is plotted in Figure 7.1 and the function given:

$$\boldsymbol{g(\nu-\nu_o)=\frac{\Delta\nu_o}{2\pi}\left[(\nu-\nu_o)^2+\left(\frac{\Delta\nu_o}{2}\right)^2\right]^{-1}}$$

$\boldsymbol{g(\nu-\nu_o)}$**:** it is a function that gives probability occurrence of a transition, at specified a frequency.

$\Delta\nu$ is the midpoint of the maximum value of probability and is called the broadening of the spectral line.

Thus, the value of the function at the top of the spectrum $\nu = \nu_o$ is

$$g_{(o)}=\frac{2}{\pi\nu_o} \quad \dots\dots$$

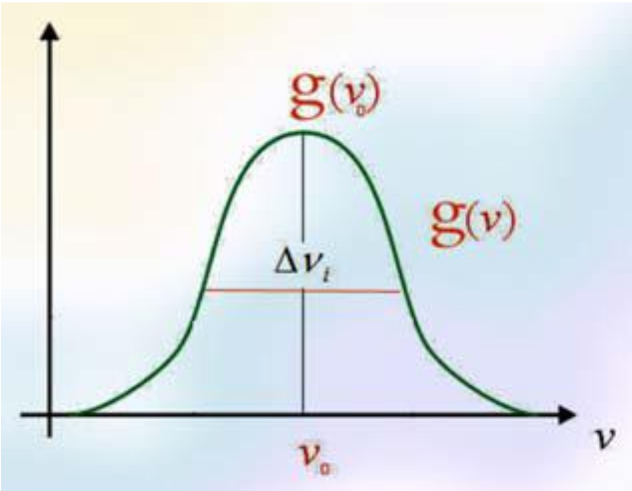

Figure 7.1: Distribution of emission intensity by Lorenz function

For example, if we take the red neon line (λ = 632.8 nm), emitted as a result of a transition between energy levels 3s where (τ_2 = 19.6 ns) and 2p4 where (τ_1 = 18.7 ns). The natural broadening is:

$$\Delta\nu_o=\frac{10^9}{2\pi\times 19.6}+\frac{10^9}{2\pi\times 18.7}$$
$$\Delta\nu_o=16.6MHz$$

Doppler Broadening

The atom emits ultraviolet and visible spectrum. When spectral analysis is performed, the separation of two spectral lines, will be determined by the Doppler broaden. and it is Resulting from the movement of atoms within the thermal energy (ambient temperature) as shown in Fig. 3.14. Where the stationary atoms emit a wavelength of $\lambda 0$, which is the centre of the spectral line. And atoms, may be emit slightly different wavelengths, due to their movement. If the atom movement is in the same path and direction as the emitted photon, its wavelength ($\lambda 1$) will be slightly shorter (ie, higher frequency) than the wavelength emitted by the stationary atom. In contrast, if the photon emitted by a moving atom moves in opposite direction to the movement of the atom, its wavelength ($\lambda 2$) is slightly longer (i.e. lower frequency). thus, if the movement of a large group of atoms, and at a different speed, the result would be a multiplication that would add a broaden to the spectral line called Doppler broadening (or Doppler widen). In Fig. 3.12, we observe the spectral line curve, where there is less energy, or slightly more than the midline energy, on either side of the highest energy (center of the line). The midline energy is produced by the emission from energy difference between two electron levels, which involved in the transition, for a group of atoms, whether these atoms are stationary or moving in the same direction at the same velocity.

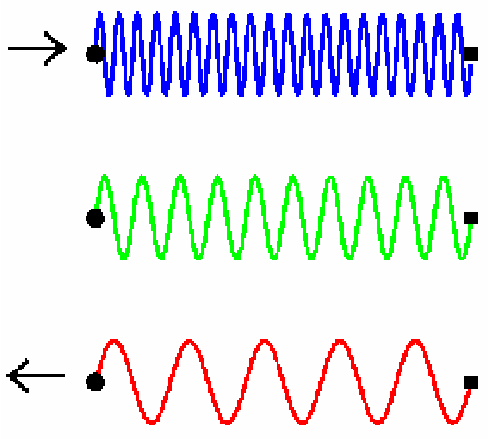

Figure 3.14: Doppler Effect.

The radiation from the atoms, moving towards the observer at a velocity of V, they have a transition frequency that differs from the frequencies emitted from those atoms when it is at stationary, due to the Doppler shift effect. Since the thermal velocities are not relative, a distribution of the atoms can be found through Boltzmann's distribution. The Doppler effect on angular frequency is given in simple form:

$$\boldsymbol{\omega = \omega_o \left(1 \pm \frac{V}{c}\right)}$$

$\boldsymbol{\omega_o}$ = Angular frequency of the emission of atoms when it at stationary position

Or the relationship can be rewrite in terms of emission frequency

$$\boldsymbol{\nu_o = \nu \left(1 \mp \frac{v}{c}\right)}$$

Where v Represents the velocity of the atom and c is the speed of the light. The shape of the spectral line g (ν-ν_o) is described as a Gaussian function, and is expressed with the function :

$$\boldsymbol{g(\nu - \nu_o)_G = \frac{2}{\Delta\nu_o}\left(\frac{ln2}{\pi}\right)^{\frac{1}{2}} exp\left[-ln2\left(\frac{\nu - \nu_o}{\frac{\Delta\nu_o}{2}}\right)^2\right]} \quad \dots\dots\dots (93)$$

Where ($\Delta\nu o$) has the following expression:

$$\boldsymbol{\Delta\nu_o = \frac{2\nu_o}{c}\left(\frac{2KT}{m}\ln 2\right)^{\frac{1}{2}}}$$

whereas:

T: is the absolute temperature of the medium

K: The Boltzmann constant m: mass of the molecule or atom of the medium.

Since the amount $\left(\frac{2kT}{M}\right)^{\frac{1}{2}}$ ***Equals the amount*** $\left(\frac{2Rt}{M}\right)^{\frac{1}{2}}$

R: general gas constant M: Molecular weight of atom of the medium

Both of which express the most probable velocity of the medium particle so that:

$$\Delta\nu_o = \frac{2\nu_o \nu_p}{c}(ln2)^{\frac{1}{2}} \dots\dots\dots$$

$$\Delta\nu_o = 7.16 \times 10^{-7}\nu_o\sqrt{\frac{T}{M}}$$

On the other hand, from the distribution of Boltzmann, we can calculate the number of atoms traveling at a speed V in the same direction as the light emitted towards the observer:

$$n(V)dV = N\sqrt{\frac{m_o}{2\pi kT}}e^{\frac{m_o V^2}{2kT}}\,dV$$

m_o= atomic mass N = total number of atoms

The distribution of radiation around the central frequency of the spectral line is given by:

$$I(\omega) = I_o e^{\frac{-m_o c^2(\omega_o-\omega)^2}{2kT\omega_o^2}}$$

This is the Gaussian shape, and spectral line broadening can be given, at a half maximum intensity, by the formula:

$$\Delta\omega_{Doppler} = \frac{2\omega_o}{c}\sqrt{2ln2\frac{kT}{m_o}}$$

Often, it is appropriate to express, by wavelength:

$$\frac{\Delta\lambda}{\lambda_o} = 2\sqrt{2ln2\frac{kT}{m_o c^2}}$$

As we move further down through the spectrum to the microwave area, the region of the transition spectra of the rotational levels of the molecule, the natural broadening of the spectral line as a source of spectrum broaden is greater than the Doppler broadening. Another condition arises to give more broadening in the spectral line. thus, When the atoms are under some pressure, some disturbances occur in the levels of rotational energy as a result of the collisions between the molecules. The so-called pressure broadening, which is reduces the differentiation between two spectral lines(resolution).

Example: Calculate the effect of the Doppler process, in broadening of the spectral line emission, from the Neon gas at room temperature، and for the laser emission known at a wavelength (632.8 nm)?

$$\Delta\nu_o = 7.16 \times 10^{-7}\nu_o\sqrt{\frac{T}{M}}$$

$$\Delta\nu o = 1.3GH_z$$

Pressure (collisions) broadening

Is a homogeneous broadening to the spectral line that arises as a result of collisions between atoms (occurring in the gaseous state) with neighbouring atoms or with the walls of the shell containing them, when these atoms are in their ground state, i.e. in the case of absorption, or between excited atoms when they are in the state of Emission. The collisions that occur cause the energy levels of the atoms to be slightly different than they were originally, so the number of ground or excited energy levels of different energies increases. Therefore, the transmission of electrons to higher levels has different energies, and thus to different wavelengths, that is, there is a significant broaden in the lines of absorption spectra, and the same process is repeated when the electrons move to low levels, which also have different energies, and thus emit different frequencies lead to broaden the Emission line. This phenomenon is more pronounced when pressure increases, as increased pressure increases the number of collisions. Their value depends on the time between two collision t_c. The shape of the resulting spectral line gives the Lorentz function, where the half width at maximum intensity, spectral (line width) is given

$$\Delta\nu_o = \frac{1}{\pi t_c} = \frac{\nu_{coll}}{\pi} \quad \dots\dots\dots\dots..(90)$$

The magnitude (t_c) can be calculated from the kinetic theory of gases where this is estimated between the free path rate and the rate of the velocity

$$t_c = \frac{(mKT)^{\frac{1}{2}}}{(8\pi)^{\frac{1}{2}} p d^2} \quad \dots\dots\dots\dots..(91)$$

Where p: gas pressure d: diameter of molecule or atom T: absolute temperature m: mass of molecule or atom. It is clear that the amount (t_c) is inversely proportional, with the pressure, and therefore the line broadening is increased by increasing the frequency of the collision.

Example: Helium-Neon Laser Gas pressure (0.67mbar) and Neon atom diameter (2.7×10^{-10}m). At room temperature, calculate the spectral line width at half maximum.

$$t_C = \frac{(mkT)^{\frac{1}{2}}}{(8\pi)^{\frac{1}{2}} P d^2}$$

$$t_c = 0.5 \times 10^{-6} sec$$

$$\Delta\nu_o = \frac{1}{\pi t_c}$$

$$\Delta\nu_o = 0.64 MHz$$

Numerical Example:

١. At room temperature, when the gas pressure is 10 Tor, the spectral line width of the laser will be 55 MHz

٢. At room temperature, when the gas pressure is 100 Tor, the spectral line width of the CO_2 laser is 500 MHz

3. When the gas pressure is more than 100 Torres, the increase in the width of the spectral line is approximately 6.5 MHz for each increase in 1 Tor

effect of the Broadening on fluorescent line emission

Figure 7.16 shows the broadening effect on the spectral line emission. Which illustrates by the comparison between the width of the line broadening due to: Natural broadening, collision broadening, Doppler broadening.

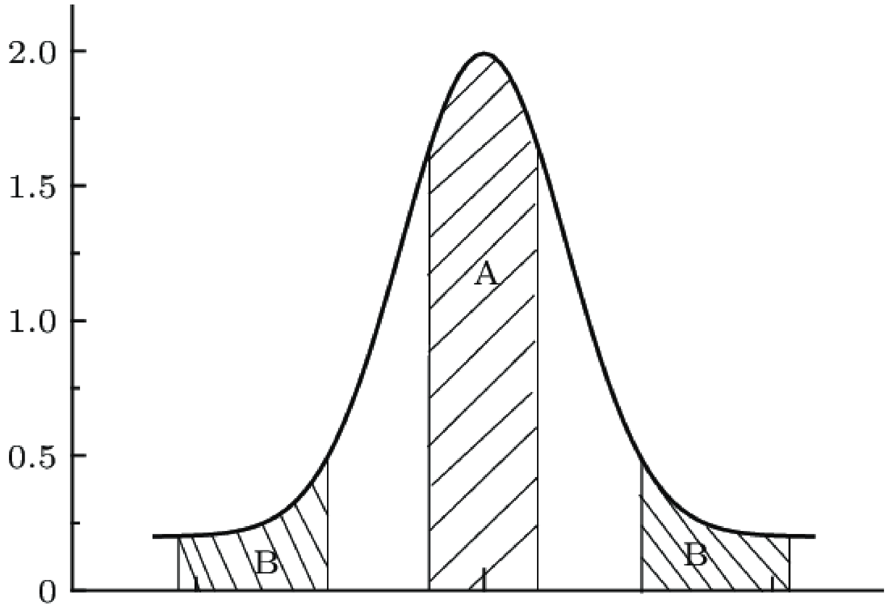

Figure 7.16: Fluorescence Linewidth broadening

Natural broadening, based on the principle of uncertainty or inaccuracy, which can be understood by quantum mechanics, Where the hypothetical life time rate can be linked for any excited energy level, to the amount of energy of this level. where atoms or molecules with short life time, it will have the inaccuracies or significant limitations in determining the measured energy of the upper level. It can be observed the curve of the emitted energy distribution as a function of the frequency takes the Lorenz form.

Collision broadening arises from spontaneous emission, and the spontaneous emission is an inevitable feature of any transition between energy levels. Where collision broadening reduces the life time of the energy level, which in turn produces an increase in uncertainty or inaccuracy in the energy of the emitted photons, leading to broadening of the emitted line spectra. The spectral line takes the appearance of the Lawrence curve, but it is larger than the appearance of the broadening of the natural line.

The broadening or width of the Doppler is one of the major contributions to the broadening of the spectral line specially in gases. Because of the thermal movement, the Doppler width is related to the distribution of the velocity of atoms or molecules. The Doppler broadening causes the wavelengths shifted toward the red and blue side of the electromagnetic spectrum. The distribution of the spectral intensity of the spectral line, with respect to the frequency, the Doppler broadening effect, takes the appearance of the Gaussian shape.

Example:

determine any of these mechanisms broaden the spectral line as, homogeneous or inhomogeneous shape. clarify your answer by the explain.

(a) Collisions between atoms in gas

(b) Impurities dispersed randomly in the crystallization of semiconductors

(c) Temperature differences between different areas of gain.

The solution:

(a). This is a homogeneous broadening because all atoms are exposed to the same effect (b). This is inhomogeneous broadening. Because the broadening or expansion of the spectral line which obtained from this effect depends on the distance between atoms and impurities. Since this distance varies from atom to atom, thus the effect is different.

(c) this effect is inhomogeneous because the different regions of the gain medium affect differently to broaden this line

same way.