There are two general classification of line broadening:

<u>Homogenous</u>: all atoms behave the same way (i.e., each effectively has the same g(v).

<u>Inhomogeneous:</u> each atom or molecule has a different g(v) due to its environment.

i.e. Broadening is Homogeneous when it affects all "atoms" equally and Inhomogeneous when it splits them into sub-groups.

في حالة الاتساع المتجانس فإن كل الذرات تشارك في عملية التضخيم لانتاج الليزر اما في حالة الاتساع الغير متجانس فإن التضخيم لليزر يحدث فقط بواسطة مجموعة محددة من الذرات

Linewidth:

In fact emission and absorption depend on photon frequency and are characterised by a linewidth

Line broadening types include:

1. **Natural, from finite lifetime (H)**
2. **Phonon, from lattice vibrations (H)**
3. **Collisional, in gases (H)**
4. **Strain, from static lattice inhomogeneities (I)**
5. **Impurity ions in host crystal (I)**
6. **Doppler, in gases (I)**

Linewidth Effects

A laser beam of intensity I (W/m^2), propagating in the z direction through a medium with gain coefficient g (m^{-1}) grows in intensity as $I = I_0 \exp(gz)$

Since g depends on wavelength, this process will increase the intensity for wavelengths near line-centre faster than for those in the wings, leading to *gain-narrowing* of the spectrum.

Linewidth properties

Atoms in either upper or lower levels of the laser medium will not interact with a perfectly monochromatic beam. This is the fact that all spectral lines have a finite wavelength or frequency spread, i.e., (fluorescent or spectral linewidth). This can be seen in both emission and absorption, and if we measured the emission of a typical spectral source as a function of frequency, we will get bell-shaped curve illustrated in Fig. (1).

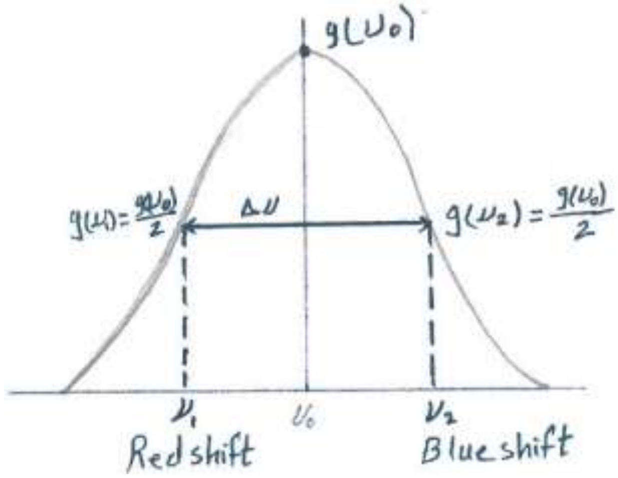


Fig. (1)

The precise shape of the curve is given by the lineshape function g(ν), which represents the frequency distribution of the radiation in a given spectral line. The precise form of g(ν) which is normalized so that the area under the curve is unity, depends on the particular mechanism causing the spectral broadening.

The most important mechanisms are collision (or pressure) broadening as a homogenous broadening and Doppler broadening as inhomogenous broadening. The shape of the emission linewidth will be either Lorentzian for homogenous broadening or Gaussian for inhomogenous broadening, as illustrated in Fig. 2, a comparison of Nd:glass (inhomogenous broadening with a Gaussian shape) and Nd:YAG (homogenous broadening with Lorentzian shape).

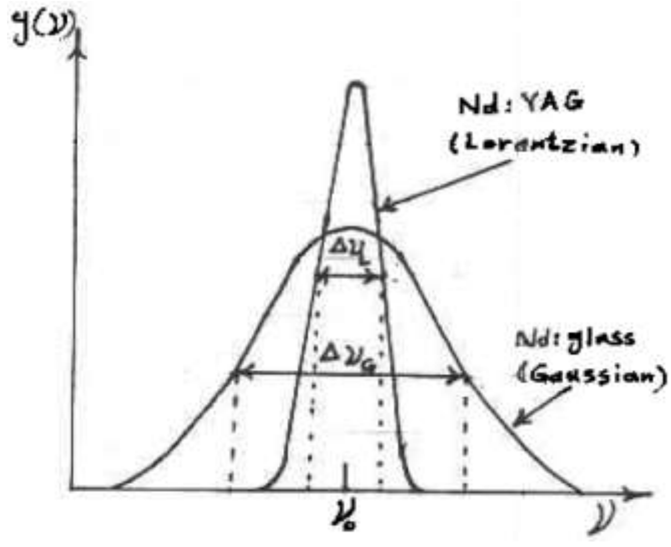
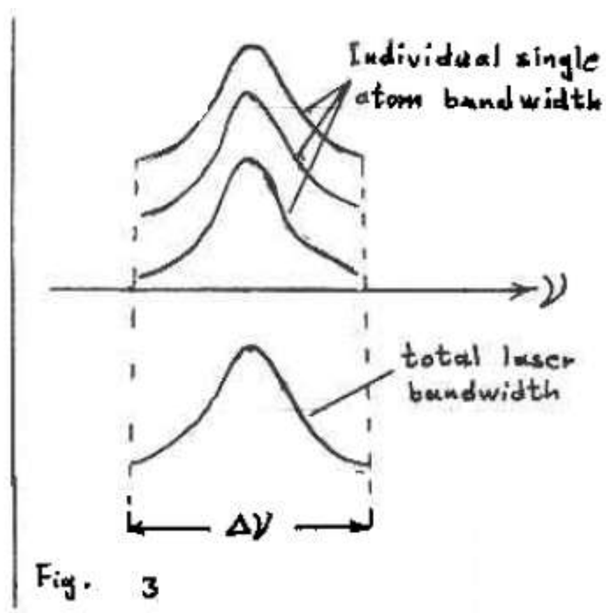


Fig. (2)

Homogenous Broadening

A line broadening mechanism is referred to as homogenous when it broadens the line of each individual atom, and therefore the whole system, in the same way.

The most important homogenous line broadening which is collision broadening in a gas (such as gas laser), it is due to collision of an atom with other atoms, ions free electron, or the walls of the resonator. In a solid, it is due to the interaction of the atom with the phonons of the crystal lattice (such as a solid – state laser material) fig. 3.



Inhomogenous Broadening

A line broadening mechanism is referred to as inhomogenous when it leads to the atomic resonance frequencies being distributed over a band of frequencies and therefore results in a broadened line for the system as a whole without broadening the line of individual atoms, fig. 4.

Doppler broadening results from the differences in frequency measured for the radiation emitted from atoms as they travel away from or towards an observer, the observed frequencies will be in the range

$$\nu *= \nu \left(1 \pm \frac{V}{c}\right)$$ **Doppler Effect Classical**

Where ***v*** is the velocity of the atom along the direction of observation and ***c*** is the speed light.

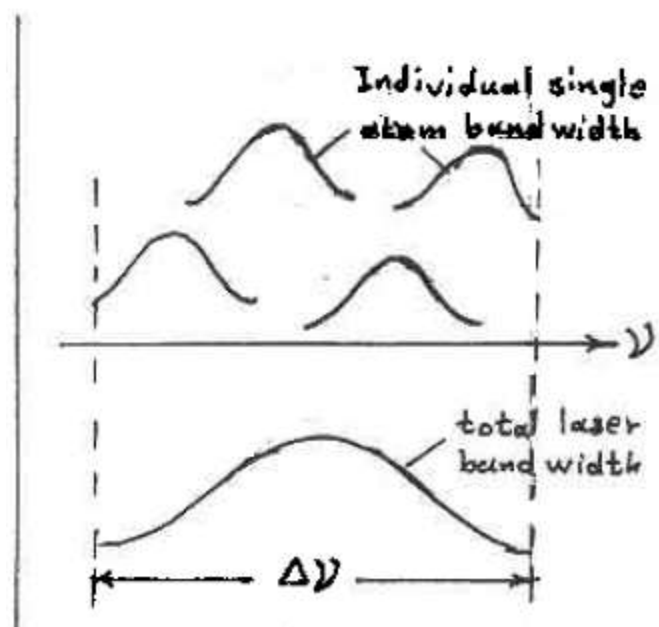


Fig. 4

Laser modes:

The output laser consists of a number of very closely spaced, discrete frequency components (very narrow spectral lines) covering a moderately broad spectral range. The discrete components are called laser modes and the spectral range they occupy is approximately the fluorescent linewidth of atomic transition giving rise to the laser output.

Longitudinal (Axial) Modes

Laser oscillations occur, when the wave within the cavity replicate itself after two reflections so that the electric fields add in phase. In other words, the mirrors form a resonant cavity and standing wave patterns are setup. The cavity resonates when there is an integer number (m) of half wavelengths spanning the region between the mirrors, as shown in Fig. 5. That there must be a mode at each mirror and this can only happen when the separation of the mirrors (L) equals a whole number multiple of $\lambda/2$.

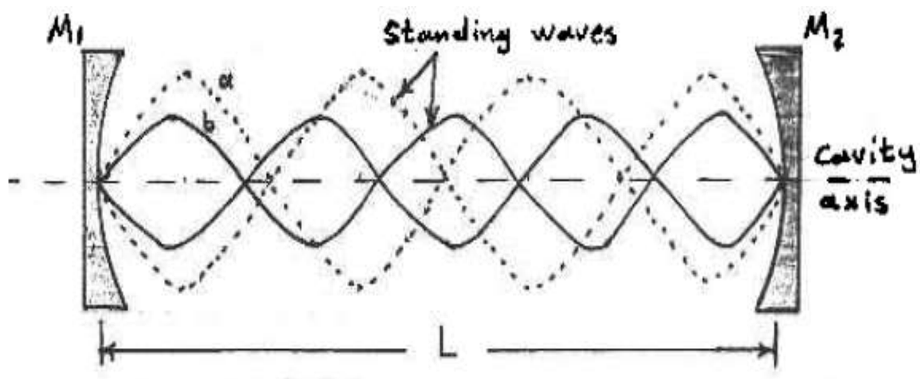


Fig. 5

Thus,

$$m\frac{\lambda}{2} = L$$

or

$$m = \frac{L}{\lambda/2} \quad \ldots (1)$$

and if the refractive index of the active medium is unity, the frequency is given as,

$$\nu_m = \frac{c}{\lambda}$$

or

$$\nu_m = \frac{mc}{2L} \ldots(2)$$

Therefore, there are an infinite number of possible oscillatory longitudinal cavity modes, each with a distinctive frequency ν_m, the frequency separation $\Delta m=1$ is given by

$$\nu_{m+1} - \nu_m = \Delta\nu = \frac{c}{2L} \ldots (3)$$

The approximate number of possible laser modes is given by the width of the Laser bandwidth divided by the distance between adjacent modes.

The longitudinal modes of the laser cavity thus consist of a large number of frequencies given by *Eq*. 2 and the separation between neighboring frequencies is equal to c/2L *i.e.* dependent only on the separation between mirrors and independent of m. , these modes are shown in Fig. 6.

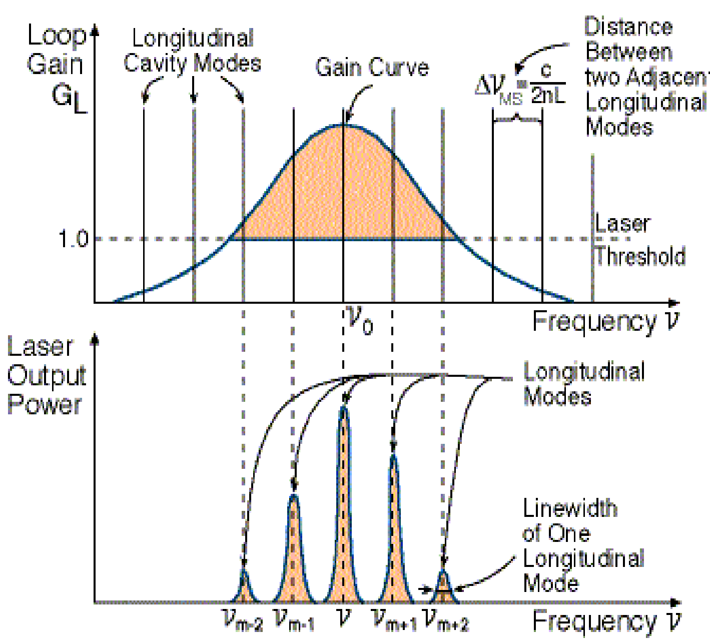


Fig. 6

عدد الأنماط التي يمكن أن تنتج ليزر تلك التي يتحقق عندها شرط الربحية اكبرمن او يساوي الخسارة كما هو واضح في المنطقة الملونة.

In fact the number of modes (m) in most lasers is very large. For Example if the central wavelength is 500nm and the mirror separation is 25cm, n has a value of 1000000, since n can be any integer, there are many possible wavelengths within the laser transition shape.

Example

The length of the optical cavity in He-Ne laser is 30 cm. The emitted wavelength is 0.6328 mm. Calculate:

1. The difference in frequency between adjacent longitudinal modes.

2. The number of the emitted longitudinal mode at this wavelength.

3. The laser frequency.

Solution

1. The equation for difference in frequency is the same as for the basic mode:

$$\Delta\nu = c/(2L) = 3*10^8\ [m/s]/(2*0.3\ [m]) = 0.5*10^9\ [Hz] = 0.5\ [GHz]$$

2. From the equation for the wavelength of the n^{th} mode:

$\lambda_n = 2L/m$
$m = 2L/\ \lambda_m = 2*0.3\ [m]/0.6328*10^{-6}\ [m\ ] = 0.948*10^6$

which means that the laser operate at a frequency which is almost a million times the basic frequency of the cavity.

3. The laser frequency can be calculated in two ways:

a) By multiplying the mode number from section 2 by the basic mode frequency:

$$\nu = m*\Delta\nu = (0.948*10^6)(0.5*10^9\ [Hz]) = 4.74*10^{14}\ [Hz]$$

b) By direct calculation:

$$\nu = c/\lambda = 3*10^8\ [m/s]/0.6328*10^{-6}\ [m\ ] = 4.74*10^{14}\ [Hz]$$

Example

The length of the optical cavity in He-Ne laser is 55 [cm]. The Laser bandwidth is 1.5 [GHz]. Find the approximate number of longitudinal laser modes.

Solution

The distance between adjacent longitudinal modes is:

$\Delta\nu = c/(2L) = 3*10^8$ [m/s]/(2*0.55 [m]) = $2.73*10^8$ [m/s] = 0.273 [GHz]

The approximate number of longitudinal laser modes:

m=Laser bandwidth /$\Delta\nu$= 1.5 [GHz]/0.273 [GHz] = 5.5 ≈ 5

The importance of Longitudinal Optical Modes at the Output of the Laser

The importance of longitudinal modes of the laser is determined by the specific application of the laser.

1. In most high power applications for material processing or medical surgery, the laser is used as a mean for transferring the energy to the target. Thus there is no importance for the longitudinal laser modes.
2. In applications where interference of electromagnetic radiation is important, such as holography or interferometric measurements, the longitudinal modes are very important.
3. In spectroscopic and photochemical applications, a much defined wavelength is required. This wavelength is achieved by operating the laser in single mode, and then controlling the length of the cavity, such that this mode will operate at exactly the required wavelength. The structure of longitudinal laser modes is critical for these applications.
4. When high power short pulses are needed, mode locking is used. This process causes constructive interference between all the modes inside the laser cavity. The structure of longitudinal laser modes is important for these applications.

Transverse modes

The longitudinal modes all contribute to a single spot of light in the laser output, whereas in general if the laser beam is shone onto a screen we observe a pattern of spots. These are due to the transverse modes of the cavity.

In most cases, however, waves which are traveling just off-axis and are able to replicate themselves after covering a more complex closed path in the resonator are referred to as transverse electromagnetic modes TEM_{mn}. They are characterized by two integers m and n, so that as Fig. 7 shows, we have TEM_{00}, TEM_{01}, TEM_{11}, … etc. modes (m gives the number of minima as the beam is scanned horizontally and n the number of minima as the beam is scanned vertically).

<u>or</u>

The intensity distribution across the width of the cavity is the Transverse Mode pattern.

The transverse mode determines the beam shape. The general form for the transverse electric modes is: TEM_{mn} where m is the number of modes in x-direction and n the respectively number of nodes in y direction.

The proffered transverse mode that oscillates within the cavity depends on: (a) On the aperture of the gain medium and (b) the radial dependence of the gain. A single transverse mode laser is restricted to give TEM_{00} output.

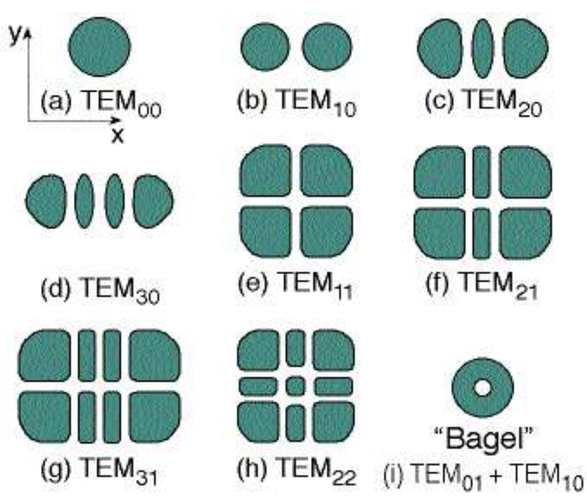


Fig. 7

A small misalignment of the laser mirrors causes different path length for different "rays" inside the cavity. Thus, the distribution of intensity is not the perfect Gaussian distribution.

The TEM_{00} transverse mode is the most wildly used, and this for several resonator the flux density is ideally Gaussian over the beam cross section; it is completely spatially coherent the beam's angular divergence is the smallest; and it can be focused down to the smallest – sized spot.

The properties and propagation of a Gaussian laser beam:

In a gain medium located within an optical resonator, the TEM_{00} Gaussian mode that develops when the single – pass gain exceeds the cavity losses have a Gaussian profile at the mirrors in the direction transverse to the direction of propagation of the beam, Fig. 8.

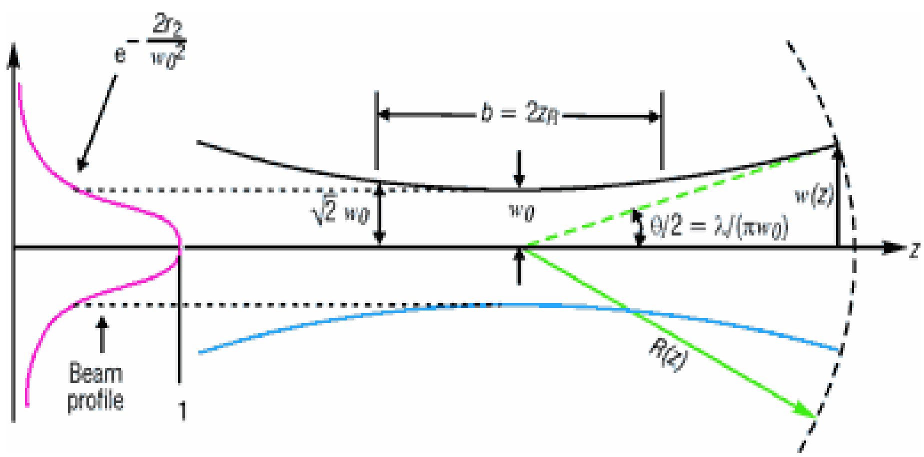


Fig. 8

A Gaussian laser beam has the following properties:

1. The beam has a Gaussian transverse profile at all locations. Such a Gaussian beam can be characterized completely at any spatial location by defining both its 'beam waist' and its 'wavefront curvature' at a specific location of the beam.

2. A Gaussian beam always has a minimum beam waist (w_o) at one location in space.
3. The transverse distribution of the intensity of a simple Gaussian beam is of the form

$$I = I_o e^{\frac{-2x^2}{W^2}}$$

Where I_o is the maximum intensity and w is the beam radius inside of which 86.5% of the energy is concentrated, as shown in Fig. 8.

The Gaussian beam minimum waist w_o for a typical laser resonator mode occurs in the region between the two mirrors of an optical resonator. For example, the minimum beam waist w_o in a confocal optical resonator (R_1=R_2=L) occur halfway between the two mirrors. As the Gaussian beam propagate it expand and diverges from that location, such that the beam waist at a distance of ±z from the minimum beam waist w_o can be described as

$$w_z = w_o \left[1 + \left(\frac{\lambda z}{\pi w_o^2}\right)^2\right]^{1/2}$$

The beam wavefront curvature of a Gaussian beam at a location z, in term of the minimum beam waist w_o and the wavelength λ, is given by

$$R_z = z \left[1 + \left(\frac{\pi w_o^2}{\lambda z}\right)^2\right]$$

The angular spread of a Gaussian beam for a value of z is given by

$$\theta_z = \frac{2\lambda}{\pi w_o}$$

As shown in Fig. 8.

The θ_z term is the full angle, at a given location z, over which the beam reduces to half of its maximum intensity at the center of beam.

Example/ an He-Ne laser operating in a single TEM_{00} mode at 632.8 nm has a mirror separation of 0.5 m with mirrors $R_1=R_2=1m$, calculate the radius and wavefront curvature of the Gaussian laser beam at a distance of 10m away from the minimum beam radius (w_o) of 0.3m?