Module 1 : Introduction and Background Material

Lecture 6 : Properties of Lasers

Objectives

In this lecture we will look at

- Control of spectral and temporal properties of a laser by the resonator.
- Longitudinal and transverse modes of a laser.
- Some important applications of lasers.

We begin by recalling that a laser consists of a medium with gain placed in Fabry -Perot Resonator. We now discuss how this can be used to control the light emission from the laser.

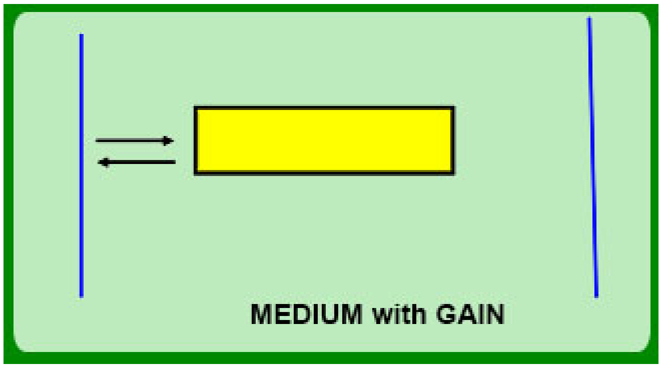

Figure 6.1 Schematic of a laser

- Aperture over which gain is available is limited by the diameter of the gain medium, a laser rod for solid state lasers or a discharge tube for the gas laser. Often, to access only the uniformly pumped region the aperture is further reduced by putting an additional aperture.
- Laser beam will diffract as it travels like any finite size beam of light must
- On reflection from plane mirror, it will diverge even more.
- Some part will not enter the gain region thus implying a loss because only the part of the wave that travels through the gain region amplifies.
- To avoid this loss the mirrors are generally replaced by spherical mirrors.
- The curvature of the two mirrors and the distance between them determines the net diffraction loss. This can be optimized once we know our gain medium and the spatial dependence of the gain.
- Only some transverse field distributions survive which reproduce themselves on successive reflection.
- such field distributions are called modes of the laser.
- Field distributions in plane perpendicular to the direction of propagation are called transverse modes
- frequencies which fulfill the earlier requirement that round trip phase should be an integral multiple of 2π give stationary field distributions are called longitudinal modes
- frequency separation between two adjacent longitudinal modes is given by $\Delta\nu = c/2l$ where *l* is the optical length (product of physical length and refractive index) of the resonator. For an optical length of 1m, Δν is 150MHz corresponding to Δω =9.42rad/sec

Any finite aperture monochromatic wave will expand due to diffraction.
There are several solutions of the scalar wave equation

$$\nabla^2 u + \frac{\omega^2}{c^2} u = 0 \qquad (6.1)$$

which preserve their form as they travel. One of these, the TEM_{00} mode has the form

$$u(\rho, z) = \frac{w_0}{w} \exp\{i(kz - \arctan\frac{z}{z_0} + \frac{k\rho^2}{2R})\} \exp(-\frac{\rho^2}{w^2}) \qquad (6.2)$$

where ρ is the radial coordinate perpendicular to the z axis which is the direction of propagation. For this beam, the size is smallest at z=0 –it expands as |z| increases. The radial distance at which the intensity falls by a factor of e^2 is *w* given by

$$w^2 = w_0^2(1+\frac{z^2}{z_0^2}) \qquad (6.3)$$

Here, z_o is the distance over which the beam area becomes double of its minimum value. It is called the Rayleigh range and is given by

$$z_0 = \frac{\pi w_0^2}{\lambda} \qquad (6.4)$$

Radius of curvature of the Gaussian beam is infinite at z=0 corresponding to a plane, as z increases it decrease to a minimum value at $z=z_0$. There after it keeps increasing to become infinite at infinite z.

$$R(z) = z(1+\frac{z_0^2}{z^2}) \qquad (6.5)$$

- If we put a spherical mirrors at any *z* with the radius of curvature matching with *R(z)* the Gaussian beam with fold back .Clearly Gaussian mode is one of the transverse modes for a Fabry Perot cavity with spherical mirrors.
- One of the surprising facts that emerge is that the divergence of a laser beam is inversely proportional to its beam waist. For a laser to reach a long distance with detectable intensity one need to start with a large dia beam and not a small size beam. There is a whole family of Gaussian like beams. In addition we have Bessel beams which travel without diffraction and many beams with singularities. Nonlinear optical propagation of such beams is a very active area of research at present.

SPECTRAL AND TEMPORAL PROPERTIES:

Spectral and temporal structure of laser is determined by several interesting phenomena.
For laser action at a particular frequency we need:

- Gain at that frequency should exceed the loss at that frequency.
- The round trip phase at that frequency should be an integral multiple of 2п.
- If there are several frequencies that satisfy these two conditions the laser would operate at the one with highest net gain if all frequencies share the gain. This is true if the lasing transitions is homogenously broadened i.e. all lasing atoms or molecules are identical.

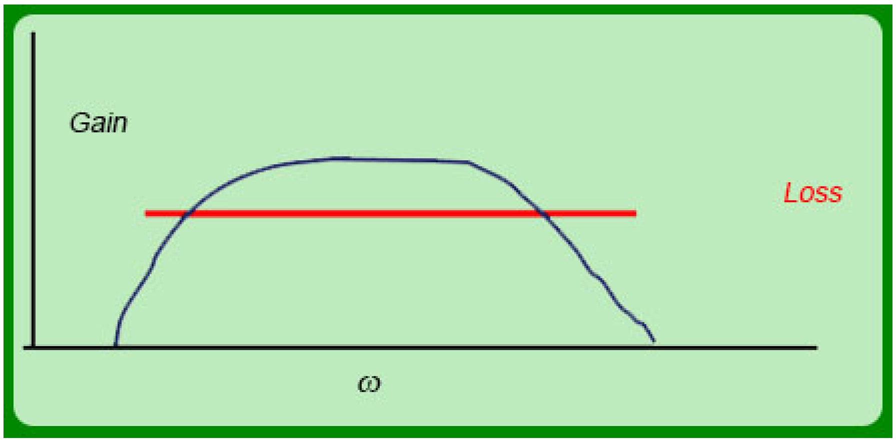

Figure 6.2 Gain and loss spectral dependence

- For inhomogenously broadened transitions different lasing atoms or molecules have different lasing spectrum, all those modes will lase which have gain above the loss line.
- To get a really narrow line width of the laser we need to restrict it to single longitudinal mode.
- To do this, introduce a frequency selective element,a diffraction grating, a prism or another short period Fabry Perot resonator or a combination of these between the two laser mirrors. A pioneering example of this is the Nitrogen laser pumped tunable dye laser first reported by Haenche. A fluorescent dye laser normally emits a wide spectrum.

To narrow the lasing bandwidth Haenche. replaced one of the laser resonator mirrors by a retro-reflecting grating and then introduced a FabryPerot etalon in the laser resonators. This is equivalent to introducing a loss mechanism in the resonator because the grating disperses different wavelength in different directions. Thus only a selected wavelength is reflected back into the gain mediun. Of the spectral part reflected by the grating the Fabry Perot etalon has high transmission only for a narrow bandwidth except which all other wavelengths suffer huge losses and are eliminated.

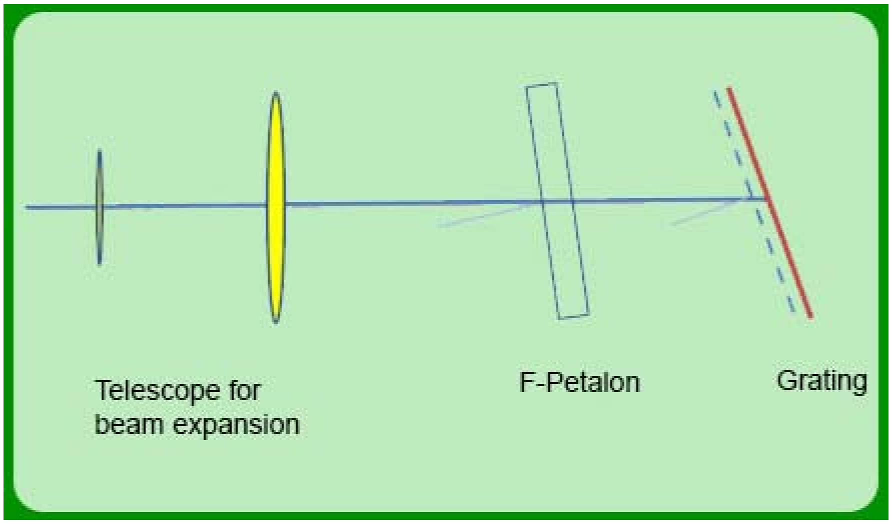

Figure 6.3 The grating and Fabry-Perot etalon combination replaces one of the mirrors in tunable dye laser, The telescope serves to expand the laser beam to increase the grating resolution. This arrangement was first used by T W Haensch, Applied Optics 11,895(1972).

- Similarly, if a shutter is placed in the laser resonator the round trip gain exceeds loss only when the shutter is open. This Q-switching gives short pulse lasers with pulse duration in nanoseconds.
- A second very important method of obtaining much shorter pulses is called mode locking. Consider a laser medium with gain spectral profile as shown in figure below.
- In this case all longitudinal modes with frequencies within positive net gain region will lase as shown by the comb of frequencies in the figure. The separation between adjacent modes is ω_R which is determined by the round trip optical length of the resonator.

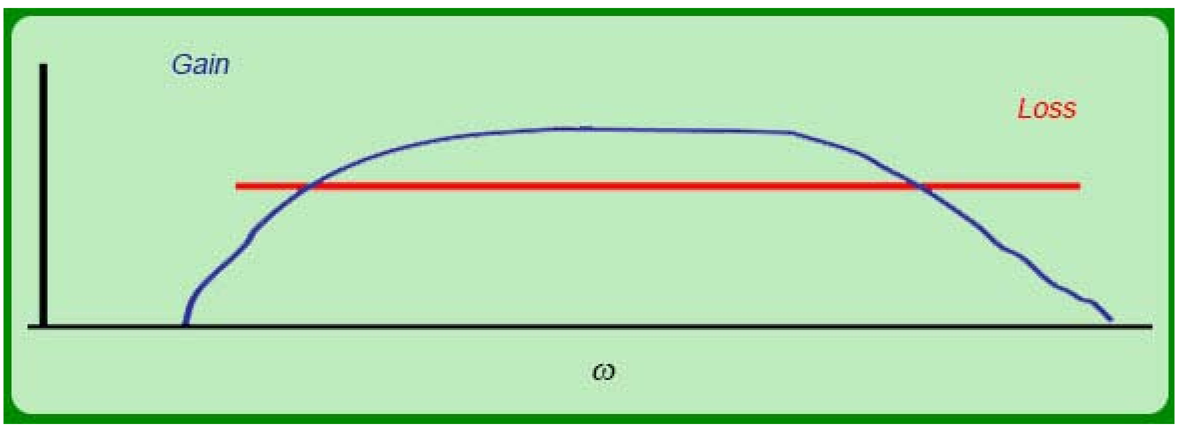

Figure 6.4 Gain and loss spectral dependence

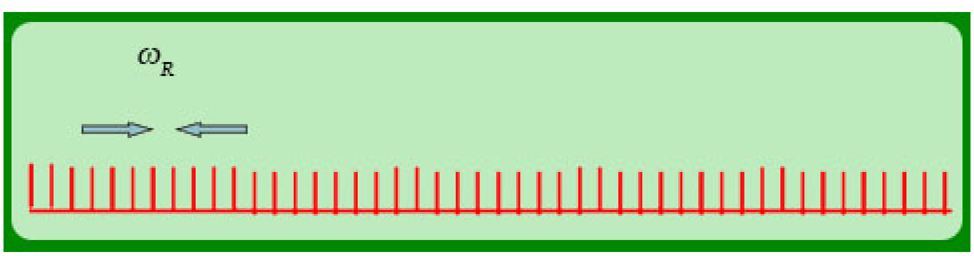

Figure 6.5 Longitudinal modes frequency comb over the losing bandwidth

- If we further assume that all modes have the same phase and equal amplitude the total coupled out field is given by

$$E(t)=E_0\sum_{-(N-1)/2}^{(N-1)/2}\exp(i\omega_0+n\omega_R t) \qquad (6.6)$$

which is easily summed to give

$$E(t)=E_0\exp(i\omega_0 t)\frac{\sin(N\omega_R t/2)}{\sin(\omega_R t/2)} \qquad (6.7)$$

- This is a series of pulses with width of the order of $N\omega_R$ and repetition rate of $\omega_R/2\pi$ as shown in the figure 6.5

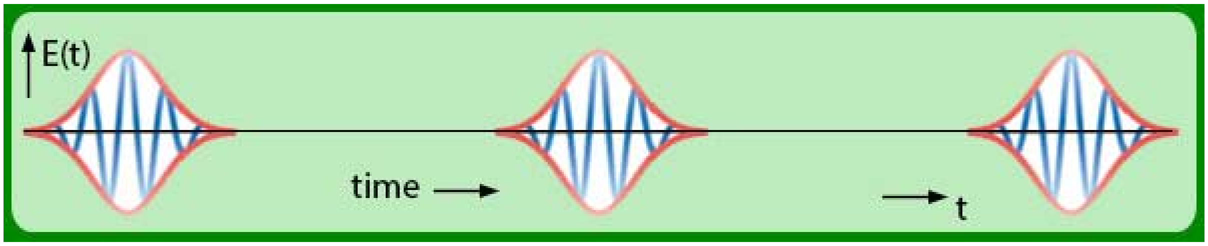

Figure 6.6 Time variation of E- field in a mode locked pulse brain

- In a real laser the mode spacing is modified by dispersion and its variation with population inversion. Several techniques are used to compensate for such effects and achieve mode locking and ultrashort pulses in the 100fs range.
- Additional techniques are used to obtain even shorter pulses.
- The spectrum of mode locked pulse train is obviously and by construction the frequency comb.
- However, if a single pulse is extracted out of this train and its spectrum measured it will be a continuous peaked spectrum with width inversely proportional to the time duration of the pulse.
- Frequency comb can be self calibrated if it spans a frequency range broad enough to contain a frequency and its second harmonic.
- Haensch and Hall were awarded Nobel prize in 2005 for such precise and absolute frequency measurement.

- Since length and time are both measured most precisely in terms of the periods of optical waves, the speed of light cannot be measured any more accurately than these standards. It was therefore decided to fix the speed of light in vacuum as a fixed quantity and define the meter, the SI unit of length, as *the length of the path traveled by light in vacuum during the time interval of 1/299 792 458 of a second*.
- This high precision control on the properties of lasers provides for ever expanding list of applications of lasers. For example:

    - Directional control: in displays, in defining a straight line in civil engineering,
    - Time control: oscillator with frequency controlled to part 1 in 10^{14} provides the new time standard.
    - Very broad band communication, becomes possible.
    - Interferometer provides standard of length
    - Laser pulses can be made very short - ~ fs. Allows time dependent studies of molecular motion, intermediates in chemical reactions, even selective chemical reactions. (Chemistry Nobel prize awarded to Ahmed Zewail in 1999) http://www.zewail.caltech.edu/nobel/index.html

- When focused tightly such ultra-short pulses provide very high intensities and the electric field of the optical wave exceeds the field that binds electrons in an atom. *This extreme nonlinear* optics is now growing very rapidly.
- Very narrow band lasers are also used for cooling atomic vapor to a very low temperature where the whole sample behaves like a single quantum entity. This has provided very important applications as well as experimental tests of very basic aspects of the quantum theory.

RECAP

In this lecture we have learned about the

- Basic properties of laser beams are reviewed briefly.
- Techniques of controlling spatial, temporal and spectral properties of laser beams are outlined.

- Some applications are mentioned.