

PROPERTIES OF LASER LIGHT

The laser light has specifications that are not available in ordinary light such as sunlight or lamps produced by common light sources such as incandescent lamps, fluorescent lamps and high intensity arc lamp. Natural light has many different wavelengths, the direction of which is emitted to all directions, and it is not coherent it means that There is no temporal relationship between the different waveforms emitted from the source. Laser radiation has certain properties not found in ordinary electromagnetic radiation: to understand the unique characteristics of laser light by knowing its contrast with other light from, less unique sources.

1 Monochromaticity

The light consists of electromagnetic waves that travel through space and at specific wavelengths. This wavelength determines the color of the radiation, where each color has a specific wavelength. Monochromatic light means one frequency or one wavelength (expressed by monochromatic and consists of mono meaning one and chromo meaning color).

we examine the white light which is the color that is interpreted by the mind when it sees all the colors combined together. When we pass white light through a prism, it analyzes into a range of different colors in it, as shown in Figure 2.2.

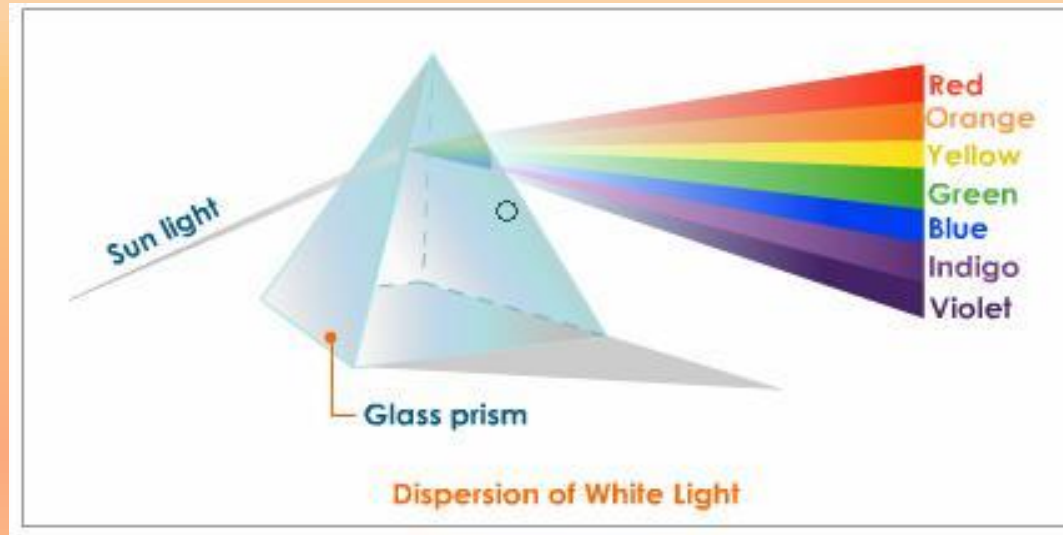


Figure 2.2: White light passing through a prism

The monochromatic light is the theoretical concept of the so-called spectral line means one wave length (λ_0).

of Fig. 2.3, in fact each spectral line has a limited spectral width ($\Delta\lambda$) around its central wavelength (λ_0).

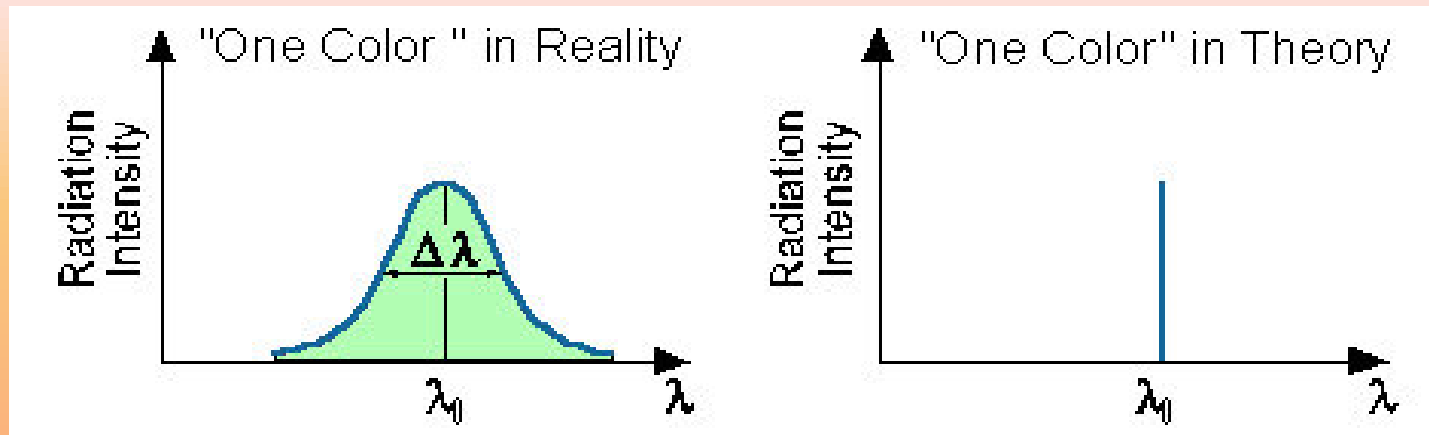
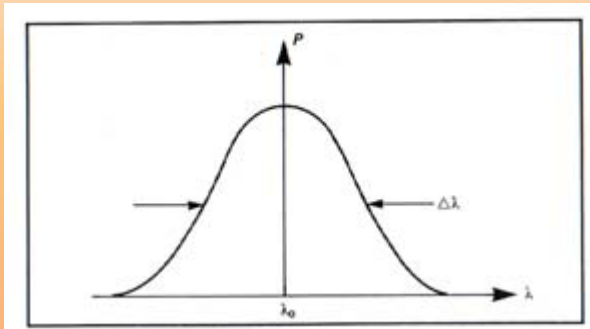


Figure 2.3: Dispersion of white light through a prism

Light from all common light sources contains many different wavelengths. White light contains most wavelengths of the visible region of the electromagnetic spectrum, or, in other words, most of the colors of the visible spectrum.

Monochromaticity



Nearly monochromatic light

Example:

He-Ne Laser

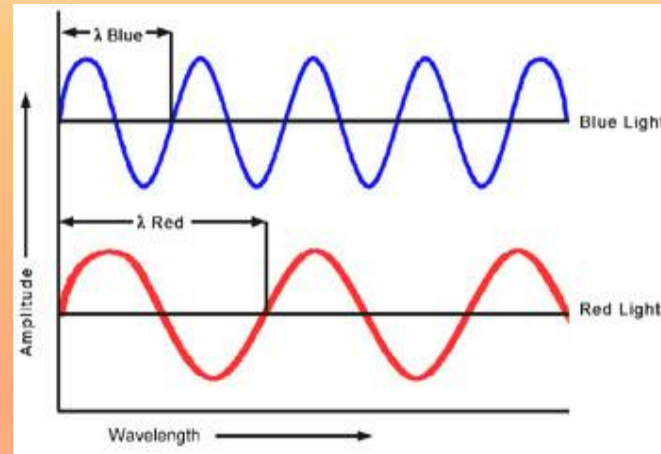
$\lambda_0 = 632.5 \text{ nm}$

$\Delta\lambda = 0.2 \text{ nm}$

Diode Laser

$\lambda_0 = 900 \text{ nm}$

$\Delta\lambda = 10 \text{ nm}$



Comparison of the wavelengths of red and blue light

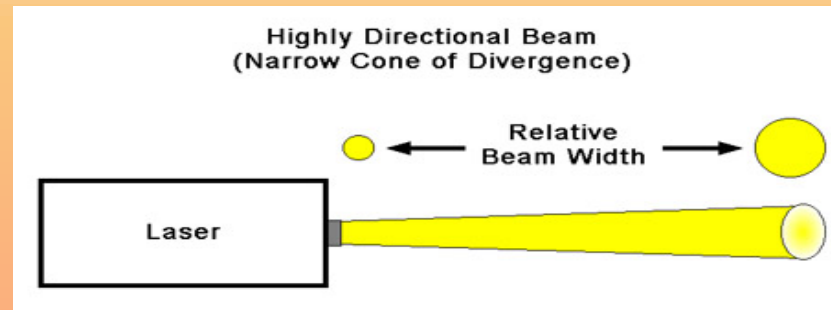
The commercial He-Ne laser wavelength is 632.8 nm, and its spectral bandwidth is about 1500 MHz (the full width at a half - maximum FWHM of it is spectral line). This means that the bandwidth of its wavelength is about 0.01 nm. On the other hand, the laser diode bandwidth, which has a wavelength of 900 nm, is about 1 nm, and when compared to a light emitting diode (LED) with a bandwidth of about 30-60 nm. The diode laser has a monochrome property tens of times more than the light emitting diode.

Typically, the frequency bandwidth of a commercial He-Ne laser is about 1500 MHz (full width at half-maximum, FWHM). In terms of wavelength, it means that at a wavelength of 632.8 nm this means a wavelength bandwidth of about 0.01 nm. On the other hand, the bandwidth of a typical diode laser with a wavelength of 900 nm is about 1 nm, as compared to LED, which has a bandwidth of approximately 30 - 60 nm.

Directionality

High- collimation laser beam Refer to the design of the laser cavity made of mirrors at the ends of the cavity and are perfectly parallel. These mirrors placed at the ends of the laser cavity reflect the light generated within the cavity by the stimulated emission back and forth in order to obtain optical density (more photons) at the same wavelength, Lead to an increase the magnification of the radiation due to the length of the path of light across the active medium of the laser. In addition, the multiple reflections produce a parallel beam, i.e., the beam is a well-collimated beam, and this means that the photons that run parallel to the cavity wall only will be reflected from both mirrors.

Directionality



Conventional light source

Divergence angle (θ_d)

Beam divergence: $\theta_d = \beta \lambda / D$

$\beta \sim 1 = f(\text{type of light amplitude distribution, definition of beam diameter})$

$\lambda = \text{wavelength}$

$D = \text{beam diameter}$

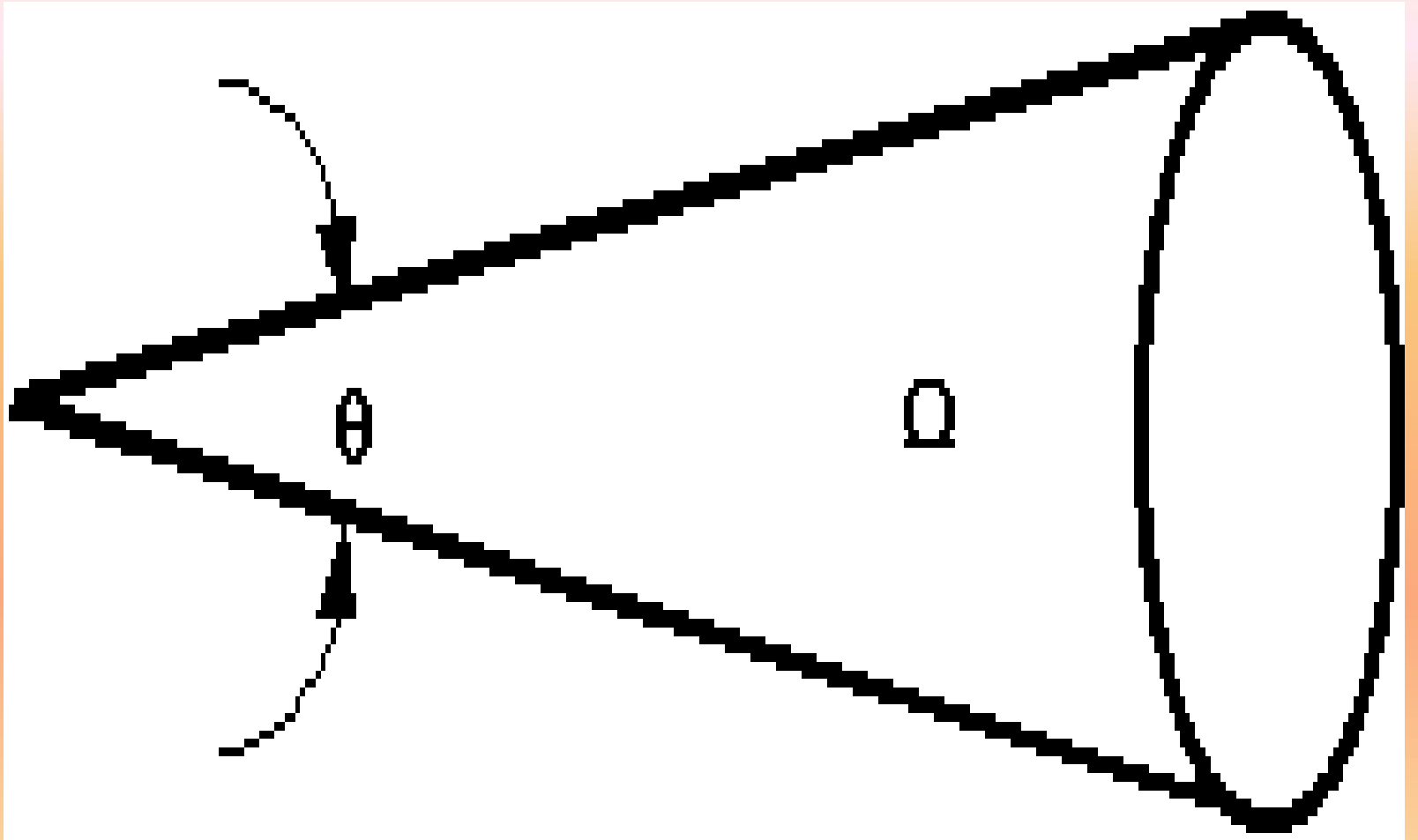
Brightness

The other characteristic that cannot be ignored is high radiation (Brightness). It is defined as the amount of energy emitted per unit surface area per unit of solid angle. It is measured in watt units per square meter for each steradian. steradian is a solid angle measurement unit, a three-dimensional measurement analogue of conventional the two-dimensional angle (plane) and measured in radians. For the small angle, the relationship between the plane angle and the solid angle is approximated to the cone with the planer angle according to the following relationship:

$$\Omega = \left(\frac{\pi}{4}\right) \theta^2$$

As shown in Figure 2.5. The diagram shows θ is the plane angle and Ω is the solid angle. The He-Ne laser has a 1 mm exit aperture diameters and the divergent angle of the laser beam of 1 mm radian. and The radiation power is $1.6 \times 10^9 \text{ W / m}^2$ - Strandian, which can be calculated in the following manner

Brightness



Brightness

The solid angle equivalent to plane angle of one mille rad is

$$\Omega = (\pi / 4) (1 \text{ m rad})^2 = 0.8 \times 10^{-6} \text{ sterad}$$

radiance (or intensity) is the power divided by the area of the laser beam and the solid angle. Thus the intensity B is

$$B = 10^{-3} \text{W} / (0.785 \times 10^{-6}) (0.8 \times 10^{-6}) = 1.6 \times 10^9 \text{ Watts/m}^2\text{-steradian}$$

The 1milliwatt helium neon light is much larger than $10^6 \text{ W} / \text{m}^2\text{-stradian}$, which is the intensity of the sun's rays, which emit more than 10^{26} watts. This is an advantage that serves many laser applications in various fields.

intensity

Beam Diameter

If we examine the laser beam cross section (laser segment) we notice that the laser light intensity distribution is not equal across the cross section. In the ideal beam, it has a symmetrical cross-section, meaning that the light intensity in the centre is greater and gradually decreases at the edges. We can examine the distribution of light intensity in the laser beam spot. It has symmetry distribution characteristics as shown in Figure 2.1.

defining the diameter of the beam as a circular shape, then a certain point can be chosen where the intensity is reduced to a certain value of its maximum value. It is possible to take advantage of the common definition of half intensity, i.e., the full width measurement at the middle of the upper limit of the intensity (FWHM) as shown in the diagram of the spectral line Figure 2.1b, equal to $1/e$ (0.368) and $1/e^2$ (0.135) of the highest value of the intensity of the radiation. In other words, the term "spot size" of the beam is meant to be "the radial distance (radius) from the centre point of the highest point to the point where the intensity is $1/e^2$." Of the highest intensity.

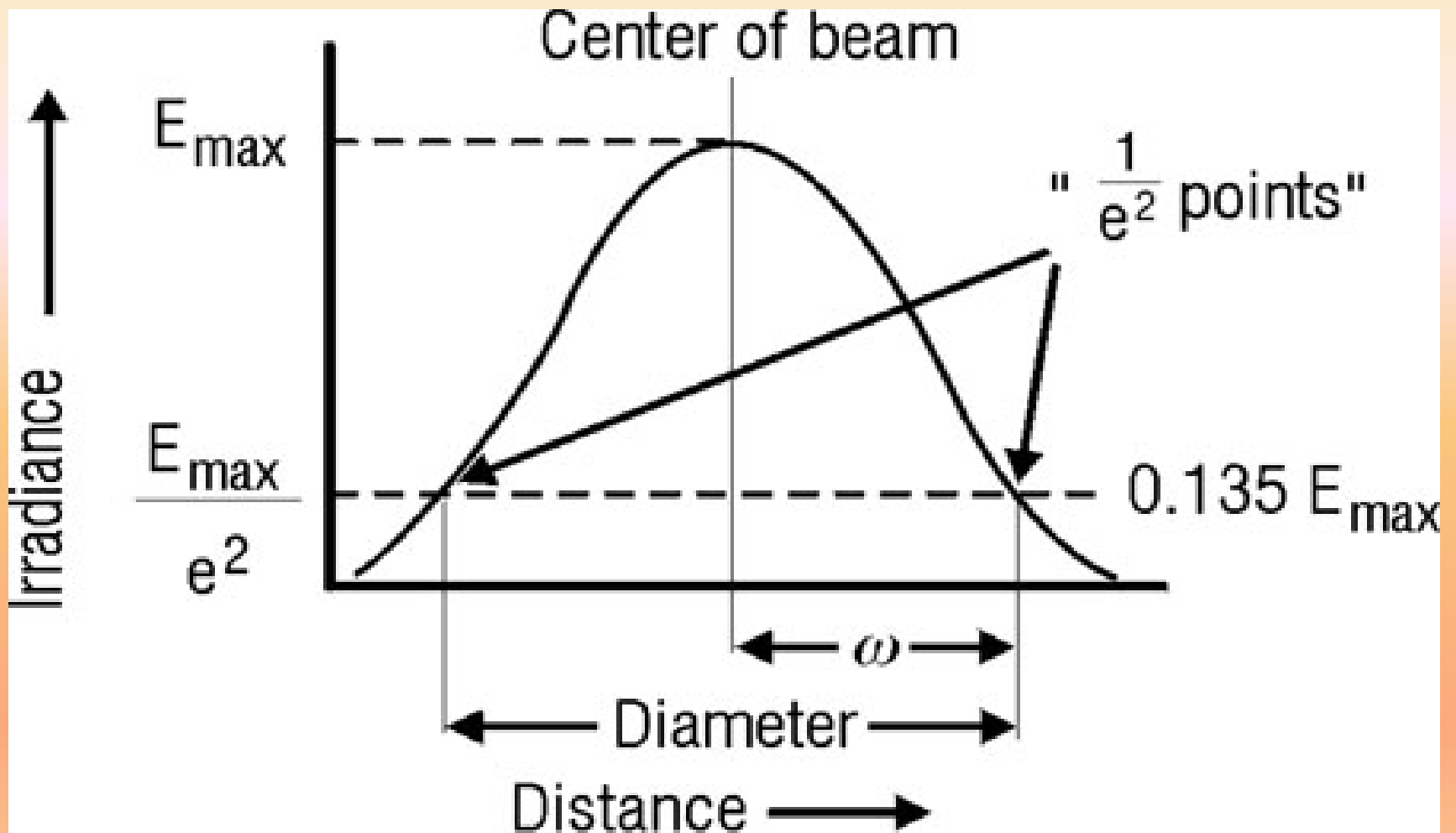


Figure 2.1 (b) Definitions of beam diameter and spot size

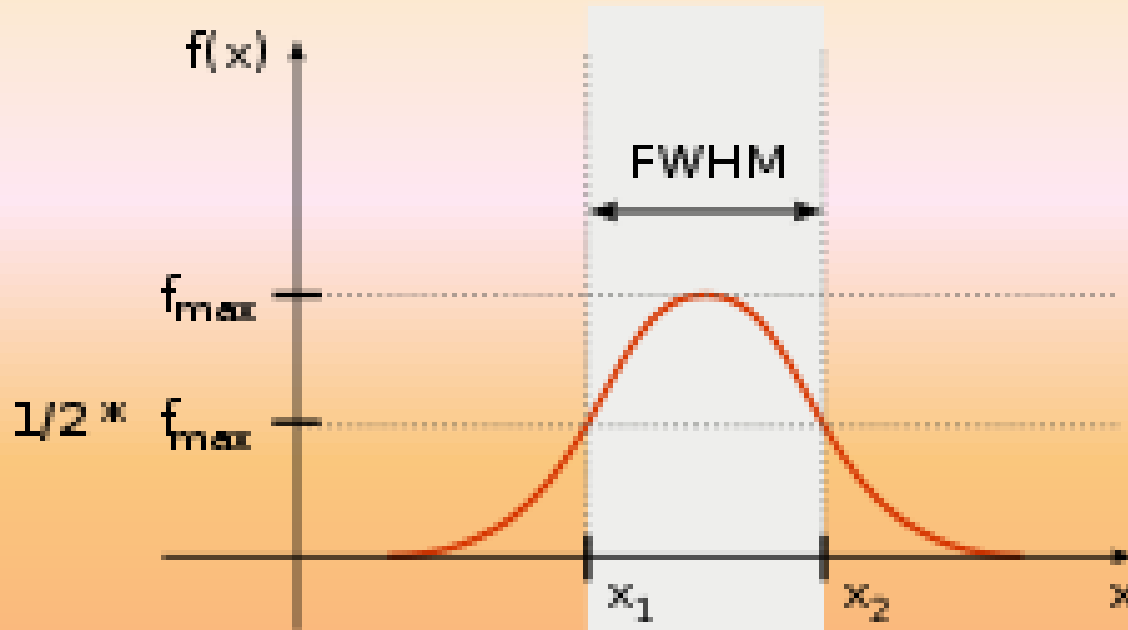
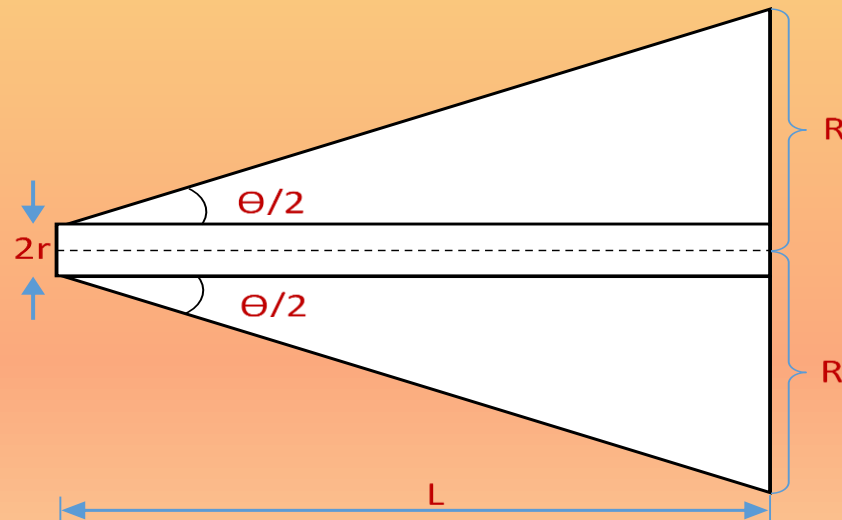


Figure 2.1 (c) full width at half maximum is given by the distance between points on the curve at which the function reaches half its maximum value.

Spot Size Measurement

R = radius of a spot illuminated by the laser beams at distance L from the laser output aperture (as shown in figure below). When measuring the size of the spot near the laser output aperture (the spot is small), then this measurement should be taken into consideration:

$$\tan\left(\frac{\theta}{2}\right) = \frac{R - r}{L} \approx \frac{\theta}{2} \quad \dots 2.2$$



Because the laser beam has a very small diverges angle, then we can use the small angle approximation. Thus, the tangent of the angle can be considered equal to the angle. The laser light produces a spot for its beam on the screen, the diameter of this spot is $(2R)$ which determines the spot size.

EXAMPLE 2.1:

The divergence angle of a laser beams of 1 milli- radian and at a distance of 10 meters great A spot of approximately 10 mm.is. The power density can be defined as the amount of laser power measured over a surface area defined by unit surface. From Figure 2.6, it is possible to obtain a higher power density than conventional or natural sources from a laser beam (see example 2.2). This is why a 5-watt laser is dangerous, and a 100-watt lamp light is not dangerous

EXAMPLE 2.2: NUMERICAL CALCULATION OF POWER DENSITY

Calculate the power density (intensity or power per unit area) at a distance of 2 meters from a 100-watt incandescent lamp, and then compare the result with a 1-megawatt helium-neon laser beam emission. The diameter of the laser beam is at the output aperture is 2 mm and the divergence angle is 1 milli-radian

Solution:

The incandescent lamp radiates light in all directions, Radiation is distributed over a surface area of a sphere with a radius of 2 meters. Surface area is: $4\pi R^2$, so the power density at a distance of 2 meters is:

$$\frac{100}{4\pi} = 0.8 \text{ mW/cm}^2$$

Compared to the incandescent lamp, at a distance of 2 meters the diameter of the laser beam increases to 4 mm (see diagram below):

$$\tan\left(\frac{\theta}{2}\right) = \frac{R - r}{L}$$

$$R = r + L \cdot \tan\left(\frac{\theta}{2}\right) = 1 + 2000 \times \tan 0.5$$

$$R = 2.1 \text{ mm} = 0.2 \text{ cm}$$

The power density of the laser is:

$$\frac{1}{0.04\pi} = 8 \text{ mW/cm}^2$$

There are many different ways to measure the divergence of the laser beam that can be illustrated. Figure 2.6 illustrates the comparison of the outward radiation of a laser and the emission of one of the standard lamps.

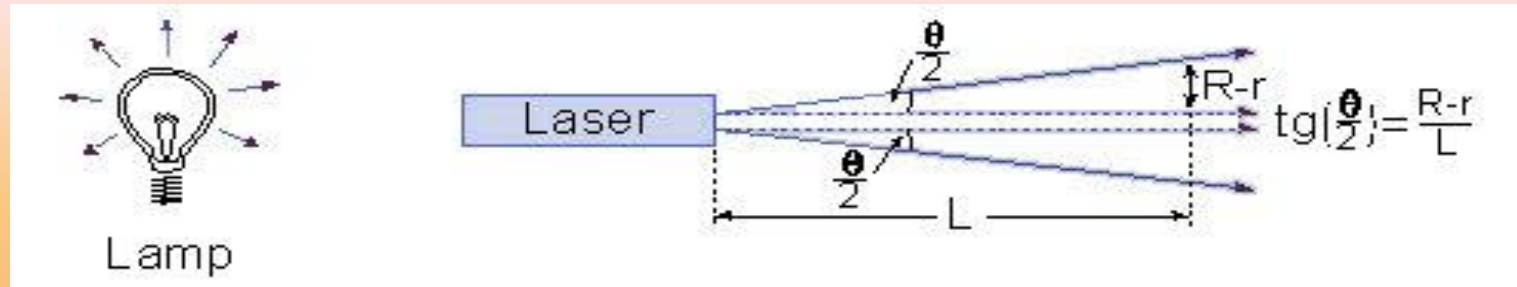
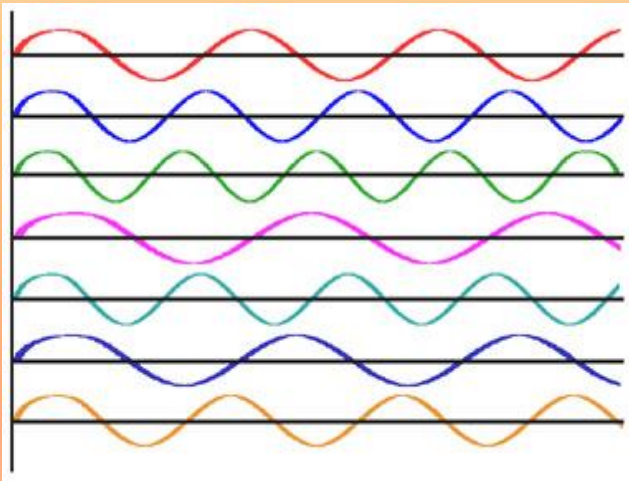


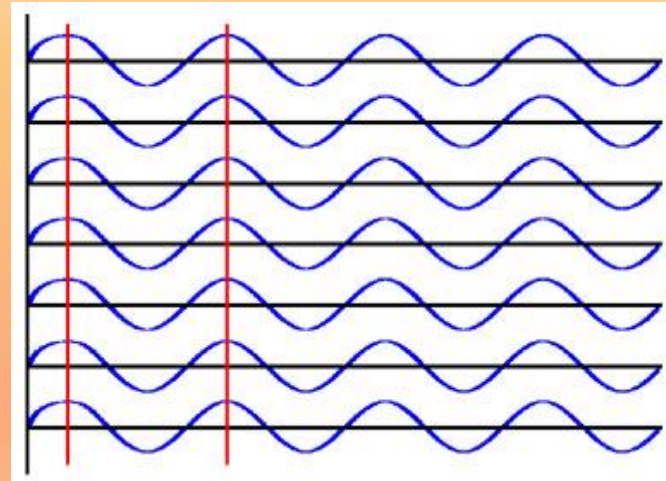
Figure 2.6: comparison between the light out of a laser, and the light out of an incandescent lamp

Again, it is not possible to generate a fully directed light beam, i.e. its parallel light beam is referred to as a directional light (collimated light). All optical beams diverge (spread) as they travel through space. However, the laser light is more directional or more collimated, and has a directional or much higher collimated than any light emitting from a conventional source and thus less divergence. In some applications, certain optical systems are added with laser beams to improve beam directionality.

Coherence

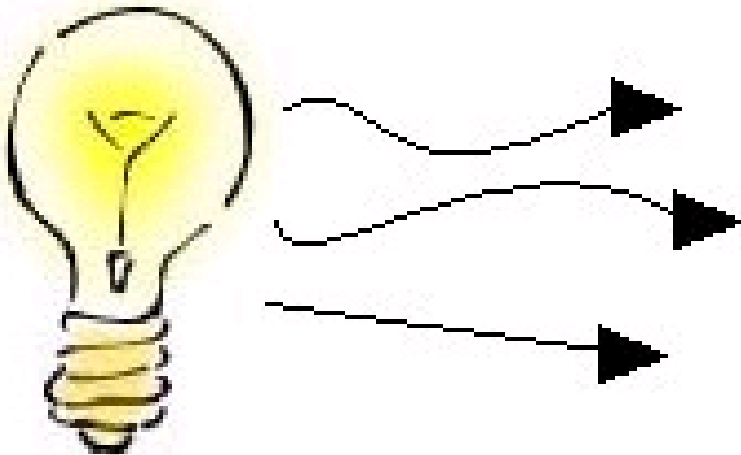


Incoherent light waves

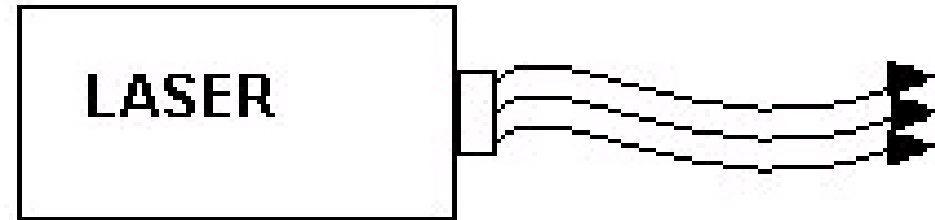


Coherent light waves

Incandescent vs. Laser Light



1. Many wavelengths
2. Multidirectional
3. Incoherent

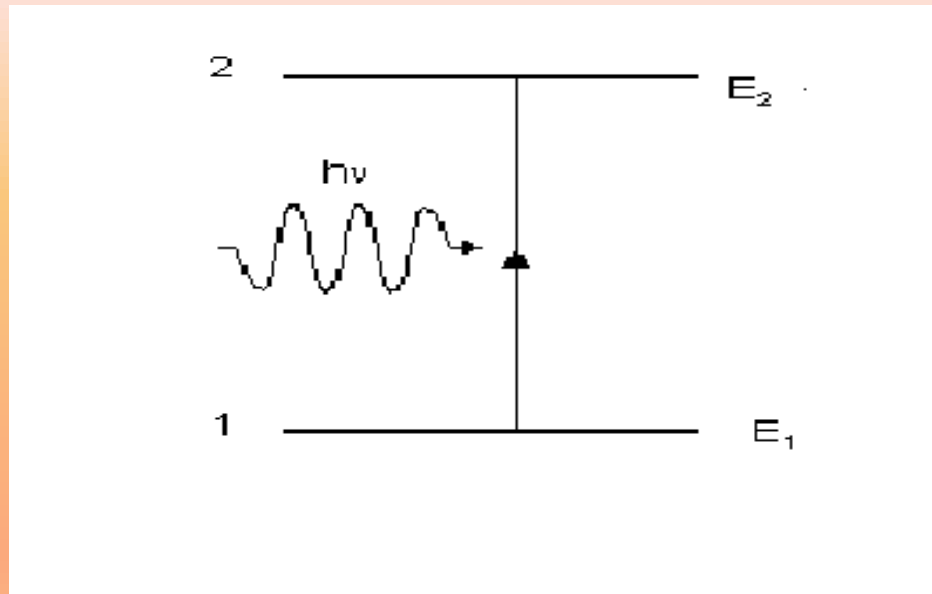


1. Monochromatic
2. Directional
3. Coherent

Basic concepts for a laser

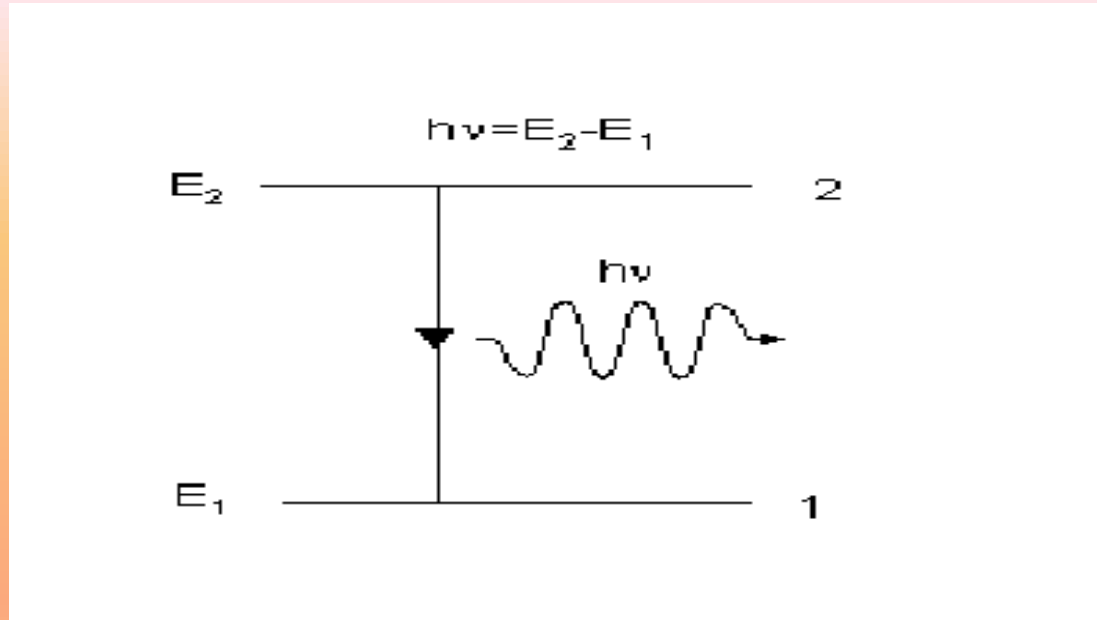
- Absorption
- Spontaneous Emission
- Stimulated Emission
- Population inversion

Absorption



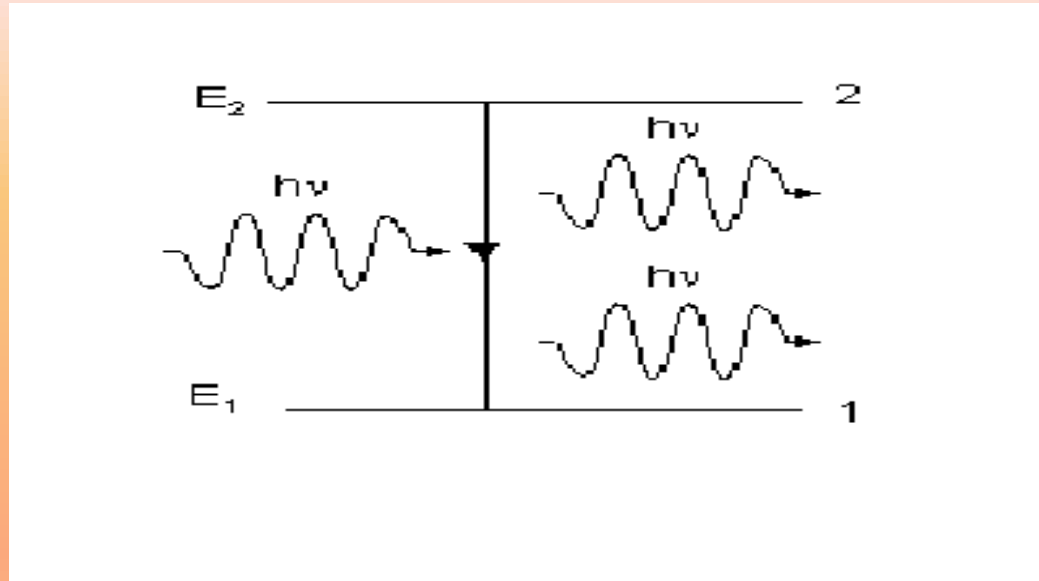
- Energy is absorbed by an atom, the electrons are **excited** into vacant energy shells.

Spontaneous Emission



- The atom decays from level 2 to level 1 through the emission of a photon with the energy $h\nu$. It is a completely **random** process.

Stimulated Emission



atoms in an upper energy level can be triggered or stimulated in phase by an **incoming photon** of a **specific energy**.

Stimulated Emission

The **stimulated photons** have unique properties:

- **In phase** with the incident photon
- **Same wavelength** as the incident photon
- Travel in **same direction** as incident photon

Population Inversion

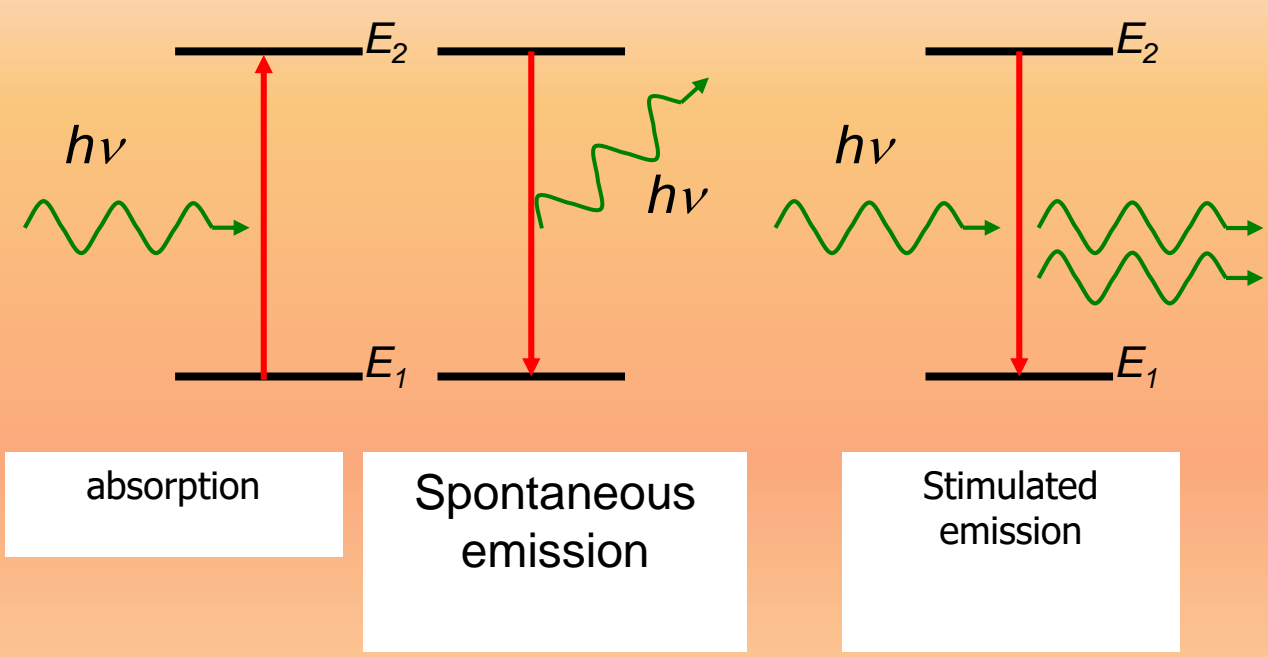
- A state in which a substance has been energized, or excited to specific energy levels.
- More atoms or molecules are in a higher excited state.
- The process of producing a population inversion is called **pumping**.
- Examples:
 - by lamps of appropriate intensity
 - by electrical discharge

Pumping

- Optical: flashlamps and high-energy light sources
- Electrical: application of a potential difference across the laser medium
- Semiconductor: movement of electrons in “junctions,” between “holes”

Two level system

$$h\nu = E_2 - E_1$$



Boltzmann's equation

$$\frac{n_2}{n_1} = \exp\left(\frac{-(E_2 - E_1)}{kT}\right)$$

- n_1 - the number of electrons of energy E_1
- n_2 - the number of electrons of energy E_2

- *Population inversion-*
 $n_2 \gg n_1$

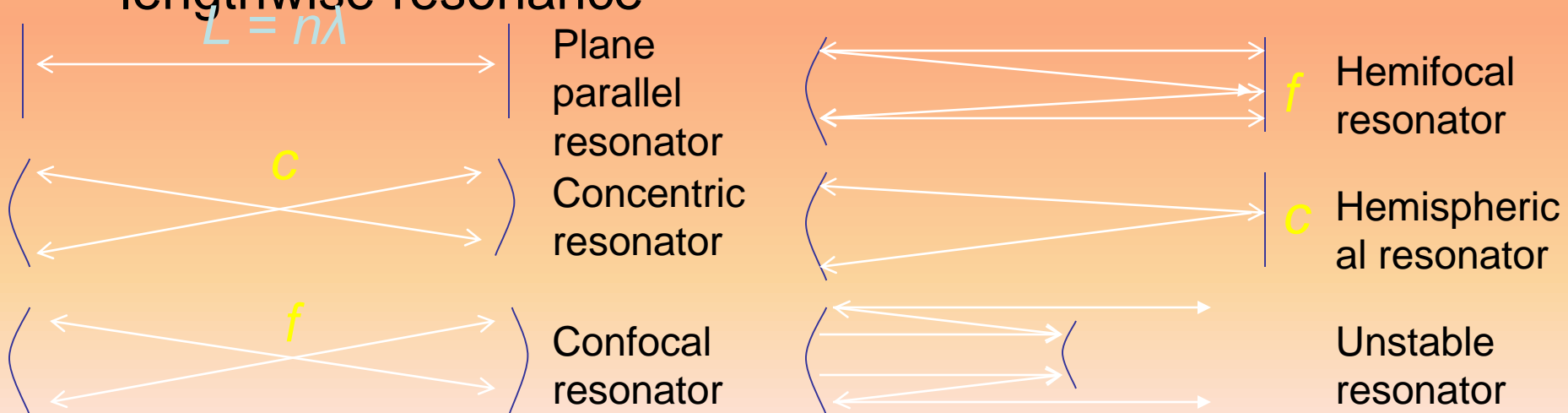


example: $T=3000$ K $E_2-E_1=2.0$ eV

$$\frac{n_2}{n_1} = 4.4 \times 10^{-4}$$

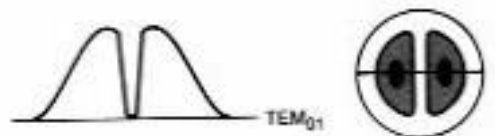
Resonance Cavities and Longitudinal Modes

Since the wavelengths involved with lasers and masers spread over small ranges, and are also absolutely small, most cavities will achieve lengthwise resonance



c: center of curvature, f: focal point

Transverse Modes



SIMILAR TO TEM₀₁,
BUT DEPENDS ON
ORIENTATION



Due to boundary conditions and quantum mechanical wave equations

TEM₀₀:

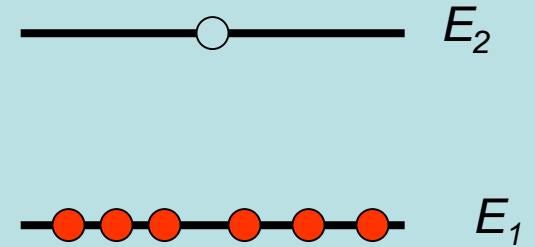
$$I(r) = (2P/\pi d^2) * \exp(-2r^2/d^2)$$

(d is spot size measured to the 1/e² points)

Einstein's coefficients

Probability of stimulated absorption R_{1-2}

$$R_{1-2} = \rho(\nu) B_{1-2}$$



Probability of stimulated and spontaneous emission :

$$R_{2-1} = \rho(\nu) B_{2-1} + A_{2-1}$$

assumption: n_1 atoms of energy ε_1 and n_2 atoms of energy ε_2 are in thermal equilibrium at temperature T with the radiation of spectral density $\rho(\nu)$:

$$n_1 R_{1-2} = n_2 R_{2-1} \quad n_1 \rho(\nu) B_{1-2} = n_2 (\rho(\nu) B_{2-1} + A_{2-1})$$

\Rightarrow

$$\rho(\nu) = \frac{A_{2-1} / B_{2-1}}{\frac{n_1 B_{1-2}}{n_2 B_{2-1}} - 1}$$

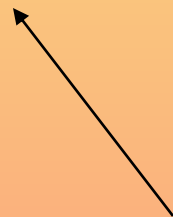
According to Boltzman statistics:

$$\frac{n_1}{n_2} = \exp(E_2 - E_1) / kT = \exp(h\nu / kT)$$



$$\rho(\nu) = \frac{A_{2-1} / B_{2-1}}{\frac{B_{1-2}}{B_{2-1}} \exp\left(\frac{h\nu}{kT}\right) - 1} = \frac{8\pi h \nu^3 / c^3}{\exp(h\nu / kT) - 1}$$

Planck's law



$$B_{1-2} / B_{2-1} = 1 \qquad \frac{A_{2-1}}{B_{2-1}} = \frac{8\pi h \nu^3}{c^3}$$

The probability of spontaneous emission A_{2-1} /the probability of stimulated emission $B_{2-1}\rho(\nu)$:

$$\frac{A_{2-1}}{B_{2-1}\rho(\nu)} = \exp(h\nu/kT) - 1$$

1. Visible photons, energy: 1.6eV – 3.1eV.
2. kT at 300K \sim 0.025eV.
3. stimulated emission dominates solely when $h\nu/kT \ll 1$!
(for microwaves: $h\nu < 0.0015\text{eV}$)

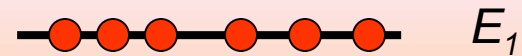
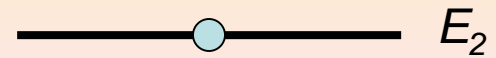
The frequency of emission acts to the absorption:

$$x = \frac{n_2 A_{2-1} + n_2 B_{2-1} \rho(\nu)}{n_1 B_{1-2} \rho(\nu)} = \left[1 + \frac{A_{2-1}}{B_{2-1} \rho(\nu)} \right] \frac{n_2}{n_1} \approx \frac{n_2}{n_1}$$

if $h\nu/kT \ll 1$.

$$x \sim n_2/n_1$$

Condition for the laser operation



If $n_1 > n_2$

- radiation is mostly absorbed absorbowane
- spontaneous radiation dominates.

if $n_2 \gg n_1$ - *population inversion*

- most atoms occupy level E_2 , weak absorption
- stimulated emission prevails
- light is amplified

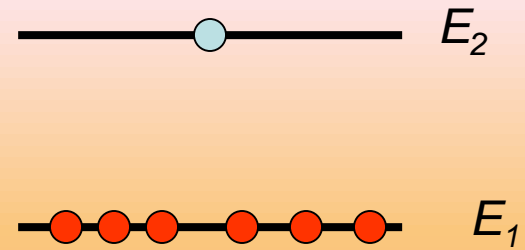
Necessary condition:
population inversion

How to realize the population inversion?

Thermal excitation:

$$\frac{n_2}{n_1} = \exp\left(\frac{-\Delta E}{kT}\right)$$

impossible.



The system has to be „pumped”

Optically,
electrically.