27/11/2024

Unique Properties of Laser Beams:

Laser radiation is characterized by extremely high degree of

1. Monochromaticity 2. Coherence, 3. Directionality, 4. Short time duration and 5. Brightness

1. **High Monochromaticity, or**

   Narrow spectral width, or

High temporal coherence

Monochromatic refers to a single wavelength, or "one color" of light. In an ideal case, the laser emits all photons with the same energy, and thus the same wavelength, it is said to be monochromatic. Laser radiation contains a narrow band of wavelengths, and this property is due to the following:

a) Only an em. wave of frequency υ_o can be amplified.

b) Since two mirrors arrangement forms a resonant cavity, oscillation – can occur only at the resonance frequencies of this cavity.

The latter circumstance leads to the laser linewidth being often much narrower than the usual line width of the transition 2 → 1 as observed in spontaneous emission, as shown in Fig. (1).

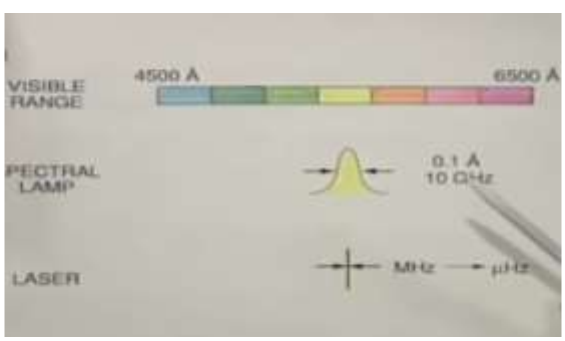

Figure (1): Comparison between the band width of lamp source and laser

If the phase difference between the two fields remains the same for any time τ we will say, there is a "*temporal coherence*".

If this occurs for any value of τ, the e.m. wave have of "*perfect time coherence*".

If this occurs for a time delay τ such that of the $0<\tau<\tau_o$ we have partial temporal coherence with a coherence time equal to τ_o, as shown in fig. (2).

The concept of temporal coherence is, at least in these cases directly connected with monochromaticity that any stationary e.m. wave with coherence time to has a band width $\Delta\upsilon$

$$\Delta\upsilon=1/\tau_o \qquad \text{.............. (1)}$$

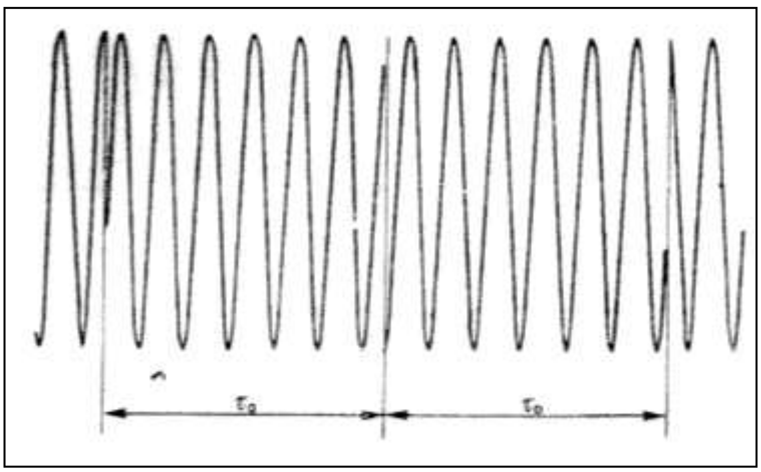

Fig. (2): Example of an e.m. wave with a coherence time of approximately τ_o

Figure (3) shows the coherence time of laser output and lamp, the upper (laser) shows the long coherence time and accordingly give narrow linewidth, so we can predict amplitude & phase at any time at a given position. While the lower (lamp) shows the short coherence time and long line width, so we cannot predict amplitude & phase at any time at a given position.

Typical applications of narrow spectral width

This property make laser uses in communication, spectroscopic, interferometry, holography, sensors.

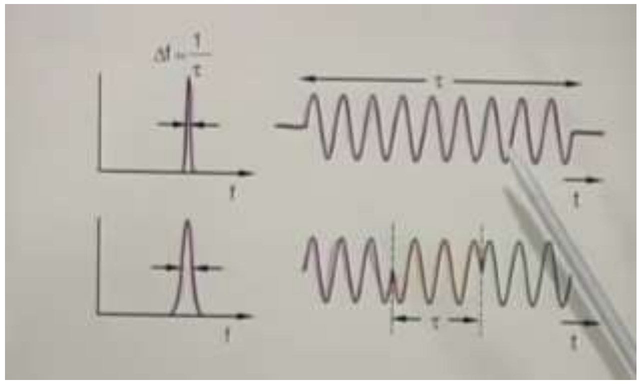

Figure (3): Coherence time between laser and lamp

2. Directionality or High collimated beam, or
Very small focused spot or,
Diffraction limited focusing
High spatial coherence

The directionality property is a direct consequence of the fact that the *active medium is placed in a resonant cavity*. In the case of the plane parallel, only a wave propagating in a direction orthogonal to the mirrors can be sustained in the cavity.

We see from figure (4), the light output from arc and we collect the light with lens at the focal length, we can see here the wide divergence which is easily estimate by the half size of the source divided by the focal length of the lens:

$$\theta_d = \frac{h}{f} \qquad \text{……………} (2)$$

So, if we don't like this angle is to be big, we either reduce the size of source and the collimation become bigger and bigger or increase the focal length of the lens and put it away far from the source and loose lighter.

The best one can do is called diffraction – limited collimation (laser) as shown in fig. (4), the divergence angle is:

$$\theta_d = \frac{\lambda}{D} \qquad \text{……………} (3)$$

The shorter the λ the better of collimation, the larger D the better of collimation, and does not depend on source size. So, the divergence angle approach to the wavelength of the source, as a result all the light collimated and we don't lose any more of light.

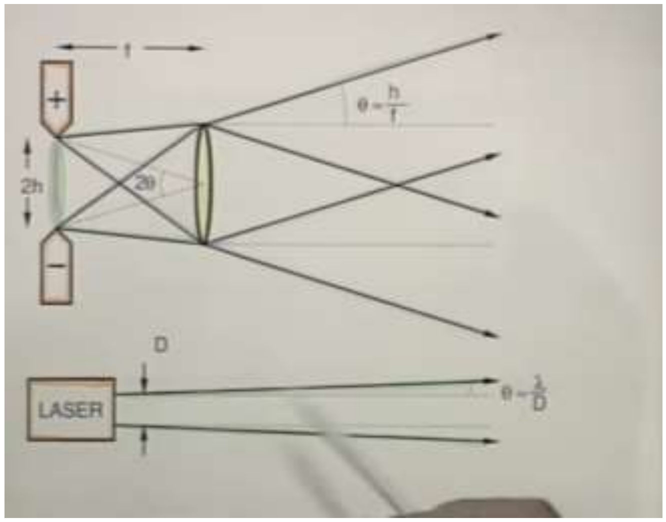

Figure (4): Divergence for lamp source and laser

Typical applications of high degree of collimation

Alignment, bar code readers, communication, radar.

Very small focused spot & Diffraction limited focusing:

Figure (5) shows how collimate the light by another type of lens to get high intensity focus spot, it is difficult and **impossible** to get spot **brighter than** that of the source. The best way can do, is to collimate the laser light by lens and focused it to small spot, the spot size is given as:

$$spot\ size = \frac{\lambda f}{D} \sim \lambda\ (f = D) \qquad \text{……………} (4)$$

Now, if f~D, then we have the spot size is equal to wavelength. So, the spot size is depended on the collimation $(\frac{\lambda}{D})$ and the wavelength. This mean that laser is ideal and close to perfect on both the collimation and focusing because in laser we can put all output in tiny spot with huge intensity.

Typical applications of small focused spot

Compact discs, laser printers, material processing, medical surgery.

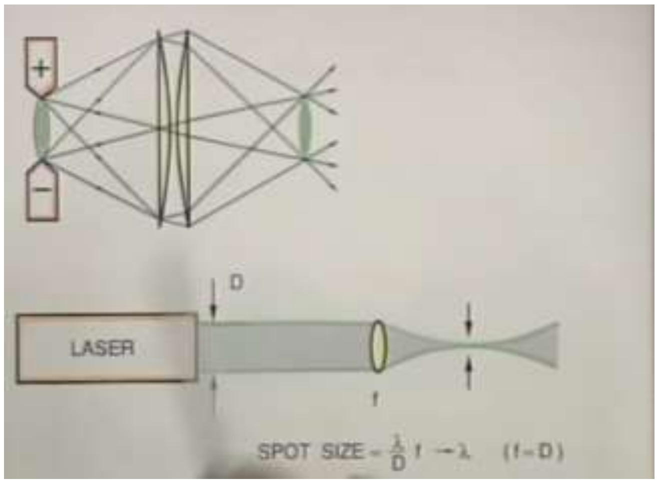

Figure (5): Comparison between the collimating of light source and laser

3. High spatial coherence:

Which mean that wave is well behave in space, and we can predict amplitude and phase at any position at a given time, as shown in upper two parts in fig. (6). While the lower part it is impossible to predict amplitude and phase at different location in space as a function of time. In case of **perfect spatial** coherence, a beam of finite aperture has unavoidable divergence due to diffraction. According to Huyghe'ns principle, the beam has a finite divergence $\theta_{d.}$ thus

$\theta_d = \beta\lambda / D$ ⟶ Diffraction limited ………….. (5)

Where λ and D are the wavelength and the diameter of the beam, β is a numerical coefficient of the order of unity, whose value depends on both the divergence and the beam diameter are defined.

It is important to point out that the two concepts of temporal and spatial coherence are independent of each other.

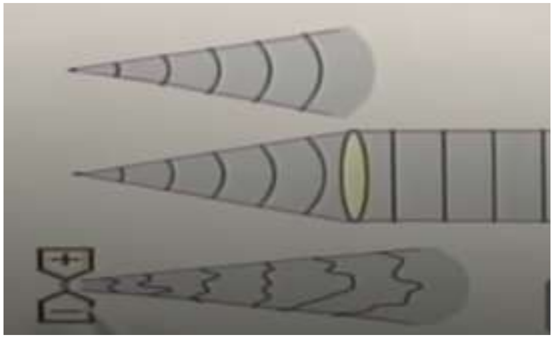

Figure (6): Spatial coherence between laser and lamp source

High power

There are two kinds of output laser, pulsed and continuous wave (cw) laser, table (1) show the wide range of powers,

Table (1): Output power laser for pulsed and cw laser

Cw	10^{-3} W	Milliwatt
	10^{-0} W	Watt
	10^{3} W	Kilowatt
	10^{6} W	Megawatt
Pulsed	10^{9} W	Gigawatt
	10^{12} W	Terawatt
	10^{15} W	Petawatt
	10^{18} W	Exawatt

Typical applications of high power:

Material processing, fusion, military, nonlinear optics.

Wide tuning range

Output laser cover wide range of wavelength, which extend from x-ray and vacuum ultra violet to far infrared wavelength, as shown in fig. (7). This mean that we can produce laser operate at any wavelength.

Typical applications of wide tuning range

Interaction with specific atoms and molecules, spectroscopic, medical, propagation.

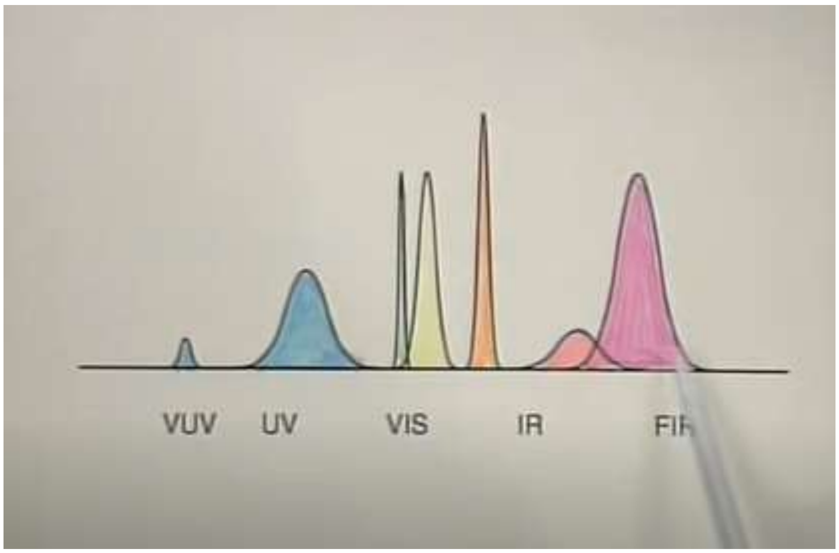

Figure (7): Wide tuning range of laser

4. Short time duration or, very short pulse widths

Short Time Duration: which implies energy concentration in time, can be considered to be the counterpart of monochromaticity, which implies energy concentration in wavelength. While in fact all lasers can be made extremely monochromatic, only lasers with a broad line width may produce pulses of very time duration.

It is possible to produce light pulses whose duration is equal to the inverse of the time width. This with gas laser whose line width is relatively narro ≈1ns, see fig. (8). Such pulse durations are not regarded as short and indeed even some flash lamps can emit light pulses with a duration less than 1ns. The line width of some solid state can be 10^{-3}-10^{-5} times larger than of a gas laser, much shorter pulses may be generated (≈10 fs). This opens up exciting new possibilities for laser research and applications.

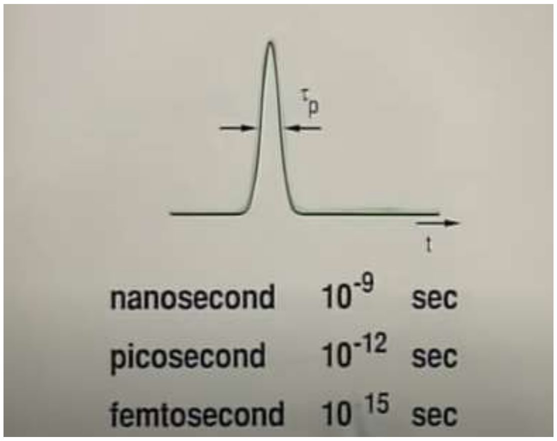

Figure (8): Short time duration for laser

5. Brightness:

It is defined as a power emitted per unit surface area per unit solid angle. The power *dp* emitted by ds (element surface area at point o of the source), into a solid angle dΩ around direction OO^- can be written as:

$$dp = B\cos\theta \, ds \, d\Omega \qquad \ldots\ldots\ldots\ldots 6$$

Where θ is the angle between OO' and the normal n to the surface. The factor cosθ arises from the physically important quantity for the emission along the OO' direction is the projection of ds on a plane orthogonal to the OO' direction, i.e. cosθds. **B** is called the source brightness at the point in the direction OO', since θ is very small, cos θ ≅ 1.

The area of the beam is $\pi D^2/4$ and

$$d\Omega = \pi \theta^2 \qquad \ldots\ldots\ldots\ldots 7$$

$$B = 4p/(\pi D \theta)^2 \qquad \ldots\ldots\ldots\ldots 8$$

If the beam is diffraction limited, we have.

$\theta = \theta_d \longrightarrow \theta_d = \beta\lambda/D$ ……………….9

:. $B = (2/\beta\pi\lambda)^2 P$ ……...............10

The maximum brightness that a beam of power p can have.

Brightness is the most important parameter of a laser beam. If the object and image are in the same medium, (air), the brightness of the image is always less than or equal to that source, depending on the equality holding of the optical system.

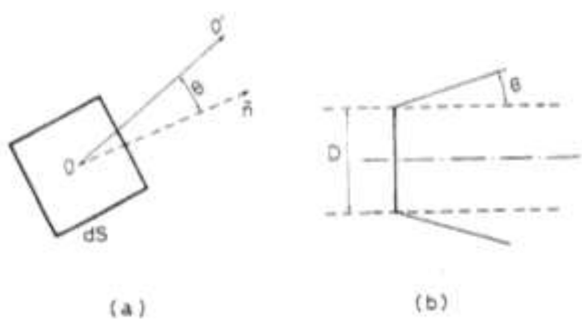

Fig. (9) Surface brightness at the point O for a general source of e.m. waves. (b) Brightness of a laser beam of diameter D and divergence θ.

To further illustrate the importance of brightness, let us consider the beam having a divergence equal to θ, to be focused by a lens of focal length f. To calculate the peak intensity of the beam in the focal plane of the lens, the beam can be decomposed into a continuous set of plane waves with an angular spread of θ around the propagation direction. Two Such waves, making an angle θ are indicated by solid and dashed lines. The two beams will each be focused to a distinct spot in the focal plane, for small angle θ', the two spots are separated by a distance $r = f\theta'$.

Since the angular spread of the plane waves is equal the beam divergence θ, the diameter d of the local spot is equal to

$d = 2f\theta$ ……..…………11

The peak intensity in the focal plane (lossless lens):

$I_p = 4p/\pi d^2 = p/\pi(f\theta)^2$ ……………….12

The beam brightness is :

$I_p = B(\pi D\theta)^2/4\pi(f\theta)^2 = \frac{\pi}{4} = B(\frac{D}{f})^2$ ……………….13

$I_p = \frac{\pi}{4} B (N.A)^2$ ………..………14

according to eq. (13), the maximum value of I_p is attained when D is equal to the lens diameter D_L and

$$N.A = \sin[\tan^{-1}(D_L/f)] \cong D_L/f \qquad \text{……………….15}$$

lens numerical aperture

According to e.q (15), the peak intensity in the local plane of a lens depends only on the beam brightness.

A laser beam of even moderate power has a brightness that is several orders of magnitude greater than that of the brightest conventional sources. This is mainly due to the highly directional properties of the laser beam. Thus the focused intensity of a laser beam can reach very large values, a feature which is exploited in many applications of lasers.

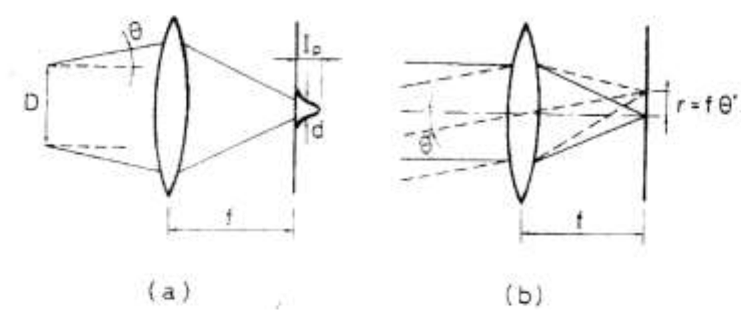

Fig (10): (a) Intensity distribution in the focal plane of a lens for a beam of divergence 0 (b) Plane-wave decomposition of the beam of a.

Typical aplications of laser

When comparing laser properties to those of other light sources, it can be readily recognized that the values of various parameters for laser light either greatly exceed or are much more restrictive than the values for many common light sources. We never use lasers for street illumination or for illumination within our houses. We don't use them for searchlights or flashlights or as headlights in our cars. Laser properties make it uses in compact disc players, in supermarket check-out scanners, in surveying in struments, and in medical applications as a surgical knife or for welding detached retina. We also use them in communication system and in radar and military targeting application.