Properties of Laser Beams

1. Laser light is highly monochromatic

Monochromaticity refers to a pure spectral color of a single wavelength. A beam is more and more monochromatic if the line spread in frequency is narrow or small. This line width is an outcome of the homogeneous broadening factors and inhomogeneous broadening factors. Despite these broadening mechanisms the line width in a laser is generally very small as compared to the normal lights.

A laser cavity forms a resonant system. The photons are emitted by the stimulated emission where in all the photons are in same phase and in the same state of polarization. Oscillations can sustain only at the resonance frequency of the cavity. This leads to the narrowing of the laser line width. So, the laser light is usually very pure in wavelength, and the laser is said to have the property of monochromaticity.

2. Laser light is highly coherent

Two beams of light are coherent when there is a constant phase relation between the two beams or the phase difference between their waves is constant; they are incoherent if there is a random or changing phase relationship, or the phase difference is not constant. Sustained interference patterns are formed only by radiation emitted by coherent sources, generally produced by splitting a single beam into two or more beams. A laser, unlike an incandescent light source, produces a beam in which all the components bear a fixed relationship to each other i.e. the laser beam is generally coherent.

For any electromagnetic (em) wave, there are two kinds of coherence viz. spatial coherence and temporal coherence.

A wave front is an imaginary surface normal to the direction of propagation of a wave such that all the points on the surface oscillate in the same phase. The wave front of a point source is spherical. The wave front for a line source is cylindrical.

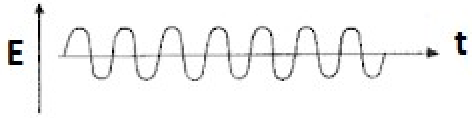
2.1 Temporal coherence

Consider a fixed point on the em wave front. If at any time the phase difference between time t and time t+Δt remains the same, where Δt is the time delay, it is said that the em wave has temporal coherence over a time Δt. If Δt is any time value, the em wave has perfect temporal coherence. If this happens only in a range $0<\Delta t<t_o$, we say it has partial temporal coherence, with coherence time equal to t_o.

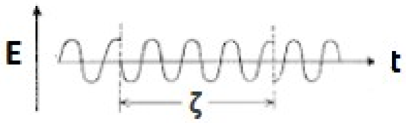
Waves with broad range of frequencies have a short coherence time since the amplitude of the wave changes quickly. White light has a broad range of frequencies. It varies quickly in phase. Hence, it has a very short coherence time. White light is called incoherent.

A wave containing only a single frequency is perfectly correlated with itself for all time delays.

The oscillating Electric field E of a perfectly coherent light wave would have a constant amplitude of vibration at any point, while its phase would vary linearly with time. As a function of time, the function would appear as shown in figure. But, no light source ever produces perfect temporal coherence of this kind.



When an excited atom returns to the ground state, it emits a pulse of short duration of the order of 10^{-10} s, after which pulse abruptly changes. Hence the electric field due to actual light will be is shown in figure.



The average time interval for which the field remains sinusoidal is known as coherence time or temporal coherence of light wave. It is denoted by ζ.

Distance = velocity × Time

The distance for which the field is sinusoidal will be $L = c \times \zeta$

Here c is the speed of light & L is the coherence length i.e. the distance for which field is si

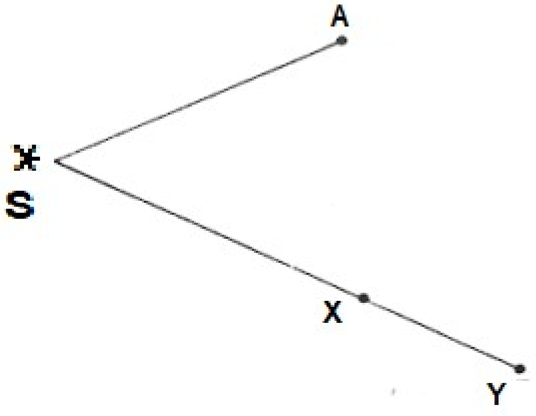
Coherence is thus related to synchronization of light in time, or along the laser beam. The duration of the synchronized emission from the laser multiplied by the speed of light is thus called the coherence length of the laser emission. This is the distance along which the photons are coherent or moving in step. To remain in phase with one another, these quanta must have approximately the same wavelength. Thus the temporal coherence is related to the monochromaticity or the spectral width of the light emitted from the laser: the broader the spectrum the shorter the temporal coherence.

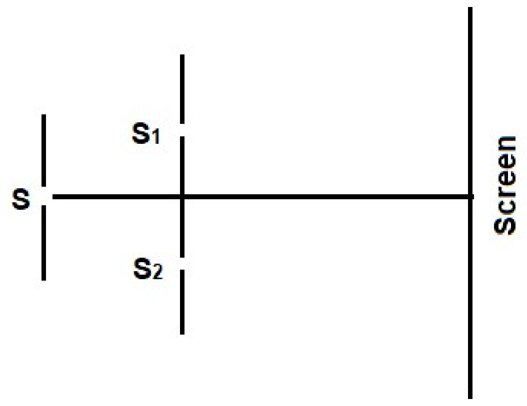
2.2 Spatial Coherence

Consider two points at time t=0 on the same wave front of a given electromagnetic wave, the phase difference of electromagnetic wave at the two points at time t=0 is 0. If for any time t>0 the phase difference of electromagnetic wave at the two points remains 0, we say the electromagnetic wave has perfect coherence between the two points. If this is true for any two points of the wave front, we say the wave has perfect spatial coherence. In practice, the spatial coherence occurs only in a limited area, so we say it the partial spatial coherence.

Let S is a source of light. Two points X and Y are such that XY << L i.e. less than the coherence length, there will be a definite phase relationship between X and Y i.e. there will be high coherence between points X and Y. However, if XY >> L, coherence will be absent between X and Y.

Consider A and X as two equidistant points from S. If the source S is a perfect point source the waves will reach points A & X in exactly the same phase, i.e., the two points will have perfect (spatial) coherence. If, however, the source S is an extended source, points X and A will no longer remain coherent. This may be understood by the Young's double-slit experiment. The light emitting from narrow slit S falls on two slits S_1 and S_2 placed symmetrically with respect to S.





S_1 and S_2 are derived from the same original source S. They will maintain a constant phase difference at all points on the screen. Hence, a stationary interference pattern will be observed on the screen. If however, the width of the slit S is gradually increased, the pattern becomes poorer and poorer in contrast and finally disappears. This is because as the source gets extended, the spatial coherence on the screen turns into incoherence. This is due to the reason that when the slit S becomes wide, the slits S_1 and S_2 receive waves from different independent points of S and hence no longer remain coherent with respect to each other.

Spatial and temporal coherence are independent. A partial temporal coherent wave may be perfectly spatially coherent. Laser light is highly coherent.

3. Directionality

Laser light has very small divergence. It is highly directional. The laser beam comes from the cavity resonator, and only waves propagating close to the resonator axis can sustain oscillations in the cavity.

Directionality of the emitted beam is governed by the mirror configuration of the laser cavity. In its simplest structure, a cavity consists of two mirrors arranged such that light bounces back and forth, each time passing through the gain medium. One of the two mirrors, the output coupler, is partially transparent, allowing the output beam to exit through it. The structure of the laser cavity determines directionality or collimation of the laser beam, which in turn determines the ability of laser beam to be focused into a small spot.

The directionality is described by the light beam divergence angle. For perfect spatial coherent light, a beam of aperture diameter D will have unavoidable divergence because of diffraction. From the theory of diffraction, the divergence angle θ_d is given by:

$$\theta_d = \beta \lambda / D$$

Here λ and D are the wavelength and the diameter of the beam respectively, β is a coefficient that depends on the type of light amplitude distribution and the definition of beam diameter. It's value is in the vicinity of unity. θ_d is called diffraction limited divergence.

If the beam is partial spatial coherent, its divergence is bigger than the diffraction limited divergence. In this case the divergence becomes $\theta = \beta \lambda /(A_c)^{1/2}$. Here A_c is the coherence area.

Consider a laser light of wavelength $\lambda = 1.06 \times 10^{-3}$ mm, $D = 2$ mm, $\beta = 1.1$, then $\theta_d = \beta \lambda / D = 1.1 \times 1.06 \times 10^{-3} / 2 = 0.5831 \times 10^{-3}$ rad = 0.033401°.

A searchlight has a divergence angle of 8-10°. A normal flashlight has a divergence of 20-30°.

4. Brightness

The brightness of a light source is defined as the power emitted per unit surface area per unit solid angle. For a laser beam of power P, with a circular beam cross section of diameter D and a divergence angle θ with the resultant emission solid angle $\pi\theta^2$, the brightness of laser beam is defined as:

$$B = 4\, P / (\pi\, D\, \theta)^2$$

The max brightness is reached when the beam is perfect spatial coherent.

$$B_{max} = 4\, P / (\pi\, \lambda\, \beta\,)^2$$

In case of limited diffraction ($\theta_d = \lambda\, \beta / D$, $D = \lambda\, \beta / \theta_d$, $\theta_d = \theta$)

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