PHY2208 Lecture 19

Properties of laser light
- Directionality
- Monochromaticity
- Coherence

Y&F sec 40-7
Pedrotti & Pedrotti sec. 21-4

In 1960 Thomas Maiman produced an optical equivalent of the MASER (Microwave Amplification by the Stimulated Emission of Radiation).

The LASER has revolutionized optical science because laser light differs from light emitted by a thermal source in three ways:

1) Directionality: A laser beam is highly collimated and has a very low angular divergence (for a 1mm beam diameter, the divergence angle is about 1 arcminute).

2) Monochromaticity: Laser light is emitted over a very narrow range of frequencies

source	wavelength (nm)	$\Delta\lambda$ (nm)
discharge lamp	589	0.1
cadmium discharge lamp	643	0.0013
HeNe laser	632	10^{-8}

3) Temporal coherence: Laser light has a much longer **coherence time** than ordinary light

The high directionality of the laser beam facilitates many of its familiar industrial and military applications.

Consider a laser beam emerging from a laser. It will have a beam diameter of ~0.5 mm. The action of the laser means that the emerging wavefronts are plane parallel to the highest degree allowed by diffraction. However the Uncertainty Principle requires a minimum angular divergence of λ/d.

Such a small projected spot size allows one to project highly visible markers onto distance targets (laser guided bombs etc).

Consider focusing this highly collimated beam by a positive lens. The size of the focused spot is limited only by diffraction (if the lens is free of aberrations).

This can produce **very high power densities** (W/m^2) which is useful for cutting or welding. To illustrate this we calculate the power/unit area generated on the retina of the eye when staring at:

a) the sun (total power output 4 x 10^{26} W)

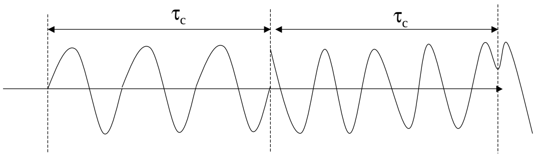
b) a diffused room light bulb (power output 60W)

c) a low-power HeNe lab laser (0.001W)

To do this we assume

the eye’s pupil diameter ~ 1mm
the solar constant ~ 1 kW m^{-2}
the diffused image of the lamp filament has diameter ~ 1cm
the laser beam diameter ~ 0.5 mm

The **coherence time** τ_c (or equivalently the coherence length $l_c = c\,\tau_c$) of a light beam depends on how long the EM wavetrain possesses a predictable phase:



e.g. consider illuminating a Michelson interferometer with light whose phase remains predictable only over a distance l_c . If one mirror is moved from the position of zero path difference by d the output signal I is given by

$$I = \left\langle \left| E(t) + E(t+\tau) \right|^2 \right\rangle$$

where $\tau = 2d / c$ and the brackets denote an ensemble average.

$$\begin{aligned} I &= \left\langle (E(t)+E(t+\tau))(E(t)+E(t+\tau))^* \right\rangle \\ &= \left\langle E(t)E^*(t) + E(t+\tau)E^*(t+\tau) \right\rangle + 2\,\mathrm{Re}(\left\langle E(t)E^*(t+\tau) \right\rangle) \\ &= 2\left\langle E(t)E^*(t) \right\rangle + 2\,\mathrm{Re}(\left\langle E(t)E^*(t+\tau) \right\rangle) \\ &= 2I_0 + 2\,\mathrm{Re}(\left\langle E(t)E^*(t+\tau) \right\rangle) \end{aligned}$$

where I_0 is the intensity which would arise if one arm was blocked.

If $\tau \ll \tau_c$ then the 2nd term is significant and $I \neq 2\,I_0$ i.e. we observe interference.

But if $\tau \gg \tau_c$ then $E(t)$ and $E(t+\tau)$ become statistically uncorrelated, and $\left\langle E(t)E^*(t+\tau) \right\rangle \to 0$

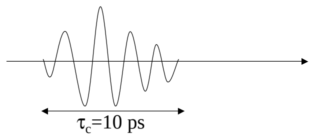
i.e. the interference effect **disappears**!

Interference effects are **only** visible if the maximum path difference is not significantly larger than l_c .

Laser light generally possesses a much longer coherence length than thermal light and so is better suited to producing interference effects (e.g. speckle patterns and holograms).

source	λ (nm)	l_c (m)	τ_c (s)
discharge lamp	589	0.003	10^{-11}
cadmium discharge lamp	643	0.3	10^{-9}
HeNe laser	632	40 000	10^{-4}

In fact, temporal coherence is essentially the same property as monochromaticity. Consider a simplified picture of a light wave of finite coherence time τ_c :



We can consider such a wavetrain to consist of a sequence of wave 'packets' of mean duration τ_c

The duration of such a packet is effectively the temporal uncertainty in the arrival time of a photon associated with that packet. This is related, via the Uncertainty Principle, to the uncertainty in the photon's energy (i.e. wavelength):

$$\Delta E \cdot \tau_c \approx h$$

Since $\Delta E = h\Delta\nu = \dfrac{hc\Delta\lambda}{\lambda^2}$ we have:

$$\tau_c \approx \frac{1}{c}\frac{\lambda^2}{\Delta\lambda} \qquad l_c \approx \frac{\lambda^2}{\Delta\lambda}$$