Wave Optics vs Photons

As an example of wave interference we look at a classic experiment, the Michelson interferometer

We use a light source that is reasonably monochromatic (single wavelength / frequency ≙ sharply defined colour)

A laser (HeNe laser → $\lambda = 632.8\,nm$;
red laser pointer : λ within 650 − 680 nm range
green laser pointer $\lambda \sim 532$ nm)

or a discharge lamp
- Na lamp (sodium, → yellow street lamp) $\lambda \sim 579$ nm
- Mercury discharge tube together with colour filter to isolate one of the atomic transition emission lines

a fluorescent light bulb with color filter

→ use a diffraction grating to observe that white light in these does not come from a continuous spectrum of colours, as is the case for a filament bulb

For these sources the electric field associated with the electromagnetic wave is assumed of the form:

$$E_\perp(x,t) = E_0 \sin(\omega t - kx)$$

$$\omega = 2\pi f = \frac{2\pi}{T}$$

$$k = \frac{2\pi}{\lambda}$$

$\hat{x}$ = direction of wave propagation

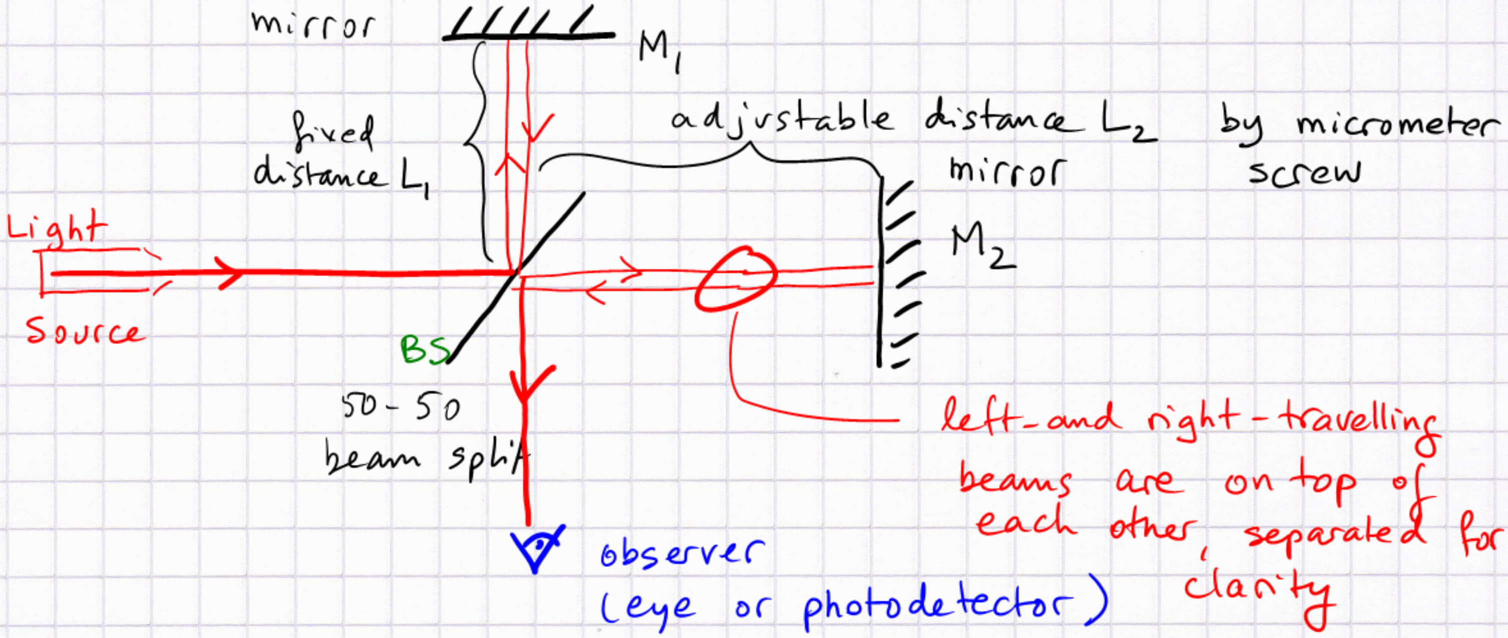
$\perp$ = perpendicular direction ; doesn't need to be fixed

This form is not valid for all times, the non-laser sources emit relatively short bursts with some randomness, nevertheless, these bursts contain many oscillations

⇒ the idea of long sinusoidal wave trains → a reasonable assumption

Now use a beam splitter = glass plate with a metal vapour deposited on one side such that about 50% of light is reflected, while 50% goes through.

Also use two mirrors (one fixed, one movable):



Follow the beam from the source:

at the BS it has a 50-50 chance to be reflected upwards towards M_1 or to pass through to M_2

The vertical beam returning from M_1 has a 50-50 chance at the BS to either pass through to the observer, or to be reflected back into the source

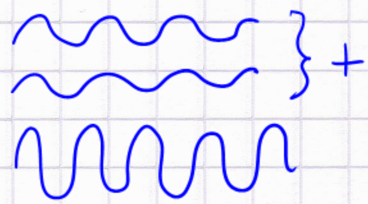
[Reflection: draw the normal; angle of incidence = angle of reflection]

The horizontal beam returning from M_2 has a 50-50 chance to either pass through the BS (into the source), or to be reflected towards the observer.

Observer: add the two arriving waves $E_\perp^{(1)}$ and $E_\perp^{(2)}$.

(A) The two waves can be in phase (the path lengths L_1 and L_2 are exactly the same, or they differ by an exact integer multiple of the wavelength λ):

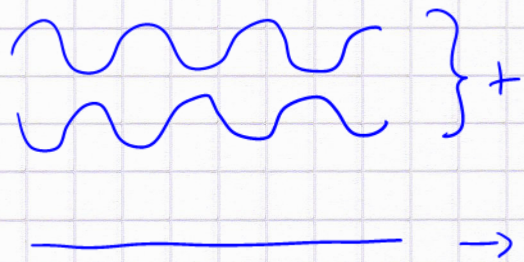
$E_\perp^{(1)} + E_\perp^{(2)}$:



→ bright light

(B) If the path length difference $L_2 - L_1$ is adjusted to be an half-integer multiple of λ:

$E_\perp^{(1)} + E_\perp^{(2)}$:



→ no light

Cases (A) and (B) are called constructive and destructive interference, respectively.

The light intensity is proportional to $(E_\perp^{(1)} + E_\perp^{(2)})^2$

no light → dark fringe

where does the light go in this case?

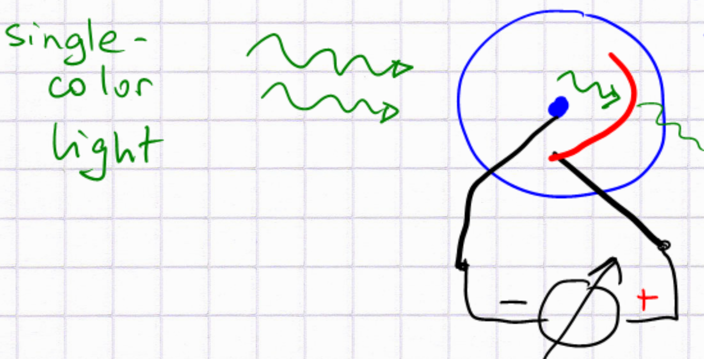
→ back into the source

Message: the wave model of light (electromagnetic wave) explains interference phenomena.

A CD = multi-slit reflective diffraction grating ↗ splits colours for similar reasons.

Philosophical problem: the wave theory of light can't explain all observed phenomena.

Example: photoelectric effect (G.28.2)



light knocks electrons out of a specially coated (alkali) electrode. Free electrons are collected at • electrode.

electrometer (voltmeter with $R_{int} \gtrsim 10^{14}\,\Omega$)

The electrometer measures a steady state:

e^- are continuously knocked out of) and collected at •

If the voltmeter reads x Volts, then the electrons have an energy of x eV → convertible to Joules

The light had to transfer more energy than x eV, since it costs energy to pull electrons out of the) photocathode. (work function).

In a wave theory one would think: more light intensity leads to higher electron energy → more Volts

Experiment: the voltage (electron energy) is practically independent of the light intensity, but it increases linearly with the light frequency $f = \frac{c}{\lambda}$ $c = 3.0\times10^8\,\frac{m}{s}$

blue light	~ 1.1	Volts
red light	~ 0.3	Volts
infrared	0	Volts

⇒ Light = photons of energy $E = hf$ h = Planck constant $\approx 6.6\times10^{-34}$ Js

So, which is it?

Light = EM wave
(explains interference)

Light = photons (particles with energy that depends on $f = \frac{c}{\lambda}$)

We have to accept some form of duality:

Light = EM wave made up of photons (particles) which carry energy $E = h\frac{c}{\lambda}$

blue light is more energetic than red light!

Amplitude of the EM wave → intensity

how many photons hit per second

- Albert Einstein explained this in 1905 → Nobel prize
- Max Planck was the first to introduce the notion that the energy associated with radiation is associated with frequency: $E = hf$

Later, in 1926: Erwin Schrödinger + Werner Heisenberg independently and in different ways explain:

Electrons bound in atoms can only be in states of certain discrete energy values. Transitions from higher to lower quantum mechanical states are accompanied by photon emission

$$E = hf = E_{el}^{higher} - E_{el}^{lower}$$

The allowed electron states are obtained from a wave equation (matter waves) → Energies are quantized very much like the allowed modes on a string