Phys 231 2021

Lecture 2

Announcements: * HW 1 due Monday 1 Feb by 5pm
→ Turn in during class / at office
→ D2L possibility
* HW Academic Integrity.

Friday: Read 3.2

Light: classical picture

The earliest quantum phenomena that were observed typically concerned the interaction between light and matter. Classical physics could attempt to describe these interactions by using a classical electromagnetic description of light. This description emerged in the late 19th century and consisted of:

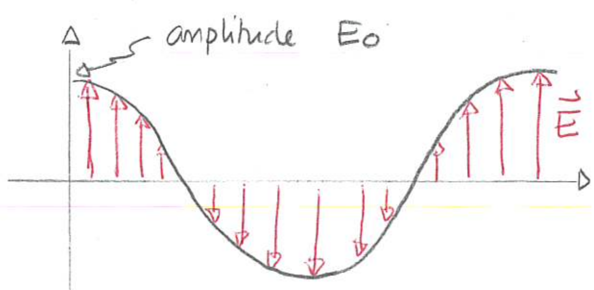
1) light is an electromagnetic wave - this is a wave of electric and magnetic fields which can propagate in a vacuum or in various materials.

Demo: Slides

Demo: PhET Radio Waves + EM fields

2) the wave can be described by the "envelope" for the electric field vectors:

Snapshot at one instant:



3) the wave travels at the speed of light

In a vacuum the speed of light is

$c = 3.0 \times 10^8 m/s$.

4) the wave can be characterized by:

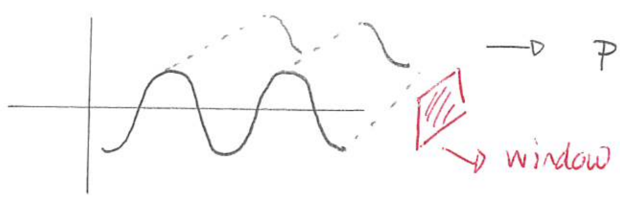
wavelength $= \lambda =$ distance between successive crests.

frequency $= f \sim$ number of crests passing given location each second.

In all cases

$$c = \lambda f$$

5) the amplitude of the wave describes the rate at which the wave transports energy.



Then classical electromagnetism predicts that the rate at which energy is transported per area, the intensity, is:

$$I = \frac{1}{2} c \epsilon_0 E_0^2 = \frac{\text{energy per second}}{\text{area of window}}$$

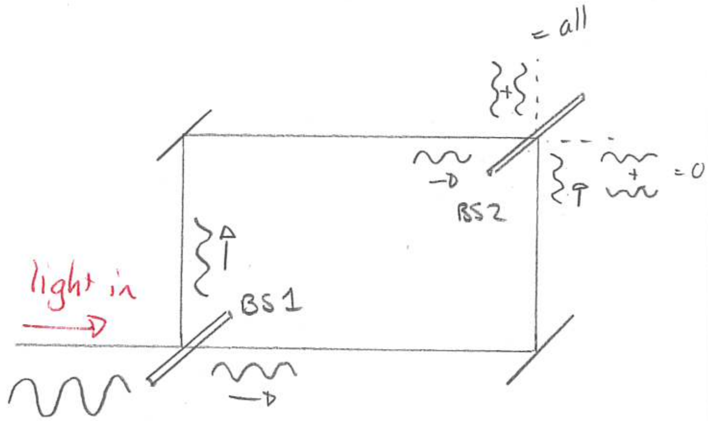
where

$\epsilon_0 = 8.85 \times 10^{-12} \ C^2/Nm^2$

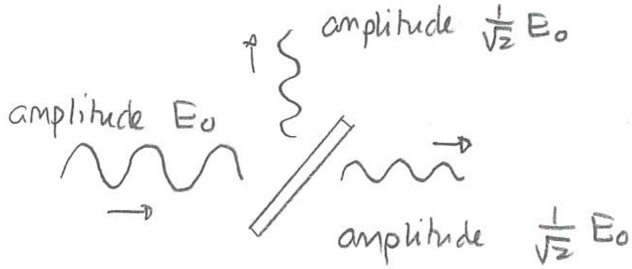
is the permittivity of free space.

Quiz 1 60% → 80%

This picture could explain the type of interference phenomena observed in the Mach-Zehnder interferometer. At each beamsplitter the waves split, with reduced amplitude. This is regardless of side of the beamsplitter that the incident wave approaches.



So for an individual beamsplitter:



We can then superimpose the after the second beamsplitter and this would yield the observed intensities at the detector.

Light + matter: photoelectric effect

What happens if one shines light on matter? In general some of the light will be transmitted and some will be reflected.

Demo PhET Bending light

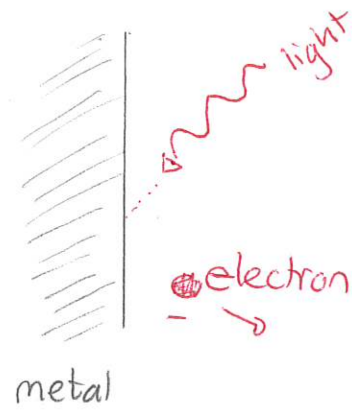
Classical electromagnetism predicts how to calculate the intensities of the reflected and transmitted light if particular properties of the material are known. In the case of a conducting material it predicts that the light will be reflected.

However, an experimental observation is that, under the correct conditions the incident light can completely free electrons from the material

Demo PhET Photoelectric Effect

— use default settings + observe electrons

This is called the photoelectric effect and was originally observed by Hertz in his experiments that demonstrated the existence of electromagnetic waves. In the process of such photoemission of electrons the energy must be conserved. The ejected electrons themselves have kinetic energy. It must also take a certain amount of energy to remove each electron. Roughly we have



energy of incident light = energy needed to remove electron + kinetic energy of electron

In order to observe this we could consider a single light source and observe the maximum kinetic energy of any ejected electron. Let

K_{max} = max kinetic energy amongst ejected electrons

Then the minimum energy needed to eject an electron from the metal is:

The work function ϕ is the minimum energy required to eject an electron from the metal

Those electrons who only needed ϕ to be ejected will have max kinetic energy. Then let E be the energy supplied by the light: Energy conservation implies

$$E = \phi + K_{max} \Rightarrow K_{max} = E - \phi$$

The work function depends on the metal and is usually measured in units of electron-Volts ($1 eV = 1.6 \times 10^{-19} J$).

Quiz 1

Various aspects of the photoelectric effect were observed and one could attempt to explain these classical

Observation	Classical explanation / prediction
1) As intensity of light increases more electrons are emitted	Greater intensity ⇒ greater total energy ⇒ more emitted
2) The maximum kinetic energy of emitted electrons does not depend on intensity it does depend on frequency	Greater intensity ⇒ more energy from incident light ⇒ more energy to each emitted electron Classical ⇒ frequency should not affect K_{max} ✗
3) For any given metal electrons are only emitted if frequency is large enough. There is a cutoff frequency (depends on metal) f_{cutoff} Electrons are only emitted if the frequency of light f satisfies $f > f_{cutoff}$	Classical ⇒ frequency does not affect energies ✗
4) If $f > f_{cutoff}$ then electrons are emitted almost instantly regardless of energy	Classical ⇒ $E = I \times time \times area$ For low intensities need more time for energy to accumulate ✗

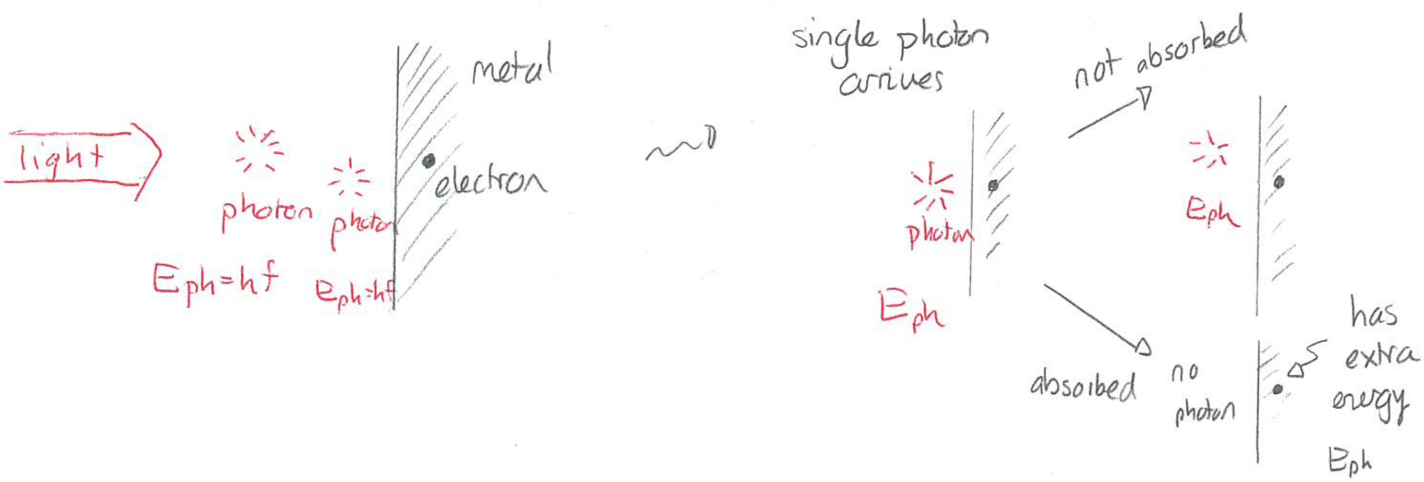
Photon explanation due to Einstein

The first picture of light that explained qualitative (and at that point untested quantitative) aspects of the photoelectric effect was due to Einstein. The explanation required a radical assumption about the nature of light that is inconsistent with classical electromagnetism.

> For light with frequency, f, the energy provided by the light can only be delivered in discrete units (or quanta). Each unit has energy
>
> $$E_{ph} = hf$$
>
> where
>
> $$h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}$$
>
> is Planck's constant.

Each unit of energy functions like a particle and these are now called photons. An additional assumption is:

> When electromagnetic radiation / light interacts with matter, either all of the energy of a photon is absorbed or else none is.



This does describe some observed phenomena of the photoelectric effect:

1) The energy of a photon must be at least equal to the work function to liberate an electron

$$E_{ph} > \phi \Rightarrow hf > \phi \Rightarrow f > \underbrace{\phi/h}_{\text{cutoff}}$$

2) The energy of any single photon is the same regardless of the intensity of light if the frequencies are the same. Low intensity light contains fewer photons than higher intensity light. All that is required to emit an electron is a single photon and thus an electron can be omitted nearly immediately for low intensity light.