

Light as electromagnetic wave and as particle

Help to understand and learn exam question 5.

(How the wave-particle duality can be applied to light?)

and to measurements „Microscopy II.”, “Light emission” and Polarimetry”.

Previous lectures about the light: 2 models

Geometrical optics (model 1)

Light-ray: extremely thin parallel light beam

1. law of rectilinear propagation
2. law of reflection
3. law of refraction (Snell's law)

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1}$$

All these laws can be deduced from a single common principle! **Fermat-principle**

Using this model, the explanation of several optical phenomena can be given as the solution of simple **geometric problems**.

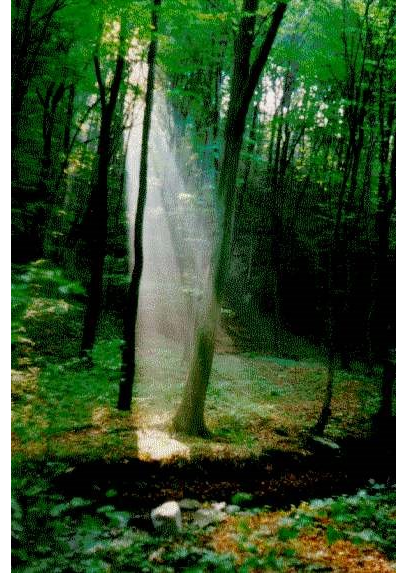
Example: Lens equation and lens-makers' equation:

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f} = (n - 1) \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

o, i : object and image distances

r_1, r_2 : radii of curvature of the lens

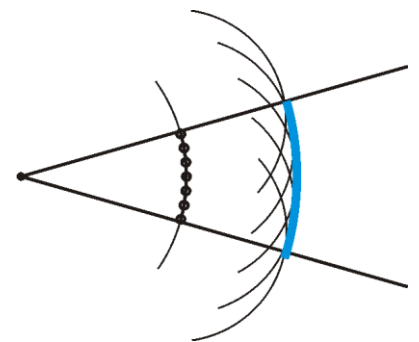
$n = n_2/n_1$: relative refractive index of the medium of the lens.



Physical or wave optics (model 2)

Its bases: **Huygens–Fresnel-principle**

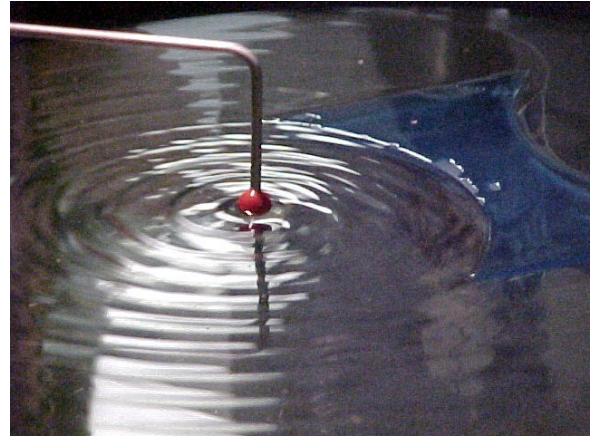
The previous 3 laws can be described by this model as well.



superposition → interference

Interference (two or more waves meet)
the most important phenomenon in connection with waves

Incoherent and coherent waves



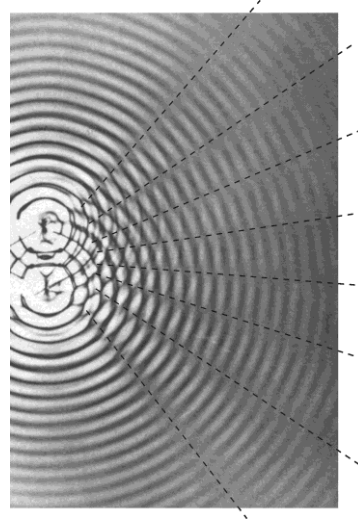
Rise of coherent waves is controlled in space and time, they are **synchronized** somehow.

E.g. „water wave”: it can be observed directly.

Because it changes slowly enough (low frequency, f ; low speed, c) and the typical (wave) size is large enough (long wavelength, λ).

„Light waves” are different.

At certain conditions **patterns** can be formed, which don't change in time, and their size is much larger than the wavelength, λ .



Maxwell studied the radio waves (electromagnetic waves) and found:

„speed of propagation of electromagnetic waves...lies so close to the **speed of propagation of light**, that it seems rather compelling to conclude that **light itself is a certain disturbance of the electromagnetic field**, propagating as a wave according to the laws of electromagnetics.”

What is light? Visible **electromagnetic radiation**

Thus the word **light** refers to **electromagnetic waves** observable to the human eye, i.e. of wavelengths **between 400 and 800 nm**.

electromagnetic wave is **transversal**

thus can be **polarized**

linearly polarized light or **plane polarized light**

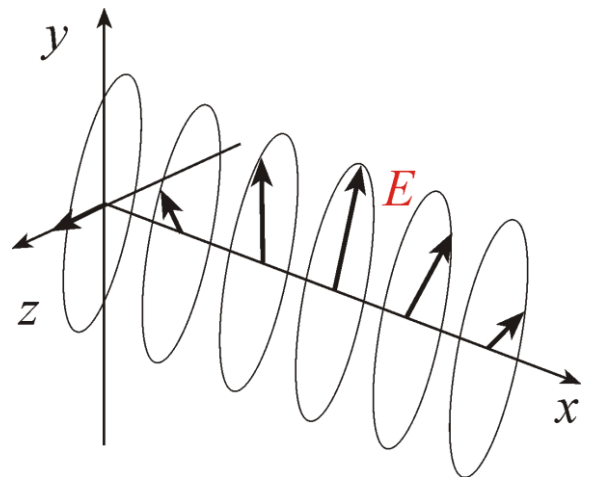


But **elliptically (or circularly) polarized light** also exists.

Optical anisotropy

E.g. in an „anisotropic matter” the **speed of a suitably linearly polarized light depends on the direction of propagation**.

The reason of it is connected to the structure of matter.



Consequences, applications: double refraction, polarization microscope, polarimetry

Hallwachs experiment:

ultraviolet irradiation causes the emission of negative charge carriers from the exposed metal surface. This phenomenon is called the **photoelectric effect**.

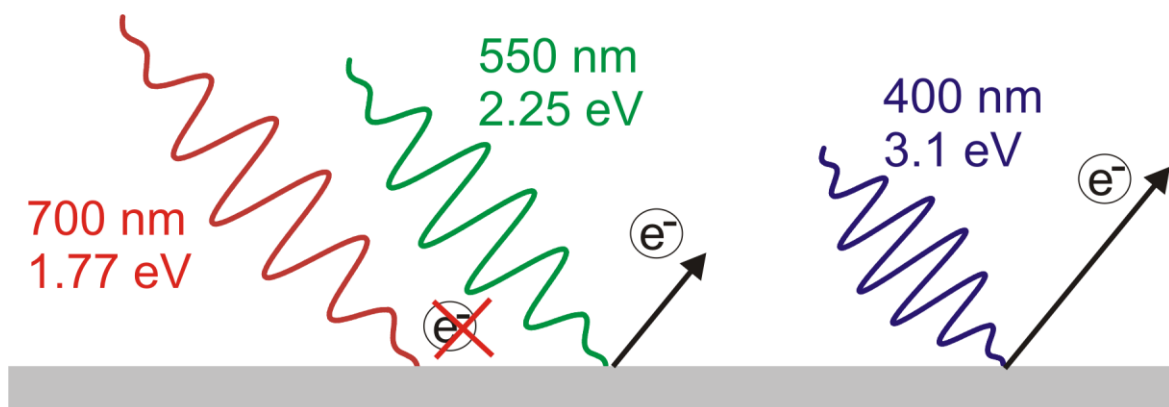
Lenard investigated the phenomenon in further detail, and concluded:

- the emitted charge carriers are **electrons**,
- **the effect does not occur under a threshold frequency** (specific for the metal), not even if we increase the intensity of the light,
- **the maximum velocity of the emitted electrons depends on the colour**, i.e. frequency **of the light**, but not the intensity (this velocity increases with higher frequencies),

These findings cannot be explained using a theory of electromagnetic waves.

Einstein: the **photon** is the elementary **particle** which carries the energy of electromagnetic radiation.

Photoelectric effect: An incident photon removes an electron from the bound electrons of an atom or molecule, while the photon is absorbed.



$$hf = W + E_{\text{kin}} = W + \frac{1}{2}m_e v^2$$

Phenomenon

Can be explained in terms of **waves**.

Can be explained in terms of **particles**.

	waves	particles
Reflection	+	+
Refraction	+	+
Interference	+	-
Polarization	+	-
Photoelectric effect	-	+

“Prehistory”

Are not all hypotheses erroneous, that assume light to be a kind of pressure or motion, propagating in some medium? Should light rays not consist of **small particles, emitted by the glowing substance?**

Newton (1642-1726): Optics

..., if we consider ... (light)rays may traverse each other without difficulties, ... seeing an object emitting light **cannot happen through a flow of substance**, originating in the object and travelling towards ourselves, **as bullets or arrows move in air**;... Thus light propagates in a different way, and **to understand this, we must use our knowledge about the propagation of **sound(waves)**.**

Huygens (1629-1695): Traité de la lumière

Electromagnetic spectrum:

