2. WAVE OPTICS

There are only two ways to live your life:
as though nothing is a miracle, or
as though everything is a miracle.
Albert Einstein

2.1. Conception of aether

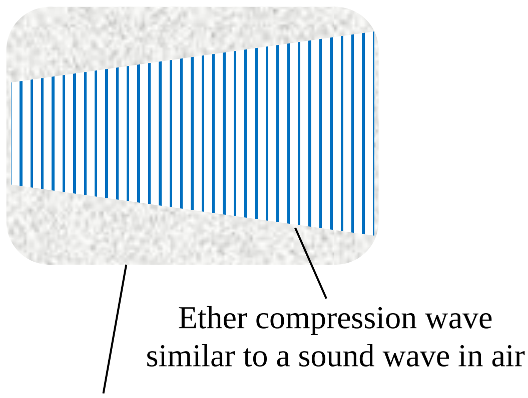
What we now call physics, until the XVIII c. named natural philosophy. Classical physics began in the XVIII c. with Isaac Newton and ended in the XIX century with James Maxwell. The triumph of the English classical school was spoiled by two Germans – Max Planck and Albert Einstein, who at the beginning of the XX c. laid the foundations of modern physics.

Till the XIX c. the straightness of light ray propagation was regarded as a postulate, which was formulated for the first time by Euclid. Later it was proved within the framework of the wave theory.

Philosophers studied the properties of light rays, but until the 17th century, it seems that no one tried to explain its physical nature. The assumption that light is a wave appeared, apparently, in the XVII century. But how to explain the mechanism of propagation of a light wave? One of the first to do this was Rene Descartes (1596–1650), a French philosopher, mathematician and physicist (Fig. 2.1). In 1637 Descartes published his "Dioptrics", in which he introduced into physics the concept of ether – subtle matter, consisting of the smallest particles that fill all space. Dioptrics is the old name of the geometric optics.

Fig. 2.1. The French philosopher and mathematician René Descartes (1596–1650)

Light bearing ether after Descartes



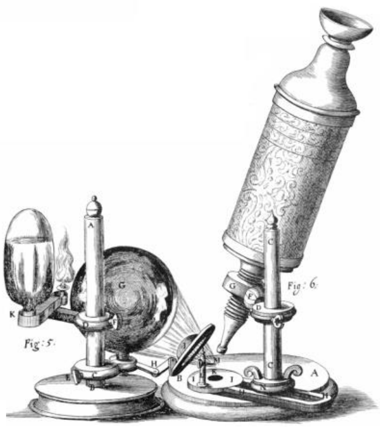
The concept of ether was needed to explain the mechanism of light propagation, therefore, ether is sometimes called luminiferous (light bearing). Many famous physicists were the proponents of the ether theory – Grimaldi, Descartes, Huygens, Newton, Fresnel and others. The ether theory explained the propagation of light wave as the process of compression and decompression of the media. Then it was already known that sound waves propagate in this way. Such waves are called longitudinal.

In 1665 appears "Physical and mathematical treatise on light, colors and rainbows" by the Italian physicist and astronomer Francesco Grimaldi, which reveals another property of light – the deflection of light in the direction of the geometric shadow. Grimaldi called this phenomenon diffraction and explained the appearance of light waves, during its collision with the obstruction, of waves deflecting towards the shadow. To explain the color of light, the scientist attributed the wave properties to light:

"It is possible that the variations of light, due to which it is constantly colored into visible colors ... is a certain wave of it with very frequent excitement, so ... it acts on the organ of vision in a specific, peculiar way."

In the same 1665 was published "Micrography" – a book by English physicist Robert Hook (Fig. 2.2), which among microscopic observations described the phenomenon of color in white light thin films, such as soap bubbles or oil stains on

Fig. 2.2. The English natural philosopher Robert Hook (1635–1703, portrait of Hook according to descriptions of contemporaries)



Hook's microscope

the water. Hook developed his oscillatory model of light and tried (without much success) to explain the phenomenon of refraction and the nature of color. He regarded light as rapid oscillations, either instantaneously or very rapidly, with a single oscillation generating in a homogeneous medium a sphere whose radius is steadily increasing with time. Hook believed that light travels like a wave on water. So in the model of light the idea of a wave front was born. Hook assumed that light oscillations were transverse as transverse were waves on water.

Fig. 2.3. The Danish scientist Rasmus Bartholin (1625–1698)

In 1666 a Danish physician, philologist, mathematician and physicist Rasmus Bartholin (Fig. 2.3) discovered a phenomenon of double refraction of a light ray in the calcite $CaCO_3$ (Fig. 2.4). Calcite crystals were originally brought from Iceland by sailors, so they were called Icelandic crystals or Icelandic spar. The Vikings used the polarization properties of the Icelandic crystals at sea to determine the direction to the Sun in cloudy weather or at dusk, scientists as evidence of the wave nature of light.

A Dutch physicist, mathematician and inventor Christiaan Huygens depicted the aether as the omnipresent, perfectly elastic medium having zero density [2.1]. In 1672 he discovered that two rays emerging from this crystal had different properties in the transverse direction. Later, this property of the wave to oscillate in a certain direction was called polarization. Huygens believed that light is the longitudinal vibrations of the ether. Longitudinal waves have only one polarization; therefore, Huygens could not explain such a difference in the properties of ordinary and extraordinary rays. This difference can be easily explained by assuming the transverse nature of light

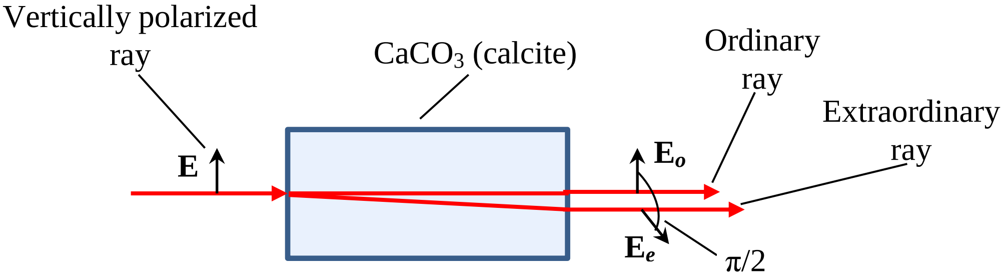


Fig. 2.4. Double refraction of light ray in the calcite crystal

waves.

In 1656 Huygens invented the pendulum clock which was the most accurate timekeeper for the next 275 years. Huygens derived a well-known formula for the oscillation period of a pendulum:

$$T = 2\pi\sqrt{l/g},$$

where l is the length of the pendulum and g is the gravitational acceleration.

The most important contribution to optics was the *Huygens principle* formulated in 1678. According to this principle, each point of the medium reached by the wavefront of light excitation can be considered as a source of an elementary spherical wave; adding elementary waves from different points of the wavefront, we obtain the observed wave (Fig. 2.5). Huygens did not consider the light wave as a periodic oscillation. For him, a wave is an impulse excitation, a push of ether particles that transmit this motion to each other like billiard balls.

Note that the ether has not been experimentally detected, but the possibility of its existence has not yet been rejected and new attempts are being made to detect ether using the most modern means.

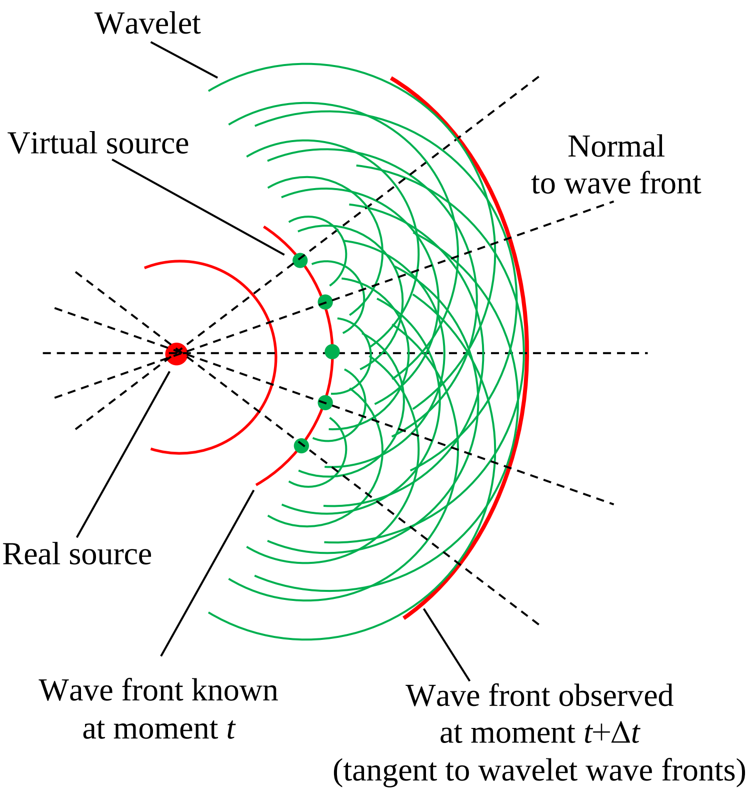


Fig. 2.5. Illustration of the Huygens principle

2.2. Conception of field

Various types of attraction have been known for a long time – both the attraction of the Earth, and the attraction of magnetized or electrified bodies.

Ancient people sometimes found magnetite minerals that can attract iron. The compass was invented more than two millennia ago in China and was originally used for fortune telling and for building houses in accordance with the principles of feng shui. The compass became a means of navigation at sea in the 11th century.

It has long been known that amber, if rubbed on cat's fur, is electrified and attracts light feathers. The word "electron" comes from the Greek name for amber, and the word "electricity" means from the Greek "like amber."

The law of attraction of distant bodies was formulated in 1686 by the English physicist Isaac Newton. This is the law of universal gravitation which defines the force of the gravitational attraction between two objects with masses m_1 and m_2:

$$F_g = G\frac{m_1 m_2}{r^2},$$

where G is the gravitational constant ($G = 6{,}67\cdot10^{-11}$ N·m^2·kg^{-2}) and r is the distance between the centers of their masses.

We can recall here the Coulomb’s law for the electrostatic force of attraction or repulsion of two bodies carrying electric charges q_1 and q_2:

$$F_e = k_e\frac{q_1 q_2}{r^2},$$

where k_e is Coulomb’s constant ($k_e = 9\cdot10^9$ N·m^2·C^{-2}). Modern experiments have shown the validity of this law at distances from 10^{-16} to 10^8 m.

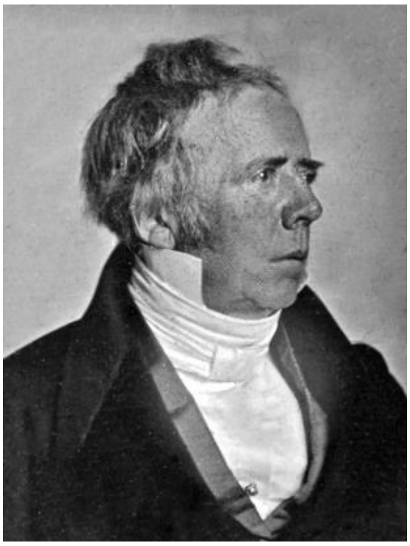


Fig. 2.6. The Danish physicist and chemist Hans Oersted (1777–1851)

Note that electrostatic attraction occurs between bodies with positive and negative charges, while gravitational attraction occurs between positive masses (negative masses have not yet been discovered).

In 1820, the Danish physicist Hans Oersted (Fig. 2.6) noticed the deflection of a magnetic arrow under the influence of an

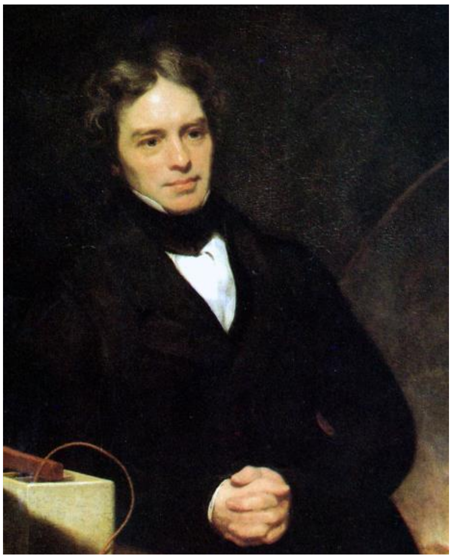


Fig. 2.7. The English scientist Michael Faraday (1791–1867)

electric current in a wire. It was the first electromagnetic experiment to demonstrate the relationship between different physical phenomena. Oersted suggested that the nature of light could also be related to electromagnetism.

How can two physical bodies spaced apart from each other by a distance *r* interact with each other? Some substance must be between the bodies, applying the force of attraction or repulsion to the bodies. The conception of such substance was proposed in 1849 by the English physicist Michael Faraday. He suggested that bodies generate physical fields through which they interact with each other. With the help of this idea he tried to explain electromagnetic phenomena.

In 1845, Faraday demonstrated the phenomenon of rotation of the plane of polarization of light in optically inactive substances (in particular, in glass and carbon disulfide CS_2) placed in the magnetic field (*Faraday effect*) [2.2]. It was the first experiment in which magnetism acted on light, though indirectly – through an optical medium. Faraday wrote in his diary:

"The light felt a magnetic effect, that is, a magnetic action was experienced by what is magnetic in the forces of matter, and the latter in turn acted on what is truly magnetic in the power of light."

On the basis of the field conception a Scottish scientist James Maxwell (Fig. 2.8) built in 1864 the well-known theory of electromagnetic field [2.3]. Based on his theory, Maxwell predicted the existence of electromagnetic waves, suggested that light is an electromagnetic wave, and even calculated the pressure of light. He proved that the light waves, more generally electromagnetic waves, propagate by means of the oscillations

Fig. 2.8. The Scottish scientist James Maxwell (1831–1879)

electric and magnetic fields in the directions perpendicular to each other and to the direction of propagation. Therefore, the light waves are transversal (Fig. 2.9).

The existence of electromagnetic waves was experimentally confirmed in 1887 by the experiments of the German physicist Heinrich Hertz.

The simplest electromagnetic waves are harmonic waves (flat and spherical) propagating in a homogeneous medium. A plane harmonic wave having a circular frequency ω and propagating along the *Z*-axis can be represented as

$$E(z,t) = E_0 \cos \omega(t - z/c)$$

or

$$E(z,t) = E_0 \cos(\omega t - kz),$$

where k is a wave number (modulus of the wave vector **k**, showing the direction of propagation of wave with wavelength λ), $k = |\mathbf{k}| = 2\pi/\lambda$.

For any waves, the product of the wavelength λ and frequency ν determines the wave velocity $V = \lambda\nu$. The speed of light in vacuum is usually denoted by the letter c. Along with the frequency ν in the formulas often use the circular frequency ω, $\omega = 2\pi\nu$.

Note that the electric field vector **E** determines direction of the light wave polarization.

<u>*Designations:*</u>
d – density of the medium, kg/m^3;
V – velocity vector; V – velocity, m/s;
k – wave vector; $k = 2\pi/\lambda$ – wave number, m^{-1};
λ – wavelength of electromagnetic wave, m;
Λ – wavelenghth of acoustic (sound) wave, m;
E – electric vector; E – strength of electric field, V/m;
H – magnetic vector; H – strength of magnetic field, A/m.

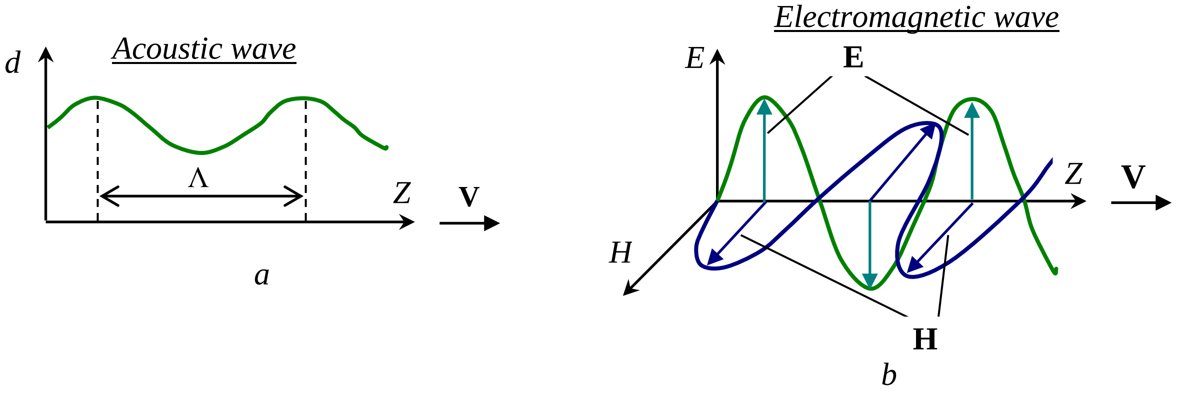


Fig. 2.9. Mechanisms of propagation of sound (*a*) and light (*b*) waves

In optics, such dimensions of quantities are usually used:
wavelength λ – meters, *m* (common to all spectral ranges); micrometers (10^{-6} *m*), *μm* or *mkm* – for infrared (IR) range; nanometers, *nm* – for visual, ultraviolet (UV) and x-ray ranges;
frequency ν – hertz (second^{-1}, s^{-1}), *Hz* or gigahertz (10^9 *Hz*), *GHz*;
circular frequency ω – radians per second, $rad{\cdot}s^{-1}$, *rad/s*;
wavenumber *k* – radians per meter, $rad{\cdot}m^{-1}$, *rad/m*; in spectroscopy $k = 1/\lambda$ – centimeters^{-1}, cm^{-1};
wave velocity *V* or *c* – meters per second, $m{\cdot}s^{-1}$, *m/s*.

The interaction of distant objects through gravitational and electromagnetic fields were the first examples of action at a distance. Before the appearance the concept of field, philosophers believed that action at a distance is transmitted using some kind of particles. In the 20th century, intermediary particles (bosons) with a mass of 100 times the mass of a proton and with a lifetime of 10^{-25} s appeared in the Standard Model of particle interaction. The action at a distance due to the quantum entanglement of particles, discovered in the same century, became even more mysterious.

The main weaknesses of the wave concept of light were the need for a medium for the propagation of a light and the difficulty in explaining the straightness of the light wave propagation.

2.3. Some history

Exert from Faraday’s diary entry of 13 September, 1845:

“Today worked with lines of magnetic force, passing them across different bodies (transparent in different directions) and at the same time passing a polarized ray of light through them and afterwards examining the ray by a Nichol prism. A piece of heavy glass which was 2 inches by 1.8 inches, and 0.5 of an inch thick, being silicon-borate of lead, and polished on the two shortest edges, was experimented with. It gave no effects when the same magnetic poles or the contrary poles were on opposite sides (as respects the course of the polarized ray) nor when the same poles were on the same side, either with a constant or intermitting current, but, when contrary magnetic poles were on the same side, there was an effect produced on the polarized ray, and thus magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile and of great value in the investigation of both conditions of natural force” [2.2].

2.4. References

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