3. DIFFRACTION OF LIGHT

3.1. First evidence of wave nature of light

Fig. 3.1. The Italian physicist Francesco Grimaldi (1618–1663)

In 1665, the «Physical and Mathematical Treatise on Light, Colors, and Rainbow» was published by the Italian physicist and astronomer Francesco Grimaldi, which reveals an unusual property of light – its deflection by an obstacle in the direction of a geometric shadow. Grimaldi called this phenomenon diffraction and explained the appearance in the light fluid, when it collides with an obstacle, of waves that deflect toward the shadow. The edge of the shadow was painted in the colors of the rainbow (Fig. 3.2).To explain the color, the scientist draws an analogy with the sound vibrations of air and attributes wave properties to light [3.1]:

> "It is possible that modifications of the light, as a result of which it is constantly painted in the so-called apparent colors ... is some of its waviness with very frequent excitement, due to which ... it acts on the organ of vision in a certain characteristic way for it".

With the term «diffraction», Grimaldi emphasized that the light, walking around

Diffraction is a wave rounding the edge of an obstacle,
the stronger the longer the wave,
and the formation of fringes on the edge of its shadow

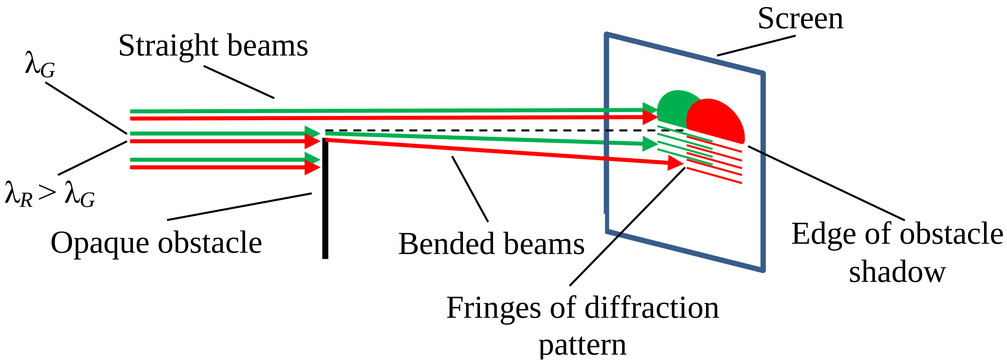

Fig. 3.2. Diffraction of the light beams at the edge of an obstacle

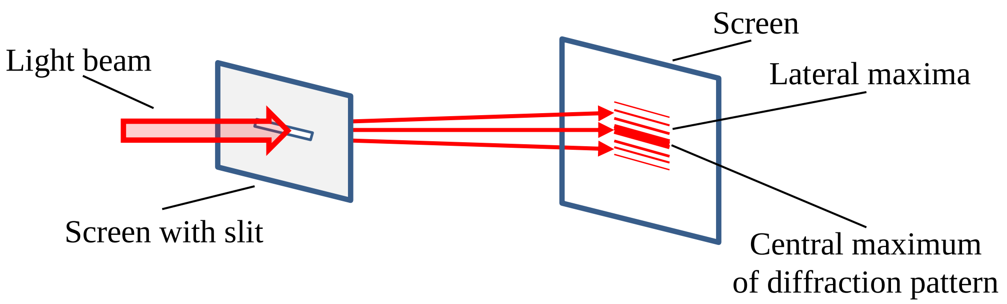

Fig. 3.3. Diffraction of the monochrome light beam at the slit

an obstacle, is decomposed into components (fractions). Grimaldi also described in his book the diffraction of light on a bird's feather. These were the first observations that clearly testified to the wave nature of light.

Let's consider the simplest cases of diffraction. The first one is diffraction of the monochrome light beam on the slit (Fig. 3.3). The diffraction pattern consists of the bright central fringe and a few parallel less bright fringes symmetrically located around the central fringe (diffraction maximum of the 0^{th} order surrounded maxima of higher orders).

The second case is diffraction on the hole (so called circular aperture). Diffraction pattern which is formed on the screen consists from the light central disk (Airy disk) and the concentric light and dark rings around the disk (Fig. 3.4). The circular aperture plays an important role in imaging. It is diffraction at the edge of the lens that creates the image. The role of the spherical surface of the glass in a lens consists only in changing the distance to the image.

The diffraction pattern is affected by the relationship between the size of the obstacle and the wavelength. For example, red light (λ = 0.6 μm) forms a diffraction pattern similar to that shown in Fig. 3.4, at a distance L = 0.5 m, if the hole has a

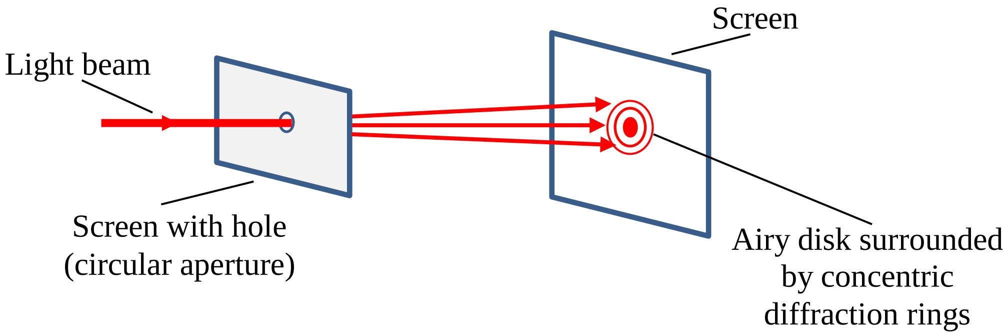

Fig. 3.4. Diffraction of the monochrome light beam at the hole

diameter d = 0.1 mm, and at a distance L = 1 km, if d = 10 mm. The diffraction pattern formed by rays converging at a relatively small distance from the obstacle (in the so-called near diffraction zone) is the result of the Fresnel diffraction.

The pattern formed by almost parallel rays at a relatively large distance from the obstacle arises as a result of the Fraunhofer diffraction. The Fraunhofer diffraction is observed in the far diffraction zone, remote from the obstacle at a distance

$$L \gg \frac{d^2}{\lambda}.$$

3.2. Distinguishing between closely spaced spotlights in image

Two closely spaced points on an illuminated rough surface, like two closely spaced stars in the sky, can be considered as point sources of light. Their images formed by lenses look like partially overlapping Airy disks.

The British scientist lord Rayleigh (Fig. 3.5) came up with a criterion that helps to cope with the problems of interpreting overlapping images of dots or lines with blurred edges (Fig. 3.6). The intensity distribution in the Airy disk is described by the function

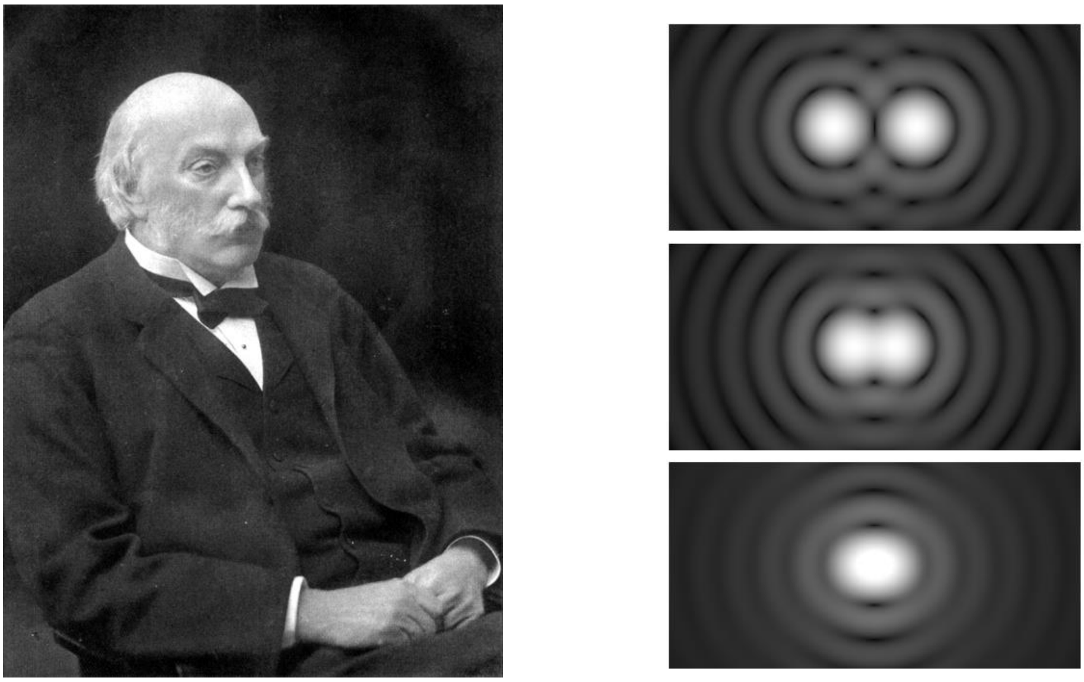

Fig. 3.5. The British scientist lord Rayleigh (John Strutt, 1842–1919).
On the right are the diffraction patterns from two point sources,
the average still resolvable by the Rayleigh criterion

$$Airy(x)=\left[\frac{2J_1(x)}{x}\right]^2,$$

where $J_1(x)$ is the first order Bessel function of the first kind. According to the Rayleigh criterion, two such overlapping distributions are distinguishable if the central maximum of the first distribution coincides with the first minimum of the second distribution (Fig. 3.6). In other words, if the trough in the total distribution exceeds a quarter of the maximum value, then we are dealing with two sources of distributions.

Rayleigh entered the history of optics with his criterion for separating images of closely spaced sources (Rayleigh criterion) and the law of light scattering on particles smaller than λ (Rayleigh scattering). This law has made clear why the sky is blue. The intensity of scattered light is proportional to $1/\lambda^4$, therefore, the blue component of the scattered light is 2 times stronger than the green component, and 5 times stronger than the red component.

Exploring the properties of gases, Rayleigh discovered *argon*. For these studies he was awarded the 1904 Nobel Prize in Physics.

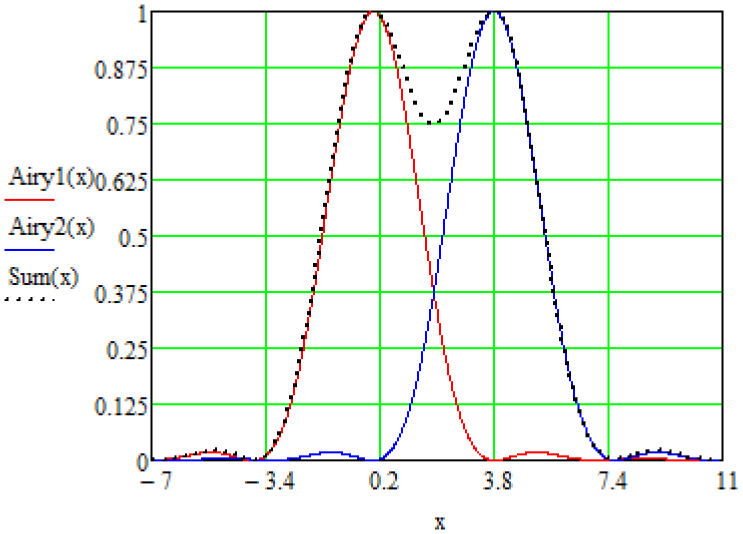

Fig. 3.6. Rayleigh criterion for distinguishing overlapping images of two point sources

3.3. Diffraction grating

Many parallel equidistant slits form a diffraction grating (Fig. 3.7). Diffraction grating is one of the most powerful optical instruments able to split the light into spectral components (waves with different wavelengths) and to send them in different

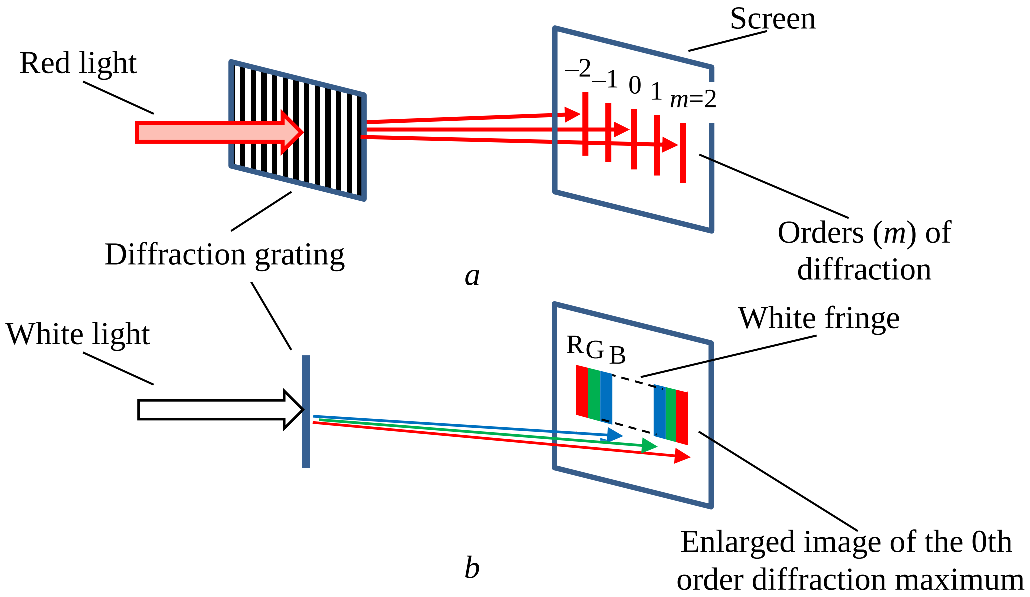

Fig. 3.7. Diffraction of red (*a*) and white (*b*) light on a grating

directions. As we know, Newton was the first who demonstrated the decomposition of white (Sun) light by the glass prism, using the phenomenon of material dispersion.

For oblique incidence of light with λ wavelength, the grating equation can be written as follows:

$$d\left(\sin\theta_i - \sin\theta_d\right) = m\lambda,$$

where d is the grating period, θ_i is the angle of incidence, θ_d is the angle of diffraction, and m is the order of diffraction.

3.4. Diffraction on crystal lattice

In 1895, Wilhelm Rȍntgen investigated the fluorescence of crystals a barium salt coated cardboard caused by cathode rays (so were named the particle beams emitted by heated cathodes; the electron was discovered by the English physicist Joseph Thomson in 1897). The objects of his study were cardboards with crystals of barium salt deposited on their surfaces. Rȍntgen accidentally noticed that a meter away from the cathode tube, where there are no cathode rays, the cardboard prepared for the next experiment glows. Subsequent experiments showed that the glow is caused by unknown rays coming from the metal elements of the tube structure onto which the cathode rays fell. The rays had a high penetrating ability, were not reflected or refracted by glass (Fig 3.8). Rȍntgen believed that the rays he discovered were longitudinal elastic vibrations of the ether. The scientist's studies were rewarded in 1904 with the first Nobel Prize in physics.

Fig. 3.8. The German physicist Wilhelm Rȍntgen (1841–1923).
On the right is the first X-ray photograph
taken by a scientist from the hand of his wife with a finger ring in 1895

The idea that crystals have spatial lattices arose among physicists at the end of the 19th century. With the discovery of X-rays, scientists began to study their polarization and diffraction. The transmission of X-rays through the crystal gave a diffraction pattern in the form of periodically arranged spots. In 1912, the German physicist Max von Laue (Fig. 3.9) explained such diffraction pattern of X-rays and confirmed their wave nature. He formulated a law that connects the diffraction angles and the size and orientations of the crystal cells (Nobel Prize 1914 in physics).

In 1913 the British physicist Henry Bragg designed a spectrometer to study X-ray diffraction. A year earlier, his son Lawrence suggested that the spatial structure of the crystal is formed by equidistant atomic planes and derived a formula for the diffraction of waves on such a spatial lattice (Fig. 3.10):

$$2d\sin\theta = m\lambda,$$

where d is the period of the spatial lattice, θ are the equal angles of incidence and diffraction of X-ray

Fig. 3.9. The German physicist
Max von Laue (1879–1960)

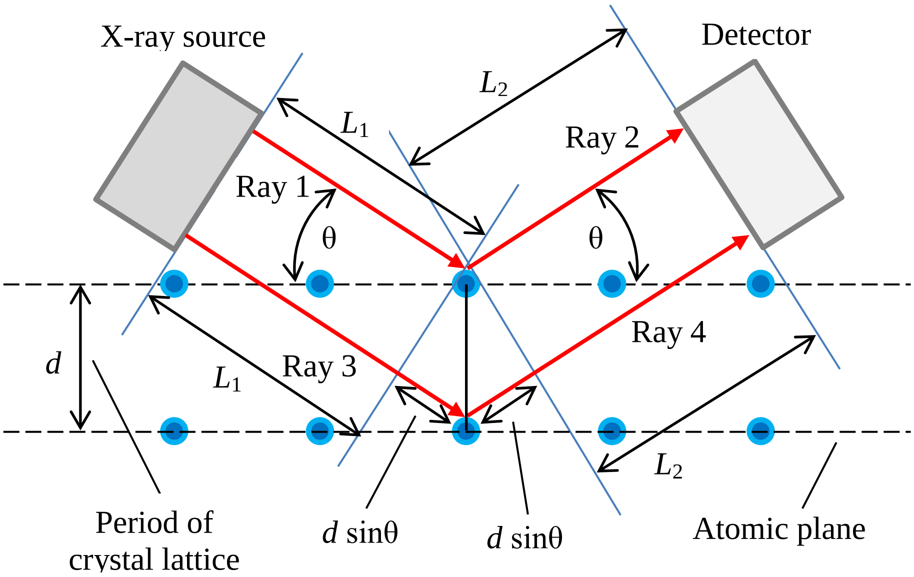

Fig. 3.10. X-ray diffraction on a spatial crystal lattice

radiation, *m* is the integer, and λ is the wavelength. Using a spectrometer and this formula, Braggs determined the lattice periods of several materials (NaCl, ZnS, diamond etc.).

In 1915, Henry and Lawrence Bragg were awarded the Nobel Prize in Physics («for their services in the analysis of crystal structure by means of X-ray»). This is the only case in the history of the Nobel Prizes when the prize was received by father and son and the only case when the prize was received at 25 (Fig. 3.11).

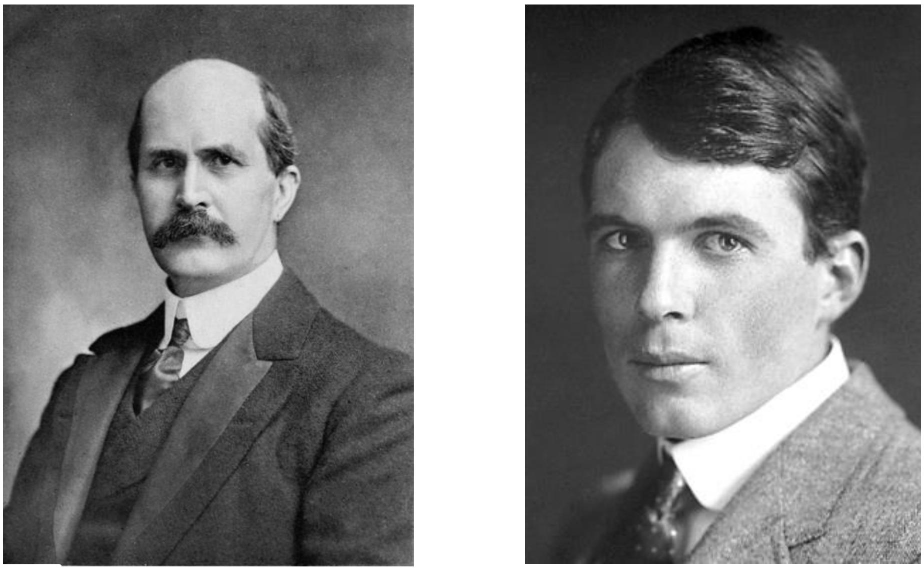

Fig. 3.11. The British physicists Henry Bragg (1862–1942) and Lawrence Bragg (1890–1971)

Diffraction also manifests itself in the propagation of radio waves: ultrashort waves (television and mobile communications) almost never go beyond the horizon directly, but only with the help of relay stations or reflections from the ionosphere, while long waves are able to go around the Earth (Fig. 3.12).

Diffraction of sound waves is manifested in the fact that we hear, for example, the voices of people around the corner of the house.

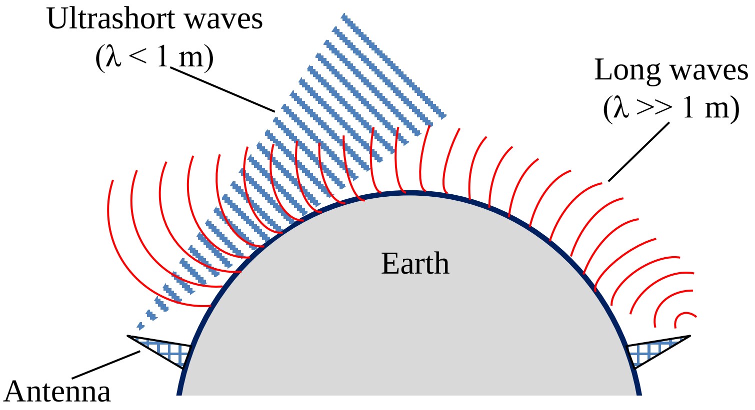

Fig. 3.12. Propagation of radio waves near the surface of the Earth.
Long waves walk around the Earth.

3.5. Some history

On March 7, 1673 Scottish mathematician and astronomer James Gregory described his observation to his publisher John Collins [3.1]:

> “Let in the sun’s light by a small hole to a darkened house, and at the hole place a feather, (the more delicate and white the better for this purpose,) and it shall direct to a white wall or paper opposite to it a number of small circles and ovals, (if I mistake them not,) whereof one is somewhat white, (to wit, the middle, which is opposite to the sun,) and all the rest severally colored.”

Gregory studied in detail the diffraction of light on a bird's feather and described the decomposition of sunlight into a spectrum, just as Isaac Newton had done with the prism a year earlier. A bird's feather became the prototype of the diffraction grating, and Gregory is considered the inventor of the grating.

3.6. References

3.1. Correspondence of scientific men of the seventeenth century. In two volumes. Vol. II . – 1841. – Oxford: At the University Press – P. 254 [Electron. resource]. – Access link:

https://books.google.com.ua/books?id=0h45L_66bcYC&pg=PA254&dq=feather+ovals&ie=ISO-8859-1&output=html&redir_esc=y