4. INTERFERENCE OF LIGHT

4.1. Discovery of the interference phenomenon

Fig. 4.1. The English scientist Thomas Young (1773–1829)

Physicists mention the name of the English scientist (physician by education) Thomas Young (Fig. 4.1) in connection with the phenomenon of interference discovered by him, as well as with the introduction of the concepts of mechanical energy and elastic modulus. Physiologists will say that Young explained the mechanism of eye focusing, invented an optometer (a device for measuring visual power) and proposed a three-color vision theory, confirmed only in 1959. Linguists and Orientalists will note that Young introduced the concept of “Indo-European languages”, that he knew 13 languages and deciphered the ancient Egyptian hieroglyphs. “The last person who knew everything: Thomas Young” was the title of one of the books about him [4.1].

Studying in 1802 string vibrations with the help of light, Young discovered that sound waves can both amplify and weaken each other. Young called this phenomenon interference. He showed that light passed through the two closely spaced slits in the plate formed on the screen alternating light and dark fringes

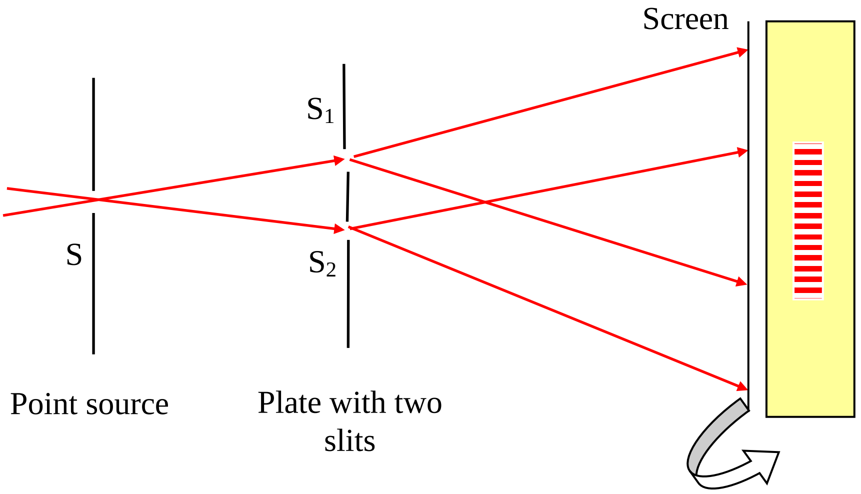


Fig.4.2. Observation of interference from two slits (Young's two-slit experiment)

(Fig. 4.2). The diffraction of light on two slits led to the formation of an interference pattern on the screen.

For almost a century, Newton’s corpuscular theory of light dominated in physics. Young introduced the concept of a light wave and, using his two-slit experiment, first measured the wavelengths of red and violet light.

In 1815, the French physicist (road engineer by education) Augustin Fresnel (Fig. 4.3) detected fringes in the shadow of a thin wire (Fig. 4.4 *a*). To exclude the influence of diffraction on the picture obtained from the mixing of two light beams, Fresnel used reflection from two slightly tilted mirrors (Fig. 4.4 *b*). Unaware of the experiment of Thomas Young, Fresnel again discovered the phenomenon of interference.

Fig.4.3. The French physicist Augustin Fresnel (1788–1827)

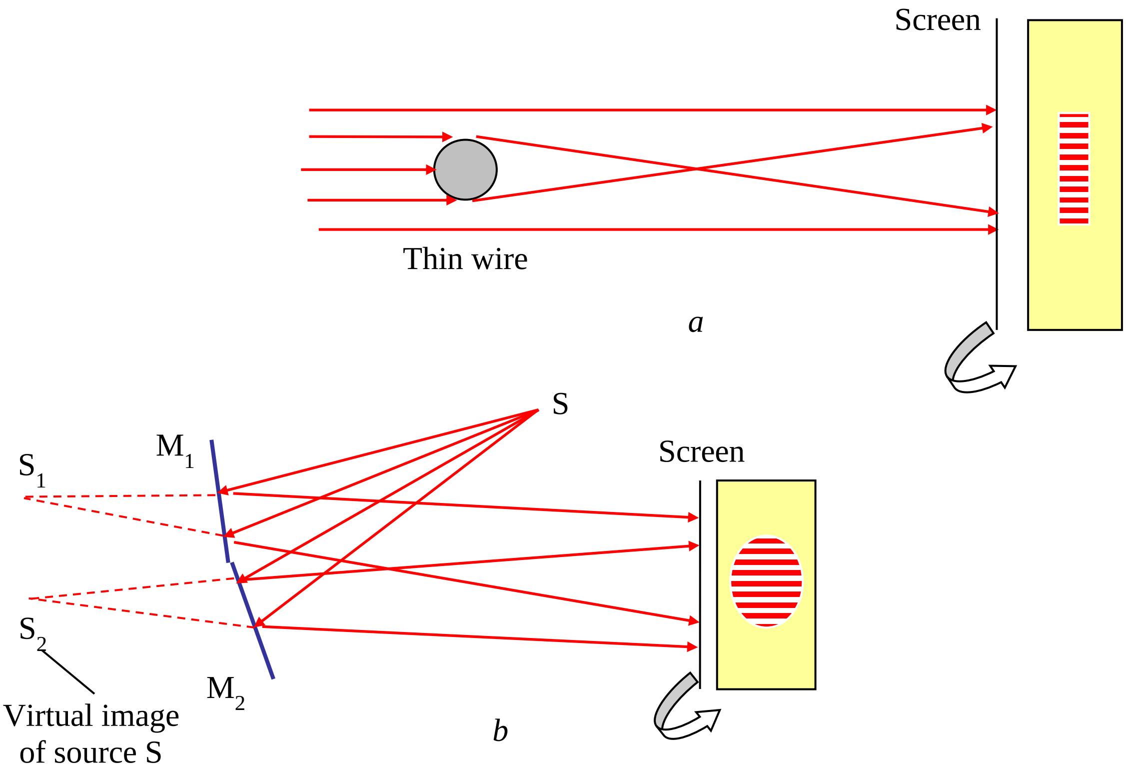


Fig. 4.4. Fresnel’s observation of interference in the area of shadow of thin wire (*a*) and with the help of two slanted mirrors M1 and M2 (*b*)

4.2. Huygens-Fresnel principle

A new proof of the wave properties of light was obtained in 1815. Fresnel applied the idea of interference to the Huygens principle and a powerful method, the Huygens-Fresnel principle, appeared in optics. Using this principle Fresnel proved the rectilinearity of light propagation (Euclid's postulate). If the Huygens principle allowed only the envelope of the wave fronts of elementary waves to be found, the Huygens-Fresnel principle makes it possible to take into account their phases when superimposing the waves. This means that the addition of waves can lead to their mutual amplification (constructive interference), or to mutual annihilation (destructive interference).

The Huygens-Fresnel principle can be formulated as follows:

Each point of the wave front can be considered as the center of the secondary disturbance generating secondary spherical waves, and the resulting light field at each point in space will be determined by the interference of these waves.

Fresnel proposed dividing the wave front into zones (Fresnel zones) when considering the transmission of light excitation (Fig 4.5). The distance from the edges of each spherical zone to the point in question *P* differs by $\lambda/2$. All zones have the same area

$$A = \frac{\pi ab}{a+b}\lambda,$$

and their radii are equal

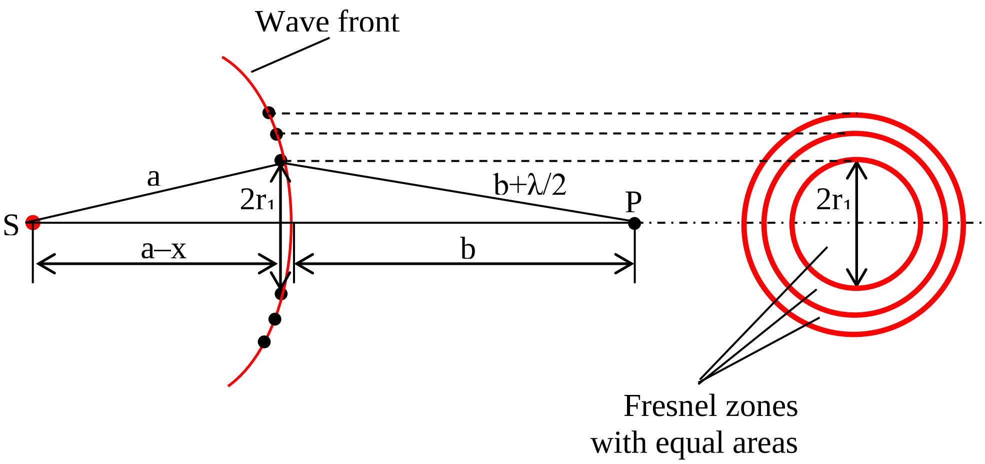


Fig. 4.5. Construction of Fresnel zones on the wave front

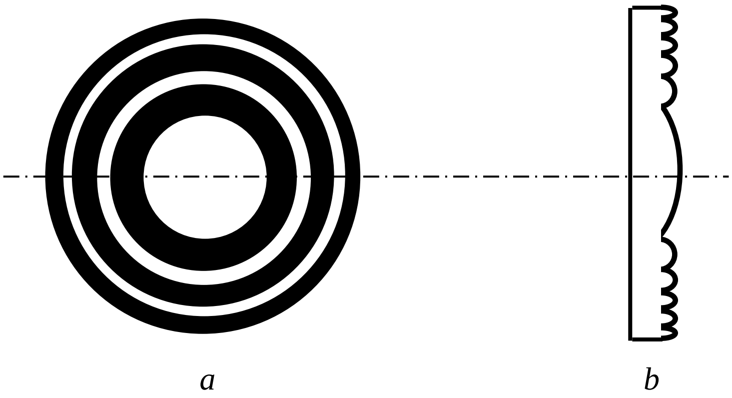


Fig. 4.6. Fresnel lenses with the closed even zones (*a*)
and with all zones acting in phase (*b*)

$$r_m = \sqrt{\frac{mab}{a+b}\lambda},$$

where m is the zone number. Fresnel accepted that the neighboring zones contribute to light excitation at point P in antiphase, and zone contribution decreases with increasing its number m. Such approach helped Fresnel to prove the straightness of light propagation. Closing even zones will lead to an increase in light excitation at point P.

4.3. Fresnel lenses

If we make a transparent zone plate with opaque even zones, then we obtain a Fresnel lens. If we make a Fresnel lens from a transparent material (glass or plastic) and make sure that even zones contribute in phase with odd ones, then the light excitation at point P becomes stronger (Fig. 4.6). Like a conventional lens, a Fresnel lens has a focal length f satisfying the formula of a thin lens:

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f},$$

where a is the distance between the lens and the subject, b is the distance between the lens and the image of the subject. The Fresnel lens is characterized by the presence of many focuses that satisfy the relation

$$f_n = \frac{f}{2n+1}; \quad n = 0, 1, 2, \ldots$$

Fresnel lens has found many uses. The lens can be made thin, light and large enough in size, since it can be stamped from transparent plastic (polycarbonate, for example, the material of optical disks). One of the modern authors called this lens an invention that saved millions of ships [4.2].

For the first time a Fresnel lens was installed on a lighthouse in 1823 and its light became visible for more than 30 km. One of the largest Fresnel lenses was installed on a lighthouse in Hawaii over a century ago (Fig. 4.7).

A Fresnel lens is used as a solar energy concentrator in solar panels. The lens makes it possible to increase the illumination of the solar panel up to 500 times and increase its efficiency. Fresnel lenses are used in some cameras and projectors, as well as hand-held magnifiers for reading.

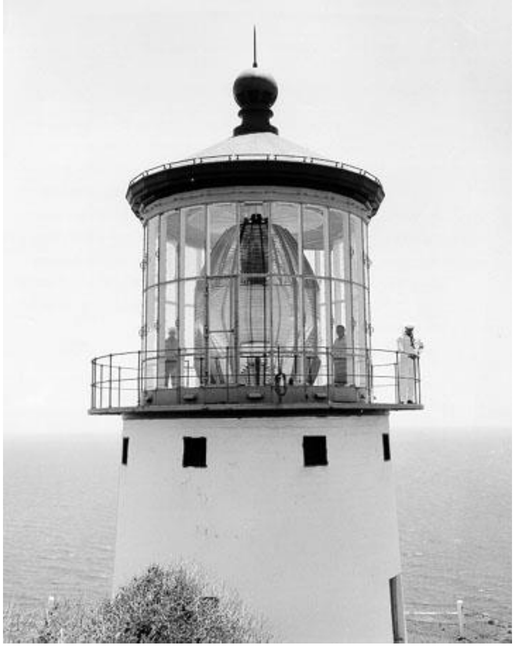


Fig. 4.7. The lighthouse with 2.6 m Fresnel lens built in 1909 in Hawaii

4.4. First attempts to verify existence of ether

Physics believed that ether exists but there was no evidence of that. In 1881 the American physicist Albert Michelson invented a device which he called an

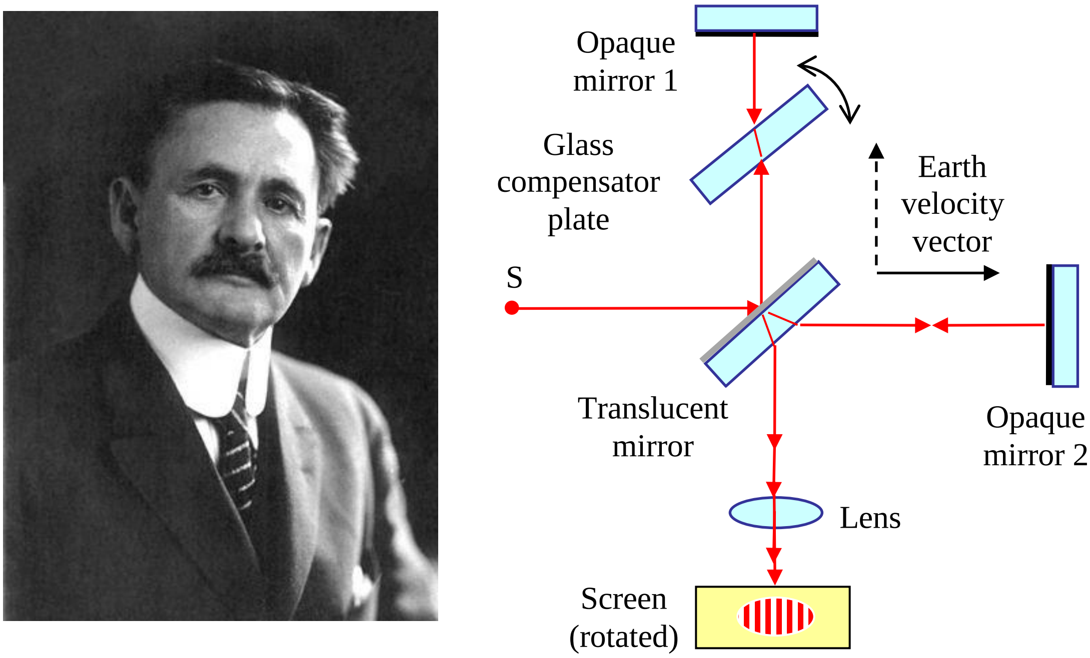


Fig. 4.8. The American physicist Albert Michelson (1852–1931) and his interferometer for detecting the "ether wind"

interferometer and tried to use it to detect the «ether wind» (Fig 4.8). In 1887 Michelson undertook an experiment with another American scientist Edward Morley known for his very accurate measurement of the atomic weight of oxygen. The scientists have suggested that the ether wind should have arisen due to the fact that the ether is stationary and the Earth orbits around the Sun at a speed of 30 km/s. If the ether wind exists, it means that it should cause a change in the optical length of the arm of the Michelson interferometer tuned along the direction of the Earth's orbital motion. A change in the optical path $\Delta L = l\Delta n$ should occur due to an increase in the refractive index n (l is the geometric length of the arm).

The researchers placed a Michelson interferometer on a stone slab (Fig. 4.9). The slab floated on the surface of the mercury and one of the arms of the interferometer could be quickly adjusted in the direction of the orbital motion of the Earth or across it. Using additional mirrors, the length of the interferometer arm was increased to 11 m. By turning the glass plate of the compensator, the optical paths in the arms of the interferometer were aligned with great accuracy. This was necessary because the device used an incoherent source – an oil lamp.

Interference can be observed when the path difference of the interfering beams (from the beam splitter to the screen) is less than the so-called coherence length $L_{coh} = c/\Delta\nu$, where $\Delta\nu$ is the optical spectrum width.

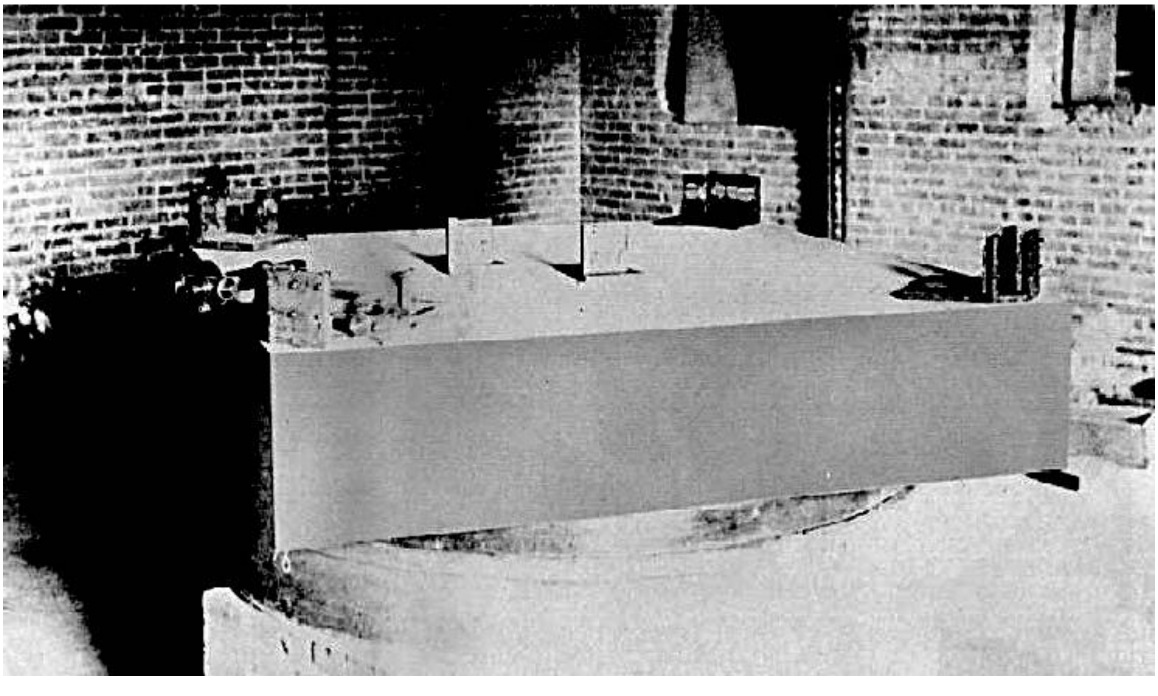


Fig. 4.9. Michelson and Morley interferometric device mounted on a stone slab that floats in mercury

The result of this experiment was negative – the ether wind was not detected. Ether detection experiments are still ongoing using the most advanced equipment. With the achieved accuracy of measuring the displacement of the fringes, $\Delta d / d = 10^{-17}$, where d is the period of the interference pattern, the ether hasn't detected.

4.5. Interferometry

In fact, Thomas Young and Augustin Fresnel used the simplest interferometers in their experiments.

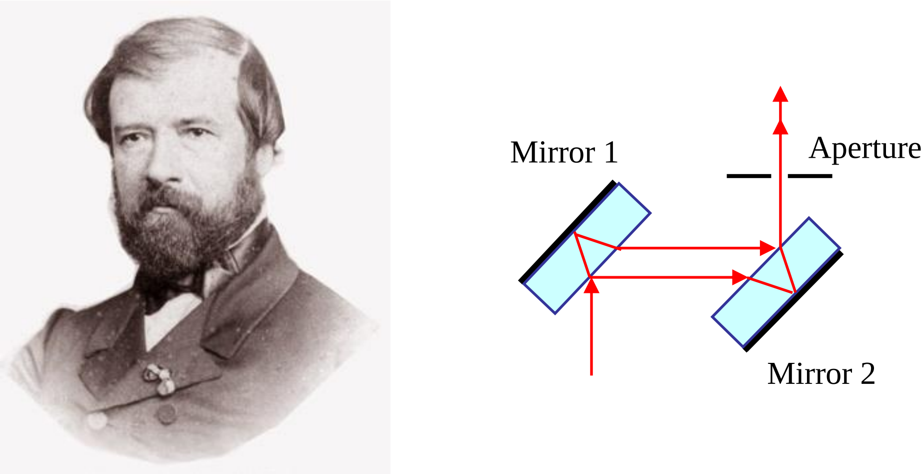


Fig. 4.10. The French physicist
Jules Jamin (1818–1886) and his interferometer

In 1856, the French physicist Jules Jamin invented a very simple interferometer consisting of only two mirrors made of thick glass (Fig. 4. 10). This interferometer allows with high accuracy to measure the refractive index of materials and gases.

The French physicist Hippolyte Fizeau proposed in 1862 the design of interferometer shown in Fig. 4.11. Fizeau interferometer is commonly used for characterizing optical surfaces of flats, mirrors, prisms and lenses.

The Austrian researchers Ludwig Mach and Ludwig Zehnder invented in 1892 the two-beam interferometer with a different arrangement of mirrors. In contrast to the Michelson interferometer, the Mach–Zehnder interferometer has the light paths traversed only once (Fig. 4.12).

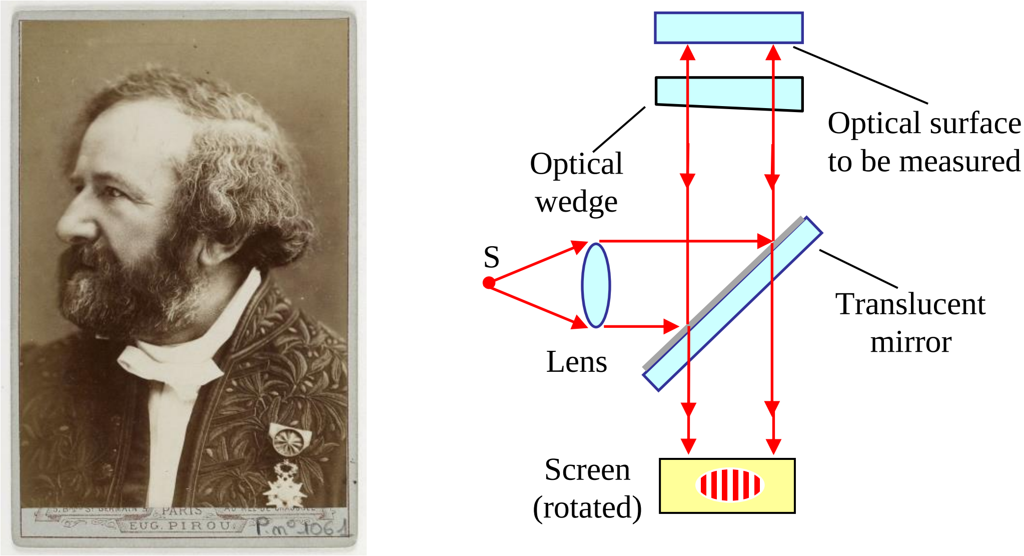


Fig. 4.11. The French physicist Hippolyte Fizeau (1819–1896) and his interferometer for characterizing optical surfaces

In 1899, the French physicists Charles Fabry and Alfred Perot invented a multibeam interferometer (Fig. 4.13). When using the resonance properties of this interferometer, it is called an optical cavity (resonator) or etalon. Interferometer due to its resonant properties has a very high spectral resolution, what is used to stabilize or measure the wavelength. The optical cavity has become an important element in the design of the laser.

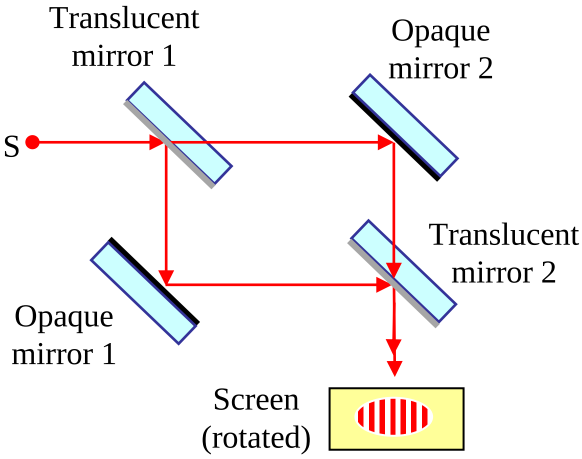


Fig. 4.12. The Mach-Zehnder interferometer

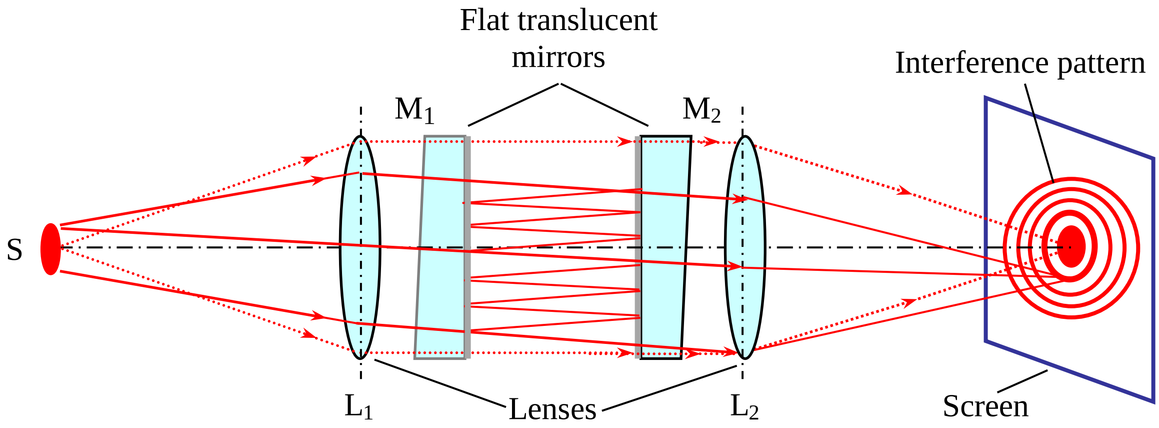


Fig. 4.13. Fabry-Perot interferometer

4.6. What do we observe - diffraction or interference?

Richard Feynman said in the one of his famous lectures on physics:

> «No-one has ever been able to define the difference between interference and diffraction satisfactorily. It is just a question of usage, and there is no specific, important physical difference between them. The best we can do is, roughly speaking, is to say that when there are only a few sources, say two, interfering, then the result is usually called *interference*, but if there is a large number of them, it seems that the word *diffraction* is more often used».

We can consider diffraction as a more general case of interference. For example, we can use the Huygens-Fresnel principle and take into consideration the superposition of waves produced by a large number of point sources placed on the edge of obstacle. This way will lead us to the rather complex mathematics, namely, the Fresnel diffraction integrals which were found only for a few simple cases.

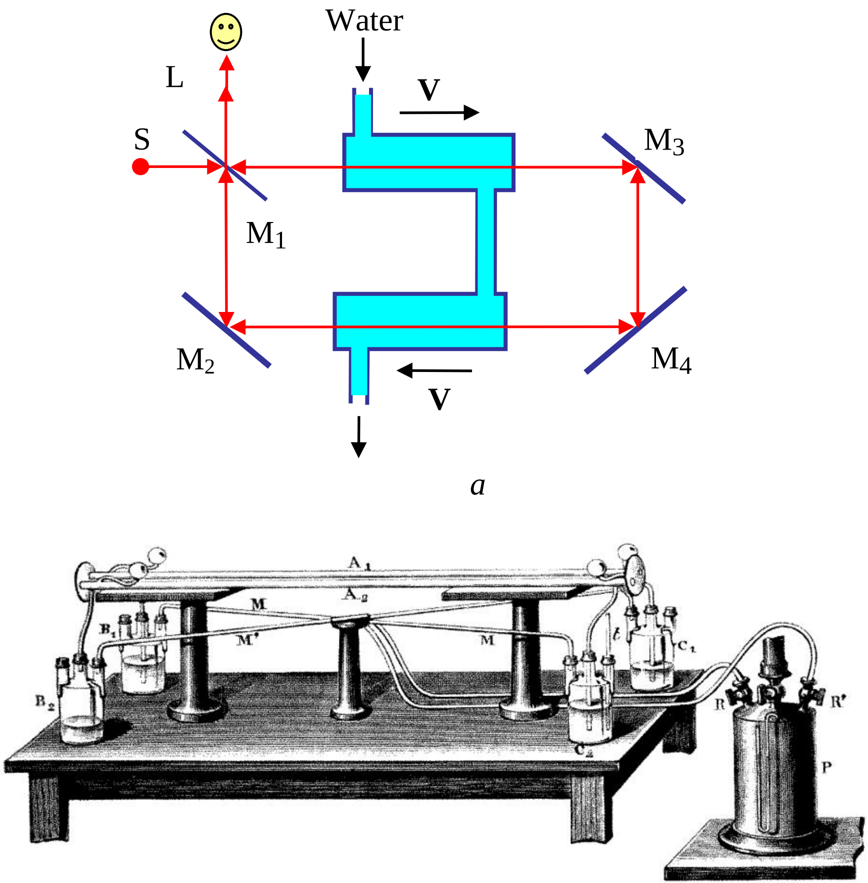
4.7. Some history

In 1818, Fresnel, analyzing the effect of the Earth's motion on optical phenomena, suggested that the moving body partially captured the ether.

This assumption allowed Fresnel to explain the influence of the motion of the refractive medium on light. He found that for the observer the speed of light in the moving optical medium is equal to

$$u = \frac{c}{n} \pm \left(1 - \frac{1}{n^2}\right) V ,$$

where n is the refractive index and V is the medium velocity relative to the observer.



a

b

Fig. 4.14. Scheme of the Fizeau experiment on capturing light with a moving medium (*a*) and view of the Fizeau setup

The Fresnel's capture coefficient $k_{Fr} = 1 - 1/n^2$ corresponds to the orthogonality of the directions of light propagation and the motion of the optical medium.

In 1851, the French physicist Hippolyte Fizeau decided to check whether the light would be captured by moving water. Fizeau placed a cuvette with running water in the shoulders of the interferometer, so that in one shoulder light flowed downstream and in the other against the current (Fig. 4.14 *a*). Noticing the position of the interference fringes at the outlet of the interferometer in stationary water, Fizeau saw that the moving water really captures the light and there is a displacement of the fringes by the value predicted by Fresnel. This experiment confirmed the Fresnel hypothesis of partial capture of the ether, if the ether existed, although in this case, when the directions of motion of the medium and light were parallel and the medium was dispersive, the capture coefficient was described by the Lorentz formula:

$$k_{Lr} = 1 - \frac{1}{n^2} - \frac{\lambda}{n}\frac{dn}{d\lambda},$$

where n is the refraction index of the moving medium and $dn/d\lambda$ is the material dispersion.

4.8. References

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