6. REFLECTION, REFRACTION, AND ABSORPTION OF LIGHT

6.1. Reflection

The angle of reflection of light ray equals the angle of its incidence. This law was known to Euclid in the 3rd century BC. The law of reflection suggests that the reflecting surface is flat and mirror. Such reflection is called specular or mirror. If the reflective surface is rough, then diffuse reflection is observed (Fig. 6.1). Diffuse reflection can be imagined as a diverging light beam whose axis obeys the law of reflection, and the intensity of light radiated or scattered in different directions is described by a directivity pattern (diagram).

The directivity pattern usually characterizes the angular distribution of the radiation energy of various sources (Fig. 6.2). However, it can also be used to characterize a diffusely reflecting surface.

In 1760, the book «Photometria» of the Swiss scientist Johann Lambert (Fig. 6.3) was published. In this book, Lambert described an interesting property of a diffusely reflecting surface: the brightness of the light reflected from it does not depend on the angle of view. For an ideal diffusely reflecting («matte») or diffusely radiating surface, the Lambert's cosine law holds:

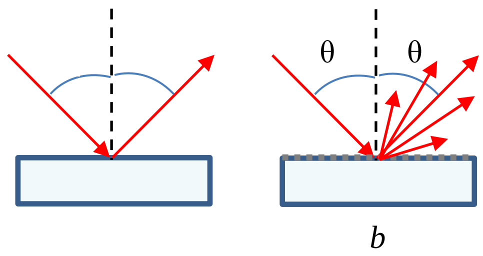


Fig. 6.1. Specular (*a*) and diffuse (*b*) reflections of light beam

$$J_\theta = J_0 \cos\theta,$$

where J_0 and J_θ are the luminous intensities perpendicular to the surface and at an angle θ, respectively. The Lambertian radiator has a circular directivity pattern, as shown in Fig. 6.2.

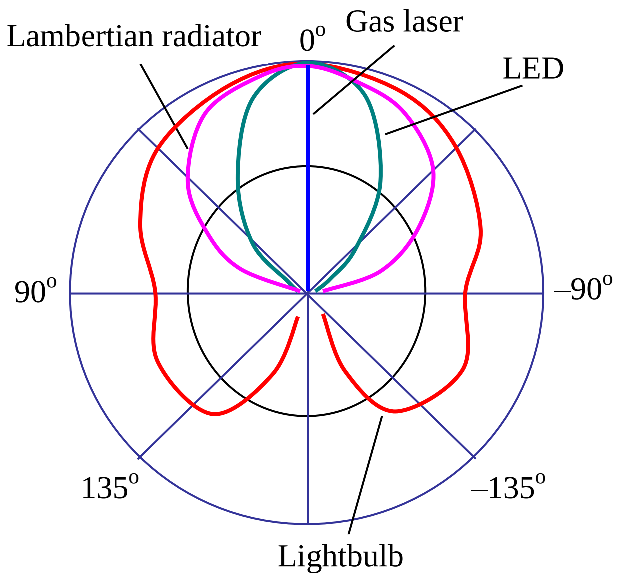


Fig. 6.2. Directivity patterns of lightbulb, LED, gas laser and Lambertian radiators

Flat matte surfaces of some materials – chalk (mineral calcite, $CaCO_3$), frosted (opal) glass, writing paper – are approaching the properties of an ideal Lambertian reflector or scatterer.

Luminous ball and disk with such properties will be indistinguishable from each other.

Fig. 6.3. The Swiss scientist Johann Lambert (1728–1777)

In optics, mirrors are the most common optical elements. Most of them have aluminum mirror coatings, like household mirrors. The reflection coefficient of such mirrors is 0.7. In order to avoid additional reflections from the glass substrate, the mirrors in the optics have external coatings. Among metal mirrors, gold-coated mirrors have the highest reflection coefficient ($R = 0.9$). Metal mirrors withstand large radiation loads and have a very wide spectral range. For lasers with a small gain of the active medium, mirrors with a high reflection coefficient are required. The active medium of a helium-neon laser has a gain less than 10^{-3} cm^{-1}, therefore, to exceed the gain over the losses (the condition for generating laser radiation), the reflection coefficients of both resonator mirrors are increased and the losses at the windows of the gas discharge tube are reduced (Fig. 6.9).

A high reflection coefficient can be achieved using multilayer dielectric coatings. A high reflection coefficient can be achieved using multilayer dielectric coatings (mainly metal oxides). Each layer of such a coating has an optical thickness $nd = \lambda/4$ and differs from neighboring layers by the refractive index. The reason for the increase in the reflection coefficient is the constructive interference of light beams reflected from the boundaries between the layers and added in phase.

By varying the number of dielectric layers, the desired reflection coefficient can be achieved. In optics, beam splitters (mirrors or prisms) are often used, which make it possible to divide a light beam into two beams with a given intensity ratio.

Finally, quite often it is necessary that the surface of the optical element has a lower reflection coefficient or practically does not reflect at all. For example, the surface of a gallium arsenide crystal (GaAs) has a reflection coefficient of 0.3. This made it possible in the first semiconductor laser to use opposite crystal facets as resonator mirrors, since the light gain in semiconductors is very high – up to

10^4 cm^{-1}. In modern semiconductor lasers, for one-sided emission of light, a mirror coating is applied to one face of the crystal, and an antireflection coating to the other (Fig. 6.4). Antireflective coatings can also be found on camera lenses and photodetector windows.

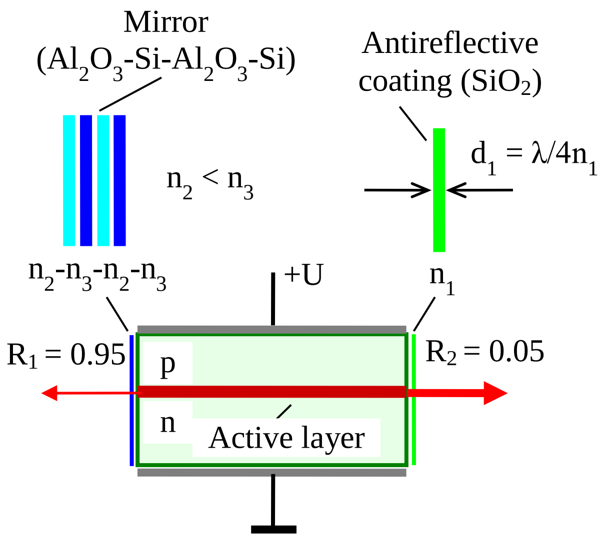


Fig. 6.4. Changing the reflectivity of a laser diode crystal using coatings

6.2. Absorption

In «Photometria» Lambert also formulated the law of light absorption: the loss of light intensity ΔI in a medium is directly proportional to intensity I and path length Δl, that is $\Delta I = \alpha I_0 \Delta l$, where α is the attenuation coefficient. From this relation it follows that the light intensity after passing through the medium path l becomes equal

$$I(l) = I_0 \exp(-\alpha l).$$

This relationship is usually called the Beer–Lambert–Bouguer law, paying tribute to other scientists who have studied the absorption of light in various media.

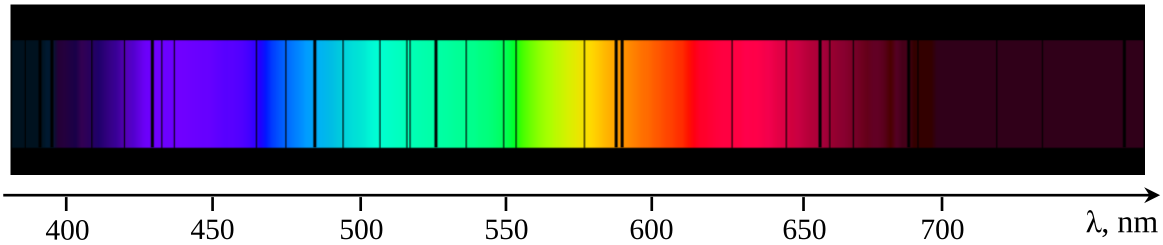
The French mathematician, physicist, and astronomer Pierre Bouguer (1698–1758) defined experimentally in 1727 the loss of light passing through a given extent of the atmosphere.

The German physicist, chemist, and mathematician August Beer (1825–1863) discovered in 1852 that *the transmittance T of a solution remains constant if the product of concentration C and path length l stays constant*, that is $T = C_1 l_1 = C_2 l_2 = C_3 l_3 = \ldots$. This is the Beer's law.

In the general case, the attenuation of light in a medium is determined by three processes – absorption, Mie scattering, and Rayleigh scattering, therefore, the attenuation coefficient α in the Beer–Lambert–Bouguer law is actually the sum of three coefficients:

$$\alpha = \alpha_{abs} + \alpha_{Mie} + \alpha_{Ray}.$$

Light absorption is associated with the quantized transfer of photon energy to electrons bound in atoms. A photon is absorbed if its energy is enough to transfer an



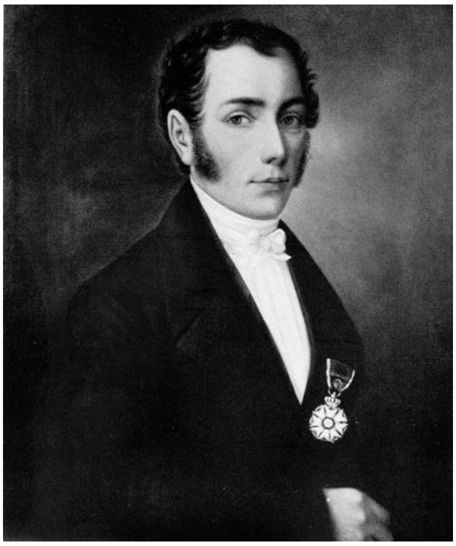


Fig. 6.5. The Bavarian physicist Joseph von Fraunhover (1787–1826) and Fraunhover lines in the solar spectrum

electron to a higher energy level of the atom. Otherwise, the photon flies freely through the material. Atoms have a characteristic set of spectral absorption lines.

In 1802, William Wollaston, studying the spectrum of solar radiation, noticed several dark lines in it [6.1]. Over 570 such lines were discovered in 1814 and applied to the spectrum of solar radiation by the Bavarian physicist Joseph von Fraunhofer (Fig. 6.4). (Note: before the unification of Germany and the formation in 1871 of the German Empire, Bavaria was an independent state).

Fraunhofer marked the most distinguishable lines in Latin letters. He noticed that the *D* line of the solar spectrum is in the same place as the sodium emission line. At first, Fraunhofer used a prism to observe the spectra, and then he introduced the diffraction grating into the practice of spectroscopy. He managed to make a grating having 300 lines per millimeter. This achievement was surpassed only in 1883, when the American physicist Henry Rowland made a grating with 800 strokes per millimeter.

In 1859, the German scientists Gustav Kirchhoff and Robert Bunsen explained the origin of the dark lines in the solar spectrum. They managed to do this using the spectroscope they developed (Fig. 6.6). Dark lines turned out to be absorption lines of atmospheric gases.

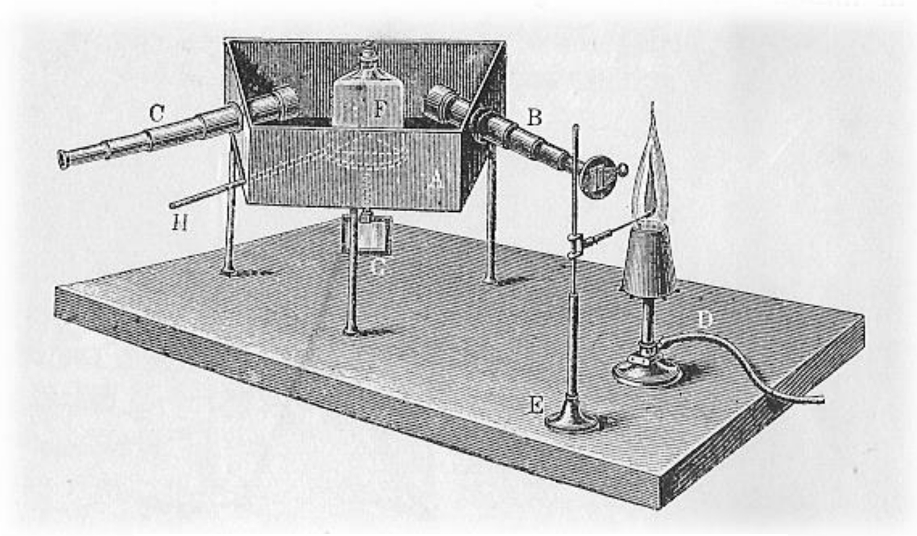


Fig. 6.6. Spectroscope of Kirchhoff and Bunsen

Robert Bunsen (Fig. 6.7) was a chemist and studied the radiation of heated materials. The Bunsen methane burner is still used for soldering, melting and sterilization. Bunsen, on the advice of his friend Kirchhoff, began to study the emission spectra of heated substances and the absorption spectra of transparent materials. Once, while examining mineral water, he discovered absorption lines that were not previously observed. By distillation of 40 tons of water, he managed to get 14 g of an unknown substance, which he called "cesium" (after the Latin word for deep blue). Bunsen discovered that the pure metals that he obtained by electrolysis have unique spectra by which their presence can be recognized.

Numerous studies conducted by Kirchhoff and Bunsen in 1860 laid the foundations for spectral analysis. Kirchhoff formulated the law of inversion, according to which the emission lines of matter and its absorption lines coincide. In other words, if a substance absorbs radiation with a wavelength λ, then it radiates when heated to a high temperature at the same wavelength λ.

Fig. 6.7. The German chemist Robert Bunsen (1811–1899)

6.3. Refraction

In 1821, Augustin Fresnel came to the conclusion that the polarization of light is associated with the transverse nature of light vibrations, and the existence of unpolarized light is explained by rapid random changes in the direction of polarization. In

1823, Augustine Fresnel reported to the French Academy of Sciences the results of his research on the reflection of polarized light from the boundary of two dielectrics. Fresnel derived formulas for the amplitude reflection coefficients of light polarized in the plane of incidence and perpendicular to it:

$$r_\perp \equiv r_s = -\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}, \qquad r_\| \equiv r_p = \frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)},$$

where θ_1 is the angle of incidence, θ_2 is the angle of refraction, s is the index which was historically attributed to perpendicular (German «senkrecht) plane of polarization. The «minus» sign in the first formula means that at the moment of reflection the reflected wave loses half the wavelength (there is a phase shift of the wave by π).

In the case of normal incidence $\theta_1 = 0$ these formulas with the help of the Snell's law are reduced to one formula:

$$r = r_\| = r_\perp = -\frac{n_2 - n_1}{n_2 + n_1}.$$

The corresponding formulas for power reflection coefficients can be written as

$$R_\perp = r_\perp^2 = \left[\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)}\right]^2, \qquad R_\| = r_\|^2 = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}\right]^2,$$

$$R = r^2 = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2.$$

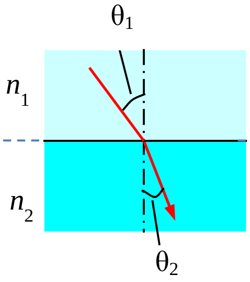
Fig. 6.8 shows how the parameters of the incident and refracted light are related to the parameters of the medium.

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$ – Snell's law of refraction $\qquad \frac{V_1}{V_2} = \frac{n_2}{n_1} \quad c = \lambda\nu \quad \nu_1 = \nu_2 \quad \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$

n_1, – refractive index of a less dense medium;

V_1, ν_1, λ_1 – velocity, frequency and wavelength of light in it, respectively

θ_1 – angle of incidence



n_2 – refractive index of a denser medium;

V_2, ν_2, λ_2 – velocity, frequency and wavelength of light in it, respectively

θ_2 – angle of refraction

Fig. 6.8. The relationships between the parameters of light upon refraction

6.4. Use of the Brewster's law

From the formula for $R_{\|}$ it follows that if $\theta_1 + \theta_2 = 90^{\circ}$ than $R_{\|} = 0$. In other words, if light polarized in the plane of incidence falls on the boundary of two dielectrics at the Brewster's angle, then it does not reflect (almost does not reflect).

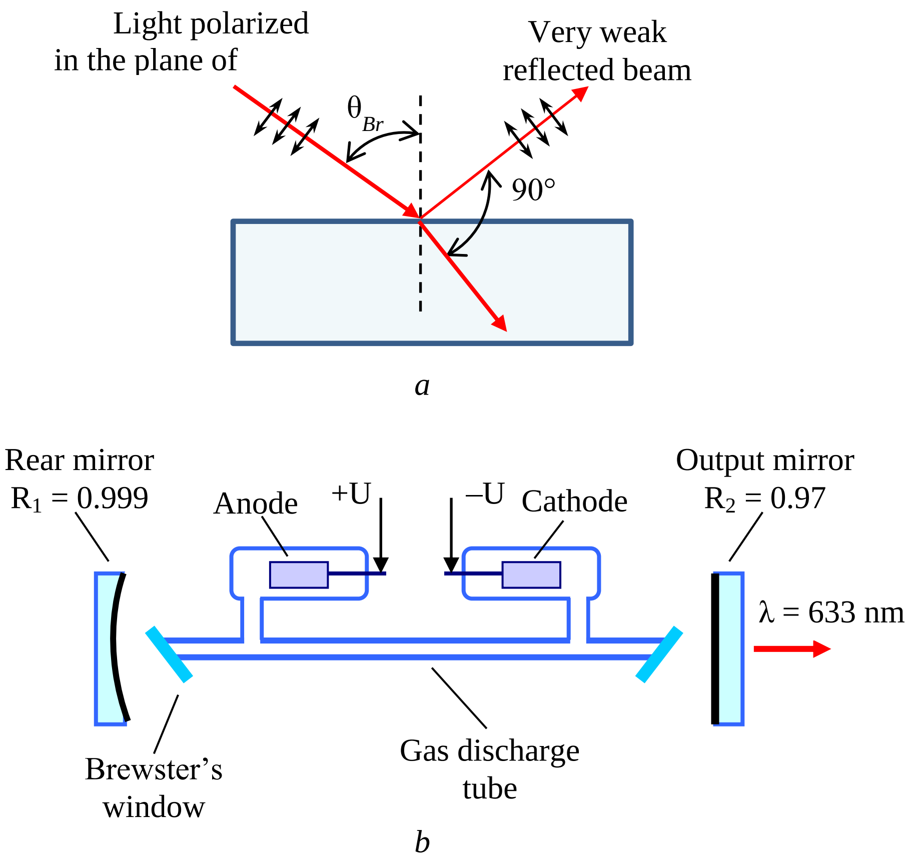


Fig. 6.9. Brewster's law for light polarized in the plane of incidence (*a*) and its use in the He-Ne laser (*b*)

6.5. Total internal reflection

There are two cases of total internal reflection (TIR) of light. The first case is the incidence of light on the boundary of two media at an angle of over 89° (glancing incidence). With a glancing light beam, the properties of the material on whose surface the light falls do not matter (Fig. 6.10, *a*). This is used to focus *X*-rays that are not refracted by glass (glass refractive index for *X*-rays $n = 1$).

More important in optics is the second case, when light falls on the surface of a less dense transparent medium with a correspondingly lower refractive index. For example, a light beam propagating in water or glass falls on the boundary of this medium with air. In accordance with the Snell's law, in this situation there is a critical angle of incidence of light at which the refracted beam glides along the boundary and does not cross it (Fig. 6.10, *b*). This angle is called the critical angle of total internal reflection θ_{TIR} and it is determined by the ratio of the refractive indices of a more dense (n_1) and less dense (n_2) medium:

$$\frac{\sin\theta_{TIR}}{\sin(\pi/2)} = \frac{n_2}{n_1}, \quad \theta_{TIR} = \arcsin\frac{n_2}{n_1}.$$

Based on this type of total internal reflection, fiber and integrated optics are built (Fig. 6.11). The optical fiber contains a core having a higher refractive index than the surrounding it cladding. The most common are quartz glass fibers. Such fibers are used in fiber optic communication lines and in various sensors.

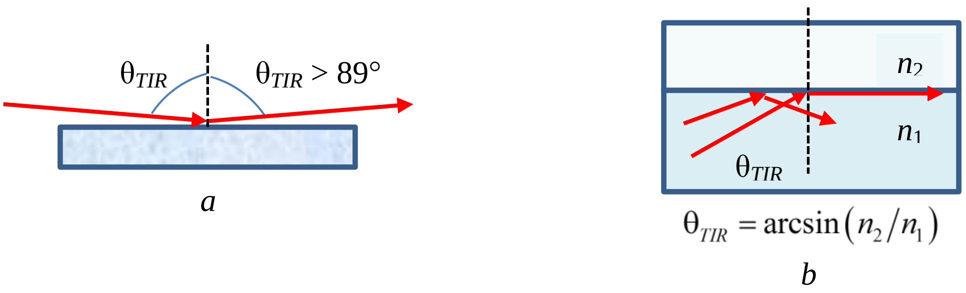


*Fig. 6.10.*Total internal reflection of light in the case of glancing incidence (*a*) and when falling at an angle determined by the Snell's law (*b*)

Integral optics is based on planar waveguides made on the surface of glass or crystalline substrates by diffusion, cathode sputtering, and epitaxy methods. Planar light sources, photodetectors, modulators, interferometers, and other optical and optoelectronic devices have been created that allow the development of integrated optical circuits similar to integrated electronic circuits.

Optical devices are faster than electronic devices and more immune to electromagnetic interference.

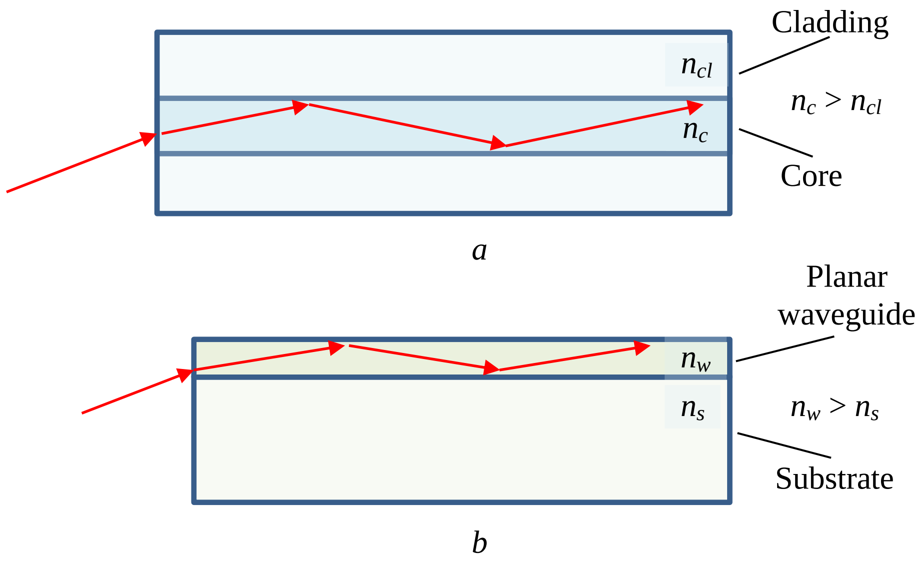


Fig. 6.11. Structures of optical fiber (*a*) and integral optical waveguide (*b*)

6.6. References

6.1. W. H. Wollaston. A method of examining refractive and dispersive powers, by prismatic reflection. – Philosophical Transactions of the Royal Society, 1802, 92. – P. 365–380; see especially p. 378 [Electron. resource]. – Access link: https://royalsocietypublishing.org/doi/pdf/10.1098/rstl.1802.0014