5. POLARIZATION OF LIGHT WAVES

5.1. Types of polarization

In physics, polarization has two meanings – the polarization of the material and the polarization of the wave. The first means that material particles having opposite properties, for example, an electric charge, are displaced under the action of an external force in different directions. The second means that the transverse vibrations of the wave have a predominant direction.

Light can be unpolarized, partially polarized, and completely polarized. This means that unpolarized light consists of waves in which the electric vector **E** oscillates in an arbitrary direction (Fig. 5.1 *a*). Partially polarized light has the preferred directions of oscillation of the vector **E** (Fig. 5.1 *b*). For example, direct sunlight is unpolarized, reflected from water – partially polarized. Completely polarized light contains waves with identical oscillations of the vector **E**. Completely polarized light is an idealization. The radiation of some gas lasers having an extremely narrow spectrum approaches this idealization. Let's first take a look at completely polarized radiation as simpler for consideration.

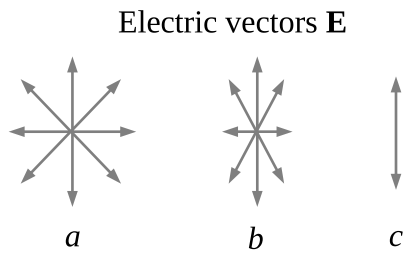
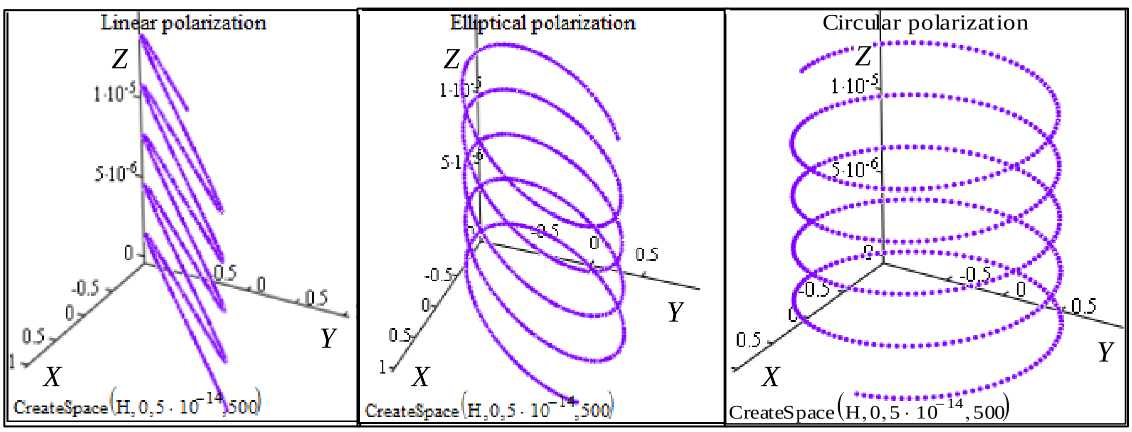


Fig. 5.1. Electric vectors **E** of unpolarized (*a*), partially polarized (*b*) and completely polarized (*c*) light



$\Delta\varphi_1 = 0$ $\Delta\varphi_2 = \pi/4$ $\Delta\varphi_3 = \pi/2$

Fig. 5.2. The trajectory of the end of the electric field vector **E** at different phase differences Δφ between the ordinary and extraordinary waves

The state of polarization of the completely polarized light is determined by the kind of the motion of the end of the vector **E.** If the electric vector oscillates in a plane, then such light is called linearly polarized or plane-polarized (Fig. 5.2 *a*). If the end of the vector draws a circular or elliptical spiral, then the light is called circularly (Fig. 5.2 *b*) or elliptically polarized (Fig. 5.2 *c*). It is possible to obtain circular polarization by superimposing two plane waves having one frequency ν and a phase shift $\Delta\varphi = \pi/2$. If $\Delta\varphi = \pi/4$, we obtain the wave with an elliptical polarization. This opportunity is provided to us by birefringent crystals.

5.2. Polarizers

In 1828, the Scottish geologist and physicist William Nicol (Fig. 5.3) invented a polarizer, which converts unpolarized radiation to plane-polarized. He took a crystal of Icelandic spar in the shape of a parallelepiped and cut it diagonally. Then he glued the formed triangular prisms with a Canada balsam, joining the opposite sides of the parallelepiped (Fig. 5.4). So Nicol formed the interface between two media (crystal and glue), on which an ordinary ray had a total internal reflection, and an extraordinary ray was not reflected. This became possible due to the fact that the refractive indices of the crystal for ordinary and extraordinary rays were n_o = 1.66 and n_e = 1.49, and glue, respectively, n_g = 1.54.

Another type of polarizing prism was proposed almost at the same time by the English chemist and physicist William Wollaston (Fig. 5.5). The Wollaston prism consists of two glued triangular prisms with perpendicular optical axes. The prism is made from Icelandic spar or crystalline quartz. The difference between the prisms made of these crystals is the angular separation of the ordinary and extraordinary rays. For example, in the case of a cubic prism, a polarizer made of Icelandic spar has an angle of 20° between ordinary and extraordinary rays, and a quartz polarizer – only 1°. The Wollaston prism is more technologically advanced than the Nicol prism, therefore, over

Fig. 5.3. The Scottish scientist William Nicol (1766–1851). Nicol reads to his blind uncle H. Moyes (engraving by W. Ward, 1806)

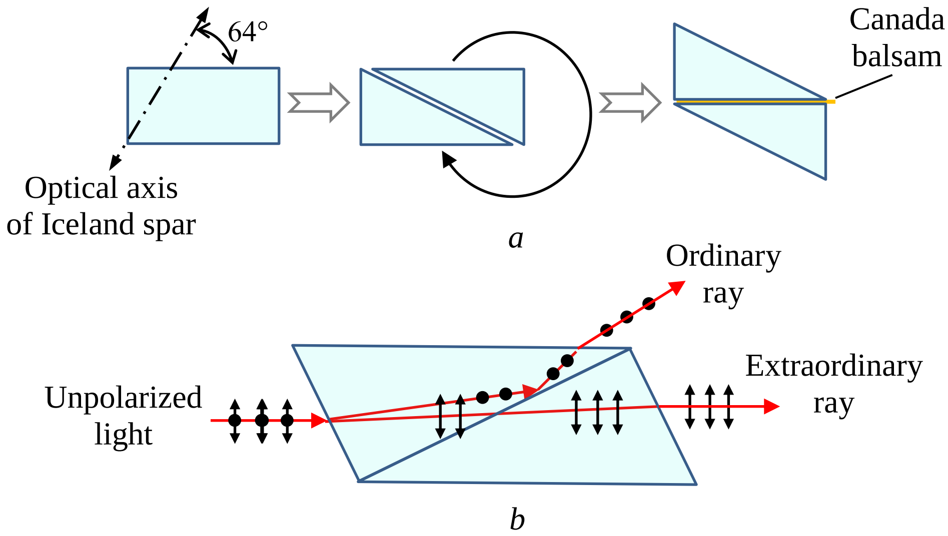


Fig. 5.4. Nicol prism – manufacturing (*a*) and use as a polarizer (*b*)

time, replaced it.

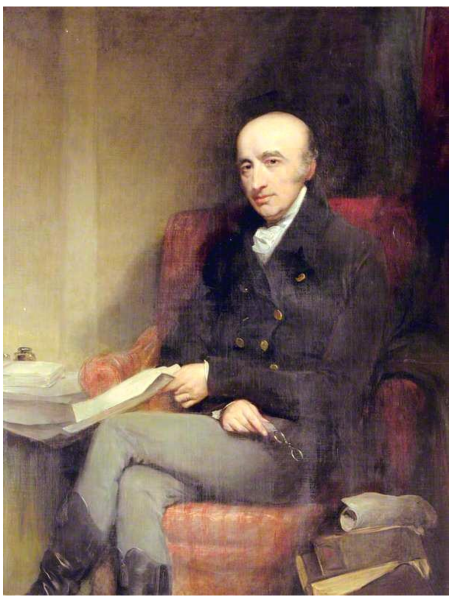
Prism polarizers have the following advantages:

– a wide spectral range (350–2300 nm for Icelandic spar and 200–2300 nm for quartz);

– extremely high polarization extinction ratio (20000:1, the ratio of powers of output beams with perpendicular polarizations);

– a high threshold for optical damage (10 J/cm^2 for 20-ns pulse of infrared radiation with λ = 1064 nm).

Another type of polarizing device is a wire grid polarizer. This polarizer is made in the form of a plastic, glass or crystal substrate on which an aluminum



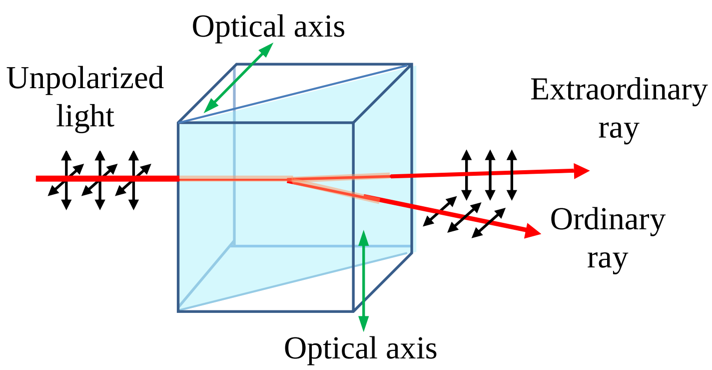


Fig. 5.5. The English scientist William Wollaston (1766–1828) and his prism

microwire array is deposited. Crystalline polarizers are usually used in the range of 2–30 μm, although polarizers with a quartz substrate can operate in the ultraviolet, visible and near infrared ranges. Glass and crystalline polarizers operate in the temperature range of –40–200°C and withstand powerful laser radiation.

In addition to expensive prismatic polarizers, there are also cheap film polarizers (polarizing filters) [5.1]. They are made from a film of polyvinyl alcohol doped with iodine and stretched during manufacturing. In this case, the polymer molecules line up along the direction of extension. The valence electrons of iodine can only move along chains of molecules and absorb a component of unpolarized light whose plane of polarization is parallel to the chains.

5.3. Convertors of polarization

Unpolarized radiation can be converted to polarized radiation and vice versa. Plane-polarized radiation can be converted to elliptically/circularly polarized radiation and vice versa. In addition, you can rotate the plane of polarization. All this is done by polarization converters.

Polarization conversion is usually carried out by means of plates made of a birefringent material. After passing such a plate, a phase difference Δφ arises between ordinary and extraordinary waves. Fig. 5.6 shows how the polarization of plane-polarized radiation changes depending on the phase difference Δφ between ordinary and extraordinary waves superimposed on each other. If the phase difference at the output of the plate equals π/2, then the linear polarization is converted to circular polarization, and such a plate is called a quarter wave plate (or λ/4-plate). If, however, the phase difference at the output of the plate equals π, then the linear polarization is converted to orthogonal linear polarization, and such a plate is called a half-wave plate (or λ/2-plate).

The parameters of some types of laser sensors depend on the polarization of the

Δφ	0	π/4	π/2	3π/4	π	5π/4	3π/2	7π/4	2π
Polarization									

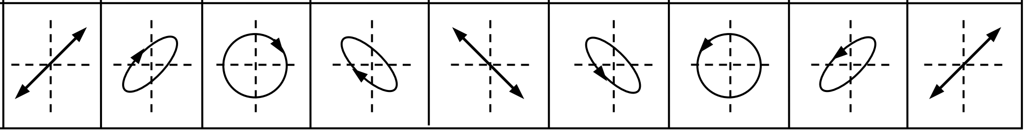


Fig. 5.6. Dependence of the polarization of radiation passing through a double-refractive medium on the phase difference Δφ between ordinary and extraordinary waves

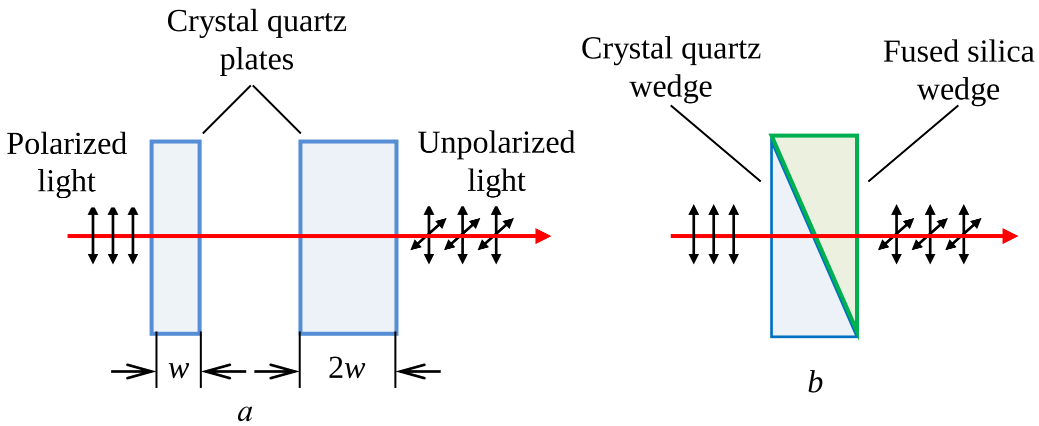


Fig. 5.7. Classical Lyot depolarizer (*a*) and wedge-shaped depolarizer (*b*)

radiation. In this case, the laser radiation, which is usually polarized, is converted to unpolarized. This is done using depolarizers.

Figure 5.7, *a* shows the Lyot depolarizer, consisting of two quartz crystals with a ratio of lengths 1: 2 and with an angle of 45° between the optical axes. This type of depolarizer was invented by the French astronomer Bernard Lyot (1897–1952). Lyot investigated the polarization properties of sunlight reflected from the surface of the planets and from their atmosphere. Comparing these properties with the polarization properties of terrestrial volcanic rocks and gases Lyot made conclusions about composition of another planets.

The wedge-shaped depolarizer consists of a wedge made of crystalline quartz, and a wedge of fused silica (quartz glass) glued to it, so that they together form a plane-parallel plate (Fig. 5.7, *b*). The crystal wedge mixes the polarizations of rays that have different phase delays within the aperture of the depolarizer. The glass wedge compensates the beam turning by the crystal wedge.

5.4. Malus's law

The French officer, physicist and mathematician Etienne-Louis Malus (Fig. 5.8) discovered in 1809 the polarization of light by reflection. Studying birefringence and the properties of polarizers, he found that turning the axis of transmission of the polarizer relative to the plane of polarization of radiation by an angle θ changes the intensity of transmitted light proportionally to the square of the cosine of this angle.

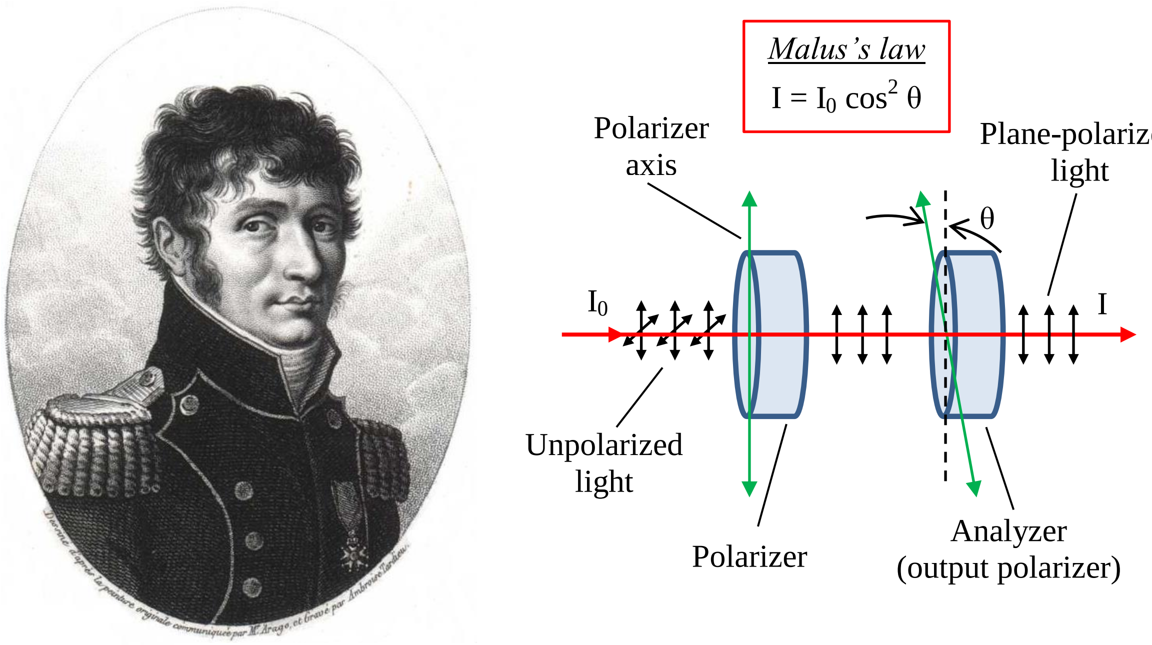


Fig. 5.8. The French physicist Etienne-Louis Malus (1775–1812) and the illustration of the Malus's law

5.5. Brewster's law

In 1811, a Scottish scientist and inventor David Brewster discovered that unpolarized light incident on the surface of the material at a certain angle appears to be maximally polarized, and the plane of polarization of the reflected light is parallel to the surface of the material (Fig. 5.9). Brewster found that this angle is determined by the relationship $\tan\theta_{Br} = n/n_0$, where n is the refractive index of the material and n_0 is the refractive index of the medium. This angle is called the Brewster's angle. For water (n = 1.33) and for glass (n = 1.52) the Brewster's angle equals 53° and 57°, respectively.

Measuring the Brewster's angles of different materials, even opaque, we can find their refractive indices.

In 1819, Brewster invented a fun toy for children – kaleidoscope. He also improved the design of the stereoscope.

Brewster's law

The reflected beam is completely polarized and the refracted beam is partially polarized if they are perpendicular to each other

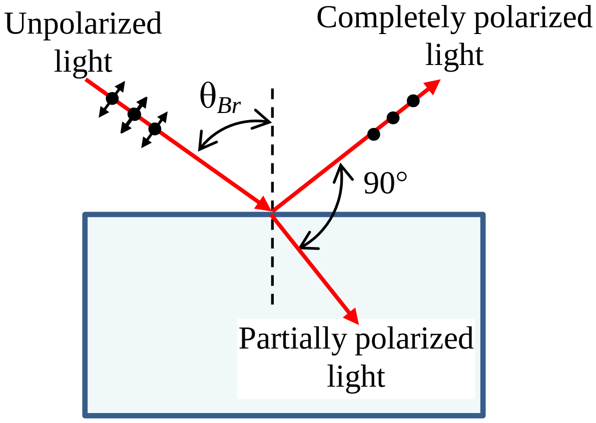


Fig. 5.9. The Scottish scientist sir David Brewster (1781–1868) and the illustration of the Brewster's law

5.5. References

5.1. Polarization optics [Electron. resource]. – Access link: https://www.edmundoptics.com/c/polarization-optics/620/