Double Reflection in Crystals and Its Use in Electro-Optic Modulators

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Double Reflection in Crystals and Its Use in Electro-Optic Modulators

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Compared with double refraction, double reflection in crystals has found almost no practical application; however, in principle, on its basis it is possible to create a number of devices performing the same functions as devices based on double refraction. The Cotton polarizer (^{1}), as far as we know, is the only device described in the literature that is based on the use of double reflection under total internal reflection of rays in a right-angled isosceles prism made of an optically uniaxial crystal. Figure 1a shows the splitting of an unpolarized ray 1 into two orthogonally polarized branches 2 and 3 in a generalized polarizer of the Cotton-polarizer type.

Without dwelling on the derivation, we give the basic calculation relations for such a polarizer, adopting the notation in Fig. 1 and denoting by n_o and n_e the refractive indices of the ordinary and extraordinary rays:

$$\sqrt{\frac{\sin^2\varphi}{n_e^2}+\frac{\cos^2\varphi}{n_o^2}}=\frac{1}{n_\varphi}\ll\sin i\gg\frac{1}{n_{2i-\varphi+\alpha}}\sqrt{\frac{\sin^2(2i-\varphi+\alpha)}{n_o^2}+\frac{\cos^2(2i-\varphi+\alpha)}{n_e^2}};\tag{1}$$

$$n_\varphi\sin i=n_{2i-\varphi+\alpha}\sin(i+\alpha);\tag{2}$$

$$\sin\alpha'=n_{2i-\varphi+\alpha}\sin\alpha.\tag{3}$$

From the standpoint of practical application in light modulators, the relations for two special cases are of interest, for $i=45^\circ$, $n_o>n_e$, $\delta n=n_o-n_e\ll n$:

$$1.\ \varphi=0:\qquad n_e>1.4142,\ \alpha\approx-\delta n/n,\ \alpha'\approx-\delta n;\tag{4}$$

$$2.\ \varphi=90^\circ:\qquad n_e>1.4142,\ \alpha\approx+\delta n/n,\ \alpha'\approx+\delta n.\tag{5}$$

Figure 1. Birefringent polarizers made of optically uniaxial crystals.

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The corresponding Cotton polarizers and the ray paths in them are shown in Fig. 1b, c.

The simplest example of an external modulator with such a Cotton polarizer for a gas laser is shown in Fig. 2a. The polarized radiation 1 of the laser, with oscillation direction P, passes along the optical axis z of an electro-optic crystal 2 (for example, $LiNbO_3$) and, without changing its polarization, in the absence of a field in crystal 2 exits the modulator along path 3. When, however, there is a field $E = E_{\lambda/2}$, producing a half-wave optical path difference of the rays in crystal 2 along the z axis, the oscillation direction of the ray emerging from the crystal is switched to the perpendicular direction, and the ray, consequently, exits the modulator along path 4.

With a gradual increase in the field strength from zero to the value $E_{\lambda/2}$, the intensity of ray 3 decreases from its maximum value.

Fig. 1. Birefringent polarizers made of optically uniaxial crystals.
1—incident unpolarized ray; $2, 3$—emergent, differently directed, orthogonally polarized rays; i—angle of incidence of ray 1 on the surface reflecting rays $2, 3$ at the prism boundary; z—optical axis of the crystal; φ—angle of orientation of the optical axis z in the prism; α—angle of divergence of rays $2, 3$ in the prism, and α'—after emergence from the prisms. a—generalized polarizer of the Cotton type; b, v—Cotton polarizers for $i = 45°$, $n_o > n_e$, $\psi = 0$ and $\varphi = 90°$; g, d, e, zh —polarizers consisting of four Cotton polarizers

to zero, while ray 4, conversely, changes from zero to the maximum value according to the laws:

$$I_3 = I_{\max} \cos^2 \left(\frac{\pi}{2} \frac{E}{E_{\lambda/2}} \right), \qquad I_4 = I_{\max} \sin^2 \left(\frac{\pi}{2} \frac{E}{E_{\lambda/2}} \right). \tag{6}$$

As can be seen from Fig. 2a, the directions of the optical axes z of crystals 2 and 5 coincide. This circumstance opens up the possibility of constructing a monoblock modulator, i.e., one constituting a single optical element made of an electro-optic crystal, as shown in Fig. 2b for

for the case of the transverse electro-optic effect (for example, $LiNbO_3$) and in Fig. 2 for the case of the longitudinal electro-optic effect (for example, KH_2PO_4).

By means of a combination of several rectangular Cotton polarizers one can increase the divergence angle of the orthogonally polarized output beams. In Fig. 1 - combinations of two rectangular Cotton polarizers are shown, and in Fig. 1 , , combinations of four.

Fig. 2. Electro-optic radiation modulators of an OQG with bireflecting polarizers.

Figure 2: Fig. 2. Electro-optic radiation modulators of an OQG with bireflecting polarizers.

Fig. 2. Electro-optic radiation modulators of an OQG with bireflecting polarizers.
1 –incident linearly polarized OQG beam; **2** –electro-optic crystal (for example $LiNbO_3$); **2′** –electro-optic crystal (for example KH_2PO_4); **3, 4** –orthogonally polarized output optical branches diverging at an angle α in the crystal and α' in air; **5** –Cotton polarizer; **6** –plane electrodes; **6′** –belt electrodes; **a** –transmission modulator made of two parts; **,** –monolithic transmission modulators based on the transverse and longitudinal effect; **,** –monolithic shutters-reflectors for modulation of the Q-factor of the OQG.

Of special interest is the bireflecting polarizer shown in Fig. 1 , which can be used as an end reflector of a laser resonator. If an electro-optic crystal is present inside the resonator, switching the plane of polarization of the light passing through it into the perpendicular position, such a reflector simultaneously performs the function of a polarizer and makes it possible to carry out internal modulation of the laser, i.e., modulation of the Q-factor of its optical resonator. In this case, the possibility also arises of creating a monolithic shutter-reflector both on the transverse electro-optic effect (see Fig. 2) and on the longitudinal one (see Fig. 2).

In the absence of a field, the reflected radiation is deflected from the axis of the OQG resonator and is led out of it; whereas in the presence of a half-wave voltage on the electrodes it is reflected strictly in the reverse direction and amplifies

generation of radiation; i.e., with rapid (5–10 ns) application of the half-wave voltage to the crystal electrodes, the resonator quality factor increases from zero to its maximum value, thereby creating the conditions for the development of a so-called giant single pulse of radiation.

The bireflecting polarizer shown in Fig. 1a possesses coaxiality of the incoming unpolarized and outgoing polarized beams and a sufficiently large angular field of view. It can therefore be successfully used in polarization microscopes and polarimetric instruments.

In conclusion, let us note that in this brief article we wished to draw the attention of physicists and engineers to the phenomenon of double reflection of light in crystals and to show, by means of several examples, how it can be used in just one area–in the synthesis of basic schemes for polarizers and electro-optical modulators. It seems to us highly promising to keep in mind and use the phenomenon of double reflection of light in the synthesis of many other polarimetric optical systems, since in this way one can apparently find the same unexpected and effective solutions as those we have demonstrated with the example of monoblock electro-optical modulators and shutters.

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