

Lecture 7: Polarization elements that we use in the lab.

Waveplates, rotators, Faraday isolators, beam displacers, polarizers, spatial light modulators.

Polarization elements are important tools for various experiments, starting from interferometry and up to quantum key distribution. This lecture is focused on the commercial polarization elements that one can buy from companies like Thorlabs, Edmund Optics, Laser Components etc. We will consider waveplates and rotators, for polarization transformations, beam displacers and polarization prisms, for the measurement of polarization states, and finally spatial light modulators, elements that use polarization for preparing structured light.

1. Waveplates.

A waveplate (retardation plate) can be most simply made out of a piece of crystalline quartz, cut so that the optic axis (z) is in its plane. Quartz is a positive uniaxial crystal, $n_e > n_o$. Therefore, for light polarized linearly along the z -axis, the refractive index $n = n_e$, and the phase (and group) velocity is smaller than for light polarized orthogonally to z -axis ($n = n_o$). One says that the z -axis is then ‘the slow axis’, and the other axis is ‘the fast axis’. The fast axis is sometimes marked by a flat cut (Fig.1).

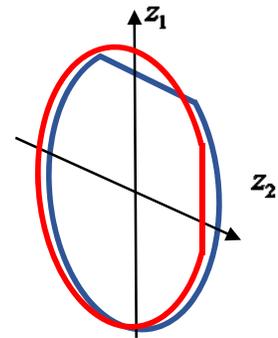


Fig.1

A multi-order plate. However, a plate of reasonable thickness (0.5 mm or thicker) will work only for a narrow bandwidth. Indeed, although at the last 2 lectures we assumed that the refractive index is wavelength-independent, in reality it depends on the wavelength. Moreover, even without dispersion the phase would be different for different wavelengths. For instance, at 600 nm, the birefringence is $\Delta n = 0.0091$, and at 700 nm, $\Delta n = 0.0090$, nearly the same over 100 nm. Then, the phase of a 0.495-mm plate will be $\delta = \frac{\pi \Delta n l}{\lambda} = 7.5\pi$ for the wavelength 600 nm. This means, it will be a HWP for this wavelength. At the same time, for the wavelength 615 nm the phase delay will be $\delta = 7.25\pi$. Such a plate will be then a QWP for 615 nm, and it will be something in between for intermediate wavelengths. Such a thick plate is called a multi-order plate. The bandwidth for which a multi-order plate will work is about 2 nm.

A zero-order plate is such, for which $\delta \equiv \frac{\pi \Delta n l}{\lambda} = 0.5\pi$ or $\delta = 0.25\pi$ exactly. Then, for $\lambda = 600$ nm the thickness of a HWP should be 33μ , and the thickness of a QWP should be 16.5μ . Such plates will have a broader bandwidth but they will be too fragile. To fix this problem, one makes a zero-order plate by sticking together two plates, with the optic axes orthogonal and thicknesses $l_{1,2} \sim 0.5$ mm. Then, the effective thickness is $l_{eff} = l_1 - l_2$.

Sometimes one uses so-called ‘true zero-order plates’. Such a plate is a thin layer of polymer (liquid crystal) between two glasses.

Dual-wavelength plates. One can calculate the thickness of a plate in such a way, that the plate will work different for different wavelengths, for instance, a HWP for one wavelength and a QWP for another one. Or, a HWP for one wavelength and a WP ($\delta = n\pi$) for another one, then it will not affect the polarization of this other wavelength. (One of the tasks is to calculate the thickness of such a plate.)

Achromatic wave-plates. Even for a zero-order plate, the bandwidth is not too large; it scales as the inverse thickness and for the example above it is $\sim 20\text{-}40$ nm. One can increase this bandwidth by compensating the $\frac{1}{\lambda}$ term in the expression for δ with the

Δn term. To do this, two different crystals are used: quartz with MgF_2 or quartz with sapphire, Al_2O_3 .

Variable waveplates. Sometimes it is necessary to vary the phase δ of a zero-order WP. As such a variable waveplate, one can use a Babinet-Soleil compensator (Fig. 2). It consists of a plate with a fixed thickness and another one, with the optic axis orthogonal, with a variable thickness. The phase of such a plate can be varied from 0 to 2π .

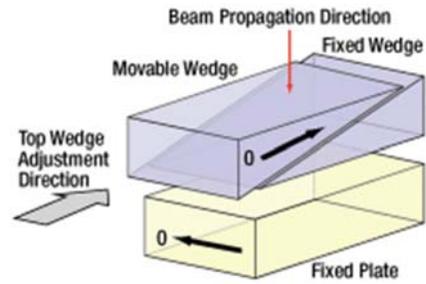


Fig. 2

2. Rotators.

In the simplest case, a polarization rotator is a plate of quartz, cut orthogonal to the optic axis (z-cut). It works only for light at a certain wavelength, but the advantage is that the rotation angle does not depend on the initial polarization.

Faraday rotators. A Faraday rotator is based on the Faraday effect: in a magnetic field H , the plane of polarization rotates by angle $\alpha \propto HL$, where L is the length of the nonlinear crystal. Unlike with a usual crystal rotator, here the direction of rotation does not depend on the light propagation direction, but only on the direction of the magnetic field.

Optical isolators. A Faraday rotator with a polarizer before and after is the main part of an optical isolator, used to transmit light only in one direction (Fig.3). The first polarizer transmits H-polarized light; the Faraday cell rotates the polarization clockwise 45 degrees, and the resulting D-polarized light is transmitted by the second polarizer. But if light propagates from right to left, it will be initially D-polarized, then, after the Faraday cell, V-polarized, and it will not pass through the first polarizer.

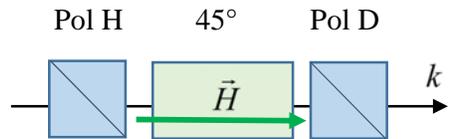


Fig. 3

3. Beam displacers.

A beam displacer (Fig. 4) is a calcite crystal with the optic axis at 45 degrees. Due to spatial walk-off, an incident unpolarized or arbitrarily polarized beam will split in it and exit as two beams, polarized vertically (extraordinary beam) and horizontally (ordinary beam). Such devices are used in several experiments: (1) interference (as demonstrated at the first lecture); (2) measurement of the polarization variables, such as the Stokes parameters S_1 , S_2 . Indeed, for the setup shown in

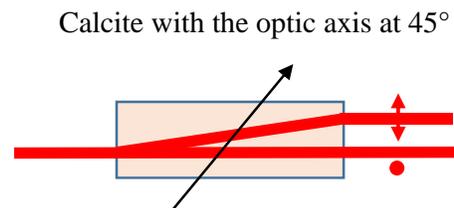


Fig. 4

Fig.4, one can put a detector into the upper beam and a detector into the lower beam, and the difference of their photocurrents will give S_1 . With the whole setup rotated by 45 degrees, the same measurement will give S_2 .

4. Prisms and polarizing beamsplitters.

Polarization prisms are aimed at separating light with orthogonal linear polarizations. Most well-known are various versions of Glan prisms. Their operation is based on the *total internal reflection* as well as on the *Brewster angle*. Total internal reflection follows from the Snell's law: for the angles of incidence and refraction θ_i, θ_r at an interface (Fig. 5),

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_2}{n_1}, \quad (1)$$

where n_1, n_2 are refractive indices in two media. If $n_2=1$ (air), the angle of total internal reflection is

$$\sin\theta_{i0} = \frac{1}{n_1}, \quad (2)$$

because in this case $\sin\theta_r=1$.

The Brewster angle is defined as

$$\tan\theta_B = \frac{n_2}{n_1}, \quad (3)$$

For light incident at this angle, the reflected light contains no p-component (polarized in the plane of incidence). Condition (3) means that the reflected and the refracted beams are orthogonal (Fig. 5). Indeed, from Snell's law, (3) means that $\sin\theta_i = \cos\theta_r$, i.e., that the reflected and the refracted beams are orthogonal. This can be explained in simple terms: a p-polarized wave makes electrons in medium 2 oscillate in the transverse direction; then they do not emit field polarized in this direction.

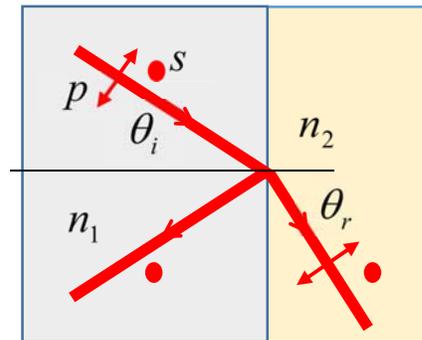


Fig. 5

A *Glan-Taylor prism* is shown in Fig. 6. Two halves, separated by an air gap, are made of calcite, which has a large birefringence and a small dispersion. For instance, at 532 nm, $n_o=1.66$ and $n_e=1.49$. The optic axes for both halves are vertical (blue arrows). The incident light hits the interface (with the air) at an angle that is larger than the total internal reflection angle for the o-wave (s-polarized); so all o-polarized light is reflected. But for e-polarized light, the angle is close to the Brewster angle, so no p-polarization is reflected, it is all transmitted.

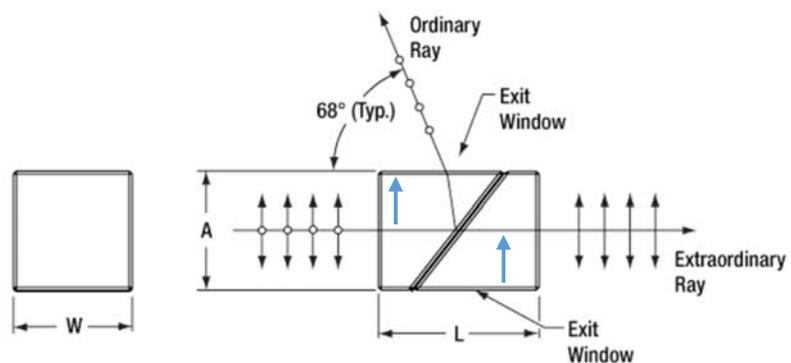


Fig. 6

Because the angle of incidence is only a bit larger than the total internal reflection angle, the prism will not work for divergent beams, only for parallel beams.

A *Glan-Laser prism* is about the same but it stands a higher intensity.

A *Glan-Thompson prism* has a slightly different structure (Fig. 7). The angle of incidence on the interface is larger, and the optic axis is now horizontal (blue arrows). Because of the large angle

of incidence, one uses cement in the gap instead of the air. This reduces the tolerance to damage but increases the range of angles for which the prism works.

A *Wollaston prism* (Fig. 8) is made of two calcite parts at optical contact (no gap!), with the optic axes orthogonal to each other. A horizontally polarized beam is an e-beam in the first half but an o-beam in the second one. For a vertically polarized beam it is the other way round. Therefore, at the boundary one beam goes from a denser medium into a less dense one, and is refracted up, the other one is refracted down. The separation of the beams can be from 1° to 20° .

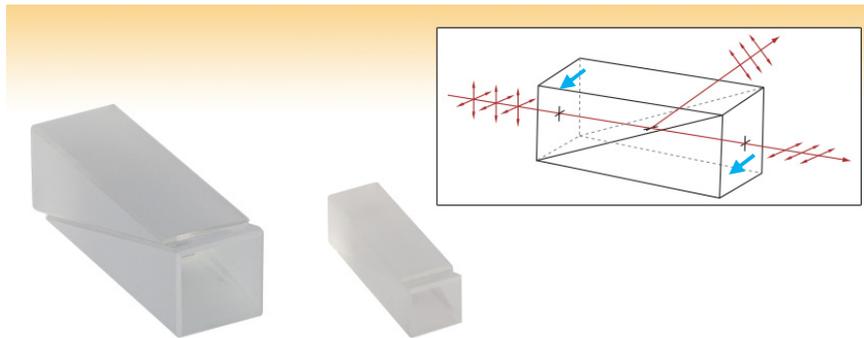


Fig. 7

Polarizing cubes. In such a cube, the interface (at 45°) has a dielectric coating, such that the p polarization is not reflected due to the Brewster effect. The o-polarization is partly reflected, partly transmitted, but it can be made to be reflected completely due to the interference.

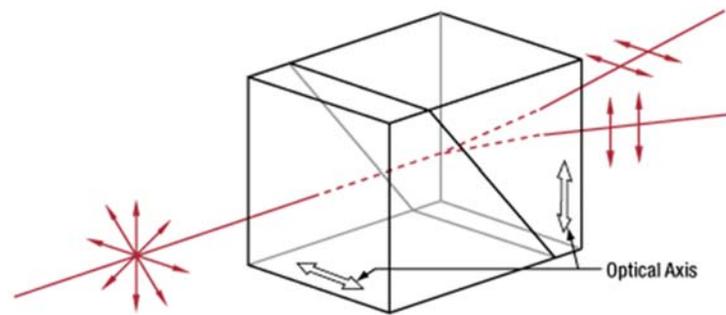


Fig. 8

5. Brewster windows are used to eliminate reflection for a certain polarization. They are tilted to the incident light by the Brewster angle. As a result, there is no loss for the p-polarization. These windows, for instance, can be part of a laser. If a laser has Brewster windows, it is immediately clear how the radiation is polarized.

6. Spatial light modulators.

This is a device for modulating the phase of a beam (sometimes also the amplitude) spatially. This is made by using a liquid crystal (Fig. 9). Molecules of the liquid crystal (shown by green arrows) are oriented by the electric field, applied independently to every pixel. As a result, in every pixel there is a different orientation of all molecules. Depending on their orientation, the refractive index for light with a certain polarization will be different. Correspondingly, different will be the phase acquired at each pixel.

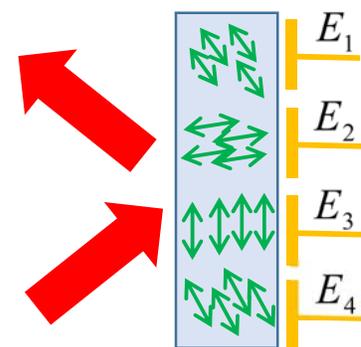


Fig. 9

This way one can write a different phase on every pixel. To impose this phase on a beam, usually a blazed grating is also written on the SLM. Light diffracted by the grating will carry additional phase, which is recorded as well. Superposition of these

distributions (a blazed grating and an additional phase distribution) defines the phase profile of the beam.

Literature:

1. M. Born and E. Wolf, Principles of Optics, sections 14.1-14.3.
2. https://www.thorlabs.com/navigation.cfm?guide_id=8
3. http://www.hamamatsu.com/resources/pdf/ssd/x10468_series_etc_kacc1172e.pdf