Polarization Components

Polarized light carries valuable information about the various physical parameters that have been acting on it. Magnetic fields, chemical interactions, molecular structures, and mechanical stress all affect optical polarization. Applications relying on these polarization changes include astrophysics, agricultural production, electric power generation, and molecular biology.

Polarization states are linear, circular, or elliptical according to the paths traced by electric field vectors in a propagating wave train. Unpolarized light (such as from an incandescent bulb) is a combination of all linear, circular, and elliptical states. Randomly polarized light, in reference to laser output, is composed of two orthogonally linearly polarized collinear beams whose power randomly varies over time. Although random, this radiation is always linearly polarized.

Depolarized light is usually linearly polarized light that has been randomized by either temporal or spatial retardation variations across or along the beam. If the various retardations are integrated enough, the beam will appear to be depolarized. The randomization process usually varies the linear polarization in a fairly smooth and predictable manner.

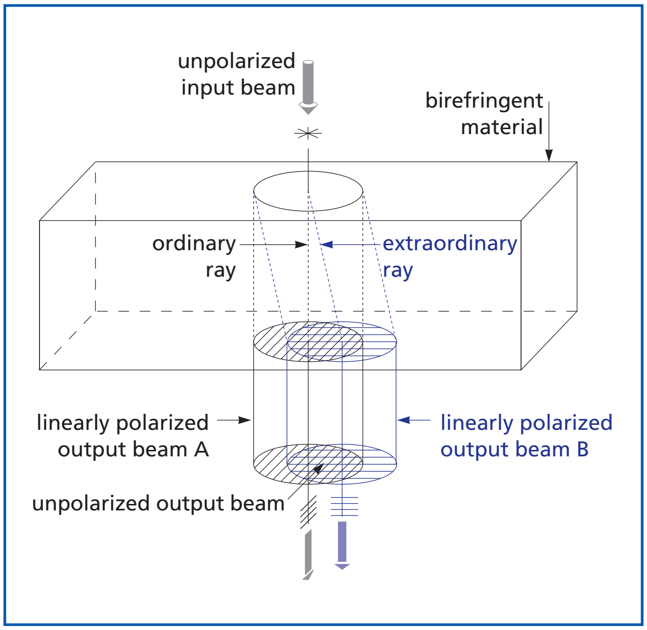
BIREFRINGENCE

A birefringent crystal, such as calcite, will divide an entering beam of monochromatic light into two beams having opposite polarization. The beams usually propagate in different directions and will have different speeds. There will be only one or two optic axis directions within the crystal in which the beam will remain collinear and continue at the same speed, depending on whether the birefringent crystal is uniaxial or biaxial.

If the crystal is a plane-parallel plate, and the optic axis directions are not collinear with the beam, radiation will emerge as two separate, orthogonally polarized beams. The beam will be unpolarized where the beams overlap upon emergence. The two new beams within the material are distinguished from each other by more than just polarization and velocity. The rays are referred to as extraordinary (E) and ordinary (O). These rays need not be confined to the plane of incidence. Furthermore, the velocity of these rays changes with direction. Thus, the index of refraction for extraordinary rays is also a continuous function of direction. The index of refraction for the ordinary ray is constant and is independent of direction.

The two indices of refraction are equal only in the direction of an optic axis within the crystal. The dispersion curve for ordinary rays is a single, unique curve when the index of refraction is plotted against wavelength. The dispersion curve for the extraordinary ray is a family of curves with different curves for different directions. Unless it is in a particular polarization state, or the crystalline surface is perpendicular to an optic axis, a ray normally incident on a birefringent surface will be divided in two at the boundary. The extraordinary ray will be deviated; the ordinary ray will not. The ordinary ray index n, and the most extreme (whether greater or smaller) extraordinary ray index n_E, are together known as the principal indices of refraction of the material.

If a beam of linearly polarized monochromatic light enters a birefringent crystal along a direction not parallel to the optical axis of the crystal, the beam will be divided into two separate beams. Each will be polarized at right angles to the other and will travel in different directions. The original beam energy, which will be divided between the new beams, depends on the original orientation of the vector to the crystal.



Double refraction in a birefringent crystal

The energy ratio between the two orthogonally polarized beams can be any value. It is also possible that all energy will go into one of the new beams. If the crystal is cut as a plane-parallel plate, these beams will recombine upon emergence to form an elliptically polarized beam.

The difference between the ordinary and extraordinary ray may be used to create birefringent crystal polarization devices. In some cases, the difference in refractive index is used primarily to separate rays and eliminate one of the polarization planes, for example, in Glan-type polarizers. In other cases, such as Wollaston and Thompson beamsplitting prisms, changes in propagation direction are optimized to separate an incoming beam into two orthogonally polarized beams.

QUARTZ WAVEPLATES: OPTICAL ACTIVITY VS BIREFRINGENCE

Birefringence is applicable to nonactive crystals, such as calcite, that have a specific direction and index of refraction exactly equal for the ordinary and extraordinary rays. Active crystals, such as quartz, have no such axis, so there is no direction within the crystal in which the indices of refraction are equal. These types of materials exhibit a phenomenon known as optical activity, whereby the axis of incident, linearly polarized light appears to rotate as it propagates along the optic axis. The optic axis for active crystals is the direction in which the index difference between the O and E indices is minimum.

Melles Griot quartz retardation plates do not use the principle of optical activity to create a phase retardation. Instead, the crystals are cut with the optic axis parallel to the surfaces of the plate. When quartz is used in this manner, the retardation is caused by the birefringence of the quartz, not the optical activity of the material.

DICHROISM

Dichroism is selective absorption of one polarization plane over the other during transmission through a material. Sheet-type polarizers are manufactured from organic materials imbedded into a plastic sheet. The sheet is stretched, aligning molecules and causing them to be birefringent, and then dyed. The dye molecules selectively attach themselves to aligned polymer molecules, so that absorption is high in one plane and weak in the other. The transmitted beam is linearly polarized. Polarizers made of such material are very useful for low-power and visual applications. The usable field of view is large (up to grazing incidence), and diameters in excess of 100 mm are available.

POLARIZATION BY REFLECTION

When a beam of ordinary light is incident at the polarizing angle on a transmissive dielectric such as glass, the emerging refracted ray is partially linearly polarized. For a single surface (with n = 1.50) at Brewster's angle, 100% of the light whose electric vector oscillates parallel to the plane of incidence is transmitted. Only 85% of the perpendicular light is transmitted (the other 15% is reflected). The degree of polarization from a single-surface reflection is small.

If a number of plates are stacked parallel and oriented at the polarizing angle, some vibrations perpendicular to the plane of incidence will be reflected at each surface, and all those parallel to it will be refracted. By making the number of plates within the stack large (more than 25), high degrees of linear polarization may be achieved. This polarization method is utilized in Melles Griot polarizing beamsplitter cubes which are coated with many layers of quarter-wave dielectric thin films on the interior prism angle. This beamsplitter separates an incident laser beam into two perpendicular and orthogonally polarized beams.

THIN METAL FILM POLARIZERS

Optical radiation incident on small, elongated metal particles will be preferentially absorbed when the polarization vector is aligned with the long axis of the particle. Melles Griot infrared polarizers utilize this effect to make polarizers for the near-infrared. These polarizers are considerably more effective than dichroic polarizers.

Polarizing thin films are formed by using the patented Slocum process to deposit multiple layers of microscopic silver prolate spheroids onto a polished glass substrate. The exact dimensions of these spheroids determine the optical properties of the film. Peak absorption can be selected for any wavelength from 400 to 3000 nm by controlling the deposition process. Contrast ratios up to 10,000:1 can be achieved with this method.

CALCITE

Calcite, a rhombohedral crystalline form of calcium carbonate, is found in various forms such as limestone and marble. Since calcite is a naturally occurring material, imperfections are not unusual. The highest quality materials, those that exhibit no optical defects, are difficult to find and are more expensive than those with some defects. Applications for calcite components typically fall into three broad categories: laser applications, optical research, and general use. Melles Griot offers most calcite components in several quality grades, to meet those various needs.

There is no generally agreed upon set of quality specifications for commercial calcite. Most manufacturers base their quality ratings on U.S. military specification MIL-G-174B. Since these specifications are actually written for optical glass, they are inadequate to describe completely the quality and performance of calcite. There are three main areas of importance in defining calcite quality.

Spectral Properties

Trace amounts of chemical impurities, as well as lattice defects, can cause calcite to be colored, which change absorption. For visible light applications, it is essential to use colorless calcite. For near-infrared applications, material with a trace of yellow is acceptable. This yellow coloration results in a 15% to 20% decrease in transmission below 420 nm.

Wavefront Distortion (Striae)

Striae, or streaked fluctuations in the refractive index of calcite, are caused by dislocations in the crystal lattice. They can cause distortion of a light wavefront passing through the crystal. This is particularly troublesome for interferometric applications. Melles Griot uses a simple letter system for classifying the effect of striae in calcite:

A–Less than $\lambda/10$ peak-to-peak wavefront distortion over the clear aperture. This substantially exceeds MIL Spec Grade A specified by paragraph 3.3.8.1 in MIL-G-174B.

B–No more than $\lambda/4$ peak to peak of wavefront distortion over the clear aperture. This is essentially equivalent to MIL Spec Grade A.

C–No more than one wave peak to peak over the clear aperture. This is essentially equivalent to MIL Spec Grade B.

Scatter

Small inclusions within the calcite crystal account for the main source of scatter. They may appear as small cracks or bubbles. In general, scatter presents a significant problem only when the polarizer is being used with a laser. The amount of scatter centers that can be tolerated is partially determined by beam diameter and power. Scatter in Melles Griot calcite is indicated by a simple number designation. Scatter evaluation designators are based on performance when illuminated with 5-mW red HeNe laser:

0–The material is free from any visible scatter centers.

1–Some visible grayness due to scatter.

2–Numerous individually visible scatter centers.

MELLES GRIOT CALCITE GRADES

Melles Griot has selected the most applicable combinations of calcite qualities, grouped into four grades:

Laser Grade

Components that meet both striae category **A** and scatter category **0**.

Low-Scatter Grade

Components that meet scatter category **0** and striae category **B** or **C**.

Optical Grade

Components that meet either combined categories **A1** or **B1**.

Standard Grade

Components that meet either combined categories **A2** or **B2** or **C1**.

Notice that, in all except the laser grade, several categories are encompassed for each grade. Where two or more categories are included in a grade, a component meeting this grade will meet one, but not all, individual categories. For example, a component carrying a quality specification of optical grade (categories **A1** or **B1**) will exhibit low scatter and have between one-tenth and one-quarter wave of peak-to-peak wavefront distortion.

CALCITE OPTICAL POLARIZERS

Although many forms of calcite polarizers have been designed, the Glan-Taylor, Glan-Thompson, and Wollaston are the most useful. All Glan-type prisms are designed so that both entrance and exit faces are normal to the intended direction of use. The prism angle has been cut so that the O ray is totally internally reflected at the first face. In the Glan-Thompson prism, two halves are cemented together. In the Glan-Taylor and Glan-Laser prisms, the two polarizer halves are separated by an air space. Although the air space allows the prisms to handle substantially higher power and greater ultraviolet transmission than cemented prisms, the useful angular field is reduced and loss caused by internal Fresnel reflections is slightly increased. In general terms, the acceptance angle for a Glan-Taylor polarizer is typically 8.5 degrees, and for a Glan-Thompson polarizer, it is 18.5 degrees. Wollaston prisms transmit both linearly polarized beams. The beams, polarized in mutually perpendicular planes, emerge from the prism in different directions. Both beams may be manipulated independently farther down the optical path.

OPEN TRANSMISSION AND EXTINCTION RATIO

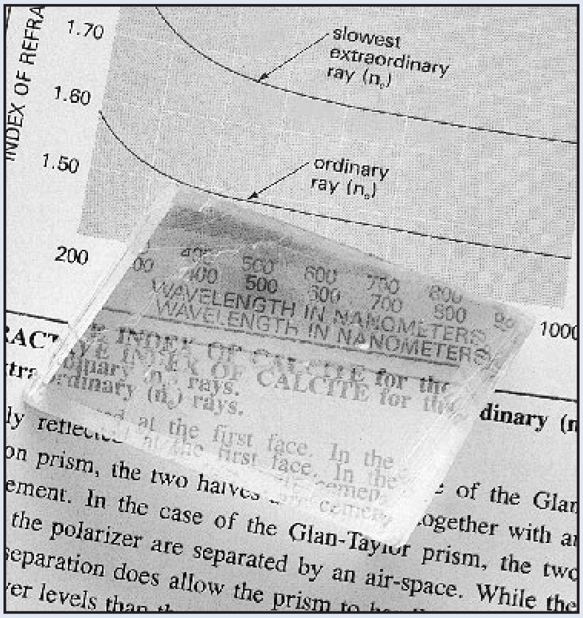
The open transmission of a pair of polarizers with their polarization directions parallel to each other is denoted by the quantity H_0. The extinction ratio, or transmission of a pair of polarizers with perpendicular polarization direction, is denoted by the quantity H_{90}.

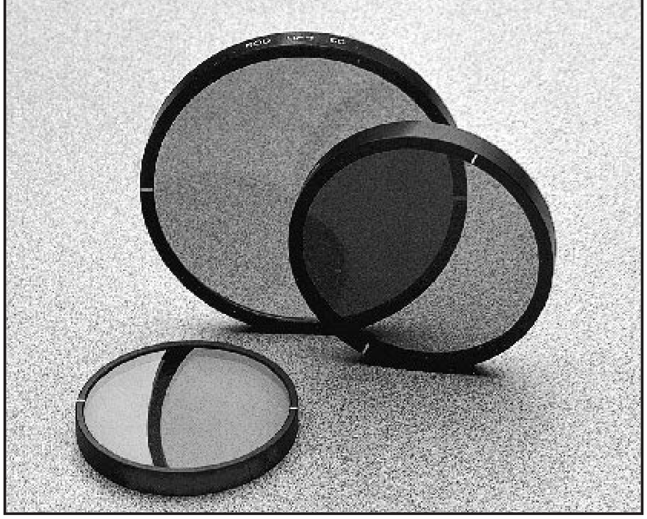
APPLICATION NOTE

Calcite for Polarizers

Calcite is a natural, birefringent material. The calcite miner must understand and search for the calcite outcroppings that are of optical quality. Then, the raw calcite must be internally examined through a small, polished window to determine how the crystal will be cut and used. Finally, the calcite must be cut, ground, and polished at exact angles to its optical axis.

These skills are very different from those found in a more normal optical fabrication shop. Melles Griot calcite is mined and manufactured by skilled, carefully trained technicians who understand these special requirements.





Available in:
✔ **Production Quantities**

Dichroic Sheet Polarizers

Dichroic sheet polarizers are used to subject one of the two orthogonal polarizations (either ordinary or extraordinary) to strong absorption. Melles Griot polarizers are made of a plastic dichroic polarizing sheet sandwiched between selected strain-free glass plates.

- Dichroic sheet polarizers offer large apertures and acceptance angles.
- They provide excellent extinction ratios and are simple to mount.
- They are suited for low-power applications.
- They are constructed for use in the visible spectrum.

SPECIFICATIONS: DICHROIC SHEET POLARIZERS

Wavelength Range: 350–650 nm

Transmission (Ratio of Total Output to Total Unpolarized Input): $\frac{1}{2}(k_1+k_2) = 32\%$

Open Transmission for Pair of Polarizers (H_0): ≥20%

Extinction Ratio (H_{90}):
10^{-4} for visible white light, closed pair of polarizers

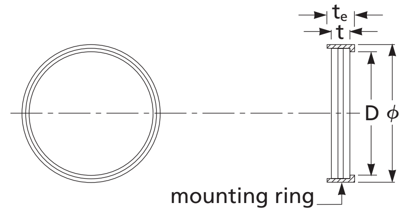
Useful Field Angle: 90º (can be used at grazing incidence)

Diameter: $\phi \pm 0.25$ mm

Thickness: $t \pm 0.5$ mm

Surface Quality: 80–50 scratch and dig

Mounting:
Between two glass discs, hermetically mounted in a black anodized aluminum ring; polarization plane of maximum transmission indicated by engravings on the outside edge

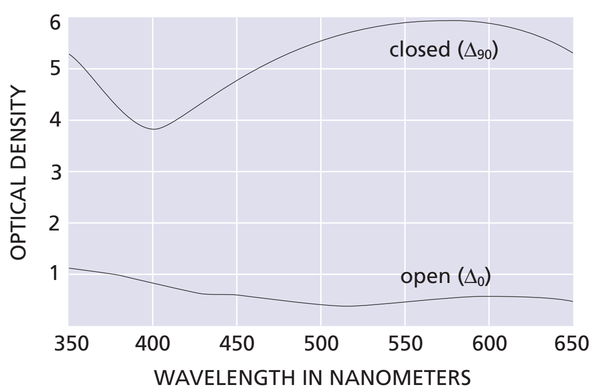


03 FPG dichroic sheet polarizers

Dichroic Sheet Polarizers

Outside Diameter ϕ (mm)	Clear Aperture D (mm)	Thickness t (mm)	Ring Thickness t_e (mm)	PRODUCT NUMBER
12.5	9.0	2.5	4.0	03 FPG 019
20.6	16.9	2.5	4.0	03 FPG 001
30.2	26.5	2.5	4.5	03 FPG 003
41.3	38.4	2.5	4.8	03 FPG 005
50.8	45.4	2.5	5.3	03 FPG 007
63.5	58.0	3.5	5.6	03 FPG 009
82.6	76.0	3.5	5.6	03 FPG 011
93.0	85.0	3.5	6.0	03 FPG 013
103.0	94.0	3.5	6.0	03 FPG 015
119.0	110.0	3.5	6.0	03 FPG 017

For sheet polarizer holders, see Chapter 24, Lens, Filter, and Polarizer Mounts.



Optical density for pair of 03 FPG dichroic sheet polarizers

APPLICATION NOTE

Variable Transmittance Using Two Sheet Polarizers

The transmittance T of a single-sheet polarizer in a beam of linearly polarized incident light is given by

$$T = k_1 \cos^2(\theta) + k_2 \sin^2(\theta)$$

where θ is the angle between the plane of polarization of the incident beam (more accurately, the plane of the electric field vector of the incident beam) and the plane of preferred transmission of the polarizer. The orientation of the plane of preferred transmission is clearly marked by engravings on the mount. The principal transmittances of the polarizer, k_1 and k_2, are both functions of wavelength. Ideally, $k_1 = 1$, and $k_2 = 0$. In reality, k_1 is always somewhat less than unity, and k_2 always has some small but nonzero value.

If the incident beam is unpolarized, and the angle θ is redefined to be the angle between the planes of preferred transmission (planes of polarization) of two sheet polarizers in near contact, the transmittance of the pair is given by

$$T_{pair} = k_1 k_2 \sin^2\theta + \tfrac{1}{2}(k_1^2 + k_2^2)\cos^2\theta .$$

If we define

$$H_{90} = T_{pair}(90°) = k_1 k_2$$

and

$$H_0 = T_{pair}(0°) = \frac{1}{2}(k_1^2 + k_2^2)$$

the above formula can be simplified to

$$T_{pair} = H_{90}\sin^2\theta + H_0\cos^2\theta$$
$$= H_{90} + (H_0 - H_{90})\cos^2\theta$$

The quantity H_{90} is called the closed transmittance or extinction ratio, and the quantity H_0 is called the open transmittance. Both quantities are wavelength dependent. Because of the large ranges of open and closed transmission, it is convenient to plot the optical densities corresponding to these transmissions, rather than the transmissions themselves. The open and closed optical densities are defined as follows:

$$\Delta_0 = \log\left(\frac{1}{H_0}\right)$$

and

$$\Delta_{90} = \log\left(\frac{1}{H_{90}}\right).$$