# What is Polarization?

Polarization is a property that is common to all types of vector waves. In classical physics, light is modeled as a sinusoidal electromagnetic wave in which an oscillating electric field and an oscillating magnetic field propagate through space. Since the magnetic field is always perpendicular to the electric field, we usually sketch just the electric field when visualizing the optical wave's oscillations. Polarization is defined in terms of the pattern traced out in the transverse plane by the electric field vector as a function of time.

Light is called natural or unpolarized if its plane of polarization fluctuates randomly around the direction of light beam propagation, so that, on average, no direction is favored. For example, most naturally produced light (sunlight, firelight) is unpolarized. In any other case, the light beam can be considered to consist of partially polarized or fully polarized light.

The polarization of a light beam can be represented by its electric field vector. Its optical power is a scalar quantity that is proportional to the mean square of the electric field amplitude.

Let z be the direction of propagation. Then, the polarization vector is in the x-y plane. By superposition of the x- and y-vector components at time t at any location, the polarization vector can be expressed:

$$\vec{E}(t) = \vec{E}_x(t) + \vec{E}_y(t)$$
$$= E_x \cos(\varpi t + \delta_x)\vec{e}_x + E_y \cos(\varpi t + \delta_y)\vec{e}_y$$

where $E_X$ and $E_Y$ are the amplitudes of the x and y components of the electric field; $e_x$, $e_y$ are the unit vectors of the x-y orthogonal reference system; $\varpi$ is the angular frequency; and δx and δy are the phases of the electric field in the x and y directions, respectively. The phase difference is δ = δx - δy .

Figure 1 shows electric field vectors in the x-y plane as a function of time. Figure 1(a) shows the two orthogonal electric field components with a relative phase difference of δ. In Figure 1(b) there is no phase difference between the two orthogonal components.

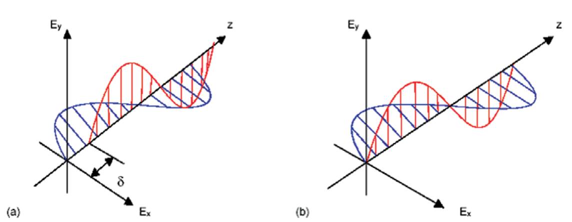


Fig. 1 Spatial representation of x- and y- electric field components over time. (a) with a phase difference, (b) no phase difference.

Polarized light may be classified into three groups by the values of δ, Ex , and Ey : linearly polarized, circularly polarized and elliptically polarized light. Linearly polarized light has no phase difference between the x and y electric field components (δ=0). Circularly polarized light has a fixed phase difference of 90 degrees, and the amplitudes of the two electric field components are the same (ie. δ = 90˚ and Ex = Ey ). The polarization state is elliptical for all other values of δ, Ex, and Ey .

## Poincaré Sphere and Stokes Vectors

The Poincaré sphere is used to describe the polarization and changes in polarization of a propagating electromagnetic wave. It provides a convenient way of representing polarized light, and of predicting how any given retarder will change the polarization form. Any given polarization state corresponds to a unique point on the sphere. The two poles of the sphere represent left- and right-hand circularly polarized light. Points on the equator indicate linear polarizations. All other points on the sphere represent elliptical polarization states. An arbitrarily chosen point H on the equator designates horizontal linear polarization, and the diametrically opposite point V designates vertical linear polarization.

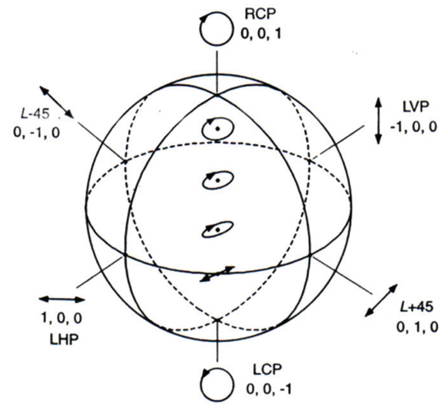


Fig. 2 Poincaré sphere representation of polarization states

The Stokes parameters have a simple physical interpretation related to Poincaré sphere representation. They also have a physical interpretation related to intensity measurement.

In a given Oxyz reference system (Oz being the direction of propagation of light), the Stokes vector can be expressed as:

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I_0 \\ I_x - I_y \\ I_{+45} - I_{-45} \\ I_L - I_R \end{bmatrix}$$

where $I_0$ is the total power of the light, $I_x$, $I_y$ are the x- and y-linearly polarized light intensities, $I_{+45}$, $I_{-45}$ are the 45˚ and -45˚ linearly polarized light intensities, and $I_L$, $I_R$ are the left and right hand circularly polarized light intensities.

If we normalize [$S_1$ $S_2$ $S_3$] by $S_0$, we will get the SOP [$s_1$ $s_2$ $s_3$], which are the coordinates of one point on the Poincaré sphere.

The degree of polarization (DOP) is defined by:

$$DOP = \sqrt{s_1^2 + s_2^2 + s_3^2}$$

with a value between 0 and 1.

Whenever DOP=0, light is said to be unpolarized, and whenever DOP=1, it is totally polarized. Intermediate cases correspond to partially polarized light.

DOP can also be expressed as:

$$DOP = \frac{I_{pol}}{I_{pol} + I_{unp}}$$

where $I_{pol}$ , $I_{unp}$ are the intensity of polarized light and unpolarized light, respectively.

### What is Birefringence?

In a homogenous or isotropic medium, light propagates at the same speed regardless of polarization state. This speed, **v**, can be expressed as:

$$\mathbf{v} = c/n$$

where c is the speed of light in a vacuum, and n is the index of refraction of the medium.

If the light is propagating in an anisotropic medium, the transmission speeds of light polarized along different directions are different. One may use two special orthogonal axes called principal axes to express the transmission properties of the medium.

Usually, this can be expressed through different indices of refraction, such as the ordinary index ($n_0$) and extraordinary index ($n_e$). The difference between $n_0$ and $n_e$ is called birefringence. Birefringence is also called double refraction.

Therefore, the index of refraction is a measure of how fast light transmits through a medium. If a medium is birefringent, plane-polarized light launched into one principal axis travels through the medium faster than plane-polarized light in the other principal axis. As a result, the two polarization components of a light signal projected along the two axes will experience a relative phase difference as they propagate through the material.

If an optical pulse is launched into a fiber made of a birefringent material with its polarization aligned with either of the fiber's principal axes, then the pulse transmits through the fiber and emerges in the same state of polarization in which it was launched. However, if we launch the pulse with randomly oriented polarization, then part of the pulse transmits along one of the principal axes, and part of the pulse transmits along the other principal axis. Because of the medium's birefringence, the two parts of the pulse travel at different speeds. Consequently, the pulse becomes broadened because the two parts exit the fiber at slightly different times, and the state of polarization changes.

### What is PMD?

PMD stands for polarization mode dispersion. It occurs when different polarization components of light inside a fiber travel at slightly different speeds, as shown in Figure 3. PMD is caused directly by the birefringence of the optical fiber. The major causes of the birefringence are the asymmetry of the fiber-optic strand, where the fiber core is slightly oval or out-of-round, and mechanical stresses on the fiber. The asymmetry may be inherent in the fiber from the manufacturing process, or it may be a result of mechanical stress on the deployed fiber. The inherent asymmetries of the fiber are fairly constant over time, while mechanical stress due to movement or temperature change of the fiber can vary, resulting in a dynamic aspect to PMD. 1st order PMD is called differential group delay (DGD).

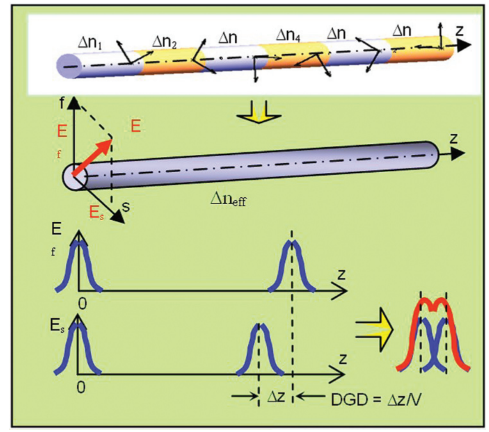


Fig. 3 A real fiber is like many retardation plates with different orientations and birefringences in series. It is equivalent to a single retardation plate having a slow and fast axis, and an effective birefringence. An optical pulse broadens because the two polarization components travel with different speeds.

Because of its dynamic properties, PMD does not have a single, fixed value for a given section of fiber. Rather, it is described in terms of average DGD, and a fiber has a distribution of DGD values over time. The probability of a DGD with a certain value at any particular time follows the Maxwellian distribution shown in Figure 3. As an approximation, the maximum instantaneous DGD is about 3.2 times the average DGD of a fiber.

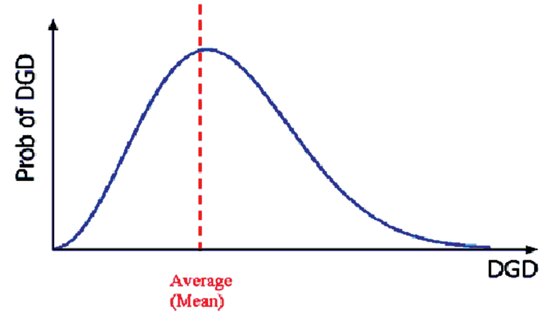


Fig. 4 Maxwellian distribution of DGDS