Lab #6

Polarization

Contents:

Pre-Laboratory Exercise

Bring a pair of polarized sunglasses or other polarized optics to measure in the lab.

Introduction

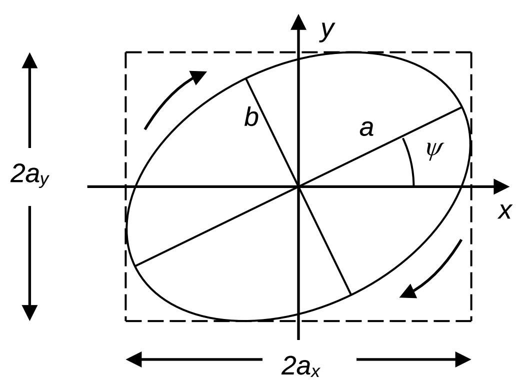
The purpose of this lab it to gain familiarity with the concept of polarization, and with various polarization components including glass-film polarizers, polarizing beam splitters, and quarter wave and half wave plates. We will also investigate how reflections can change the polarization state of light.

Within the paraxial limit, light propagates as an electromagnetic wave with transverse electric and magnetic (TEM) field directions, where the electric field component is orthogonal to the magnetic field component, and to the direction of propagation. We can account for this vector (directional) nature of the light wave without abandoning our scalar wave treatment if we assume that the $\hat{x}$ -directed electric field component and $\hat{y}$ -directed electric field component are independent of each other. This assumption is valid within the paraxial approximation for isotropic linear media. The "polarization" state of the light wave describes the relationship between these $\hat{x}$ -directed and $\hat{y}$ -directed components of the wave.

If the light wave is monochromatic, the *x* and *y* components must have a fixed phase relationship to each other. If the tip of the electric field vector $\mathbf{E} = E_x \hat{x} + E_y \hat{y}$ were observed over time at a particular *z* plane, one would see that it traces out an ellipse. We say, therefore, that monochromatic light is elliptically polarized, and the shape traced by the tip of the electric field vector is called the polarization ellipse. In general, we can write the components of the electric field as:

$E_x = a_x \cos(\omega t - kz)$ $E_y = a_y \cos(\omega t - kz + \phi)$

which are parametric equations for the ellipse illustrated on the following page.



It is possible to use a local coordinate system to describe the ellipse in terms of its major axis component *a* and minor axis component *b*, along with the angle ψ that the major axis makes with respect to the laboratory *x* axis. The *ellipticity* of the polarization state is specified by *b/a*, and we call ψ the polarization angle. Note that the ellipticity is defined in terms of field amplitudes, so it can be calculated as the square root of the ratio I_{min}/I_{max}.

Experimentally it is common to specify the polarization state in terms of yet another set of parameters called the **Stokes parameters**, which are defined as follows:

$$S_0 = I = \left\langle {a_x}^2 \right\rangle + \left\langle {a_y}^2 \right\rangle = \left\langle a^2 \right\rangle + \left\langle b^2 \right\rangle$$
$$S_1 = Q = \left\langle {a_x}^2 \right\rangle - \left\langle {a_y}^2 \right\rangle = I\left\langle \cos(2\chi)\cos(2\psi) \right\rangle$$
$$S_2 = U = 2\left\langle a_x a_y \cos\phi \right\rangle = I\left\langle \cos(2\chi)\sin(2\psi) \right\rangle$$
$$S_3 = V = -\left\langle 2a_x a_y \sin\phi \right\rangle = I\left\langle \sin(2\chi) \right\rangle$$

where χ is defined by $\tan\chi = \pm b/a$, the positive sign indicating left-handed polarization and the negative sign indicating right-handed polarization. The handedness of the polarization takes its name from a consideration of the time course of the tip of the electric field vector in a fixed *z* plane. If the vector traverses the ellipse clockwise, when viewed from the direction in which the wave is propagating (that is, looking toward minus *z*), the polarization sense is right handed. The angle brackets indicate averages over time, and are included for the case in which the light is polychromatic and the magnitude and angle parameters are random functions of time. From the Stokes parameters the degree of polarization is

$$DoP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}.$$

When the light has no circular polarization component $S_3 = 0$ and the degree of linear polarization is

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}.$$

If the light also has no 45° linear polarization component, so that it can be described purely in terms of horizontally and vertically polarized components, then $S_2 = 0$ and the degree of linear polarization can be calculated as

$$DoLP = \frac{I^s - I^p}{I^s + I^p} = \frac{I^{TE} - I^{TM}}{I^{TE} + I^{TM}},$$

where the superscripts *s* and *p* indicate the irradiance components oriented perpendicular and parallel to the plane of incidence (defined by the incident and reflected ray). Note that *s* polarization is the same as *TE* polarization and *p* polarization is the same as *TM* polarization (where TE indicates that the electric field is transverse to the plane of incidence and TM indicates that the magnetic field is transverse to the plane of incidence).

In class we discussed Jones calculus, which uses a two-element vector to describe the polarization state of light. The two elements of the Jones vector are the two complex field amplitudes (i.e. amplitudes and accompanying phases). This method can be used only with fully polarized light, and Stokes vectors are required to describe partially polarized light.

1. Polarization of the HeNe laser

You are to characterize the polarization state of light emitted by a HeNe laser. To facilitate these and later measurements, you may find it convenient to rotate your laser in the mount until the polarization state is either vertical or horizontal.

a) Measure the power of your laser beam.

b) Insert a polarizer and adjust the rotation angle to measure the maximum transmitted power. What is the maximum transmittance of the polarizer?

c) Adjust the polarizer for minimum transmittance and measure the transmitted power. What is the degree of linear polarization of the transmitted light? (you can simply calculate DoLP as the difference of your two orthogonal polarized irradiances divided by the sum).

2. Polarizer extinction ratio

Polarizers found in the laboratory can be polaroid film, glass/film sandwiches, calcite crystal, dielectric, stacked Brewster plates or wire grid types. The cheapest are the film types, and these also have respectable extinction ratios (on the order of 20-30 dB). They have limited power capability, and their spectral range is limited to the visible. The best polarizers are calcite crystals, which can operate from the UV through the IR and can exhibit extinction ratios of 60 dB! These polarizers are expensive! (thousands of $ for one piece, compared to hundreds of $ for glass sandwich polarizers). They also have a limited size, owing to the availability of natural calcite crystals, and they are sensitive to incidence angle of the laser beam. Dielectric polarizers (of which the polarizing beam splitters are an example) offer a compromise of reasonable cost, good extinction ratios and medium power handling capability.

Note: polarizers in a rotation mount labeled “MLO” are the newer devices from Meadowlark Optics Company. These are better polarizers than the unlabeled ones (no fingerprints please!).

a) Place a high-quality glass/film sandwich polarizer in front of the laser and adjust for maximum transmission. Place a second polarizer after the first and adjust for and measure the maximum transmittance. This second polarizer is the one we are measuring. Why did we use the first one? Now adjust the second polarizer for minimum transmission and calculate the extinction ratio in dB according to $10\log(I_{max}/I_{min})$.

b) Based on your measurements, was your laser polarization measurement in part 1 limited by the extinction ratio of the polarizer, or the purity of polarization of the light source?

c) Measure and comment on the extinction ratio for a pair of sunglasses (or similar).

3. Wave Plates

A wave plate is a device with birefringence, meaning that the refractive index is different for different polarization states (i.e., waves will propagate with different speeds depending on the orientation of the electric field vector). Uniaxial crystals can be used for wave plates if the optic axis is contained in the plane defined by the front surface of the device. In this case a beam polarized in the direction of the optic axis will see a different index of refraction (the extraordinary index n_e) from a beam polarized orthogonally to it (which sees the ordinary index n_o). The result is that the two waves will propagate at different speeds, and accumulate a phase difference given of $\Delta\phi = \frac{2\pi}{\lambda_o} d(n_o - n_e)$. If $\Delta\phi = \pi$, the two waves will be out of phase, and we call this device a half-wave plate. Such a device can be used to rotate the plane of polarization of a linearly polarized beam. If $\Delta\phi = \pi/2$, the device is called a quarter-wave plate. It can be used to convert a linearly polarized beam into a circularly polarized one.

Waveplates are chromatic, meaning that the relative phase shift imparted depends on the wavelength of the beam. The waveplates we will use in the lab are not crystalline, but are made from a birefringent polymer coating on glass. The center wavelength for $\lambda/4$ and $\lambda/2$ operation is 632.8 nm for these devices.

a) Find the axis of your $\lambda/2$ plate. To do this, first place a polarizer between your laser and your detector and rotate the polarizer to achieve maximum extinction (that is, the laser polarization and analyzer are crossed). Make note of this polarizer 90º reference angle, which is 90º relative to the laser direction of polarization, which we may call the 0º polarizer reference angle. (We measure the extinction, because it is more precise to find the minimum in the lab than trying to locate the maximum when the analyzer and laser polarization are aligned.)

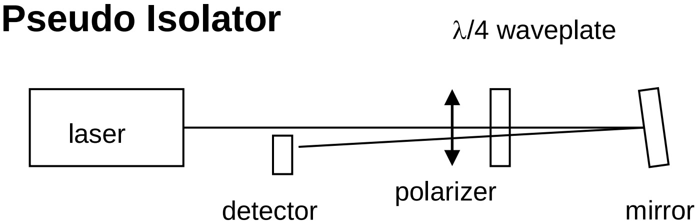
b) Insert the waveplate between the laser and the (still crossed) analyzer and adjust the waveplate rotation angle until the transmission is again minimized. Now the waveplate is aligned with the beam polarization. Make note of this wave plate reference angle.

c) With the wave plate rotated to 0° (i.e., set at the wave plate reference angle), rotate the polarizer to find the maximum and minimum transmittances. From these data determine the ellipticity $(I_{min}/I_{max})^{1/2}$ and polarization angle. Define the polarization angle as relative to the 0º polarizer reference (which is the input beam polarization angle).

d) Repeat (c) with the wave plate rotated to 22.5 º and then repeat again for the wave plate rotated to 45º relative to the wave plate reference angle. The "polarization angle" in these cases are found as the difference between the previously found 0º polarizer reference angle and the new polarizer angle that gives maximum transmittance through the rotated wave plate.

e) Repeat these steps for the $\lambda/4$ plate and discuss your observations.

4. Pseudo Isolator



You can construct a pseudo optical isolator using a polarizer and a quarter-wave plate. An optical isolator is a device that permits light to pass in only one direction. The pseudo isolator will let polarized light pass in the forward direction and attenuate back-reflections from the forward beam. The idea is illustrated above. Linearly polarized light passes through the polarizer and is converted to right hand circularly polarized light by the quarter wave plate. Upon reflection, this beam will change handedness, and upon passage back through the quarter wave plate it is linear again but orthogonal to the polarizer.

(a) Construct a pseudo isolator using a polarizer and your $\lambda/4$ plate. Measure the isolation ratio I_{max}/I_{min} that you get for a beam reflected back through the wave plate and the polarizer, when the wave plate is adjusted for minimum transmission of the reflected beam.

5. References

1. D. Goldstein, "Polarized Light," 3rd ed., CRC Press, 2010 (best reference for a complete coverage of polarization, Mueller calculus, and Jones calculus).
2. E. Hecht, "Optics," 4th ed., Addison-Wesley, 2002 (excellent overall reference for polarization, but beware some small differences of notation).
3. Bahaa E. A. Saleh and Malvin Carl Teich, "Fundamentals of Photonics," 2nd ed., Wiley, 2007.
4. The original version of this lab write-up was written by D. Dickensheets with liberal use of Marty Fejer's lab notes for Applied Physics 304, Winter 1991, Stanford University. Modified 2005-2012 by J. Shaw.