Measurements of Polarization Phenomena

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The experiment involved measuring polarization phenomena including the Brewster angle, extinction ratio for polarized light (Malus's Law) and birefringence of a custom sapphire crystal [1]. The Brewster angle for BK7 was $303.5^\circ \pm 0.08^\circ$and the calculated index of refraction was 1.5112 ± 0.0046. For dielectric and metal mirrors used in this study, the phase shift was $20.90^\circ \pm 0.12^\circ$. Maximum and minimum intensity values from the Malus's law plot were $9.96\,\mathrm{V} \pm 0.02\,\mathrm{V}$ and $0.02\,\mathrm{V} \pm 0.01\,\mathrm{V}$ respectively. Using the two intensity values, the extinction ratio was 456.40 ± 210.69. The difference between the two angles is $89.95^\circ \pm 0.14^\circ$, with a 0.33σ deviation. The resulting angle was approximately perpendicular, therefore the experiment verified Malus's Law. The cosine squared fit exhibited a low chi squared. A low chi squared meant that intensities were detected and converted properly into voltages, proving that the diode detector had a linear response. The two α angles for the first and second birefringence minimums of the sapphire crystal were $28.07^\circ \pm 0.04^\circ$and $27.69^\circ \pm 0.03^\circ$respectively. The weighted average of the two c-axis values is $28.88^\circ \pm 0.04^\circ$.

Background

The term polarization refers to a property of light being polarized, but also the production of polarized light [2]. The Sun is the main source of light seen on Earth, and the emitted light is unpolarized. The blue sky that we observe is a result of Rayleigh scattering. An application of polarization is reducing reflected light off of surfaces such as the ocean or wet roads. Light is reflected off reflective surfaces and causes large amounts of intense light projected into our eyes. The intense light is polarized by reflection and unpolarized sunlight becomes linearly polarized at defined angles, usually horizontally. Light is a transverse electromagnetic wave and thus it can be polarized. To suppress harsh light reflections one needs a vertical linear polarizer to eliminate the reflected light and to allow propagation of unpolarized light.

Sunlight above the atmosphere is not polarized. This is predicament for cameras mounted on satellites above Earth orbit, and especially near the Lagrange point 1 (L1). The Solar Dynamics Observatory (SDO) is a NASA satellite currently in L1. The SDO is equipped with a coronagraph camera able to study variations in the solar irradiance [3]. To obtain images seen in figure 1, polarizers allow limited light into the camera to be converted from the coronagraphs. Polarized images of the Sun allow us to observe powerful and bright solar event propagation with defined structures.

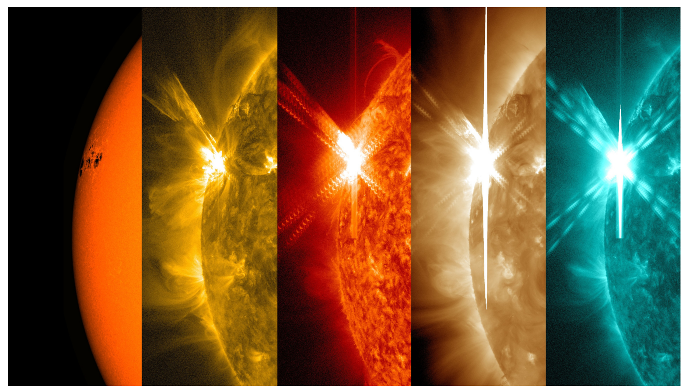

Figure 1. SDO coronagraph images at different wavelengths, polarized visible light to 304 Å.

Apparatus

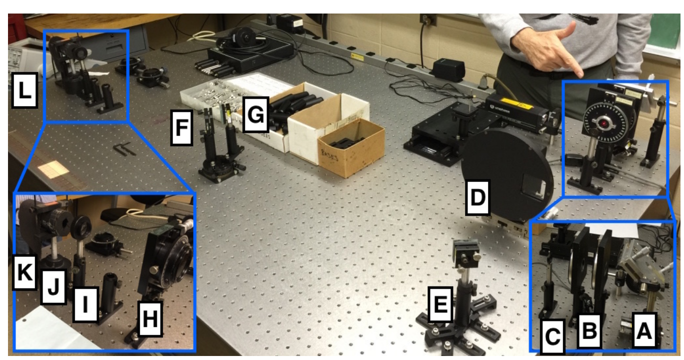

Figure 2. A) Laser source B) Variable linear polarizer C) Iris D) Chopper E) Mirror F) BK7 G) Mirror H) Lens I) Light sheath J) Detector K) Oscilloscope

The experiment apparatus involved several components in the path of a Helium-Neon (HeNe) laser source seen in figure 2. The HeNe laser source (A) initially passes through a variable linear polarizer (B) that can select a vertical, horizontal, or linear state in between. The polarized source is then passed through an iris (C) and light chopper (D). The iris allows the baseline and signal to be viewed simultaneously on the oscilloscope. From the chopper, the laser is reflected off of an initial mirror (E) to the BK7 (F), reflected off the BK7 to a second mirror(G), and from the second mirror to a lens (H). The lens ejects a parallel transport to the diode detector (J) and a measurement is read off the oscilloscope (K). To reduce background light, a sheath (I) is placed between the lens and the detector. For the sapphire birefringence procedure, the reflecting array including components (F and G), are replaced with the custom sapphire crystal on a rotating pedestal.

Procedure

This study consisted of observing the polarization phenomena, production and measurements of various states of polarization, polarizing components and systems, and observing the birefringence of sapphire. Using the apparatus in figure 2, we measured the Brewster angle and the relative phase shift of linearly polarized light upon reflection from a metal mirror and a dielectric. The next part of the experiment involved manipulating the angle of polarization. The result of varying polarization angles affected the output voltages, which was compared to Malus's Law. Finally, a custom sapphire crystal was used to observe birefringence and the angle of the crystal c-axis. The apparatus (F-G) components, seen in figure 2, were replaced with a the custom sapphire crystal at a neutral perpendicular angle. The sapphire crystal was tilted at various angles to measure the minimum amplitude angles clockwise and counterclockwise from the neutral angle perpendicular to the HeNe laser beam.

Calculation of Results

Brewster angle measurement

The index of refraction measured for BK7 is 1.5112±0.0046. This answer was calculated from the Brewster angle, which is 303.5°±0.08°. This value was subtracted from 360°resulting in an angle of 56.5°. The tangent of the resulting angle was multiplied by the refractive index of air. The experimental index value was compared to the accepted value at the HeNe wavelength, 1.515, which corresponds to a 0.83σ deviation.

Production and measurement of various states of polarization

A dielectric and a metal mirror were set to 46°and the polarizer was set to 166°. We observed that the signal was not completely extinguished meaning there is elliptical polarization.

$$\phi = \cos^{-1}\left(\frac{I_+ - I_-}{2\sqrt{I_x I_y}}\right) \tag{1}$$

Values in equation 1 included the phase angle, ϕ, and intensities at the angles, -45°, 0°, 45°, and 90°. The corresponding angles with respective intensities were I_x (90°), I_y (0°), I_- (-45°), and I_+ (45°). Intensities for I_x I_y I_-, and I_+ were 1.45 V±0.15 V, 1.56 V±0.16 V, 2.93 V±0.29 V, and 0.12 V±0.01 V. The measured relative phase shift, ϕ, is ±20.90°±0.12°.

Polarizing components and systems

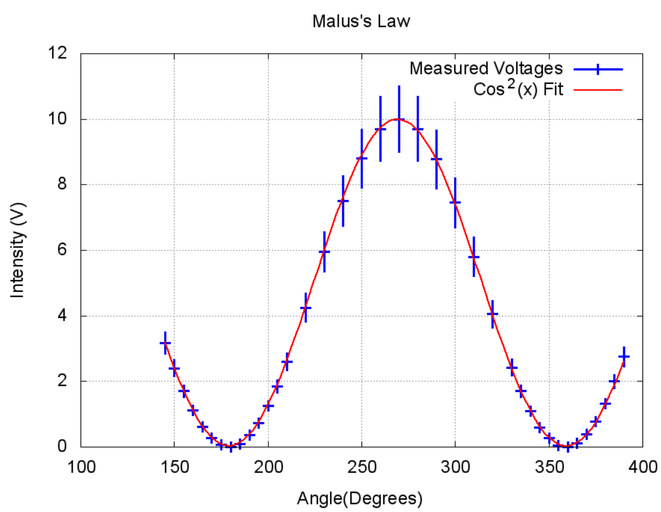

Figure 3. Intensities from an initial <2 V angle (145°) to a final angle at <2 V (390°). The data in blue is fit with a cosine squared fit.

$$I = I_0 \cos^2(\theta - \theta_c) + C \tag{2}$$

Equation 2 was used as a fit for our data values. The quantity, I_0, is the maximum intensity peak value, θ_c is the angle of the maximum peak, and C is a constant that is regarded as the minimum intensity value. The cosine squared fit yield maximum and minimum intensity values of 9.96 V±0.02 V and 0.02 V±0.01 V, respectively. Using the two intensity values, the extinction value was determined with the maximum over minimum intensity, which yields 456.40±210.69. The plotting program determined the reduced chi squared of the fit, $\frac{\chi^2}{ndf}$, to be 0.002. The cosine squared fit showing a relatively low chi squared value meaning that intensities were detected and converted properly into voltages, proving that the diode detector had a linear response.

According to Malus's law, the polarizer will transmit a wave of the largest amplitude at the plane of transmission, conversely, rejecting the relative perpendicular component [4]. A cosine squared fit was used to find the maximum amplitude angle, 269.35°±0.07°, and a quadratic fit was used to find the minimum amplitude angle, 179.40°±0.07°. The difference between the two angles is 89.95°±0.14°. With a 0.33σ deviation, the resulting angle is perpendicular, therefore the experiment verifies Malus's Law.

Birefringence of sapphire

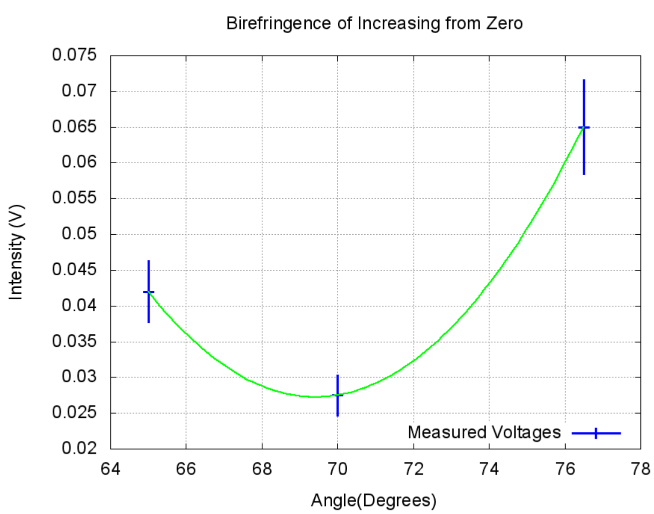

Figure 4. The intensity versus angle for the minimum angles of the polarizer. The intensity include values under 2 V, and a quadratic function is fit to the points with angles between 65°-77°.

Figures 4 and 5 both yielded minimum amplitude angles of the sapphire crystal. Both figures show intensity versus angles and were fit with quadratic equations. The first birefringence minimum angle, θ_1 between angles 65°-77°is 69.40°±0.20°. The second birefringence minimum angle, θ_2, between angles 280°-300°is 292.90°±0.17°. Figure 4 showed three points, and since we use a second degree polynomial that fits with three parameters.

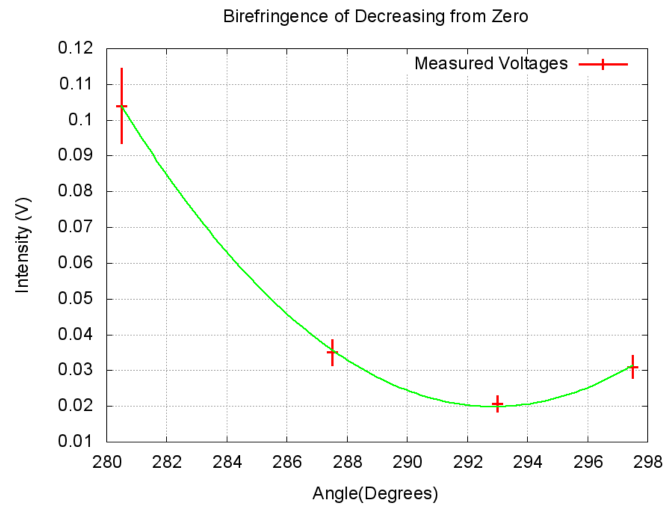

Figure 5. The intensity versus angle for the minimum angles of the polarizer. The intensity include values under 2 V, and a quadratic function is fit to the points with angles between 280°-300°.

$$\alpha = \tan^{-1}\left(\frac{n_{air}\sin(\theta_3)}{n_e}\right) \tag{3}$$

Equation 3 was derived from Snell's law and a provided equation for a full 90°rotation for the apex angle, α. The apex angle represents the maximum amplitude peak, similar to the Malus's law in figure 3. The two figures 4 and 5 are the two minimums, and the apex angle is where the major amplitude peak lies. The equation includes the constants n_{air}=1.000293 and n_e=1.756. The two minimum angle values, θ_1 and θ_2, were substituted for θ_3.

The two α angles for the first and second birefringence minimums for the sapphire crystal c-axis were 28.07°±0.04°and 27.69°±0.03°, respectively. The weighted average of the two c-axis values is 28.88°±0.04°.

Discussion

More data points should be added to birefringence of the sapphire crystal procedure. For a quadratic fit with three parameters, four or more points are sufficient for plotting with uncertainty as seen in the second minimum.

[1] Web. 16 Dec. 2015. http://www.phys.hawaii.edu/~teb/phys480l/Optics.txt.
[2] Web. 16 Dec. 2015. http://www.phys.hawaii.edu/~teb/Polarization_Hecht.pdf.
[3] Web. 16 Dec. 2015. http://sdo.gsfc.nasa.gov/mission/instruments.php.
[4] Nussbaum, Allen, and Richard A. Phillips. Contemporary Optics for Scientists and Engineers. Englewood Cliffs, N.J.: Prentice-Hall, 1976. Print.