A Simple Apparatus for Optical Polarization Experiments

Kelly Krieble and Joseph L. Powlette, Moravian College, Bethlehem, PA

The phenomenon of polarization is usually covered, although very briefly, in most introductory college and high school physics classes. Experiments such as Malus’s law are often performed with inexpensive linear polarization filters or lenses from polarized sunglasses. Investigations of more complex forms of polarization, using retarders such as quarter-wave plates (QWPs) and half-wave plates (HWPs), are often omitted because the acquisition of equipment necessary for multiple setups can be cost-prohibitive. We present here a simple rotational apparatus for accurate polarization measurements and applications using inexpensive substitutes of QWP and HWP for use with common laser wavelengths.

Background

The impetus for this work developed from a workshop on lasers that we offered to local high school physics teachers in 1999. In that workshop each participant constructed his/her own HeNe laser and used it to perform a number of optics experiments, including those involving polarized light. These polarization experiments utilized a simple but inexpensive apparatus for controlling the angular alignment of the optical components. In addition to performing the standard Malus’s law experiment, participants could also perform experiments to produce and measure circularly polarized light using a QWP, and measure the rotation of the plane of polarization using an HWP. Data from experiments using this apparatus are presented.

Apparatus

A photograph of the apparatus as used in a typical polarization experiment is shown in Fig. 1. The entire system is mounted on an optics bench (the bench we use is produced by PASCO, although any optics bench could be used). White PASCO “Viewing Screens,” modified by drilling a ½-in hole through them to allow the passage of light, act as supports for the various components.

A typical rotational apparatus consists of a CD holder, a CD, a 360° protractor scale, magnetic...
mounts, a small spacer, and a polarizing element (linear, QWP, or HWP, depending on the experiment). A piecewise schematic of the apparatus is shown in Fig. 2. The outer clear plastic shell of a typical CD case (available at retail stores such as Wal-Mart for approximately $1 each) is not used except for storage of the apparatus; however, the CD holder inside the case is used. Several ½-in width magnetic strips are attached to the back of the CD holder so that the apparatus may then be affixed onto the steel PASCO viewing screens. The CD is placed into the holder so that it is free to rotate about the center mount. A 360° angular protractor is scanned and the image attached to the CD using a Memorex CD label maker kit (the file for a scale version of this angular protractor is available on our website). A reference mark made at the top of the holder allows the CD to be oriented such that angular measurements can be made to within ±1°. The polarizer (or other optical element) is mounted on a small ring spacer (washer) and then attached to the front of the CD, allowing for angular positioning and measurement of the polarizer orientation. The transmission axis of the attached polarizer is oriented to align with the 0° mark of the angular scale by using the known transmission axis of a previously calibrated polarizer. The CD holder has an axial opening of approximately ¼-in diameter that allows a beam of light to pass through. In addition, the clear region around the center of the CD is blackened so that extraneous light is not transmitted through the CD. Because the magnetic mounting keeps the apparatus in place and allows the CD with the mounted polarizer to rotate, the entire apparatus acts as a stable, rotatable, optical element. The entire apparatus can be removed from the viewing screen and placed in the plastic cover of the CD holder for storage.

Experiments

Two simple experiments using this apparatus are presented: one for producing and measuring circularly polarized light and the other for measuring the rotation of the plane of polarization of linearly polarized light. A brief discussion of the pertinent aspects of polarization will be presented for each experiment; however, we refer the reader to several excellent articles on the subject for a more in-depth discussion of polarization phenomena.

Polarization and the Optical Elements

Most polarization experiments are performed using commercial-grade quarter-wave plates and half-wave plates. We investigated the feasibility of substituting inexpensive materials for these optical elements. Good results using QWPs and HWPs constructed from multiple layers of ordinary brands of cellophane tape have been reported.

The method of manufacture of these tapes is, in part, responsible for their unusual optical properties. Made up of long polymer chains, the molecules of these tapes tend to align themselves when the material is put under stress, as in the process of producing the thin tape. As a result, this alignment causes the optical properties, most notably the index of refraction, to vary in an anisotropic manner within the tape. This anisotropy results in birefringence, i.e., two perpendicular transmission axes having different indices of refraction. Light polarized along the direction of the smaller index will travel faster than light polarized along the higher index direction. These directions are designated as the fast axis and the slow axis, respectively. A linearly polarized plane wave entering normal to the surface of the tape, with its polarization axis oriented in an arbitrary direction relative to these axes, will have electric field vector components along these axes. These components will be shifted in phase.
relative to each other as they emerge from the tape because the components travel at different speeds through the tape. A phase shift of 90° causes the tape to act as a QWP, while a phase shift of 180° causes the tape to act as an HWP. A wave plate is a QWP or HWP only for a specific wavelength and will exhibit different relative phase shifts for other wavelengths.

A Soleil-Babinet compensator was used to determine the relative phase shift for several commercially available brands of tape. Two different light sources were selected for use because they would be the most common types available to most instructors: a HeNe laser (λ = 633 nm) and a diode laser pointer (λ = 650 nm). Results for these phase shift values are given in Table 1. Of the tapes that were sampled, the Manco brand HP260 carton packing tape was found to be the best QWP and the Walgreen’s brand ¾-in Crystal Clear transparent tape was found to be the best HWP (each in conjunction with the diode laser pointer wavelength.)

### Circularly Polarized Light

Circularly polarized light results from the addition of two orthogonal electric field vectors of equal amplitude (from a coherent source) that differ in phase by 90°. The resultant electric field vector will be constant in magnitude and rotate about the direction of propagation of the light wave. To generate circularly polarized light, linearly polarized light is passed through a QWP, with the fast (or slow) axis of the plate rotated 45° from the transmission axis of the linear polarizer. This procedure will create the required two equal-amplitude components with the necessary 90° relative phase shift.

The experimental arrangement for the circular polarization experiment is shown in Fig. 1. The individual components (polarizers and QWP) are each placed on their own rotation apparatus mount and must be oriented properly before data can be collected. The transmission axis of the first polarizer is aligned with the polarization direction of the diode laser pointer to ensure that the incident light is linearly polarized. A second polarizer (the analyzer) is adjusted with its transmission axis at a right angle to the first, and the light transmitted through the analyzer is detected by a Vernier light sensor interfaced to a computer. A QWP constructed from one layer of HP260 tape attached to a glass microscope slide is inserted between the crossed polarizers and rotated until the output measured by the light sensor is minimized. This orientation of the QWP defines the fast (or slow) axis of the QWP relative to the incident polarization direction because linearly polarized light aligned along either the fast or slow axis emerges unaffected. The QWP is then rotated 45° from this direction. The linearly polarized light incident on the QWP will therefore be oriented at an angle of 45° relative to the fast and slow axes, thus producing electric field components of equal amplitude along each of the axes. In addition, the QWP will create a phase shift of 90° between the fast and slow components of the wave, thereby producing circularly polarized light.

The analyzing polarizer is then adjusted to various angles and intensity measurements made as a function of the rotation angle of the analyzer. The intensity data as a function of analyzing polarizer angle for the HP260 tape is plotted on polar graph paper and

<table>
<thead>
<tr>
<th>Sample Tape</th>
<th>Fractional Wavelength Retardation (633 nm)</th>
<th>Diode Pointer (650 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manco HP260 packing tape</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>Manco Crystal Clear carton sealing tape</td>
<td>no effect</td>
<td>no effect</td>
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<tr>
<td>Manco EZ-Start packing tape</td>
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<tr>
<td>Scotch 3M Tear-by-Hand packing tape</td>
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<td>0.52</td>
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<tr>
<td>Scotch 3M mailing tape</td>
<td>no effect</td>
<td>no effect</td>
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<tr>
<td>Scotch 3M ½-in 600 transparent tape</td>
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<td>not measured</td>
</tr>
<tr>
<td>Scotch 3M ½-in double stick tape</td>
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<td>no effect</td>
</tr>
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<td>Scotch 3M ½-in transparent tape</td>
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</tr>
<tr>
<td>Scotch 3M ¼-in Magic tape</td>
<td>no effect</td>
<td>no effect</td>
</tr>
<tr>
<td>Walgreen’s ¾-in Crystal Clear transparent tape</td>
<td>0.60</td>
<td>0.49</td>
</tr>
<tr>
<td>Walgreen’s ¾-in transparent tape</td>
<td>~1.0</td>
<td>not measured</td>
</tr>
<tr>
<td>Tartan 3690 packing tape</td>
<td>0.55</td>
<td>0.42</td>
</tr>
</tbody>
</table>
shown in Fig. 3. If the transmitted light is circularly polarized, then the output intensity of the light should remain constant as the analyzing polarizer is rotated because the magnitude of the electric field vector (and hence the intensity) remains constant. The resulting plot is circular (constant intensity) to within approximately ±10%.

**Rotation of the Plane of Polarization**

If linearly polarized light is incident on an HWP that is oriented with its fast axis making an angle θ relative to the polarization direction of the incident light, the light will be resolved into components along the fast and slow axes as indicated in Fig. 4(a). Upon emerging from the HWP, there will be a phase shift of 180° between the two components. This phase shift has the effect of flipping one of the components of the resolved field, as in Fig. 4(b). The resulting output polarization direction is therefore rotated by an angle of 2θ relative to the incident polarization direction.

To illustrate the phenomenon of the rotation of the plane of polarization of a linearly polarized wave, an HWP made from Walgreen’s Crystal Clear tape attached to a microscope slide is used as the optical element.6 The setup of the experiment is similar to that for circularly polarized light except that we use a visual determination rather than a light sensor, because the human eye is an excellent detector. In addition, a 12-V halogen bulb, mounted in a PASCO lens holder, is used as the light source instead of the laser diode pointer. While the laser source would produce better results, the use of a white light source allows the student to play a more active role. The wavelength dependence of the HWP is also illustrated by observing the spectral properties of the transmitted light.

For this experiment the minimum intensity of the transmitted light is again determined, however, in a slightly different manner. Since we are using a white light source, a range of wavelengths (polarized by the initial polarizer) are incident on the tape. If the HWP is rotated by an amount θ relative to the initial polarization direction, only the polarization axis of a specific red wavelength (and approximately nearby wavelengths) will be rotated by 2θ. By orienting the ana-
alyzing polarizer 90° from the rotated direction, the red component of the light will be minimized and the complementary color (cyan) will be seen by an observer, resulting in an intensity minimum.

The first polarizer is aligned vertically (although any alignment direction would suffice because there is no preferred polarization direction of the white light source), and the analyzing polarizer is oriented at 90° to the first polarizer to extinguish all transmitted light. The HWP is then placed between the polarizers and its orientation adjusted so that the red transmitted light is at a minimum (the observer looks for cyan transmitted light). The HWP is then rotated through an angle θ_{half} and the analyzing polarizer is adjusted to again observe the cyan transmitted light (minimizing the red light transmitted). The angle θ_{A} through which the analyzing polarizer must be adjusted to produce this minimum is then determined from the rotation apparatus of the analyzing polarizer.

Figure 5 shows a plot of θ_{A} vs. θ_{half} for the Walgreen’s Crystal Clear packing tape as an HWP. The line represents a linear fit of the data and has a slope of 1.95 ± 0.01 (fit equation is also shown).

Conclusion

We have shown that inexpensive and readily available materials can be fashioned into an apparatus that permits experiments with polarized light. Experience with student results, as well as our own measurements using these components, indicates that the essential features of polarized light can be easily demonstrated. Such an apparatus can therefore be usefully incorporated into the introductory physics laboratory to enhance the student’s understanding of optics in general and polarized light in particular.

References

5. The Manco brand tape can be found on several Internet sites (such as http://www.shoplet.com/office/db/g12251.html, listed as item number MCOHP260C), while the Walgreen brand tape can be found at your local Walgreen pharmacy.
6. For this experiment, the Tartan and Scotch tear-by-hand packing tape would also work well.
7. Files indicated in the paper may be downloaded from our departmental website at http://home.moravian.edu/public/phys/. Navigate through the “Events” bullet to the Laser Symposium workshop.

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Kelly Krieble is an assistant professor of physics at Moravian College and received his B.S. from Moravian College, and his M.S. and Ph.D. from Lehigh University. His current research interests include Mossbauer spectroscopy and the hydraulic jump.

Joseph L. Powlette is a professor and chair of the physics department at Moravian College, having taught there for the last 40 years. His current research interests include the magneto-optical Kerr effect in thin films.

Department of Physics and Earth Science, Moravian College, 1200 Main St., Bethlehem, PA 18018; kriebiek@moravian.edu; powlette@cs.moravian.edu