MODELING THE EFFECTS OF CHROMATIC ABERRATIONS IN OPTICAL SYSTEMS

by

Trevor Hall

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Professor José M. Sasián

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*Wyant College of Optical Sciences*
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ABSTRACT

In this thesis, some optical systems that share the common theme of chromatic aberrations are designed using Zemax OpticStudio. The chromatic aberrations of various lens materials that operate in the visible, infrared, and ultraviolet range are first investigated through their chromatic focal shift plots. A telecentric lens system, a telecentric pupil relay lens system, and a telecentric pupil relay lens system are examined to obtain their chromatic aberration information through their chromatic focal shift graphs. The rotational properties of a wedge prism are also studied by observing how the prism mitigates aberration for a tilted object as a function of different parameters such as the f-number of the system. Achromatic wedge pairs are then modeled using the same materials that operate in the visible spectrum as the lens materials that also function in the visible spectrum. The chromatic aberration that results from both the achromatic wedge pair and their respective lens are also compared. Overall, the thesis develops with some interesting examples exhibiting and correcting chromatic aberration.
CHAPTER 1. INTRODUCTION

1.1 Overview of Thesis

The purpose of this thesis is to observe and model chromatic aberration in a variety of optical systems through Zemax OpticStudio.

Chapter 1 presents an overview of the thesis and a discussion of longitudinal chromatic aberration. Much of this thesis implements longitudinal chromatic aberration theory.

In chapter 2, the results of chromatic focal shift plots for a variety of achromatic thin lenses made of various materials are discussed. Section 2.1 explores lens materials that work in the visible spectrum and the findings are organized by the material manufacturer. Section 2.2 covers the substances that operate in the infrared spectrum. Finally, the outcomes for materials that function in the ultraviolet range are explained in section 2.3.

For chapter 3, the chromatic properties for both telecentric and telecentric relay lens systems using off-the-shelf lenses are studied. Section 3.1 discusses creating a telecentric lens system with and without a field flattening lens. Chromatic focal shift graph data employing lenses from manufacturers like Thorlabs and Edmund Optics is also included. In section 3.2, the telecentric lens system with a field flattener is used to find both a telecentric image relay system and a telecentric pupil relay lens system. The same off-the-shelf lenses used to get the chromatic focal shift plot data for each manufacturing group are again utilized.

Chapter 4 explores the influence optical wedge prisms can have on a lens system and the chromatic aberrations of an achromatic wedge pair. Section 4.1 investigates the effects a wedge prism has on turning a beam of light that passes through a lens system. Changing parameters like the f-number of the lens system and the wedge material affect how much the wedge must rotate to center the beam of light are discussed. Section 4.2 examines the amount of primary and secondary dispersion an achromatic wedge system has. The same materials as the visible thin lens materials in section 2.1 are
utilized to acquire the results. The secondary spectrum of the wedge prisms with their respective thin lens systems is also compared.

Chapter 5 concludes the thesis and contains a discussion of future work that could be implemented. Some of this potential future work includes a focus on more advanced optical systems to get more chromatic aberration information for these systems. This future work would also consist of confirming whether the optical designs are accurate by contrasting them with their physically created counterparts in a lab setting.

1.2 Discussion of Longitudinal Chromatic Aberration

When light refracts from a surface, such as from a lens, the light does not necessarily focus at the ideal image plane, due to its wavelength. The law of refraction causes light of shorter wavelengths to bend more easily and reach the optical axis in front of the ideal image plane [1]. Light of longer wavelength has more difficulty bending off the lens, so it reaches the optical axis after the ideal image plane. The distance between the light’s focal plane and the ideal image plane along the optical axis is called longitudinal chromatic aberration [1]. When observing visible light, blue light refracts more readily, while red light takes longer to focus along the optical axis [2]. Green light is typically used as a reference point to compare longitudinal chromatic aberration for both red and blue light. However, there are ways to control where certain wavelengths of light focus by altering the lens radii of curvature and distances between the lenses in the optical system.

In Zemax OpticStudio and other similar lens design software, there are chromatic focal shift plots that visualize the primary and secondary spectra of a lens system. The primary spectrum is the space between the largest and smallest wavelength focus planes. The secondary spectrum is defined as the distance between the reference wavelength light focus plane and either the largest or smallest wavelength focus plane. When the primary spectrum is zero, the system is considered achromatic since it corrects for two wavelengths of light by focusing them at the same location [3]. In a three wavelength
system, an achromatic system focuses the largest and smallest wavelength at the same spot. There is also the case of an apochromatic system where three wavelengths of light focus at a uniform location. With more wavelengths of light added, there are more cases of multiple cases of light focusing at an identical place [3]. However, many common systems are either achromatic or apochromatic.
CHAPTER 2. CHROMATIC FOCAL SHIFT

2.1 Chromatic Focal Shift in the Visible Spectrum

Chromatic focal shift plots are created through Zemax OpticStudio by generating a thin lens with the front surface being made of one glass material and the rear surface being made of a different glass material. Chromatic focal shift plots are a graphical method for visualizing the longitudinal chromatic aberration. The merit function found in OpticStudio is used to optimize the lens and obtain an effective focal length of 100 mm [4]. The axial color difference between the smallest and largest wavelengths are set to zero to acquire an achromatic system [4]. For the case of the visible spectrum, the smallest wavelength is 400 nanometers (nm), while the largest wavelength is 700 nm to encompass the entire visible spectrum.

![Schott Glass Abbe Diagram](image)

Figure 2.1 Schott Glass Abbe Diagram [5]
Considering how many applications of optical systems are conducted in the visible spectrum, the lens materials that operate in the visible will be discussed first. Numerous substances that work in the visible spectrum can be found on the Schott Abbe Diagram, as seen in Figure (2.1). Amongst these materials, the more commonly used substances are found along the Schott curve found in the figure include crown glasses like BK7 and flint glasses like F4 [4]. An example of the lens prescription used for these thin lenses can be found in Figure (A.1) under the appendix. The primary chromatic focal shift results for these common materials are listed in Table (2.1). The substances for their front and back surfaces are swapped since some of the lenses with material combinations like BaF52/BK7 and BK7/PSK57 have very distinct focal shift magnitudes when they are flipped. The chromatic focal shift data are attained by optimizing the thin lens to have an effective focal length of 100 millimeters (mm) and having zero axial color difference between the red and blue waves to create an achromatic lens. The radii of curvature are varied for both sides to acquire the optimized thin lenses. Some examples of chromatic focal shift graphs can be observed in Figures (2.2) and (2.3), with Figure (2.2) having a negative focal shift and Figure (2.3) having a positive focal shift. Many of these focal shift values range from -300 to -200 microns (µm) due to some overlap with the materials used.
Table 2.1 Primary Chromatic Focal Shift Data for Glasses along the Schott Glass Abbe Diagram Curve

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>F4</td>
<td>-233.5353</td>
</tr>
<tr>
<td>F4</td>
<td>BK7</td>
<td>-233.5353</td>
</tr>
<tr>
<td>BK7</td>
<td>BaF52</td>
<td>-242.3343</td>
</tr>
<tr>
<td>BaF52</td>
<td>BK7</td>
<td>-242.2757</td>
</tr>
<tr>
<td>K10</td>
<td>FK54</td>
<td>-61.0861</td>
</tr>
<tr>
<td>FK54</td>
<td>K10</td>
<td>-61.0861</td>
</tr>
<tr>
<td>KzFSN2</td>
<td>FK52</td>
<td>-30.7072</td>
</tr>
<tr>
<td>FK52</td>
<td>KzFSN2</td>
<td>-30.7072</td>
</tr>
<tr>
<td>K10</td>
<td>LF5</td>
<td>-236.4743</td>
</tr>
<tr>
<td>LF5</td>
<td>K10</td>
<td>-236.4743</td>
</tr>
<tr>
<td>K5</td>
<td>F4</td>
<td>-229.4030</td>
</tr>
<tr>
<td>F4</td>
<td>K5</td>
<td>-229.4030</td>
</tr>
<tr>
<td>KF9</td>
<td>SF8</td>
<td>-255.8767</td>
</tr>
<tr>
<td>SF8</td>
<td>KF9</td>
<td>-255.8767</td>
</tr>
<tr>
<td>N-ZK7</td>
<td>SF15</td>
<td>-270.9407</td>
</tr>
<tr>
<td>SF15</td>
<td>N-ZK7</td>
<td>-270.9407</td>
</tr>
<tr>
<td>BK10</td>
<td>SF4</td>
<td>-250.0895</td>
</tr>
<tr>
<td>SF4</td>
<td>BK10</td>
<td>-250.0895</td>
</tr>
<tr>
<td>KF9</td>
<td>SF56A</td>
<td>-285.7224</td>
</tr>
<tr>
<td>SF56A</td>
<td>KF9</td>
<td>-285.7224</td>
</tr>
<tr>
<td>N-PK51</td>
<td>SF11</td>
<td>-198.8813</td>
</tr>
<tr>
<td>SF11</td>
<td>N-PK51</td>
<td>-198.8813</td>
</tr>
<tr>
<td>F2</td>
<td>BK10</td>
<td>-231.4325</td>
</tr>
<tr>
<td>BK10</td>
<td>F2</td>
<td>-231.4325</td>
</tr>
</tbody>
</table>

Figure 2.2 Example of Negative Focal Shift Achromatic System with BK7/BaF52
Somewhat uncommon materials that work in the visible spectrum are included in Tables (2.2) through (2.5) to attain a better representation for visible spectrum materials. Figure (2.4) introduces an example of an apochromatic lens system consisting of FK52 and KZFSN2, to demonstrate how apochromatic lens systems can be made with two materials.

**Table 2.2** Primary Chromatic Focal Shift Data for LaF Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLF1</td>
<td>LaF33</td>
<td>958.8839</td>
</tr>
<tr>
<td>LaF33</td>
<td>LLF1</td>
<td>958.8839</td>
</tr>
<tr>
<td>BK7</td>
<td>LaF33</td>
<td>-191.2605</td>
</tr>
<tr>
<td>LaF33</td>
<td>BK7</td>
<td>-190.5777</td>
</tr>
</tbody>
</table>

**Table 2.3** Primary Chromatic Focal Shift Data for LaK Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaK10</td>
<td>FK51</td>
<td>-66.0058</td>
</tr>
<tr>
<td>FK51</td>
<td>LaK10</td>
<td>-66.0058</td>
</tr>
</tbody>
</table>

**Table 2.4** Primary Chromatic Focal Shift Data for PSK Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>PSK57</td>
<td>453.5097</td>
</tr>
<tr>
<td>PSK57</td>
<td>BK7</td>
<td>1377.2406</td>
</tr>
<tr>
<td>Material 1</td>
<td>Material 2</td>
<td>Primary Chromatic Focal Shift (µm)</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>ULTRAN20</td>
<td>K10</td>
<td>-61.5467</td>
</tr>
<tr>
<td>K10</td>
<td>ULTRAN20</td>
<td>-61.5467</td>
</tr>
<tr>
<td>KZFSN2</td>
<td>ULTRAN20</td>
<td>-36.9457</td>
</tr>
<tr>
<td>ULTRAN20</td>
<td>KZFSN2</td>
<td>-36.9457</td>
</tr>
</tbody>
</table>

Table 2.5 Primary Chromatic Focal Shift Data for ULTRAN Group Glasses

Figure 2.4 Example of Apochromatic System with FK52/KZFSN2

To make the list of chromatic focal shift data more comprehensive, lens materials that function in the visible spectrum are incorporated from every glass catalog found within Zemax OpticStudio. Arton is the first manufacturer covered, as seen in Table (2.6), and then the rest of the manufacturers are discussed in alphabetical order. Tables (2.6) through (2.17) give the primary chromatic focal shift for each set of materials. A fair number of materials in each manufacturing group are obtained to have a statistical representation of the collection, considering the vast number of possible combinations one could make with the number of materials present in each set.

With Arton in particular, the chromatic focal shift plots had an intriguing shape that resembles an apochromat that has been shifted to the right. An example of such a graph can be observed in Figure
(2.5). The values in Table (2.6) have high magnitudes of primary chromatic focal shift compared with other results seen in other tables.

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX4900</td>
<td>F4520</td>
<td>1326.1737</td>
</tr>
<tr>
<td>F4520</td>
<td>DX4900</td>
<td>1326.1737</td>
</tr>
<tr>
<td>D4532</td>
<td>D4531F</td>
<td>-3926.3172</td>
</tr>
<tr>
<td>D4531F</td>
<td>D4532</td>
<td>-3926.3172</td>
</tr>
</tbody>
</table>

**Table 2.6** Primary Chromatic Focal Shift Data for Arton Group Glasses

![Graph of Chromatic Focal Shift](image)

**Figure 2.5** Example of Arton Chromatic Focal Shift with F4520/DX4900

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAF4</td>
<td>BAK2</td>
<td>-229.4108</td>
</tr>
<tr>
<td>BAK2</td>
<td>BAF4</td>
<td>-229.4108</td>
</tr>
<tr>
<td>BASF2</td>
<td>E-BK7</td>
<td>-241.3079</td>
</tr>
<tr>
<td>E-BK7</td>
<td>BASF2</td>
<td>-241.3079</td>
</tr>
<tr>
<td>E-F5</td>
<td>E-FKS5</td>
<td>-227.9946</td>
</tr>
<tr>
<td>E-FKS5</td>
<td>E-F5</td>
<td>-227.9946</td>
</tr>
<tr>
<td>KZFS4</td>
<td>LAF7</td>
<td>-323.9776</td>
</tr>
<tr>
<td>LAF7</td>
<td>KZFS4</td>
<td>-323.9776</td>
</tr>
<tr>
<td>LASF02</td>
<td>P-FK01S</td>
<td>-103.8484</td>
</tr>
<tr>
<td>P-FK01S</td>
<td>LASF02</td>
<td>-103.8484</td>
</tr>
<tr>
<td>PK2</td>
<td>Q-SF65</td>
<td>-278.8107</td>
</tr>
<tr>
<td>Q-SF65</td>
<td>PK2</td>
<td>-278.8107</td>
</tr>
</tbody>
</table>

**Table 2.7** Primary Chromatic Focal Shift Data for Hikari Group Glasses
### Table 2.8 Primary Chromatic Focal Shift Data for Hoya Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCD1B</td>
<td>PCD4</td>
<td>-18.5625</td>
</tr>
<tr>
<td>PCD4</td>
<td>FCD1B</td>
<td>-18.5625</td>
</tr>
<tr>
<td>BSC7</td>
<td>E-C3</td>
<td>-261.9129</td>
</tr>
<tr>
<td>E-C3</td>
<td>BSC7</td>
<td>-261.9129</td>
</tr>
<tr>
<td>BACD14</td>
<td>LAC8</td>
<td>-72.6684</td>
</tr>
<tr>
<td>LAC8</td>
<td>BACD14</td>
<td>-72.6684</td>
</tr>
<tr>
<td>TAC8</td>
<td>FD60</td>
<td>-321.7127</td>
</tr>
<tr>
<td>FD60</td>
<td>TAC8</td>
<td>-321.7127</td>
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<tr>
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<td>FF5</td>
<td>-474.0869</td>
</tr>
<tr>
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<td>-474.0869</td>
</tr>
<tr>
<td>LAF3</td>
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<td>-239.6908</td>
</tr>
<tr>
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<td>TAFD30</td>
<td>-191.9214</td>
</tr>
<tr>
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<td>TAF3</td>
<td>-191.9214</td>
</tr>
<tr>
<td>MP-BACD12</td>
<td>ADF1</td>
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</tr>
<tr>
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<td>MP-BACD12</td>
<td>-92.1000</td>
</tr>
<tr>
<td>ATC1</td>
<td>BAC6</td>
<td>-101.4993</td>
</tr>
<tr>
<td>BAC6</td>
<td>ATC1</td>
<td>-101.4993</td>
</tr>
<tr>
<td>CF4</td>
<td>FD41</td>
<td>-262.6391</td>
</tr>
<tr>
<td>FD41</td>
<td>CF4</td>
<td>-262.6391</td>
</tr>
<tr>
<td>FEL6</td>
<td>NBF2</td>
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</tr>
<tr>
<td>NBF2</td>
<td>FEL6</td>
<td>614.0539</td>
</tr>
</tbody>
</table>

### Table 2.9 Primary Chromatic Focal Shift Data for Kopp Glass Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K9611</td>
<td>K6250</td>
<td>-583.8804</td>
</tr>
<tr>
<td>K6250</td>
<td>K9611</td>
<td>-583.8804</td>
</tr>
<tr>
<td>K4289</td>
<td>K3625</td>
<td>-456.1693</td>
</tr>
<tr>
<td>K3625</td>
<td>K4289</td>
<td>-456.1693</td>
</tr>
</tbody>
</table>

### Table 2.10 Primary Chromatic Focal Shift Data for LightPath Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0550</td>
<td>D-ZK3M</td>
<td>-339.5873</td>
</tr>
<tr>
<td>D-ZK3M</td>
<td>C0550</td>
<td>-339.5873</td>
</tr>
<tr>
<td>ECO550</td>
<td>L-LAL12M</td>
<td>-379.5055</td>
</tr>
<tr>
<td>L-LAL12M</td>
<td>ECO550</td>
<td>-379.5055</td>
</tr>
</tbody>
</table>
Table 2.11 Primary Chromatic Focal Shift Data for Nikon Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7054</td>
<td>NIFS-U</td>
<td>-183.6035</td>
</tr>
<tr>
<td>NIFS-U</td>
<td>7054</td>
<td>-183.6035</td>
</tr>
<tr>
<td>NIFS-A</td>
<td>NICF-V</td>
<td>66.3582</td>
</tr>
<tr>
<td>NICF-V</td>
<td>NIFS-A</td>
<td>66.3582</td>
</tr>
</tbody>
</table>

Table 2.12 Primary Chromatic Focal Shift Data for Ohara Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-LAL7Q</td>
<td>S-NBH58</td>
<td>-254.4458</td>
</tr>
<tr>
<td>S-NBH58</td>
<td>S-LAL7Q</td>
<td>-254.4458</td>
</tr>
<tr>
<td>S-LAL21</td>
<td>S-NPH7</td>
<td>-316.9607</td>
</tr>
<tr>
<td>S-NPH7</td>
<td>S-LAL21</td>
<td>-316.9607</td>
</tr>
<tr>
<td>APL1</td>
<td>BAH10</td>
<td>-196.4719</td>
</tr>
<tr>
<td>BAH10</td>
<td>APL1</td>
<td>-196.4719</td>
</tr>
<tr>
<td>BAH27</td>
<td>BAH10</td>
<td>-284.4900</td>
</tr>
<tr>
<td>BAH10</td>
<td>BAH27</td>
<td>-284.4900</td>
</tr>
<tr>
<td>BSM9</td>
<td>FPL52</td>
<td>-66.6259</td>
</tr>
<tr>
<td>FPL52</td>
<td>BSM9</td>
<td>-66.6259</td>
</tr>
<tr>
<td>L-TIM28</td>
<td>LAH58</td>
<td>-399.6582</td>
</tr>
<tr>
<td>LAH58</td>
<td>L-TIM28</td>
<td>-399.6582</td>
</tr>
<tr>
<td>LAM7</td>
<td>LAL13</td>
<td>-303.0282</td>
</tr>
<tr>
<td>LAL13</td>
<td>LAM7</td>
<td>-303.0282</td>
</tr>
<tr>
<td>NSL3</td>
<td>PBH1</td>
<td>-244.2641</td>
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<td>-244.2641</td>
</tr>
<tr>
<td>PBH53</td>
<td>PBL6</td>
<td>-302.7699</td>
</tr>
<tr>
<td>PBL6</td>
<td>PBH53</td>
<td>-302.7699</td>
</tr>
<tr>
<td>PBM9</td>
<td>PHM52</td>
<td>-191.6429</td>
</tr>
<tr>
<td>PHM52</td>
<td>PBM9</td>
<td>-191.6429</td>
</tr>
<tr>
<td>SSL5</td>
<td>TIH11</td>
<td>-330.9942</td>
</tr>
<tr>
<td>TIH11</td>
<td>SSL5</td>
<td>-330.9942</td>
</tr>
<tr>
<td>TPH55</td>
<td>YGH51</td>
<td>-356.6497</td>
</tr>
<tr>
<td>YGH51</td>
<td>TPH55</td>
<td>-356.6497</td>
</tr>
</tbody>
</table>

While most of the chromatic focal shift plots are for achromats, the combination of N-PK51 and S-BAL35 found in Table (2.13) from Optimax gave another apochromatic system, as shown in Figure (2.6).
<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-PK51</td>
<td>S-BAL35</td>
<td>17.4539</td>
</tr>
<tr>
<td>S-BAL35</td>
<td>N-PK51</td>
<td>17.4539</td>
</tr>
<tr>
<td>S-BSM2</td>
<td>S-FPL51</td>
<td>-62.5939</td>
</tr>
<tr>
<td>S-FPL51</td>
<td>S-BSM2</td>
<td>-62.5939</td>
</tr>
<tr>
<td>S-LAH53</td>
<td>S-LAL8</td>
<td>-254.0946</td>
</tr>
<tr>
<td>S-LAL8</td>
<td>S-LAH53</td>
<td>-254.0946</td>
</tr>
<tr>
<td>S-LAM7</td>
<td>S-NPH2</td>
<td>-469.6673</td>
</tr>
<tr>
<td>S-NPH2</td>
<td>S-LAM7</td>
<td>-469.6673</td>
</tr>
<tr>
<td>S-TIH4</td>
<td>S-TIL6</td>
<td>-277.1737</td>
</tr>
<tr>
<td>S-TIL6</td>
<td>S-TIH4</td>
<td>-277.1737</td>
</tr>
<tr>
<td>S-TIM5</td>
<td>S-TIM28</td>
<td>-300.5050</td>
</tr>
<tr>
<td>S-TIM28</td>
<td>S-TIM5</td>
<td>-300.5050</td>
</tr>
</tbody>
</table>

Table 2.13 Primary Chromatic Focal Shift Data for Optimax Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSC517642C</td>
<td>DBC607567A</td>
<td>-237.8025</td>
</tr>
<tr>
<td>DBC607567A</td>
<td>BSC517642C</td>
<td>-237.8025</td>
</tr>
<tr>
<td>DBC620603B</td>
<td>DEDF728284A</td>
<td>-271.8713</td>
</tr>
<tr>
<td>DEDF728284A</td>
<td>DBC620603B</td>
<td>-271.8713</td>
</tr>
<tr>
<td>EDF673322A</td>
<td>LDF805254A</td>
<td>-434.2291</td>
</tr>
<tr>
<td>LDF805254A</td>
<td>EDF673322A</td>
<td>-434.2291</td>
</tr>
</tbody>
</table>

Table 2.14 Primary Chromatic Focal Shift Data for Pilkington Group Glasses

Figure 2.6 Apochromatic System with N-PK51/S-BAL35
### Table 2.15 Primary Chromatic Focal Shift Data for RPO Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-K59_MOLD</td>
<td>EKPC</td>
<td>1566.0831</td>
</tr>
<tr>
<td>EKPC</td>
<td>D-K59_MOLD</td>
<td>1566.0831</td>
</tr>
<tr>
<td>S-LAL18_MOLD</td>
<td>TAF1_MOLD</td>
<td>-172.7789</td>
</tr>
<tr>
<td>TAF1_MOLD</td>
<td>S-LAL18_MOLD</td>
<td>-172.7789</td>
</tr>
</tbody>
</table>

### Table 2.16 Primary Chromatic Focal Shift Data for Sumita Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-PFK80</td>
<td>K-CD45</td>
<td>-160.3635</td>
</tr>
<tr>
<td>K-CD45</td>
<td>K-PFK80</td>
<td>-160.3635</td>
</tr>
<tr>
<td>K-LAFK50</td>
<td>K-PG375</td>
<td>-122.8195</td>
</tr>
<tr>
<td>K-PG375</td>
<td>K-LAFK50</td>
<td>-122.8195</td>
</tr>
<tr>
<td>K-PSFN3</td>
<td>K-VC90</td>
<td>-431.8743</td>
</tr>
<tr>
<td>K-VC90</td>
<td>N-PSFN3</td>
<td>-431.8743</td>
</tr>
<tr>
<td>K-LASFN17</td>
<td>K-BAF9</td>
<td>-67.9605</td>
</tr>
<tr>
<td>K-BAF9</td>
<td>K-LASFN17</td>
<td>-67.9605</td>
</tr>
<tr>
<td>K-SK18</td>
<td>K-FK5</td>
<td>-191.6798</td>
</tr>
<tr>
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</tr>
<tr>
<td>SFLDN3</td>
<td>LASFN19</td>
<td>-388.6432</td>
</tr>
<tr>
<td>SK2</td>
<td>SSK5</td>
<td>-234.9318</td>
</tr>
<tr>
<td>SSK5</td>
<td>SK2</td>
<td>-234.9318</td>
</tr>
</tbody>
</table>

### Table 2.17 Primary Chromatic Focal Shift Data for Zeon Group Glasses

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330R</td>
<td>F52R</td>
<td>-5154.3111</td>
</tr>
<tr>
<td>F52R</td>
<td>330R</td>
<td>-5154.3111</td>
</tr>
<tr>
<td>K26R_25</td>
<td>ZEONEX_480R_2017</td>
<td>-690.1080</td>
</tr>
<tr>
<td>ZEONEX_480R_2017</td>
<td>K26R_25</td>
<td>-690.1080</td>
</tr>
</tbody>
</table>
2.2 Chromatic Focal Shift in the Infrared Spectrum

There are applications in optics that require the system to function in the infrared spectrum, such as thermal imaging, that require operating with lens materials that perform well in these wavelengths. Since the infrared spectrum consists of a wider range of wavelengths compared to the visible spectrum, lens substances typically are not viable across the entire spectrum. The analysis of these materials is split to those that work in the 1 to 2 µm range in Table (2.18), the 1.5 to 3.5 µm range in Table (2.19), and the 4 to 10 µm range in Table (2.20). Some of these substances span a wider range of wavelengths than others, like AMTIR1 and AMTIR2, range from 1 to 10 µm. However, substances like NICF-U only span from 1 to 2 µm.

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NICF-U</td>
<td>AMTIR1</td>
<td>-395.3591</td>
</tr>
<tr>
<td>AMTIR1</td>
<td>NICF-U</td>
<td>-395.3591</td>
</tr>
<tr>
<td>NICF-U</td>
<td>AMTIR2</td>
<td>-335.9112</td>
</tr>
<tr>
<td>AMTIR2</td>
<td>NICF-U</td>
<td>-335.9112</td>
</tr>
</tbody>
</table>

Table 2.18 Primary Chromatic Focal Shift Data for Infrared Lenses that work in the 1 to 2 µm Range

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-Silica</td>
<td>Silicon</td>
<td>1232.9726</td>
</tr>
<tr>
<td>Silicon</td>
<td>F-Silica</td>
<td>1232.9726</td>
</tr>
<tr>
<td>AgCl</td>
<td>ALN</td>
<td>351.0056</td>
</tr>
<tr>
<td>ALN</td>
<td>AgCl</td>
<td>351.0056</td>
</tr>
<tr>
<td>BaF2</td>
<td>ALN</td>
<td>591.049</td>
</tr>
<tr>
<td>ALN</td>
<td>BAF2</td>
<td>595.448</td>
</tr>
<tr>
<td>BaF2</td>
<td>AgCl</td>
<td>609.7406</td>
</tr>
<tr>
<td>AgCl</td>
<td>BaF2</td>
<td>609.7406</td>
</tr>
<tr>
<td>Silicon</td>
<td>ALN</td>
<td>1780.0712</td>
</tr>
<tr>
<td>ALN</td>
<td>Silicon</td>
<td>1780.0712</td>
</tr>
<tr>
<td>AgCl</td>
<td>Silicon</td>
<td>-599.0300</td>
</tr>
<tr>
<td>Silicon</td>
<td>AgCl</td>
<td>-599.0610</td>
</tr>
<tr>
<td>BaF2</td>
<td>Silicon</td>
<td>-1786.4685</td>
</tr>
<tr>
<td>Silicon</td>
<td>BaF2</td>
<td>-1786.4685</td>
</tr>
<tr>
<td>F-Silica</td>
<td>AgCl</td>
<td>339.9918</td>
</tr>
<tr>
<td>AgCl</td>
<td>F-Silica</td>
<td>339.9918</td>
</tr>
<tr>
<td>F-Silica</td>
<td>ALN</td>
<td>275.3928</td>
</tr>
<tr>
<td>ALN</td>
<td>F-Silica</td>
<td>275.3928</td>
</tr>
<tr>
<td>F-Silica</td>
<td>BaF2</td>
<td>132.8241</td>
</tr>
<tr>
<td>BaF2</td>
<td>F-Silica</td>
<td>132.8241</td>
</tr>
</tbody>
</table>

Table 2.19 Primary Chromatic Focal Shift Data for Infrared Lenses that work in the 1.5 to 3.5 µm Range
Table 2.20 Primary Chromatic Focal Shift Data for Infrared Lenses that work in the 4 to 10 µm Range

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZNS_IR</td>
<td>AMTIR1</td>
<td>150.6892</td>
</tr>
<tr>
<td>AMTIR1</td>
<td>ZNS_IR</td>
<td>150.6892</td>
</tr>
<tr>
<td>ZNS_IR</td>
<td>AMTIR2</td>
<td>215.2648</td>
</tr>
<tr>
<td>AMTIR2</td>
<td>ZNS_IR</td>
<td>215.2648</td>
</tr>
<tr>
<td>ZNS_IR</td>
<td>AMTIR3</td>
<td>198.3915</td>
</tr>
<tr>
<td>AMTIR3</td>
<td>ZNS_IR</td>
<td>198.3915</td>
</tr>
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<td>AMTIR1</td>
<td>AMTIR2</td>
<td>486.9273</td>
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<td>486.9273</td>
</tr>
<tr>
<td>AMTIR1</td>
<td>AMTIR3</td>
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</tr>
<tr>
<td>AMTIR3</td>
<td>AMTIR1</td>
<td>-486.1354</td>
</tr>
<tr>
<td>AMTIR2</td>
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<td>266.9544</td>
</tr>
<tr>
<td>AMTIR3</td>
<td>AMTIR2</td>
<td>266.9544</td>
</tr>
</tbody>
</table>

Examples of infrared positive and negative chromatic focal shift plots are provided in Figures (2.7) and (2.8), respectively.

Figure 2.7 Example of Positive Focal Shift Achromatic System with F-Silica/AGCL
There have been studies that have investigated the chromatic focal shifts of infrared materials \cite{6}. Herman et al use short wavelength infrared substances that range from 0.9 to 1.7 µm and long wavelength infrared materials that spanned from 8 to 12 µm \cite{6}. Despite their optical layouts being more complex, their chromatic focal graph results are close to the ones found in this thesis \cite{6}. However, the magnitudes of their primary chromatic focal shifts are roughly half of the results obtained in this thesis \cite{6}. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{focal_shift.png}
\caption{Example of Negative Focal Shift Achromatic System with BaF2/Silicon}
\end{figure}
2.3 Chromatic Focal Shift in the Ultraviolet Spectrum

Unfortunately, less lens materials work in the ultraviolet region compared with the visible and infrared spectra, despite its use in applications like lithography. The ultraviolet range includes wavelengths that span from 100 nm to 400 nm. Since there are less substances to work with, the chromatic focal shift data collected in Table (2.21) lack variety in contrast with the other two spectra data. As seen by both Table (2.21) and Figure (2.9), all the chromatic focal shift values are positive and either 6422.4185 µm or 1111.3078 µm. The materials selected besides SUPRASIL are very similar to each other in terms of focal shift since they all share the same shift values.

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERASIL</td>
<td>HOMOSIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HOMOSIL</td>
<td>HERASIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HERASIL</td>
<td>HOQ</td>
<td>6422.4185</td>
</tr>
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<td>HOQ</td>
<td>HERASIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HERASIL</td>
<td>INFRASIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>INFRASIL</td>
<td>HERASIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HERASIL</td>
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<td>1111.3078</td>
</tr>
<tr>
<td>SUPRASIL</td>
<td>HERASIL</td>
<td>1111.3078</td>
</tr>
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</tr>
<tr>
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<td>INFRASIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>INFRASIL</td>
<td>HOMOSIL</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HOMOSIL</td>
<td>SUPRASIL</td>
<td>1111.3078</td>
</tr>
<tr>
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<td>HOMOSIL</td>
<td>1111.3078</td>
</tr>
<tr>
<td>HOQ</td>
<td>INFRASIL</td>
<td>6422.4185</td>
</tr>
<tr>
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<td>HOQ</td>
<td>6422.4185</td>
</tr>
<tr>
<td>HOQ</td>
<td>SUPRASIL</td>
<td>1111.3078</td>
</tr>
<tr>
<td>SUPRASIL</td>
<td>HOQ</td>
<td>1111.3078</td>
</tr>
<tr>
<td>INFRASIL</td>
<td>SUPRASIL</td>
<td>1111.3078</td>
</tr>
<tr>
<td>SUPRASIL</td>
<td>INFRASIL</td>
<td>1111.3078</td>
</tr>
</tbody>
</table>

Table 2.21 Primary Chromatic Focal Shift Data for Lenses that work in the Ultraviolet Range
Researchers like Hung et al have implemented fused-silica lenses in a focusing lens system to observe their aberrations through optical path difference fan graphs [7]. Though they did not examine the chromatic focal shift plots, they did optimize their systems to minimize chromatic aberrations when monitoring their results [7].

**Figure 2.9** Example of Positive Focal Shift Achromatic System with Herasil/Suprasil
CHAPTER 3. OFF THE SHELF LENS SYSTEMS

3.1 Telecentric Lens Systems

Off-the-shelf lenses can be useful when one wishes to construct lens systems with less strict specifications to save both time and money since the lenses do not have to be custom-made. In this context, telecentric and telecentric relay lens systems are modeled using off-the-shelf lenses from lens vendors like Edmund Optics and Thorlabs. Going off the line of thinking from *Introduction to Lens Design*, the specifications of an achromatic doublet are first acquired from one of the lens vendors [8]. Three of these achromats are then implemented into the system [8]. The optical system becomes telecentric by varying two distance parameters, the length between the first achromat and the stop along with the space between the first achromat and the second achromat [8]. Zero ray angle at the image is optimized while varying these length parameters to obtain a telecentric system. An example of this telecentric system can be seen in Figure (3.1). A sample lens prescription can be examined in Figure (A.2).

![Figure 3.1 Telecentric System Layout utilizing Achromatic Doublet 45-180 from Edmund Optics](image)

From this optimized setup, aberrations like their secondary spectrum can be observed through their chromatic focal shift plots. An example of a telecentric chromatic focal shift graph can be seen in Figure (3.2). The primary chromatic focal shift values are listed in Table (3.1). All these secondary spectrum values end up being positive despite the achromats coming from different vendors.
Figure 3.2 Chromatic Focal Shift Plot for Telecentric System for Achromatic Doublet L-AOC026 from Ross Optical

<table>
<thead>
<tr>
<th>Lens Vendor</th>
<th>Achromat</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmund Optics</td>
<td>45-180</td>
<td>462.1271</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-350</td>
<td>148.9041</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-353</td>
<td>90.1038</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC034</td>
<td>168.8573</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC049</td>
<td>147.6322</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC073</td>
<td>172.0316</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC026</td>
<td>106.2423</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC103</td>
<td>86.2163</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC155</td>
<td>435.0856</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH018-080</td>
<td>160.6988</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH025-125</td>
<td>234.5973</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH050-100</td>
<td>121.9549</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC127-075</td>
<td>108.1593</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC254-200</td>
<td>240.3884</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC508-250</td>
<td>346.7102</td>
</tr>
</tbody>
</table>

Table 3.1 Primary Chromatic Focal Shift Data for Telecentric Lenses
After constructing this telecentric system, a field flattener lens from the same respective lens vendors is introduced and the system is made telecentric again afterwards. The system becomes telecentric by varying the length between the stop and the first achromat along with the distance between the last achromat and the field flattener to make the ray angle zero. An example of this telecentric system with a field flattener can be examined in Figure (3.3). A sample lens prescription for this system can be viewed in Figure (A.3).

![Telecentric System Layout](image)

**Figure 3.3** Telecentric System Layout using 45-180 and Field Flattener 48-320 from Edmund Optics

An example telecentric system with a field flattener chromatic focal shift plot can be observed in Figure (3.4). The primary chromatic focal shift data for these systems are collected in Table (3.2). The secondary spectrum values are all positive, like the previous telecentric system, even with the field flattener introduced.
Figure 3.4 Chromatic Focal Shift Plot for Telecentric System with Field Flattener for Achromatic Doublet ACH018-080 and Field Flattener PVS057 from Sunex

<table>
<thead>
<tr>
<th>Lens Vendor</th>
<th>Achromat</th>
<th>Field Flattener</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmund Optics</td>
<td>45-180</td>
<td>48-320</td>
<td>506.5270</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-350</td>
<td>48-680</td>
<td>336.3750</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-353</td>
<td>48-271</td>
<td>115.1832</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC034</td>
<td>SPC025</td>
<td>184.9878</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC049</td>
<td>SPC046</td>
<td>180.5440</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC073</td>
<td>SPC028</td>
<td>211.8577</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC026</td>
<td>L-PCC027</td>
<td>137.2070</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC103</td>
<td>L-PCC018</td>
<td>123.5868</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC155</td>
<td>L-PCC031</td>
<td>476.9531</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH018-080</td>
<td>PVS057</td>
<td>192.8437</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH025-125</td>
<td>PVS062</td>
<td>261.7296</td>
</tr>
<tr>
<td>Sunex</td>
<td>ACH050-100</td>
<td>PVS049</td>
<td>151.6271</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC127-075</td>
<td>LC1975</td>
<td>145.1881</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC254-200</td>
<td>LC5289</td>
<td>274.7925</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC508-250</td>
<td>LC5952</td>
<td>373.5580</td>
</tr>
</tbody>
</table>

Table 3.2 Primary Chromatic Focal Shift Data for Telecentric Lenses with Field Flattener
3.2 Image and Pupil Relay Lens Systems

Using the telecentric system found in Figure (3.3), the lens elements of the system can be reversed and optimized for zero ray angle. The system is then made into a double pass while the mirror is removed, and the lens elements are reversed to acquire a telecentric image relay system. An example of an image relay system can be seen in Figure (3.5). A paraxial lens is included at the end of the system to obtain the chromatic focal shift plots since the systems are afocal without the focusing paraxial lens.

For an example lens prescription for this system, please refer to Figure (A.4)

![Image Relay System Layout employing 45-180 and 48-320 Edmund Optics](image)

**Figure 3.5** Image Relay System Layout employing 45-180 and 48-320 Edmund Optics

The secondary spectrum of these image relay systems can be inspected through their chromatic focal shift plots. An example of this chromatic focal shift graph is shown in Figure (3.6). Table (3.3) contains the magnitudes of the chromatic focal shift values.
The telecentric system found in Figure (3.3) becomes a double pass while removing the mirror and reversing the rear lens elements to acquire a telecentric pupil relay system. A paraxial focusing lens is introduced after the pupil relay lens system so the chromatic focal shift of the system can be
determined. An example of a pupil relay system can be observed in Figure (3.7). Figure (A.5) contains a sample lens prescription.

![Figure 3.7 Pupil Relay System Layout using 45-180 and 48-320 from Edmund Optics](image)

The secondary spectrum of these pupil relay systems can be examined through their chromatic focal shift plots. Figure (3.8) contains an example of this chromatic focal shift. The magnitudes of the chromatic focal shift plots can be seen in Table (3.4). While off-the-shelf lenses are good for quick and inexpensive setups, they may not be entirely ideal for every application.

![Figure 3.8 Pupil Relay System Chromatic Focal Shift Plot for Achromatic Doublet PAC049 and Field Flattener SPC046 from Newport](image)
<table>
<thead>
<tr>
<th>Lens Vendor</th>
<th>Achromat</th>
<th>Field Flattener</th>
<th>Primary Chromatic Focal Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmund Optics</td>
<td>45-180</td>
<td>48-320</td>
<td>-27.1818</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-350</td>
<td>48-680</td>
<td>-173.9540</td>
</tr>
<tr>
<td>Edmund Optics</td>
<td>45-353</td>
<td>48-271</td>
<td>-27.8691</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC034</td>
<td>SPC025</td>
<td>-107.8761</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC049</td>
<td>SPC046</td>
<td>-70.2276</td>
</tr>
<tr>
<td>Newport</td>
<td>PAC073</td>
<td>SPC028</td>
<td>-57.5601</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC026</td>
<td>L-PCC027</td>
<td>-109.9630</td>
</tr>
<tr>
<td>Ross Optical</td>
<td>L-AOC103</td>
<td>L-PCC018</td>
<td>-276.5005</td>
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<td>L-PCC031</td>
<td>-25.4085</td>
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<td>ACH025-125</td>
<td>PVS062</td>
<td>-54.8686</td>
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<td>ACH050-100</td>
<td>PVS049</td>
<td>-37.5184</td>
</tr>
<tr>
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<td>AC127-075</td>
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<td>-74.6736</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC254-200</td>
<td>LC5289</td>
<td>-23.0574</td>
</tr>
<tr>
<td>ThorLabs</td>
<td>AC508-250</td>
<td>LC5952</td>
<td>-20.6308</td>
</tr>
</tbody>
</table>

**Table 3.4** Primary Chromatic Focal Shift Data for Telecentric Pupil Relay System

Sun et al. determine that a telecentric relay lens system can be used for their camera system [9]. They correct for their chromatic aberrations by utilizing doublets like the telecentric relay system discussed in this thesis [9]. However, they did not analyze their relay lens system by looking at the chromatic focal shift plot [9]. They instead observe the spot diagram, Modulus Optical Transfer Function (MTF) graph, distortion plot, and relative illumination graph [9].
CHAPTER 4. OPTICAL WEDGE SYSTEMS

4.1 Single Wedge with Monochromatic Light

The concept of how introducing an optical wedge prism affects the angle at which light travels will now be explored. To test how the wedge tilt influences light, the wedge is placed near the image plane in a 4f telecentric system with the object plane tilting at various angles. An example of how the telecentric system is laid out can be seen in Figure (4.1). In that figure, the object is on the left and the light travels through two paraxial thin lenses and the wedge before reaching the image plane. The example lens prescription for this system can be viewed on Figure (A.6).

![Figure 4.1 Layout of an f/2 Telecentric 4f System with 5° tilted Object and P-SF68 Wedge](image)

The object’s tilt, the f-number of the system, and the wedge’s index of refraction are all altered to determine how much the wedge tilts to have a better quantitative understanding of how optical wedges tilt to correct the lens system. The performance of the system’s root-mean-square (RMS) is also quantified to observe how effective the wedge is at remedying the light rays in the optical system. These results can be found in Table (4.1).
Table 4.1 Effects of Changing the F/#, Object Tilt, and Wedge Material on RMS and Wedge Tilt

<table>
<thead>
<tr>
<th>Object Tilt</th>
<th>System F/#</th>
<th>Wedge Material</th>
<th>Wedge Index of Refraction</th>
<th>RMS Performance</th>
<th>Wedge Tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>F/2</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.178825</td>
<td>-2.778°</td>
</tr>
<tr>
<td>1°</td>
<td>F/2</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.170000</td>
<td>-2.205°</td>
</tr>
<tr>
<td>1°</td>
<td>F/2</td>
<td>P-SF68</td>
<td>1.7052</td>
<td>0.732311</td>
<td>-2.232°</td>
</tr>
<tr>
<td>1°</td>
<td>F/4</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.024445</td>
<td>-2.819°</td>
</tr>
<tr>
<td>1°</td>
<td>F/4</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.023042</td>
<td>-2.232°</td>
</tr>
<tr>
<td>1°</td>
<td>F/8</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.003632</td>
<td>-2.819°</td>
</tr>
<tr>
<td>1°</td>
<td>F/8</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.732311</td>
<td>-2.232°</td>
</tr>
<tr>
<td>2°</td>
<td>F/2</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.689580</td>
<td>-5.548°</td>
</tr>
<tr>
<td>2°</td>
<td>F/2</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.618948</td>
<td>-4.430°</td>
</tr>
<tr>
<td>2°</td>
<td>F/2</td>
<td>P-SF68</td>
<td>2.0052</td>
<td>0.501145</td>
<td>-3.816°</td>
</tr>
<tr>
<td>2°</td>
<td>F/4</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.105048</td>
<td>-5.665°</td>
</tr>
<tr>
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<td>F/4</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.092490</td>
<td>-4.507°</td>
</tr>
<tr>
<td>2°</td>
<td>F/4</td>
<td>P-SF68</td>
<td>2.0052</td>
<td>0.089484</td>
<td>-3.874°</td>
</tr>
<tr>
<td>2°</td>
<td>F/8</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.018851</td>
<td>-5.696°</td>
</tr>
<tr>
<td>2°</td>
<td>F/8</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.016233</td>
<td>-3.889°</td>
</tr>
<tr>
<td>2°</td>
<td>F/8</td>
<td>P-SF68</td>
<td>2.0052</td>
<td>0.015685</td>
<td>-3.889°</td>
</tr>
<tr>
<td>5°</td>
<td>F/2</td>
<td>BK7</td>
<td>1.5168</td>
<td>4.208112</td>
<td>-11.682°</td>
</tr>
<tr>
<td>5°</td>
<td>F/2</td>
<td>SF4</td>
<td>1.7552</td>
<td>3.773261</td>
<td>-9.553°</td>
</tr>
<tr>
<td>5°</td>
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<td>P-SF68</td>
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</tr>
<tr>
<td>5°</td>
<td>F/4</td>
<td>BK7</td>
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<td>0.808554</td>
<td>-12.168°</td>
</tr>
<tr>
<td>5°</td>
<td>F/4</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.705730</td>
<td>-9.905°</td>
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<tr>
<td>5°</td>
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<td>P-SF68</td>
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<td>0.672904</td>
<td>-8.569°</td>
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<tr>
<td>5°</td>
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<td>BK7</td>
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<td>14.929166</td>
<td>-17.264°</td>
</tr>
<tr>
<td>5°</td>
<td>F/8</td>
<td>SF4</td>
<td>1.7552</td>
<td>13.890783</td>
<td>-14.415°</td>
</tr>
<tr>
<td>5°</td>
<td>F/8</td>
<td>P-SF68</td>
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<td>13.54464</td>
<td>-12.561°</td>
</tr>
<tr>
<td>10°</td>
<td>F/2</td>
<td>BK7</td>
<td>1.5168</td>
<td>14.929166</td>
<td>-17.264°</td>
</tr>
<tr>
<td>10°</td>
<td>F/2</td>
<td>SF4</td>
<td>1.7552</td>
<td>13.54464</td>
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<tr>
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<td>-14.415°</td>
</tr>
<tr>
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<td>F/4</td>
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<td>1.5168</td>
<td>3.272788</td>
<td>-18.218°</td>
</tr>
<tr>
<td>10°</td>
<td>F/4</td>
<td>SF4</td>
<td>1.7552</td>
<td>2.994882</td>
<td>-15.185°</td>
</tr>
<tr>
<td>10°</td>
<td>F/4</td>
<td>P-SF68</td>
<td>2.0052</td>
<td>2.900599</td>
<td>-13.219°</td>
</tr>
<tr>
<td>10°</td>
<td>F/8</td>
<td>BK7</td>
<td>1.5168</td>
<td>0.774982</td>
<td>-18.500°</td>
</tr>
<tr>
<td>10°</td>
<td>F/8</td>
<td>SF4</td>
<td>1.7552</td>
<td>0.704193</td>
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</tr>
<tr>
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<td>F/8</td>
<td>P-SF68</td>
<td>2.0052</td>
<td>0.680159</td>
<td>-13.412°</td>
</tr>
</tbody>
</table>

From Table (4.1), the wedge tilt magnitude increases overall to accommodate for the rising object tilt. However, the wedge needs to tilt less when the system f-number and index of refraction grow. The wedge must turn in the opposite direction of the object to counteract its rotation and direct the flow of light to the image plane. The increasing f-number implies the stop gets smaller and lets less light into the system. With a reduced amount of light present, the wedge does not have to rotate itself...
as much to direct the light to the image plane. A wedge with a higher index of refraction causes light to refract at a larger angle than a wedge with a lower index of refraction. As a result of this higher index, a wedge does not have to revolve as greatly to direct the light to the image plane.

From Table (4.1), the RMS performance diminishes overall as the system f-number and index of refraction increase. The RMS performance worsens as the object tilt increases. With the f-number escalating, there is a lower amount of light for the wedge to correct the angle for and improve the RMS performance with its decreased value. Since the larger index of refraction wedge does not rotate itself as much, less light strays off that improves the RMS performance. With the object tilting itself more and the wedge having to turn in response, the RMS performance suffers since the likelihood of light straying off from the center of the image plane increases.

To provide a visual of how the RMS Wavefront behaves as a result of the wedge rotating, an RMS Wavefront vs Field plot is included in Figure (4.2). The further out the field rays are from the center of the object, the more RMS wavefront error accumulates.

![Figure 4.2 RMS Wavefront vs Field Plot for f/2 Telecentric 4f System with 5° tilted Object and P-SF68 Wedge](image.png)
Jia et al utilize an optical wedge prism in their modified Mach-Zehnder interferometer system [10]. In their experiment, Jia et al move the wedge prism on a motorized translation stage and record how significantly the wedge turns to match the other arm of the interferometer [10]. Jia et al determined that there is a linear relationship between wedge translation and wedge rotation much like there is a proportional relationship between object rotation and wedge rotation as mentioned in Table (4.1) [10].
4.2 Achromatic Wedge Pair with Visible Light

Since there is a better understanding of how wedges can correct for light rotating from section 4.1, the concept of how a pair of wedges can correct for chromatic aberrations can be introduced. As seen in Figure (4.3), a wedge prism system consisting of two different materials to obtain chromatic aberration data is created. A merit function found in Figure (4.4) is utilized to acquire the real ray angle of incidence for red, green, and blue light. A sample lens prescription for this achromatic wedge pair system may be studied in Figure (A.7). The tilt is varied about the x-axis to optimize the wedge system. The difference between the green and red light incident angles is taken to find the secondary dispersion that the chromatic focal shift plots typically give. The difference between the red and blue incident angles is also provided to confirm that an achromatic system is obtained by having zero primary dispersion. The weight for the incident angles and secondary dispersion are set to zero in the merit function. A wedge that focuses light naturally without optimizing its performance allows for an accurate reading on the secondary spectrum while the primary spectrum is being minimized. This merit function is used rather than studying the chromatic focal shift plots since the graphs did not properly display how the wedges are achromatic, whereas the merit function gives the information needed to prove the system is achromatic.
Employing the merit function, the same list of materials found in chapter 2 are covered to get a comparison between the achromatic thin lens and achromatic wedge system in terms of their secondary spectra. The Schott glass substances compiled in Table (2.1) are first included and the primary and secondary dispersion data for the achromatic wedge are listed in Table (4.2). From the dispersion data, the wedges are optimized to minimize the dispersion with many of the magnitudes being on the order of $10^{-11}$ degrees. The secondary dispersion has a similar result to the findings from Table (2.1) at around $10^{-4}$ degrees. However, much of these values are the opposite sign likely due to how the secondary dispersion is defined compared with how the chromatic focal shift plot displays the secondary spectrum.

The Arton materials found in Table (2.6) are introduced next since its results are more distinct than many of the achromatic thin lenses. From the Arton substances in Table (4.3), the dispersion
continues to be near zero while the value of the secondary spectrum is on the order of magnitude at around $10^3$ just like their thin lens counterparts.

<table>
<thead>
<tr>
<th>Front Wedge</th>
<th>Back Wedge</th>
<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>F4</td>
<td>9.886e-11</td>
<td>4.624e-4</td>
</tr>
<tr>
<td>F4</td>
<td>BK7</td>
<td>6.342e-11</td>
<td>4.931e-4</td>
</tr>
<tr>
<td>BK7</td>
<td>BaF52</td>
<td>1.455e-11</td>
<td>4.639e-4</td>
</tr>
<tr>
<td>BaF52</td>
<td>BK7</td>
<td>2.387e-11</td>
<td>4.927e-4</td>
</tr>
<tr>
<td>K10</td>
<td>FKS4</td>
<td>-3.147e-11</td>
<td>9.745e-5</td>
</tr>
<tr>
<td>KzFSN2</td>
<td>FKS2</td>
<td>-2.926e-11</td>
<td>-1.905e-5</td>
</tr>
<tr>
<td>FKS2</td>
<td>KzFSN2</td>
<td>-2.736e-11</td>
<td>-1.802e-5</td>
</tr>
<tr>
<td>K10</td>
<td>LF5</td>
<td>5.648e-11</td>
<td>4.281e-4</td>
</tr>
<tr>
<td>LF5</td>
<td>K10</td>
<td>5.749e-11</td>
<td>4.515e-4</td>
</tr>
<tr>
<td>K5</td>
<td>F4</td>
<td>5.428e-11</td>
<td>4.221e-4</td>
</tr>
<tr>
<td>F4</td>
<td>K5</td>
<td>5.761e-11</td>
<td>4.484e-4</td>
</tr>
<tr>
<td>KF9</td>
<td>SF8</td>
<td>-5.388e-11</td>
<td>4.181e-4</td>
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<tr>
<td>SF8</td>
<td>KF9</td>
<td>5.978e-11</td>
<td>4.639e-4</td>
</tr>
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<td>N-ZK7</td>
<td>SF15</td>
<td>6.007e-11</td>
<td>4.652e-4</td>
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<td>SF15</td>
<td>N-ZK7</td>
<td>6.771e-11</td>
<td>5.242e-4</td>
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<tr>
<td>BK10</td>
<td>SF4</td>
<td>5.541e-11</td>
<td>4.290e-4</td>
</tr>
<tr>
<td>SF4</td>
<td>BK10</td>
<td>6.502e-11</td>
<td>5.028e-4</td>
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<tr>
<td>KF9</td>
<td>SF56A</td>
<td>9.734e-12</td>
<td>4.291e-4</td>
</tr>
<tr>
<td>SF56A</td>
<td>KF9</td>
<td>1.812e-11</td>
<td>5.029e-4</td>
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<tr>
<td>N-PK51</td>
<td>SF11</td>
<td>1.295e-11</td>
<td>3.077e-4</td>
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<td>N-PK51</td>
<td>1.297e-11</td>
<td>3.593e-4</td>
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<tr>
<td>F2</td>
<td>BK10</td>
<td>9.122e-13</td>
<td>4.877e-4</td>
</tr>
<tr>
<td>BK10</td>
<td>F2</td>
<td>6.013e-12</td>
<td>4.506e-4</td>
</tr>
</tbody>
</table>

**Table 4.2** Primary and Secondary Dispersion for Wedge Materials along the Schott Glass Abbe Diagram Curve

<table>
<thead>
<tr>
<th>Front Wedge</th>
<th>Back Wedge</th>
<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX4900</td>
<td>F4520</td>
<td>-4.914e-11</td>
<td>1.057e-3</td>
</tr>
<tr>
<td>F4520</td>
<td>DX4900</td>
<td>6.972e-11</td>
<td>1.047e-3</td>
</tr>
<tr>
<td>D4532</td>
<td>D4531F</td>
<td>1.772e-10</td>
<td>6.931e-3</td>
</tr>
<tr>
<td>D4531F</td>
<td>D4532</td>
<td>-3.085e-10</td>
<td>-9.968e-3</td>
</tr>
</tbody>
</table>

**Table 4.3** Primary and Secondary Dispersion for Arton Wedge Materials
Table 4.4 Primary and Secondary Dispersion for Materials that Previously gave Apochromatic Plots

The substances previously found to make apochromatic thin lenses are included and their dispersion and secondary dispersion are attained in Table (4.4). The primary dispersion continues to be near zero, while the secondary spectrum matches the magnitude of their respective thin lenses.

Table 4.5 Primary and Secondary Dispersion for Hikari Wedge Materials

The achromatic wedge primary and secondary dispersion of the remaining chapter 2 materials are listed in Tables (4.5) through (4.15). Again, the magnitudes of the primary dispersions are near zero for all the manufacturer materials. The findings of the secondary dispersion for all the manufacturing groups correlate well with their respective thin lens counterpart. However, the sign of secondary dispersion is opposite of the thin lens, likely due to how the secondary dispersion is defined.
<table>
<thead>
<tr>
<th>Front Wedge</th>
<th>Back Wedge</th>
<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCD1B</td>
<td>PCD4</td>
<td>9.929e-11</td>
<td>3.056e-5</td>
</tr>
<tr>
<td>PCD4</td>
<td>FCD1B</td>
<td>2.676e-11</td>
<td>3.300e-5</td>
</tr>
<tr>
<td>BSC7</td>
<td>E-C3</td>
<td>2.988e-11</td>
<td>8.910e-4</td>
</tr>
<tr>
<td>E-C3</td>
<td>BSC7</td>
<td>-2.150e-11</td>
<td>8.918e-4</td>
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<td>BACD14</td>
<td>LAC8</td>
<td>9.134e-12</td>
<td>2.168e-5</td>
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<tr>
<td>LAC8</td>
<td>BACD14</td>
<td>5.240e-11</td>
<td>2.295e-5</td>
</tr>
<tr>
<td>TAC8</td>
<td>FD60</td>
<td>7.061e-11</td>
<td>6.654e-4</td>
</tr>
<tr>
<td>FD60</td>
<td>TAC8</td>
<td>1.346e-11</td>
<td>6.946e-4</td>
</tr>
<tr>
<td>FDS18</td>
<td>FF5</td>
<td>1.401e-12</td>
<td>6.669e-4</td>
</tr>
<tr>
<td>FF5</td>
<td>FDS18</td>
<td>1.401e-11</td>
<td>5.457e-4</td>
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<td>-3.976e-10</td>
<td>3.971e-4</td>
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<td>LAF3</td>
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<td>TAF3</td>
<td>TAFD30</td>
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<td>5.097e-4</td>
</tr>
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<td>TAF3</td>
<td>9.653e-11</td>
<td>5.343e-4</td>
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<td>MP-BACD12</td>
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<td>NBF2</td>
<td>FEL6</td>
<td>1.098e-11</td>
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**Table 4.6 Primary and Secondary Dispersion for Hoya Wedge Materials**

<table>
<thead>
<tr>
<th>Front Wedge</th>
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<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K9611</td>
<td>K6250</td>
<td>-1.967e-10</td>
<td>4.141e-4</td>
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<tr>
<td>K6250</td>
<td>K9611</td>
<td>2.366e-11</td>
<td>3.852e-4</td>
</tr>
<tr>
<td>K4289</td>
<td>K3625</td>
<td>-1.759e-12</td>
<td>1.328e-3</td>
</tr>
<tr>
<td>K3625</td>
<td>K4289</td>
<td>1.968e-10</td>
<td>1.345e-3</td>
</tr>
</tbody>
</table>

**Table 4.7 Primary and Secondary Dispersion for Kopp Glass Wedge Materials**

<table>
<thead>
<tr>
<th>Front Wedge</th>
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<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-ZK3M</td>
<td>C0550</td>
<td>-1.370e-11</td>
<td>6.860e-4</td>
</tr>
<tr>
<td>ECO550</td>
<td>L-LAL12M</td>
<td>-5.418e-14</td>
<td>2.766e-3</td>
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<tr>
<td>L-LAL12M</td>
<td>ECO550</td>
<td>4.697e-10</td>
<td>4.344e-3</td>
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</tbody>
</table>

**Table 4.8 Primary and Secondary Dispersion for LightPath Wedge Materials**
### Table 4.9 Primary and Secondary Dispersion for Nikon Wedge Materials

<table>
<thead>
<tr>
<th>Front Wedge</th>
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<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
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</thead>
<tbody>
<tr>
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<td>7054</td>
<td>1.070e-11</td>
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<tr>
<td>NIFS-A</td>
<td>NICF-V</td>
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<td>-1.974e-4</td>
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<tr>
<td>NICF-V</td>
<td>NIFS-A</td>
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### Table 4.10 Primary and Secondary Dispersion for Ohara Wedge Materials

<table>
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<th>Primary Dispersion (°)</th>
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<tr>
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<td>S-NBH58</td>
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<td>S-NPH7</td>
<td>S-LAL21</td>
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<td>APL1</td>
<td>BAH10</td>
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<td>APL1</td>
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<td>BAH10</td>
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<td>4.777e-4</td>
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<td>4.679e-4</td>
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<td>BSM9</td>
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<td>1.601e-3</td>
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<td>PBH1</td>
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<td>HLS3</td>
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<td>PBM9</td>
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### Table 4.11 Primary and Secondary Dispersion for Optimax Wedge Materials

<table>
<thead>
<tr>
<th>Front Wedge</th>
<th>Back Wedge</th>
<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-BSM2</td>
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</tr>
<tr>
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<td>S-BSM2</td>
<td>8.738e-13</td>
<td>1.004e-4</td>
</tr>
<tr>
<td>S-LAH53</td>
<td>S-LAL8</td>
<td>2.842e-11</td>
<td>5.254e-4</td>
</tr>
<tr>
<td>S-LAL8</td>
<td>S-LAH53</td>
<td>2.782e-11</td>
<td>4.976e-4</td>
</tr>
<tr>
<td>S-LAM7</td>
<td>S-NPH2</td>
<td>-7.871e-12</td>
<td>7.481e-4</td>
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<td>S-LAM7</td>
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<td>8.223e-4</td>
</tr>
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<td>S-TIH4</td>
<td>S-TIL6</td>
<td>6.593e-11</td>
<td>4.940e-4</td>
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<tr>
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### Table 4.12 Primary and Secondary Dispersion for Pilkington Wedge Materials

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<th>Primary Dispersion (°)</th>
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<tbody>
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<td>1.279e-11</td>
<td>5.689e-4</td>
</tr>
<tr>
<td>EDF673322A</td>
<td>LDF805254A</td>
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</table>

### Table 4.13 Primary and Secondary Dispersion for RPO Wedge Materials

<table>
<thead>
<tr>
<th>Front Wedge</th>
<th>Back Wedge</th>
<th>Primary Dispersion (°)</th>
<th>Secondary Dispersion (°)</th>
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</thead>
<tbody>
<tr>
<td>D-K59_MOLD</td>
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<td>1.203e-10</td>
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</table>
Li et al determine how to minimize the deflection angle of an achromatic double Risley prism [11]. They reveal how rotation along the x axis can influence the direction in which rotation occurs along the y axis both experimentally and mathematically through their model [11]. Though Li et al did not observe chromatic focal shift, their analysis of achromatic Risley prisms could apply to an achromatic wedge prism in terms of the deflection angle analysis and obtaining chromatic focal shift plots for Risley prisms.
CHAPTER 5. CONCLUSION & FUTURE WORK

5.1 Conclusion

In chapter 2, the results of chromatic focal shift plots for a variety of materials in an achromatic doublet thin lens in the visible, infrared, and ultraviolet spectra were discussed. Chapter 3 covered the chromatic properties for both telecentric and telecentric relay lens systems using off-the-shelf lenses. Chapter 4 explored the concept of how optical wedge prisms can influence a lens system and how its chromatic aberrations for both a single optical wedge and an achromatic wedge pair is observed.

Optical wedges were included in this discussion since chromatic aberrations can influence the results of other optical devices besides lenses. A better understanding of optical wedges was obtained by examining their chromatic aberrations and rotational properties.

Chromatic aberrations are a prevalent topic within lens design and optical engineering. By being aware of them, one can hopefully correct them to obtain an optimized system. If one cannot, then one should factor in these aberrations when considering the results of the optical system in question. Exploring their effects in a variety of different systems allows for a better grasp of how these chromatic aberrations present themselves in these situations. This study also allows for a better appreciation for chromatic aberrations since it creates significantly more exposure to them than had previously been compiled and studied.

5.2 Future Work

Considering how many optical systems have chromatic aberrations, the analysis could be extended further to these optical systems. For example, the chromatic aberrations of a system that has mirrors implemented in it could be studied. With more optical systems included, further connections between these new systems and the original outcomes could be found to attain a more comprehensive understanding of chromatic aberrations for these optical systems.
The results of these conclusions could be verified by purchasing and physically creating the optical systems implemented in Zemax OpticStudio to compare with the chromatic aberration data. While these results are trusted to be accurate, being able to confirm these conclusions by evaluating them with their respective physical layout would improve the validity of these findings.
APPENDIX

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<th>Material</th>
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<th>Mech Semi-Dia</th>
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**Figure A.1 Example Lens Prescription for a Thin Achromatic Doublet**

The sample thin achromatic doublet lens prescription can be observed in Figure (A.1) where the radii of curvature for both the front and back substances are varied to obtain a 100 mm focal length lens with no axial color.

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<td>6.000</td>
<td>12.500 U</td>
<td>12.500 U</td>
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**Figure A.2 Example Lens Prescription for an off-the-shelf Telecentric Lens System**

A model off-the-shelf telecentric lens prescription can be examined in Figure (A.2) where the achromatic doublet lenses themselves are fixed in radii of curvature and diameter, but the distances change to get a telecentric system.
The example off-the-shelf telecentric lens system with a field flattener lens prescription can be studied in Figure (A.3) where only the distance between the lenses alter to become telecentric.

Figure A.3 Example Lens Prescription for an off-the-shelf Telecentric Lens System with Field Flattener

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<td>19.050</td>
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Figure A.4 Example Lens Prescription for an off-the-shelf Image Relay Telecentric Lens System

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The model off-the-shelf image relay telecentric lens prescription can be viewed in Figure (A.4) where the telecentric system is flipped with the reverse elements function and is mirrored with the pickup function to obtain the image relay lens system. The paraxial thin focusing lens is added at the end of the optical system to attain the chromatic focal shift plots. The focal length for the paraxial focusing lens is set to 15 mm for all the image relay systems since it provides reasonable values for the chromatic focal shift magnitudes while working well with the focal lengths of the rest of the system.

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<td>15000 U</td>
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**Figure A.5 Example Lens Prescription for an off-the-shelf Pupil Relay Telecentric Lens System**

A sample off-the-shelf pupil relay telecentric lens prescription can be observed in Figure (A.5) where the telecentric system is mirrored with the pickup function to obtain the pupil relay lens system with the paraxial thin focusing lens added at the end to acquire the chromatic focal shift plots. The focal length for the paraxial focusing lens is set to 10 mm for all the pupil relay systems since it provided
reasonable results for the chromatic focal shift values while working with the focal lengths of the rest of the system.

Figure A.6 Example Lens Prescription for a Paraxial Lens System with Optical Wedge

An example paraxial lens system with optical wedge lens prescription can be examined in Figure (A.6) where there are the two paraxial lenses with an irregularly shaped stop made from BK7 controls the amount of spherical aberration, astigmatism, and coma in the system to attain the lowest RMS values. The stop also controls the f-number of the system through its diameter. The decenter about Y is the how much the object turns in radians. The wedge follows with its tilt about X under the element tilt being the amount the wedge had to tilt in degrees. The second element tilt represents the other end of the wedge rotating to accommodate for the front end.

Figure A.7 Example Lens Prescription for an Achromatic Wedge Pair

The sample achromatic wedge pair prescription can be seen in Figure (A.7) where the front part of the wedge is fixed while the rear wedge material varies in rotation to get the primary and secondary dispersion values for the visible light that goes through the wedge.
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