Design of Multiband Optics using Updated Athermal/Achromatic Glass Map

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Introduction

- The $\gamma \times \nu$ vs. $\nu$ diagram is a graphical method that describes a technique for effectively achromatizing doublets that are athermal.
  - Where $\gamma$ is the thermal power of a material and $\nu$ is the Abbe number.

- This method has historically been used within one spectral region; however, it does not work well for wider spectral regions.
  - Specifically, Abbe number is a good approximation for the dispersion properties of a material only within one spectral region at a time.

- We propose incorporating *instantaneous Abbe number* and *peak wavelength* (minimum dispersion wavelength) into both the graphical method and other achromatization/athermalization methods.
Why Image Multiple Bands in the Infrared?

- Each infrared region captures unique information and has unique strengths and weaknesses.
- Combining multiple bands allows for better object discrimination and allows more information about a scene to be collected.
- Currently, each band must be imaged through separate optics/apertures, increasing SWaP.
- Furthermore, for finite conjugate applications, parallax between channels can limit performance.

Index of refraction across wide bands

- Near the electronic absorption edge, index of refraction behaves analogously to optical glasses in the visible region with partial dispersions, $P$, less than 0.5
  - I.e. the “bow” of the curve is positive
- Near the vibrational absorption cutoff, partial dispersions are greater than 0.5
  - I.e. the “bow” of the curve is negative
- Dual or wide band designs work across both of these sub-regions, requiring careful consideration of material pairing
Infrared Glass Dispersion

Dispersion curves for a few infrared optical materials are plotted. Notice that dispersion increases approaching both the electronic and vibrational band edges for most materials.
Infrared Glass Dispersion cont.
Thermal Effects on IR Glasses

Thermal power: \( \gamma = \frac{1}{(n_{ref}-1)} \frac{\partial n}{\partial T} - \alpha \)

- \( \frac{\partial n}{\partial T} \) is the change of index with respect to temperature, \( n_{ref} \) is the index of refraction at the reference temperature, and \( \alpha \) is the linear coefficient of thermal expansion.
- The chart below shows thermal powers for some common IR materials.
Athermalization:

- For three elements, the relative power of the elements can be expressed as:

\[
\begin{align*}
\phi_1 &= \frac{\phi_{\text{tot}} v_1 (T_2 v_2 - T_3 v_3)}{D} \\
\phi_2 &= \frac{\phi_{\text{tot}} v_2 (T_3 v_3 - T_1 v_1)}{D} \\
\phi_3 &= \frac{\phi_{\text{tot}} v_3 (T_1 v_1 - T_2 v_2)}{D}
\end{align*}
\]

Where: \[D = v_1 (T_2 v_2 - T_3 v_3) + v_2 (T_3 v_3 - T_1 v_1) + v_3 (T_1 v_1 - T_2 v_2)\]

- Many infrared materials have \(n > 2.5\), which allows the elements to be bent for minimum or zero spherical aberration.
## Listing of a few of the recent NRL glasses

### Material Properties

<table>
<thead>
<tr>
<th>Glass</th>
<th>n</th>
<th>Abbe Number</th>
<th>dn/dT (ppm)</th>
<th>Density (g/cm$^3$)</th>
<th>CTE (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>V(0.9-1.7)</td>
<td>V(3-5)</td>
<td>V(8-12)</td>
<td></td>
</tr>
<tr>
<td>&quot;Old&quot; Materials</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Ge</td>
<td>4.02495</td>
<td>108</td>
<td>785</td>
<td>400.0</td>
<td>5.35</td>
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<tr>
<td>M-ZnS (CLEARTRAN)</td>
<td>2.25223</td>
<td>39</td>
<td>113</td>
<td>23</td>
<td>38.7</td>
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<tr>
<td>ZnSe</td>
<td>2.43316</td>
<td>29</td>
<td>178</td>
<td>57</td>
<td>63.0</td>
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<tr>
<td>BaF2</td>
<td>1.45670</td>
<td>123</td>
<td>45</td>
<td>7</td>
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<tr>
<td>CdTe</td>
<td>2.68831</td>
<td>15</td>
<td>165</td>
<td>156</td>
<td>50.0</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRL Materials</td>
<td></td>
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<tr>
<td>MILTRAN</td>
<td>2.49036</td>
<td>31</td>
<td>93</td>
<td>20</td>
<td>4.50</td>
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<tr>
<td>NRL-1</td>
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<td>23</td>
<td>162</td>
<td>48</td>
<td>-18.0</td>
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<tr>
<td>NRL-2</td>
<td>2.70669</td>
<td>15</td>
<td>175</td>
<td>142</td>
<td>36.5</td>
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<tr>
<td>NRL-3</td>
<td>2.39893</td>
<td>22</td>
<td>160</td>
<td>48</td>
<td>-6.0</td>
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<td>NRL-4</td>
<td>2.64846</td>
<td>16</td>
<td>201</td>
<td>235</td>
<td>-19.2</td>
</tr>
<tr>
<td>NRL-5</td>
<td>2.47755</td>
<td>19</td>
<td>200</td>
<td>127</td>
<td>6.9</td>
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<td>NRL-6</td>
<td>3.17170</td>
<td>-</td>
<td>111</td>
<td>258</td>
<td>164.0</td>
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<tr>
<td>NRL-7</td>
<td>2.38655</td>
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<td>161</td>
<td>47</td>
<td>-7.8</td>
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<td>NRL-8</td>
<td>2.66328</td>
<td>15</td>
<td>189</td>
<td>185</td>
<td>0.3</td>
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<tr>
<td>NRL-9</td>
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<td>162</td>
<td>50</td>
<td>-4.9</td>
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<td>NRL-10</td>
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<td>195</td>
<td>134</td>
<td>21.5</td>
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<td>NRL-11</td>
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<td>164</td>
<td>52</td>
<td>-3.4</td>
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<tr>
<td>NRL-12</td>
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<td>165</td>
<td>56</td>
<td>0.5</td>
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<tr>
<td>NRL-13</td>
<td>2.49002</td>
<td>21</td>
<td>166</td>
<td>60</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Glass maps for the SWIR/MWIR/LWIR

- Glass maps for the SWIR, MWIR, and LWIR show a lack of correlation of dispersion properties between the various wavelength regions
- Abbe number is ill-suited for multi-band material selection

Abbé Number, \[ \nu = \frac{n_{\text{center}} - 1}{n_{\text{short}} - n_{\text{long}}} \]

Defining *Instantaneous Abbe Number* and *Peak Wavelength*

- \( \nu \)-number is a convenient way of simply describing the dispersion within a wavelength band of interest.
- With wide wavelength bands however, \( \nu \)-number and partial dispersion do not sufficiently describe the dispersion characteristics.
- Instantaneous \( \nu \)-number:
  \[
  \nu' = -\frac{1}{2} \frac{n(\lambda)-1}{(dn(\lambda)/d\lambda)}
  \]
- Peak wavelength is defined as the wavelength where: \( \frac{d^2n}{d\lambda^2} = 0 \)
Instantaneous Abbe Number for more IR materials
Example 1: A classic MWIR Athermalized Achromatic Triplet

- Let $\phi_{tot} = 0.01$ (f=100mm)
- Then: 
  \[
  D = \phi_1(T_2v_2 - T_3v_3) + \phi_2(T_3v_3 - T_1v_1) + \phi_3(T_1v_1 - T_2v_2) = 1.484
  \]
  \[
  \phi_{si} = \frac{\phi_{tot} \phi_1(T_2v_2 - T_3v_3)}{D} = 1.675 \phi_{tot}
  \]
  \[
  \phi_{ge} = \frac{\phi_{tot} \phi_2(T_3v_3 - T_1v_1)}{D} = -1.05 \phi_{tot}
  \]
  \[
  \phi_{znS} = \frac{\phi_{tot} \phi_3(T_1v_1 - T_2v_2)}{D} = 0.375 \phi_{tot}
  \]

\[
\begin{align*}
  f_{si} &= 59.7\text{mm} \\
  f_{ge} &= -95.2\text{mm} \\
  f_{znS} &= 267\text{mm}
\end{align*}
\]
Example 1: A classic MWIR Athermalized Achromatic Triplet
Athermal Glass Map: Redefined

Instead of simply plotting v-number versus thermal power, we multiply the thermal and chromatic power for each material (vertical axis) and plot that against its peak wavelength (horizontal axis).
Using the new glass map

- To construct a corrected group of lenses, we first select two glasses that are widely separated in $\gamma \times \nu$, while maintaining the same peak wavelength.
- We then choose a third and/or fourth material that is widely separated in peak wavelength from the first two.
- In order for the solution to be athermalized, all of the glasses must approximately sum to zero along $\gamma \times \nu$ (vertical) axis.
Example 2: IRG23, NRL-4 and ZnS Thin Lens Solution

- NRL-4 and IRG23 provide chromatic correction
- ZnS minimized thermal focal shift
- The powers of each lens are:
  - $\Phi_1 = -0.041 \Phi$
  - $\Phi_2 = -3.25 \Phi$
  - $\Phi_3 = 4.35 \Phi$

Depth of focus is approximately 0.8 mm
Example 3: IRG23, NRL-4, CaFl and ZnS
Thin Lens Solution

- NRL-4 and IRG23 provide chromatic correction
- CaFl and ZnS minimized thermal focal shift
- The powers of each lens are:
  - $\Phi_1 = 1.41 \Phi$
  - $\Phi_2 = -1.26 \Phi$
  - $\Phi_3 = 1.03 \Phi$
  - $\Phi_4 = -0.22 \Phi$

Depth of focus is approximately 0.8 mm
Example continued: Thick Lens Solution

- Thick lens combination: IRG23, NRL-4, CaFl and ZnS
- The powers of each lens are:
  - \( \Phi_1 = 1.45 \Phi \)
  - \( \Phi_2 = -1.25 \Phi \)
  - \( \Phi_3 = 1.02 \Phi \)
  - \( \Phi_4 = -0.21 \Phi \)

Depth of focus is approximately 0.8 mm
Athermal Glass Map: Redefined

- Instead of simply plotting v-number versus thermal power, we multiply the thermal and chromatic power for each material (vertical axis) and plot that against its peak wavelength (horizontal axis)
Example 4: Lens Design using NRL-4, ZnS, Si and CaF2 material pairs with IRG26

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>2-6 µm</td>
</tr>
<tr>
<td>EFL</td>
<td>20 mm</td>
</tr>
<tr>
<td>F/#</td>
<td>3</td>
</tr>
<tr>
<td>FOV</td>
<td>±25°</td>
</tr>
<tr>
<td>MTF @ 40 lp/mm</td>
<td>&gt; 20%</td>
</tr>
<tr>
<td>BWD</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Distance to Cold Stop</td>
<td>25 mm</td>
</tr>
</tbody>
</table>
Example: Chromatic and Thermal Focal Shift

Depth of focus is approximately 0.072 mm
Example: MTF Performance over temperature
Conclusions

- Incorporating *instantaneous Abbe number* and *peak wavelength* into a graphical method for athermalization and achromatization shows promise for extending this and other methods to multi-band design.
- Material combinations have been tested using this method, and the presented example illuminates its potential.
- New NRL chalcogenide materials show promise for supplementing the IR glass map.
Acknowledgements & References

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- Rochester Precision Optics for supporting this work

References:

Thank you for your attention!

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Questions?