Lens Design Tips

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Opti 517
Anatomy of a Lens

- **Outer diameter (OD)**
- **Clear aperture (CA)**
- **Clear aperture (which may go to the annulus)**
- **Annulus or sag flat**
- **Sag**
- **Center thickness (CT)**
- **Edge thickness (ET)**

Usually fine ground. Edge blackening reduces stray light.

Sharp corners ($\leq 90^\circ$) usually chamfered to 0.5 mm face width.
Used Optical Beams and Footprints

Lens diameter does not necessarily define the used footprint for a given field
Lens Geometry: Edge Thickness

- Lenses are usually oversized 1-2 mm during fabrication
  - Chipping may occur at the edges, prompting the oversize margin
  - If too little margin, scratch/dig specifications may be compromised
- On steep radii surfaces, allow for more oversize margin
- In CODE V, the MNE general constraint (minimum edge thickness) in AUTO only constrains the ET over the clear apertures
  - To constrain ET over a larger physical diameter during AUTO, use
    \[ \text{ET} \geq 1.0 \text{ mm} \]

```
ET > 1.0 mm
Oversized for fabrication
```

```
Margin for manufacturing
```

```
Max ray heights
Margin for mounting and coating tooling
```

```
Final ET sized appropriately
```

\[ \text{ET} \geq 1.0 \text{ mm} \]
Lens Geometry: Long Radius

- Long radii are hard to test
  - During use of test plates in production
  - On a radius slide or on an interferometer
- If a radius approaches 20x the outer diameter, make the surface flat
- To constrain this in CODEV, use a user-defined constraint in AUTO
  @ratio_Sj == 0.5*absf((rdy_sj)/(sd_sj))
  DSP ratio_Sj
  @ratio_Sj < 20
Lens Geometry: Aspect Ratio

High aspect ratios risk surface irregularities due to springing after deblocking.

In CODE V, the aspect ratio can be constrained during AUTO with

ATC Sk [MEC [overage_factor [overage_constant]]] \( \geq \) target

ATE Sk [MEC [overage_factor [overage_constant]]] \( \geq \) target

For example, ATC S3 MEC 1.0 1.0 > 3 < 12.5
Lens Geometry: Focal Length

Å Lens centering machines (e.g., from Trioptics) work off beam deviations
Å Long focal length singlets and doublets can lead to measurement errors
Å Simple optimization constraint can save fabrication difficulties with centering
   - $|EFL_{\text{component}}| < 500$ mm to avoid problems
   - In CODE V, use the constraint in AUTO
     \[ \text{EFY } Sj..k < \text{pos\_target} \text{ or EFY } Sj..k > \text{neg\_target} \]
   - You can also use
     \[ @\text{EFLjk} = \text{absf}\left(\text{efy } sj..k\right) \]
     \[ \text{DSP } @\text{EFLjk} \]
     \[ @\text{EFLjk} < \text{target} \]

![Image of Trioptics top with headlens](image1.png)

![Image of V-Chuck and Trioptics bottom](image2.png)
Spherical Aberration as an Assembly Metric

- A well-designed optical system balances every surface's spherical aberration to minimize the sum of the spherical aberration content at the image plane.
- Lateral shear of spherical wavefronts produces coma.
- Coma produces the largest MTF drop to MTF compared to other aberrations.
- Constraining the maximum surface spherical aberration reduces the sensitivity of the surface to decenter and reduces the costs of tolerances and assembly.
Surface Spherical Aberration Theory

Spherical wavefront hits a surface with $W_{040}$ SA

\[ W(\rho) = 2W_{040}\rho^4 \]

\[ W(x, y) = 2W_{040}(x^2 + y^2)^2 \]

**Lateral shear:** differentiate wrt $x$

\[ \frac{\partial W(x, y)}{\partial x} = 2W_{040}(4x^3 + 4xy^2 + y^4) \approx 8W_{040}x^3 \]

\[ \frac{\Delta W}{\Delta x} = 8W_{040}\rho^3 \cos^3 \theta \]

$\Delta x = Decenter Tolerance$

$\Delta W = Wavefront with tolerance \Delta x$

$\Delta W = \Delta x \cdot 8 \cdot W_{040} \cdot Coma$

Reduced surface SA reduces axial coma induced by tilted and decentered elements.
SA Desensitization in Optical Design

Optical Design iteration #1
*without Surface SA constraints*

Minimizing the maximum surface SA "spreads the pain" among all the elements

Optical Design iteration #2
*With Surface SA constraints*
Surface SA Goal Based on F/# and MTF Drop

<table>
<thead>
<tr>
<th>Maximum Surface SA (λ)</th>
<th>Commercial</th>
<th>Diffraction Limited</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(&lt; \frac{215}{F/#^3})</td>
<td>(&lt; \frac{22}{F/#^3})</td>
</tr>
<tr>
<td>Allowed MTF drop due to tolerances (spatial frequency 0.5 of optical cutoff)</td>
<td>-20%</td>
<td>-2%</td>
</tr>
</tbody>
</table>

These are empirically based on measured data for many lens assemblies fabricated at Edmund Optics.

Target the maximum surface SA based on the allowable MTF drop and the system f/number.
Constraining the Maximum Surface SA

To constrain the surface spherical aberration in waves for surface Sk in AUTO, use the following (for dimensions in mm)

```
AUTO
...
^sa_target == 2
^ref == (ref)
^sa_sk == absf((sa_sk)/8/((wl w^ref)/1e6)/2)
dsp ^sa_sk
^sa_sk < ^sa_target
...
```
Optical System Color Correction Regimes

- Refractive optical systems have to color correct for the defocus due to glass dispersion.
- There are many solutions available, primary, achromatic, apochromatic, etc.
- The level of correction and first order optical properties can impose heavy requirements on glass tolerances.

<table>
<thead>
<tr>
<th></th>
<th>Primary Color</th>
<th>Achromatic</th>
<th>Apochromatic</th>
</tr>
</thead>
<tbody>
<tr>
<td># wavelengths for common focus</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Defocus</td>
<td>( \frac{EFL}{V} )</td>
<td>( EFL \frac{\Delta P}{\Delta V} )</td>
<td>Complex</td>
</tr>
<tr>
<td>Relative Defocus</td>
<td>100( \cdot ) Diffraction DoF</td>
<td>8( \cdot ) Diffraction DoF</td>
<td>&lt;0.25( \cdot ) Diffraction DoF</td>
</tr>
<tr>
<td>Component Relative EFL</td>
<td>100</td>
<td>~50</td>
<td>~25</td>
</tr>
<tr>
<td>Relative Surface SA</td>
<td>1</td>
<td>4</td>
<td>17</td>
</tr>
</tbody>
</table>
Achromatic Lens Design

Correcting secondary color requires consideration of a parameter called the partial dispersion.

Partial dispersion is defined for four wavelengths across the spectral band:

\[ P = \frac{(n_{\lambda_1} - n_{\lambda_2})}{(n_{\lambda_3} - n_{\lambda_4})} \]

Correcting secondary color takes special glasses whose partial dispersions are different from "normal" glasses.

- These glasses cost significantly more than "normal" glasses.
- Most glasses follow a "normal" line.

The technique is to find two glasses that have reasonably similar partial dispersions, but have different V values:

- Use these glasses with the standard achromatic equations to solve for the lens powers.

If the V values are too close together, the lens powers will be strong, and the lenses will be "fat."

- This will introduce significant spherochromatism (change in spherical aberration with wavelength) due to the higher angles of incidence.
Partial Dispersion Map

From GlassView™ From OPTICS 1, Inc.

Partial = (n5 - n4) / (n3 - n1)

Schott glasses

Normal line

PSK53
10 X Cost of BK7

FK51
25 X Cost of BK7

FK54
38 X Cost of BK7

PK51A
29 X Cost of BK7

LKSK2
38 X Cost of BK7

KZFSN5
8 X Cost of BK7

LAF10
19 X Cost of BK7

KZFSN4
6 X Cost of BK7

FK52
37 X Cost of BK7

FK53
25 X Cost of BK7

SF2

Abbe Number

Partial dispersion
0.7174
0.7120
0.7066
0.7012
0.6957
0.6903
90.7
76.6
62.6
48.5
34.4
20.4
Reduction of Secondary Color

BK7 vs SF2
SF2 is 1x cost of BK7

PSK53 vs KZFSN4
PSK53 is 10x cost of BK7
KZFSN4 is 6x cost of BK7
Apochromatic Design

Apochromatic lenses (significantly reduced secondary color) can be designed using three different glasses

**Power**

$$\Phi_{\text{total}} = \Phi_1 + \Phi_2 + \Phi_3$$

**Axial Color**

$$\delta \Phi = \frac{\Phi_1}{V_1} + \frac{\Phi_2}{V_2} + \frac{\Phi_3}{V_3} = 0$$

**Secondary Color**

$$\delta \Phi_{\text{sec}} = \frac{\Phi_1 P_1}{V_1} + \frac{\Phi_2 P_2}{V_2} + \frac{\Phi_3 P_3}{V_3} = 0$$

Tij is the slope of the line between glasses i and j

All three lenses will be as weak as possible if glasses are selected with large E1, E2, E3

**Solve For Power**

$$\Phi_1 = -\frac{T_{23}}{E_1} V_1 \cdot \Phi_{\text{total}}$$

$$\Phi_2 = -\frac{T_{31}}{E_2} V_2 \cdot \Phi_{\text{total}}$$

$$\Phi_3 = -\frac{T_{12}}{E_3} V_3 \cdot \Phi_{\text{total}}$$

$$T_{12} = \frac{P_1 - P_2}{V_1 - V_2}$$

$$T_{23} = \frac{P_2 - P_3}{V_2 - V_3}$$

$$T_{31} = \frac{P_3 - P_1}{V_3 - V_1}$$

$$E_1 = -\frac{\Gamma}{V_2 - V_3}$$

$$E_2 = -\frac{\Gamma}{V_3 - V_1}$$

$$E_3 = -\frac{\Gamma}{V_1 - V_2}$$

$$\Gamma = [V_1(P_2 - P_3) + V_2(P_3 - P_1) + V_3(P_1 - P_2)]$$
Apochromatic Design Example

Select:
S-FPL51
S-TIL27
S-NPH2

<table>
<thead>
<tr>
<th>Surface Name</th>
<th>Surface Type</th>
<th>Y Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Refract. Mode</th>
<th>Semi-Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Asphere</td>
<td>20,651,000</td>
<td>11,847,000</td>
<td>FPL51</td>
<td>CHARA</td>
<td>14.000000</td>
</tr>
<tr>
<td>2</td>
<td>-32,197,000</td>
<td>1,123,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-49,716,000</td>
<td>2,000,000</td>
<td></td>
<td>TIL27</td>
<td>CHARA</td>
<td>14.000000</td>
</tr>
<tr>
<td>4</td>
<td>44,198,000</td>
<td>3,028,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>60,474,000</td>
<td>10,394,000</td>
<td></td>
<td>NPH2</td>
<td>CHARA</td>
<td>14.000000</td>
</tr>
<tr>
<td>6</td>
<td>84,714,000</td>
<td>7,049,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gamma = 0.555633
E1 = -0.041226
E2 = 0.012445
E3 = -0.017623
T12 = 0.000434
T13 = 0.001557
T31 = 0.000762
Apochromatic Example Performance

Compare with standard N-BK7 ï F2 doublet
Surface Axial Color

- Optical design tools for material selection have become very adept at locating new solutions for color correction
  - Glass substitution and Hammer in Zemax
  - Glass Expert in Code V
- Unfortunately, solutions can be found which are very sensitive to material dispersion tolerances
  - Commercial dispersion tolerances typically range between 0.8% and 0.5%

<table>
<thead>
<tr>
<th>Schott1</th>
<th></th>
<th>Ohara2</th>
<th></th>
<th>CDGM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>ΔV</td>
<td>Grade</td>
<td>ΔV</td>
<td>Grade</td>
</tr>
<tr>
<td>Step 1</td>
<td>± 0.2%</td>
<td>Standard</td>
<td>± 0.8%</td>
<td>Grade 1</td>
</tr>
<tr>
<td>Step 2</td>
<td>± 0.3%</td>
<td>Request</td>
<td>± 0.3%</td>
<td>Grade 2</td>
</tr>
<tr>
<td>Step 3</td>
<td>± 0.5%</td>
<td></td>
<td></td>
<td>Grade 3</td>
</tr>
</tbody>
</table>

1 Schott North America Inc., “Optical Glass Catalog”, Table 1.2, (2014)

- Surface axial color is proportional to glass tolerances
Sensitivity to Glass Dispersion

Seidel chromatic aberrations of an optical system, \( y = \) marginal ray height, \( V = \) dispersion

\[
C_L = \sum_{n=1}^{\text{# of elements}} \frac{y^2}{V \cdot \text{Focal Length}}
\]

(Axial color or longitudinal chromatic aberration)

Sensitivity found by first derivative with respect to dispersion

\[
\frac{\partial}{\partial V} C_L \approx \frac{\Delta C_L}{\Delta V} = \frac{-C_L}{V}
\]

Tolerance sensitivity scales directly with aberrations

Sensitivity

Abbe Number Tolerance

\[
|\Delta C_L| = C_L \left( \frac{\Delta V}{V} \right)
\]

Reduce surface chromatic aberration! Reduce Tolerance?
Controlling Surface Axial Color

- In CODE V, use a user-defined constraint for each sensitive lens
  - For example,

    AUTO
    ...
    ^LCA_Target == 0.01
    @LCA_E2 == absf((ax s3)+(ax s4))
    @LCA_E2 < ^LCA_TARGET
    ...

- Use third-order coefficients (THO output) to identify sensitive lenses
Sample Design

Å Linescan lens requirement:
  • Polychromatic focus, high resolution
  • Red, green, or blue monochromatic high resolution without refocus
  • Apochromatic solution too costly (elements with short EFL and sensitive to mount)

Å Solution: Achromat with secondary color ~1/2 diffraction-limited DoF

<table>
<thead>
<tr>
<th>Initial Design</th>
<th>Desensitized Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max surface induced axial color</td>
<td>72 waves</td>
</tr>
<tr>
<td>Abbe Tolerance Required</td>
<td>&lt;0.1% (required melt fit)</td>
</tr>
</tbody>
</table>

Reducing surface axial color in half allowed the use of standard grade catalog glasses vs. requiring melt fitting
Passive Athermalization

Due to lenses' CTEs and \( \frac{dn}{dT} \)s and the housing's CTE, optical systems often go out of focus with changes in temperature.

- This is OK if you have a focus adjustment (man-in-the-loop)

For stand-alone systems (no man-in-the-loop), it may be necessary to design the optical system to be passively athermal.

A lens can be represented by its plano-convex equivalent

\[ F = \frac{r}{(n-1)} \]

The thermal derivative of this is

\[
\frac{dF}{dT} = \frac{1}{n-1} \frac{dr}{dT} - \frac{r}{(n-1)^2} \frac{dn}{dT} = \frac{r}{n-1} \left( \frac{1}{r} \frac{dr}{dT} - \frac{1}{n-1} \frac{dn}{dT} \right) = F \left( \alpha - \frac{1}{n-1} \frac{dn}{dT} \right)
\]

The change in focal length is then \( \Delta F = \nu \ F \Delta T \) where

\[ \nu = \alpha - \frac{1}{n-1} \frac{dn}{dT} \]

- \( \nu \) is often referred to as the thermo-optic coefficient
### Values of Optical Materials (x10^6/°C)

<table>
<thead>
<tr>
<th>Å</th>
<th>Visible glasses</th>
<th>Å</th>
<th>Infrared glasses</th>
<th>Å</th>
<th>CTE of common mount materials (x10^6/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Aluminum 6061</td>
</tr>
<tr>
<td></td>
<td>N-BK7</td>
<td></td>
<td>Germanium</td>
<td></td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>-1.5</td>
<td></td>
<td>TI-1173</td>
<td></td>
<td>416 stainless</td>
</tr>
<tr>
<td></td>
<td>BaK4</td>
<td></td>
<td>ZnS</td>
<td></td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>-0.3</td>
<td></td>
<td>ZnSe</td>
<td></td>
<td>Invar36</td>
</tr>
<tr>
<td></td>
<td>BaK50</td>
<td></td>
<td>Silicon</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>11.4</td>
<td></td>
<td>BaF₂</td>
<td></td>
<td>Titanium</td>
</tr>
<tr>
<td></td>
<td>N-SK16</td>
<td></td>
<td>63</td>
<td></td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>-3.4</td>
<td></td>
<td>BaF₂</td>
<td></td>
<td>Beryllium</td>
</tr>
<tr>
<td></td>
<td>SF4</td>
<td></td>
<td>3.8</td>
<td></td>
<td>11.6</td>
</tr>
</tbody>
</table>

It is possible to find combinations of visible glasses to make an athermal design with common mounting materials.

Most common IR materials have negative ν, so it is more difficult to make a passive athermal design.
Example of Temperature Change

- An IR lens is made of germanium for use at 10 μm
- It has a focal length of 4 inches and an aperture of 2 inches (f/2)
- The diffraction-limited depth of focus is $\pm 2\lambda f^2 = \pm 0.0032$ inches
- If we mount the lens in an aluminum mount, the change in focus is $\Delta_{\text{focus}} = 4(-127-23)\times10^{-6}/^\circ\text{C} = -0.0006$ in/$^\circ\text{C}$
- The lens defocus will exceed the diffraction depth of focus over a change in temperature of $\pm 5^\circ\text{C}$
  - Note that for military applications, the specified temperature range is typically $\pm 50^\circ\text{C}$
Passive Athermal Design

To make a lens passively athermal there are two choices:

1. Use a differential mount, using different expansion coefficients to simulate the desired mount CTE (usually negative)
   - This assumes a linear relationship between expansions, $dn/dT$ values, and required motions
   - The limitation of this method is the non-linearity of CTE values and of $dn/dT$ values over large temperature ranges
   - The final design may need to be iterated, due to imprecision or variability in the needed parameters

2. Select the materials for the optics and the lens mounts to make the system optically athermal
Example of a Differential Mount

- We need the second lens to move closer to the first lens with increasing temperature to maintain focus
  - For a simple spacer, this would require a negative spacer CTE
  - Can be done with two different materials with different CTE values

Stainless Steel (low CTE)  Aluminum (high CTE)

With increasing temperature, the lens moves in this direction
Key Concept for Optical Passive Athermalization

Å The inverse of the thermo-optic coefficient is exactly like a $V$-number for color dispersion

- Thermal Abbe number is the inverse of the thermo-optic coefficient $\beta = 1/v$

Å Doublet equations for color correction work for passive athermalization

<table>
<thead>
<tr>
<th>Color:</th>
<th>Thermal in invar housing:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_1 = \Phi_{Total} \frac{V_1}{V_1 - V_2}$</td>
<td>$\Phi_1 = \Phi_{Total} \frac{V_{\text{Thermal},1}}{V_{\text{Thermal},1} - V_{\text{Thermal},2}}$</td>
</tr>
<tr>
<td>$\Phi_2 = \Phi_{Total} \frac{V_2}{V_2 - V_1}$</td>
<td>$\Phi_2 = \Phi_{Total} \frac{V_{\text{Thermal},2}}{V_{\text{Thermal},2} - V_{\text{Thermal},1}}$</td>
</tr>
</tbody>
</table>
Thermal Defocus and Athermalization Equations

<table>
<thead>
<tr>
<th></th>
<th>Doublet</th>
<th>For ( i ) Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total System Power</strong></td>
<td>( \Phi_T = \Phi_1 + \Phi_2 )</td>
<td>( \Phi_T = \sum_i \Phi_i )</td>
</tr>
<tr>
<td><strong>Axial Color</strong></td>
<td>( \frac{\Phi_1}{V_1} + \frac{\Phi_2}{V_2} = 0 )</td>
<td>( \Delta \Phi = \sum_i \frac{\Phi_i}{V_i} = 0 )</td>
</tr>
<tr>
<td><strong>Thermal Defocus</strong></td>
<td>( \beta_1 \Phi_1 + \beta_2 \Phi_2 = 0 )</td>
<td>( \frac{\Delta \Phi}{\Delta T} = \sum_i -\beta_i \Phi_i = 0 )</td>
</tr>
<tr>
<td><strong>Thermal Defocus</strong></td>
<td>( \beta_1 \Phi_1 + \beta_2 \Phi_2 = \alpha_h \Phi_T )</td>
<td>( \frac{\Delta \Phi}{\Delta T} = \alpha_h \Phi_T - \sum_i \beta_i \Phi_i = 0 )</td>
</tr>
</tbody>
</table>

Equations assume thin lenses in contact with each other

\[ \Delta f = \beta f \Delta T \]
\[ \beta = \alpha_{lens} - \frac{1}{n-1} \frac{dn}{dT} \]
\( \beta \) = therm-optic coefficient

\[ \Delta f = f (\beta_{lens} - \alpha_{housing}) \Delta T \]
Athermal Chart – $\beta$ vs. $1/V$

Consider the equation for a line $y = mx + b$ between two points $(x_1,y_1)$ and $(x_2,y_2)$

$$y = \left(\frac{y_2 - y_1}{x_2 - x_1}\right) x + b$$

Solve for the y-intercept

$$b = \frac{y_1 x_2 - y_2 x_1}{x_2 - x_1}$$

If we plot $\beta$ vs. $1/V$, then

$$\alpha_h = \frac{\beta_1 \cdot \frac{1}{V_2} - \beta_2 \cdot \frac{1}{V_1}}{\frac{1}{V_2} - \frac{1}{V_1}}$$

where $\alpha_h$ is the CTE of the housing

Need to find two glasses on a line from the housing material CTE

- Allows two materials to satisfy both color and athermal correction
Example Athermal Design for the Visible

Want thermal defocus and axial color to be less than the $\lambda/4$ depth of focus

$\pm 2 \left( \frac{\text{#}}{\#} \right) = \pm 2 (0.587 \times 2) = 10.2$

Temperature (°C)

Chromatic Focal Shift

Thermal Defocus

(Aluminum housing)

8th Order Aspheres

S-PHM53 & S-LAM66

Geometric Spot Diameter < Airy disk

All wavelengths, all temperatures

Spherical solution only works to F/4
IR Achromatic Examples (8 – 11.5 μm)

- **Common IR achromatic pair**
  - Up to 25% less sensitivity to dispersion tolerances

- **Reduced dn/dT achromatic pair**
  - 3X lower change in focus due to temperature

\[ \begin{align*}
\text{AMTIR 1} & \quad V = 130 \\
\text{dn/dT} & = 72
\end{align*} \]

\[ \begin{align*}
\text{Germanium} & \quad V = 999 \\
\text{dn/dT} & = 400
\end{align*} \]

\[ \begin{align*}
\Delta V & = 869
\end{align*} \]

\[ \begin{align*}
\text{Zinc Selenide} & \quad V = 68 \\
\text{dn/dT} & = 74
\end{align*} \]

\[ \begin{align*}
\Delta V & = 62
\end{align*} \]