Infrared Optical Systems

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Practical Optics Seminar
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Atmospheric Transmittance

- NIR: 0.7 – 2.5 μ
- MWIR: 3.0 – 5.0 μ
- LWIR: 7.5 – 14.0 μ
Blackbody Radiation

- Blackbodies emit per the following equation

\[ W(\lambda) = \frac{c_1}{\lambda^5 \left( e^{c_2/\lambda T} - 1 \right)} \]

\[ c_1 = 2\pi c^2 h = 37418.32 \text{ W}\mu^4\text{cm}^{-2} \]

\[ c_2 = hc/k = 14387.86 \mu\text{K} \]

- The peak of the curve occurs at \( \lambda_{\text{max}} = 2898/T \)
  - Visible (\( T = 5500 \)) \( \lambda_{\text{max}} = 0.53 \mu \)
  - MWIR (\( T = 500 \)) \( \lambda_{\text{max}} = 5.8 \mu \)
  - LWIR (\( T = 300 \)) \( \lambda_{\text{max}} = 9.7 \mu \)

- The choice of spectral band to use depends on the temperature of the object you want to detect
Thermal Contrast

- Terrestrial objects are at about 300 K (~25° C)
  - The human body, for example, has a thermal contrast of about 3 – 8° C
- Thus, a typical IR scene has a contrast of only a few percent (as opposed to visible scenes, which have 100% contrast)
- To maintain the dynamic range in the important part of the image, the background is usually subtracted out
Blackbody Thermal Derivative

- Since the background is subtracted from the IR scene, the sensor really detects the change in temperature, or the thermal derivative $\frac{\partial W}{\partial T}$

$$\frac{\partial W}{\partial T} = \frac{c_1 c_2 e^{c_2/\lambda T}}{\lambda^6 T^2 (e^{c_2/\lambda T} - 1)^2}$$

Peak wavelength is at $\lambda_{max} = \frac{2410}{T}$
IR Detectors

- Two kinds of IR detectors
  - Thermal detectors – sense temperature
  - Photon detectors – sense photon energies
- Thermal detectors have a flat spectral response with wavelength
- Photon detectors have a spectral response proportional to wavelength with a peak wavelength (related to material properties such as band gaps) beyond which there is little or no response
Infrared Detectors

![Graph of RESPONSE OF VARIOUS DETECTOR MATERIALS](image)

- **Si PIN**
  - Blue Enhanced
- **Ge PIN**
- **MWIR HgCdTe**
- **LWIR PV HgCdTe**
- **Vis MWIR InSb**
- **VLWIR PV HgCdTe**
- **Si:As IBC**
- **SWIR HgCdTe**
- **Si:Ga**
- **PtSi**

**Internal Response**

- except where noted

**Wavelength (μm)**

- 0.3μm
- 1μm
- 10μm
- 30μm

**Internal Photon Response**

- 0%
- 10%
- 20%
- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%
- 100%
IR Signal

• The total signal received by the detectors is the product of the target spectral emission, the atmospheric transmittance, the optical transmittance, and the detector spectral response

\[
\text{Signal} = \int E_{\text{target}}(\lambda) \tau_{\text{atmosphere}}(\lambda) \tau_{\text{optics}}(\lambda) R_{\text{detector}}(\lambda) \, d\lambda
\]

• Of course, there’s also the radiometric factors such as target size, solid angles, f/numbers, detector size, etc., which we will not go into here

• We are also ignoring for this seminar the noise contributions such as thermal background, detector noise, electronic noise, etc.
Infrared Glasses vs. Visible Glasses

- IR glasses have significantly higher refractive indices
  - Visible glass – n ranges between 1.45 and 2.0
  - IR glasses – n ranges between 1.38 to 4.0
- Dispersion can be significantly lower (depending on spectral band)
  - Visible glasses – V ranges from 20 to 80
  - IR glasses – V ranges from 20 to 1000
- Many IR glasses are opaque in the visible
  - And most visible glasses are opaque in the IR
- IR glasses are often heavier than visible glasses
- IR glasses have significantly higher dn/dT values (factor of 10 or more higher)
- IR glasses cost more than visible glasses (by 2 or more orders of magnitude)
- Significantly fewer number of practical IR glasses than visible glasses
Visible Glass Map

Description of Symbols:
- N- or P-glass
- Lead-containing glass
- N-glass and lead-containing glass
- Glass suitable for Precision Molding

Crown → Flint

Ver. 4 July 2006
Infrared Glasses

- The list of commonly used IR materials is (unfortunately) pretty short
  - Germanium
  - Silicon
  - Zinc Sulfide
  - AMTIR 1, 3
  - Magnesium Fluoride
  - Sapphire
  - Zinc Selenide
  - Gallium Arsenide
  - Calcium Fluoride

Midwave IR glass map (3 - 5 microns)

Longwave IR glass map (8.5 - 11.5 microns)
Transmittance of IR glasses

Note:
Includes surface reflection losses from uncoated materials

From Bob Fischer
Designing With IR Glasses

- **Advantages 😊**
  - Refractive index is usually higher, so fewer lenses are needed to achieve diffraction-limited performance
  - Dispersion is often low enough such that color correction may not be necessary
  - Most IR materials can be diamond point machined, so aspherics are commonly used in designs
  - The Airy disk size and diffraction-limited depth of focus are larger for the IR than for the visible, so achieving diffraction-limited performance is easier

- **Disadvantages 😞**
  - Small choice of glasses
  - Materials are expensive (~1$/gram)
    - One-inch diameter BK7 lens $5
    - One-inch diameter germanium lens $500
    - Five-inch diameter sapphire dome Priceless
  - Some IR materials are difficult to fabricate and/or antireflection coat
    - Fragile, soft, chip easily, low thermal conductivity, etc.
  - Most IR materials have large dn/dT values, so athermalizing can be difficult
Cautions on IR Glasses and Optics Software

• There is only one source of data on Schott glasses – Schott Optical Glass
• However, there is no "source" of data on IR glasses
• Most optical software programs depend on some literature source of data for IR materials, then fit the data to Sellmeier equations
  – Some programs do a better job of this than others
• Some IR glasses, such as AMTIR, are made by a specific supplier who publishes index data on the material
  – Sometimes these data are not consistent, come from different measurement sources, and may not have sufficient significant digits
  – In these cases, if your design is sensitive to the glass dispersion, you may need to double-check the index data
• Thermal data, such as thermal expansion coefficient and dn/dT data may vary widely for some materials, depending on who measured it
  – Usually, optical software do not include these data, as there is no official "source" for these data
Spherical Aberration vs. Refractive Index

\[ K_{\text{min}} = \frac{n(2n+1)}{2(n+2)} \]

\[ \beta \text{ at } K_{\text{min}} = r^3 \phi^3 \frac{4n^2 - n}{16(n-1)^2(n+2)} \]

For germanium \( n = 4 \)

\[ \beta = \frac{0.0087}{f^3} \]
NBK7 vs. Germanium – Spherical Aberration

**NBK7**

4.0 inch EFL, f/2

**Germanium**

RMS WFE = 14.55

RMS WFE = 0.11
Example - Germanium Singlet

- We want an f/2 germanium singlet to be used at 10 microns (0.01 mm)
- Question - What is the longest focal length we can have and not need aspherics to correct spherical aberration?
- Answer
  - Diffraction Airy disk angular size is $\beta_{\text{diff}} = 2.44 \frac{\lambda}{D}$
  - Spherical aberration angular blur is $\beta_{\text{sa}} = 0.0087 / f^3$
  - Equating these gives $D = 2.44 \frac{\lambda}{f^3} / 0.0087 = 22.4$ mm
  - For f/2, this gives $F = 45$ mm

Strehl = 0.91
NBK7 vs. Germanium – Chromatic Aberration

4.0 inch EFL, f/2

NBK7 ($V_{\text{vis}} = 64.2$)

Germanium ($V_{8-12} = 942$)
Chromatic Aberration Example - Germanium Singlet

- We want to use an f/2 germanium singlet over the 8 to 12 micron band
- Question - What is the longest focal length we can have and not need to color correct? (assume an aspheric to correct any spherical aberration)
- Answer
  - Over the 8-12 micron band, for germanium $V = 942$
  - The longitudinal defocus = $F / V = F / 942$
  - The 1/4 wave depth of focus is $\pm 2\lambda f^2$
  - Equating these and solving gives $F = 4 \times 942 \times \lambda f^2 = 150 \text{ mm}$

![Graph showing Strehl = 0.86](image-url)
Surface Reflection

• Bare glass reflects a portion of the light hitting it
  – The amount reflected depends on the index of the glass, the angle of incidence of the light, and the polarization of the light

\[ R_S = \frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} \]

\[ R_P = \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')} \]

Brewster's angle = \( \tan^{-1}n \)
Single Layer Anti-reflection Coating

• The single layer is the simplest anti-reflection (AR) coating
• Let the incident medium be \( n_0 \) (usually air, so \( n_0 = 1 \)), the index of the coating be \( n_1 \), and the index of the substrate be \( n_2 \)
• The reflectivity of the surface for an incident angle \( \theta \) is

\[
R = \frac{r_1^2 + r_2^2 + 2r_1r_2 \cos X}{1 + r_1^2r_2^2 + 2r_1r_2 \cos X}
\]

where

\[
X = \frac{4\pi n_1t \cos \theta}{\lambda}
\]

– \( R \) is minimized when \( \cos X = -1 \), or when \( n_1t = \lambda/4 \)

• For normal incidence,

\[
r_1 = \frac{n_0 - n_1}{n_0 + n_1} \quad r_2 = \frac{n_1 - n_2}{n_1 + n_2}
\]

Then

\[
R = \left[ \frac{n_0n_2 - n_1^2}{n_0n_2 + n_1^2} \right]^2
\]

minimized when \( n_1 = \sqrt{n_0n_2} \)
• Many IR systems require a cooled detector
  – Typically cooled to 77 K or lower (liquid nitrogen temperatures)
• To avoid frosting up, the detectors are mounted in a thermally insulated vacuum enclosure called a dewar
• Inside the dewar, a cold shield limits the angle of radiation which can be seen by the detector
  – This increases the detector sensitivity (D*)
Cold Shield Efficiency

- All IR systems with cooled detectors have a cold shield in the dewar to minimize the background radiation
  - The size of this cold shield determines the amount of background radiation seen by the detector and hence the system sensitivity

Less than 100% cold shield efficiency (using simple imager)  
100% cold shielding efficiency (using re-imaging imager)
Aperture Stop and Pupil Aberration

- The aperture stop is usually at one of two locations
  - On the front lens
  - At the cold shield
- Whichever one it is located at, it is often imaged onto the other to minimize its size
- Pupil aberration (spherical or coma of the pupil) usually causes the image of the stop to be oversized by about 10-15%
  - If the stop is at the front objective, this requires an enlarged cold shield
    - Result is lower detector sensitivity and lower system performance
  - If the stop is at the cold shield, this requires an oversized objective
    - This increases cost and weight
Singlet Design Examples – f/2, 50 mm EFL (8 – 12 μ)

Germanium singlet (V=942)
RMS WFE = .096

AMTIR-1 singlet (V = 110)
RMS WFE = .209

ZnSe singlet (V = 58)
RMS WFE = .331

ZnS singlet (V = 23)
RMS WFE = .769
Doublet Design Examples – f/2, 50 mm EFL (8 – 12 μ)

Germanium/ZnS
RMS WFE = .065

Germanium/AMTIR-1
RMS WFE = .064

AMTIR-1/ZnS
RMS WFE = .074

ZnSe/ZnS
RMS WFE = .079
Temperature Effects

• An optical element has two properties which cause changes in optical performance with temperature
  – The coefficient of thermal expansion, CTE, usually denoted by $\alpha$ with units of length/length/$^\circ$C
  – The change in refractive index with temperature $dn/dT$
• The change in focal length of a lens with temperature is given by
  $$\Delta F = F \left( \alpha - \frac{1}{n-1} \frac{dn}{dT} \right) \Delta T$$
• Since in most cases the focal length decreases with temperature, the equation is usually stated as $\Delta F = -\nu F \Delta T$ where
  $$\nu = \frac{1}{n-1} \frac{dn}{dT} - \alpha$$
  – $\nu$ is often referred to as the thermo-optic coefficient
• The shift in focus relative to the image plane also includes the CTE of the lens mount, so the shift in focus is given by $\Delta_{\text{focus}} = - (\nu + \alpha_{\text{mount}}) F \Delta T$
### Values of Optical Materials (x10^6/°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>ν Values (x10^6/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visible glasses</strong></td>
<td></td>
</tr>
<tr>
<td>BK7</td>
<td>1.5</td>
</tr>
<tr>
<td>BaK4</td>
<td>0.3</td>
</tr>
<tr>
<td>BaK50</td>
<td>-11.4</td>
</tr>
<tr>
<td>SK16</td>
<td>3.4</td>
</tr>
<tr>
<td>SF4</td>
<td>-3.8</td>
</tr>
<tr>
<td><strong>Infrared glasses</strong></td>
<td></td>
</tr>
<tr>
<td>Germanium</td>
<td>127</td>
</tr>
<tr>
<td>TI-1173</td>
<td>34</td>
</tr>
<tr>
<td>ZnS</td>
<td>28</td>
</tr>
<tr>
<td>ZnSe</td>
<td>35</td>
</tr>
<tr>
<td>Silicon</td>
<td>63</td>
</tr>
<tr>
<td><strong>CTE of common mount materials (x10^6/°C)</strong></td>
<td></td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>23.4</td>
</tr>
<tr>
<td>416 stainless</td>
<td>9.9</td>
</tr>
<tr>
<td>Invar35</td>
<td>0.6</td>
</tr>
<tr>
<td>Titanium</td>
<td>8.7</td>
</tr>
<tr>
<td>Beryllium</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 positive 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 microns
• 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 operating temperature range is typically $\pm 50^\circ\text{C}$
Making an Athermal Doublet

- To satisfy achromatism, the two lenses of a doublet must satisfy the usual achromatic equations:
  \[ f_a = f \left( \frac{V_a - V_b}{V_a} \right) \]
  \[ f_b = f \left( \frac{V_b - V_a}{V_b} \right) \]

- To be athermalized, the lenses must also satisfy:
  \[ V_a \nu_a = V_b \nu_b \]
**IR Achromatic Doublet Examples (8 - 11.5 microns)**

- **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

Germanium
- \( V = 999 \)
- \( \frac{dn}{dT} = 400 \)
- \( \Delta V = 869 \)

Zinc Selenide
- \( V = 68 \)
- \( \frac{dn}{dT} = 74 \)
- \( \Delta V = 62 \)

AMTIR 1
- \( V = 130 \)
- \( \frac{dn}{dT} = 72 \)

8 inch EPD f/2
Infrared Optics Suppliers

- Elcan Optical Systems, Richardson, TX
- Corning NetOptix, Keene, NH
- Exotic Electro-Optics, Marietta, CA
- Optimum Optical Systems, Camarillo, CA
- II-VI Incorporated, Saxonburg, PA
- Janos Technology, Keene, NH
- DRS Optronics, Palm Bay, FL
- Coherent, Auburn, CA
- Diversified Optical Products, Salem, NH
- Telic OSTI, North Billerica, MA
References

- Handbook of Military Infrared Technology, William Wolfe, Office of Naval Research (1965)
- The Infrared Handbook, Wolfe and Zissis, Office of Naval Research (1978)