Synopsis of Choosing a Material for Use in the Infrared

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Overview

This report summarizes a November 2010 article in the trade magazine Photonics Spectra, “Choosing a Material for Use in the Infrared” by David Heinz. Heinz’s article prominently features Edmund Optics products, but the article retains a broader appeal both because it approaches IR lens selection by a combination of optical, thermal and mechanical (OTM) analysis and because it provides convenient tabular summaries of many properties of interest for 12 common IR lens materials. However, the article’s treatment of the subject of OTM design is uneven, with the optical section by far the strongest. Heinz’s thermal section is significantly weakened by his omission of the effect of changes in the index of refraction with temperature on an IR design, and his mechanical section is also somewhat cursory. I also felt that a more in-depth discussion of the basic physics underlying IR emission would be helpful to an IR designer, so I added a brief discussion of these topics in the first section of my synopsis, Basic physics driving IR design.

Basic physics driving IR design

David Heinz begins by identifying IR radiation as light with wavelengths between .78 and 1000 microns. He then presents the atmospheric transmission data shown in Figure 1, and uses this to argue that terrestrial optical systems must utilize discrete atmospheric transmission bands. Examination of Figure 1 shows that absorption makes wavelengths near 6 and 15 microns completely unusable for most applications. Most of this absorption is attributable to either water vapor (Figure 2) or CO_2; note that water vapor absorption combines with the large relative decrease in blackbody emission from cool sources (see Equation 1) to make long-wavelength terrestrial systems highly problematic. So, the vast majority of IR designs are designed for shorter wavelengths; two of the best-known market segments are surveillance systems optimized to detect a human body (λ_{peak}~9µm—see Equation 2) and military/industrial systems designed to monitor very hot processes ((λ_{peak}~2-5µm, see Equation 2).

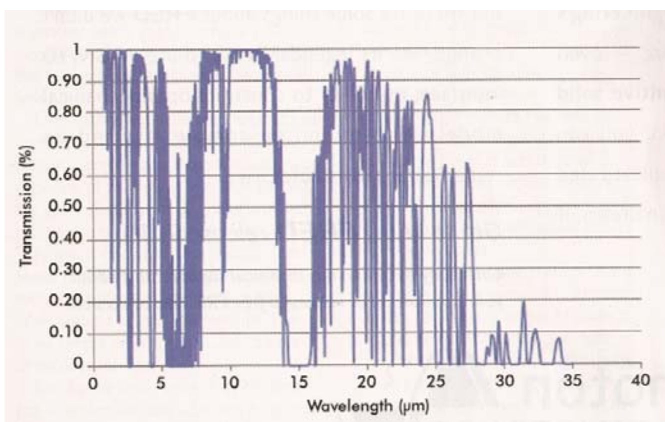

Figure 1: Atmospheric transmission spectrum made using the program IRTRANS4 to process data obtained by UKIRT (UK Infrared Telescope); figure reproduced from Reference 2.

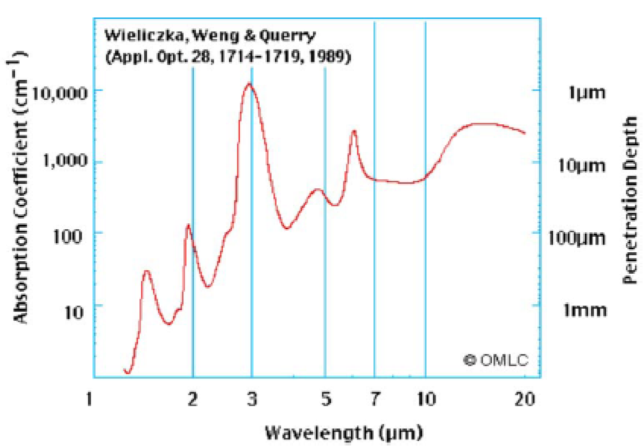

Figure 2: Absorption spectrum of water to 20 microns from Reference 3.

$$P_{total} = 5.67E^{-8} \frac{W}{m^2 - K^4} * T^4$$

Equation 1: Stefan-Boltzmann law giving the dependence of total blackbody excitance on temperature (Reference 4). Combining Equation 1 and Equation 2 shows that a blackbody with a peak emission wavelength of 5 microns (T ~ 300 C) is 256 times more powerful than a blackbody with a peak emission wavelength of 20 microns (T ~ -130 C).

$$\lambda_{peak} = \frac{2898\mu m - °K}{T} = \begin{cases} 9.4\ \mu m \text{ for } 37°\text{C Human Body} \\ 2.3\ \mu m \text{ for } 1000°\text{ C Industrial Process} \end{cases}$$

Equation 2: Wien's law and λ_{peak} for a human body and for a 1000° C industrial process

Optical properties

Heinz next discusses the optical properties he considers most important in an IR lens material

1. Transmission range
2. Refractive index (n)
3. Dispersion
4. Birefringence
5. Cost

Heinz does not provide an in-depth discussion of any of these parameters but does provides a helpful table of refractive index, transmission range and relative cost for 12 common materials (see

Table 1). Because transmission varies with wavelength, Heinz strongly recommends consulting measured transmission curves for candidate materials. These curves can be difficult to find, so Heinz recommends requesting this data from vendors. Figure 3 shows transmission curves for various IR lens materials from .2 to 30 μm; as an example of the importance of utilizing curves rather than relying on a constant transmission value, note the huge, non-monotonic changes in transmission with wavelength for Zinc Sulfide between .4 and 12 μm (dark blue dotted curve).

Table 1: Optical properties for some common IR materials from Reference 2

	Index of Refraction (Approximately)	Transmission Range [μm]	Relative Cost of Stock 25-mm-Diameter Window
Sodium Chloride	1.20 to 1.85	0.17 to 18	1
Germanium	4.05	1.8 to 23	4.7
Sapphire	1.80	0.17 to 6.5	1.9
Zinc Sulfide	2.40	0.4 to 12	5.6
Zinc Selenide	2.20	3.00 to 12	6.6
Calcium Fluoride	1.40	0.13 to 12	2.8
Magnesium Fluoride	1.38	0.11 to 7.5	5.6
Thallium Bromoiodide	2.20 to 2.40	0.5 to 40	–
Silicon	2.50	1.2 to 7	3.6
Diamond	2.30	0.25 to 4 and >7	171.0
Potassium Chloride	1.20 to 1.80	0.21 to 30	1.3
AMTIR-1	2.50	0.70 to 12+	–

Similarly, given the typical sensitivity of optical designs to refractive index, I recommend obtaining index measurement data from the actual vendor for candidate lens materials prior to making a material choice. Heinz notes that one advantage IR designs can leverage is that the typically higher index of refraction of IR materials compared to visible materials allows better correction of 3rd or higher order aberrations. However, IR materials are also often crystalline rather than amorphous like glass, and so Heinz cautions that birefringence is much more of a consideration in IR design than it is for visual systems.

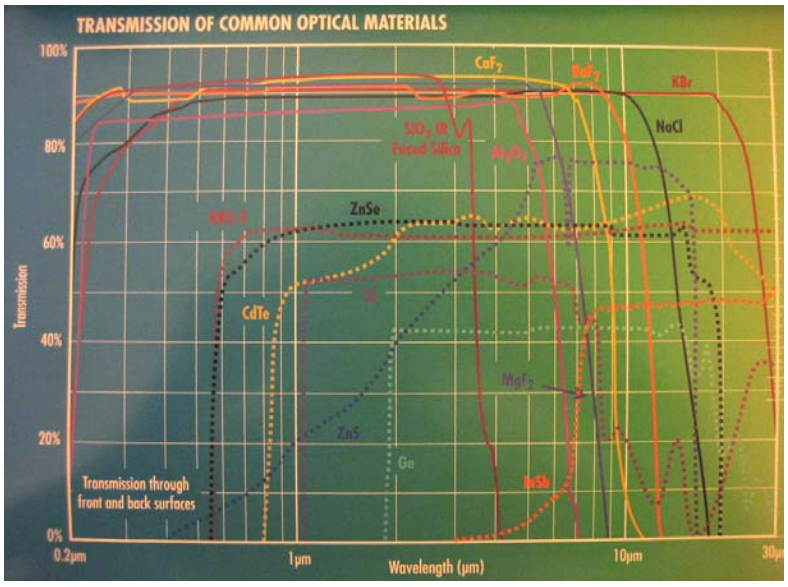

Figure 3: Transmission curves for some common IR materials from Reference 5

Thermal Properties

Heinz begins his discussion of thermal properties by noting that typical IR materials absorb an appreciable fraction of the incident light in the wavelength ranges of interest (see Figure 3), and will thus heat up under standard operating conditions to a greater extent than a typical visible wavelength glass would do. Thus the response to changes in temperature is typically a more important consideration for an IR material than for visible wavelength counterparts. Heinz lists the following 5 thermal properties as the most important in choosing an IR material:

1. Specific heat (the ratio of the material's specific heat capacity to that of water)
2. Thermal expansion coefficient or CTE
3. Melting point
4. Thermal conductivity λ
5. Thermal stability

To this list, I would add the change in material index of refraction with temperature, dn/dt, as this has a linear relationship with change in lens focal length with temperature (Reference 1).

Heinz provides a nice table summarizing 4 of his key thermal properties for the 12 IR materials introduced in the Optical Properties section (see Table 2). Heinz pays particular attention to the anisotropic thermal properties seen in crystalline materias, e.g. thermal conductivity and CTE of sapphire varies according to the direction of heat application relative to the crystal face. Heinz also briefly explains why each property is important to an IR design; for example he notes that CTE quantifies dimensional change with temperature. However, Heinz does not make explicit the relationship between focal length and the temperature-induced dimensional change nor does he even mention the importance of dn/dt to focal length. Thus, I find his treatment to be incomplete. Instead, he concludes his thermal discussion by mentioning robustness to thermal shock and melting point. Melting points are available in a variety of references besides Heinz's article, but data on resistance to thermal shock is less common. I was disappointed that Heinz did not describe what sources one might consult to determine thermal shock resistance or provide any discussion of how a designer might approach estimating this property for a given material.

Table 2: Thermal properties of common IR materials from Reference 2

	Specific Heat	Thermal Expansion [1/K]	Melting Point [K]	Thermal Conductivity [W/(m·K)]
Sodium Chloride	0.20	40×10^{-6}	1070	6.5
Germanium	0.074	6.1×10^{-6}	1210	59
Sapphire	0.18	5.6×10^{-6} (parallel) 5×10^{-6} (perpendicular)	2300	35.1 (parallel) 33.0 (perpendicular)
Zinc Sulfide	0.124	6.5×10^{-6}	2100	27
Zinc Selenide	0.0090	7×10^{-6}	1790	19
Calcium Fluoride	0.204	18.9×10^{-6}	1630	10
Magnesium Fluoride	0.24	14×10^{-6} (parallel) 8.8×10^{-6} (perpendicular)	1528	21
Thallium Bromoiodide	–	58×10^{-6}	687	0.544
Silicon	0.18	2.6×10^{-6}	1690	163
Diamond	0.124	0.8×10^{-6}	3770	2600
Potassium Chloride	0.162	36.6×10^{-6}	1050	6.7
AMTIR-1	0.07	12×10^{-6}	–	0.25

Mechanical Properties

Heinz concludes his paper by noting that for materials with similar optical and thermal properties, mechanical properties may provide a decision point. To Heinz, the most important mechanical properties are

1. Density
2. Hardness
3. Young's Modulus

Again, Heinz provides a nice table summarizing these properties for his 12 materials (Table 3).

Table 3: Mechanical properties of common IR materials from Reference 2

	Density [g/cm³]	Hardness (Knoop Number)	Young's Modulus [GPa]
Sodium Chloride	2.165	15.2	39.96
Germanium	5.35	800	102.66
Sapphire	3.98	1370	344.5
Zinc Sulfide	4.09	160	87.6
Zinc Selenide	5.42	137	70.97
Calcium Fluoride	3.18	160 to 178	75.79
Magnesium Fluoride	3.18	415	–
Thallium Bromoiodide	7.37	40.2	15.85
Silicon	2.33	1100	130.91
Diamond	3.51	5700 to 10,400	1050
Potassium Chloride	1.984	7.2	29.63
AMTIR-1	4.4	170	22

Heinz defines each quantity adequately, but does not discuss why these are key metrics or how to use them to address questions of obvious importance like "under what stress will this material break". Thus I found his mechanical section disappointing. To rectify the weakness in this section, Heinz would need at minimum to include yield and ultimate stress in Table 3, and give a reasonably in-depth discussion of how to use the mechanical metrics he provides when assessing an IR lens material.

References

Reference 1. Opti521 Lecture Notes

Reference 2. Choosing a material for use in the Infrared, David Heinz, Photonics Spectra, November 2010, pp. 32-35

Reference 3. http://people.seas.harvard.edu/~jones/es151/gallery/images/absorp_water.html

Reference 4. Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles, 2nd Edition, Robert Eisberg and Robert Resnick, 1974, John Wiley and Sons

Reference 5. Infrared Wall Chart, Raytheon Vision Systems, Goleta, CA, 2003