Optomechanical Properties of Infrared Materials

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1 Abstract

When designing an optical system, one needs to know what waveband to design for and what materials can be used in this spectral range. This report will be focusing on the infrared spectrum which as we will see, the range of materials is much more limited when comparing what is available for the visible spectrum. Optical and mechanical properties of some popular materials used in infrared designs will be supplied as well as some discussion as to what it all means.

2 Introduction

For this report the infrared waveband of interest is the infrared, its important to define what this range actually is. Two ranges typically used in optical designs are the 3 - 5µm range or 'mid-wave IR" (MWIR) and the 7.5 - 14 µm range or 'long-wave IR' (LWIR). Figure 1 shows where these ranges exist in the electromagnetic spectrum.

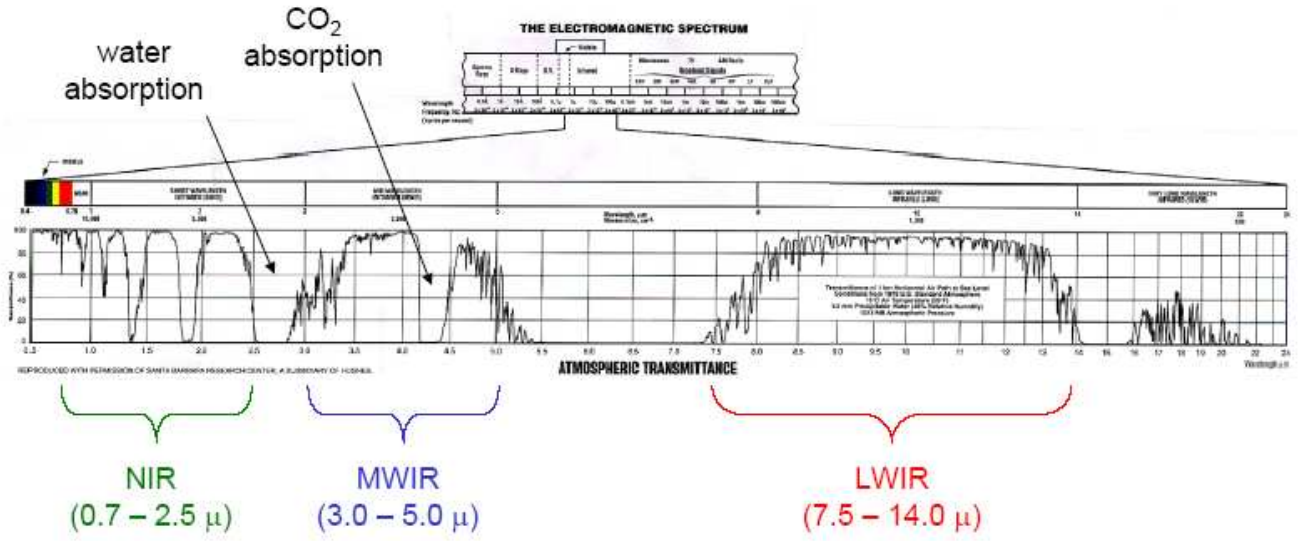

Figure 1: Atmospheric transmittance of the electromagnetic spectrum

For this report, the MWIR will be the 3 – 5µm range and the LWIR the 8 – 12µm range.

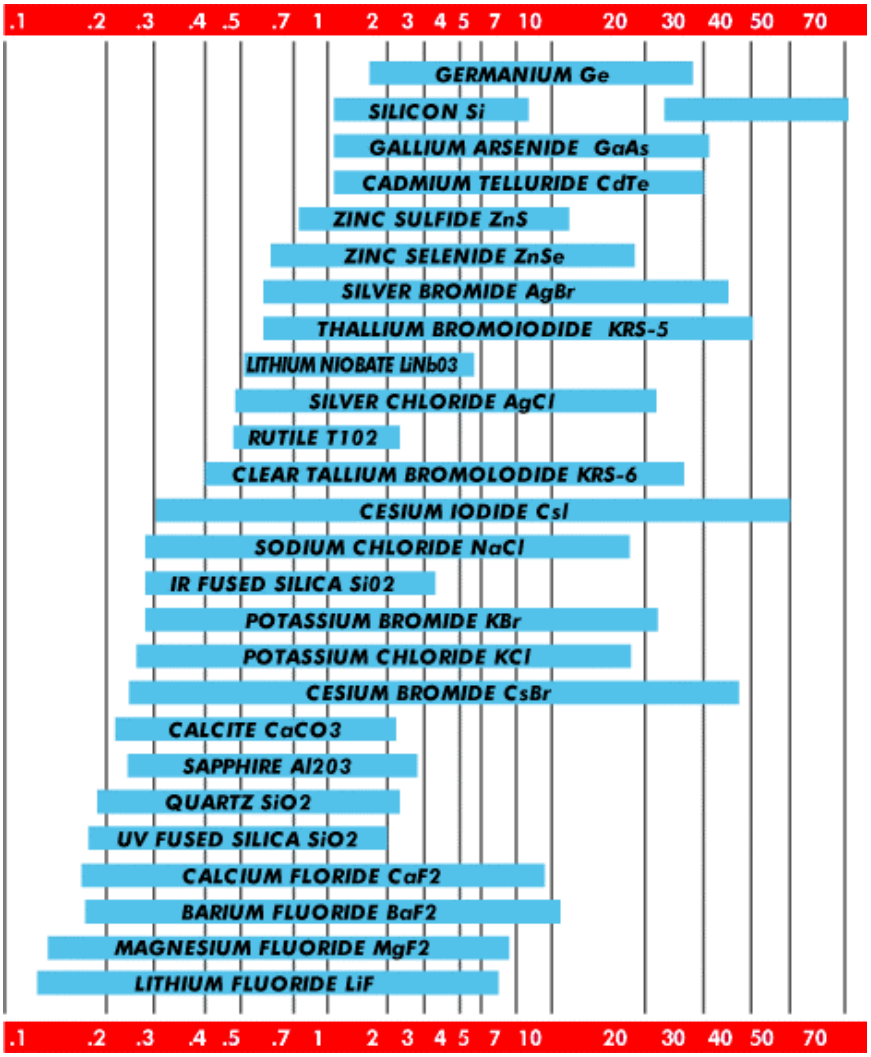

Figure 2: Transmission ranges of some optical materials

From Figure 2, we see just how limited the choices are for optical crystals and other compounds for the infrared. Other materials are available which fall in a category called chalcogenides. They are an amorphous mixture made up of two or three types of the infrared transmitting materials. I will include 3 popular types in this report: AMTIR 1, AMTIR 3 and GASIR.

Because of the high index of refraction of these materials, the Fresnel surface losses are normally higher for an uncoated piece. The reflectance ρ of an interface between n_1 and n_2 can be calculated by the following equation for normal incidence and no absorption:

$$Reflectance = \rho = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2$$

Further losses are incurred through the absorption of the bulk material itself that can be calculated by:

$$T_{abs} = e^{-\alpha t}$$

where α is the absorption coefficient of the material (at the desired wavelength) and *t* is the thickness of the material in cm.

3 Optical tables

The following tables will give useful information that designers typically use when designing IR lenses.

Material	spectral range (μm)	Index of refraction		dn/dT (x 10^{-6}/℃)
		λ = 4μm	λ = 10μm	
Germanium (Ge)	2.0 - 17.0	4.0242	4.00030	396
Silicon	1.2 - 9.0	3.4290	N/A	160
Gallium Arsenide (GaAs)	0.9 - 16.0	3.3246	3.295217	148
GASIR	1.0 - 14.0	2.5116	2.495974	55
AMTIR 1	0.7 - 14.0	2.5106	2.495324	72
AMTIR 3	3.0 - 14.0	2.6210	2.6023	56
Zinc Selenide (ZnSe)	0.55 - 20.0	2.4331	2.406523	60
Arsenic Trisufide (As_2S_3)	0.65 - 8.0	2.4112	2.381624	-8.6
Thallium Bromoiodide (KRS5)	0.6 - 40.0	2.3834	2.372015	-240
Zinc Sulfide (ZnS)	0.37 - 14.0	2.2518	2.200164	54
Sapphire	0.17 - 5.0	1.6752	N/A	13
Baruim Fluoride (BaF_2)	0.15 - 12.5	1.4558	1.40140	-15
Calcium Fluoride (CaF_2)	0.13 - 12.0	1.4096	1.30020	-11
Fused Silica (SiO_2)	0.17 - 3.3	1.388831*	N/A	11

Table 1: Optical properties of some IR materials

In the infrared, the spectral ranges are very wide compared to the visible spectrum, which means we have to deal with potentially large chromatic aberrations. Since we know how to deal with color in the visible using dispersion (Abbe) values, we then have to define something similar for the IR spectrum. But again, because index of refraction values are typically much larger than for glass, the dispersion values vary a great deal more. If we use a similar dispersion equation for the 3 –5μm range:

$$\nu_{3-5} = \frac{\left(n_{4\mu m} - 1\right)}{\left(n_{3\mu m} - n_{5\mu m}\right)}$$

And similarly for the 8 – 10µm range:

$$v_{8-12} = \frac{(n_{10\mu m} - 1)}{(n_{8\mu m} - n_{12\mu m})}$$

We can get dispersion values for the IR materials

Material	Index of Refraction			Dispersion	Index of Refraction			Dispersion
	3	4	5	V_{MWIR}	8	10	12	V_{LWIR}
Germanium (Ge)	4.04460	4.02420	4.01530	103.2	4.00530	4.00030	4.00290	1250.1
Gallium Arsenide (GaAs)	3.33551	3.32463	3.31837	135.6	3.30492	3.29522	3.28336	106.5
GASIR	2.51638	2.51163	2.50870	196.8	2.50155	2.49597	2.48904	119.6
AMTIR 1	2.51840	2.51460	2.51120	210.4	2.50360	2.49770	2.49020	111.8
AMTIR 3	2.62660	2.62100	2.61730	174.3	2.60880	2.60230	2.59420	109.7
Zinc Selenide (ZnSe)	2.43758	2.43314	2.42951	177.6	2.41731	2.40652	2.39299	57.8
Arsenic Trisufide (As_2S_3)	2.41614	2.41117	2.40721	158.1	2.39397	2.38162	2.36434	46.6
Thallium Bromoiodide (KRS5)	2.38713	2.38342	2.38115	231.1	2.37586	2.37202	2.36753	164.7
Zinc Sulfide (ZnS)	2.25719	2.25178	2.24610	112.9	2.22281	2.20016	2.17007	22.8
Baruim Fluoride (BaF_2)	1.46120	1.45580	1.45110	45.1	1.42580	1.40140	1.36960	7.1
Calcium Fluoride (CaF_2)	1.41790	1.40960	1.39900	21.7	1.34980	1.30020	1.22990	2.5
Silicon	3.43600	3.42900	3.42600	242.9	N/A	N/A	N/A	N/A
Sapphire	1.71223	1.67524	1.62399	7.7	N/A	N/A	N/A	N/A
Fused Silica (SiO_2)	1.41926	1.38883*	N/A	N/A	N/A	N/A	N/A	N/A

Table 2: Dispersion calculations for IR materials

Note the large variation in values, for example 1250 for germanium LWIR. From this table we also see where some of the material transmissions start to cut out.

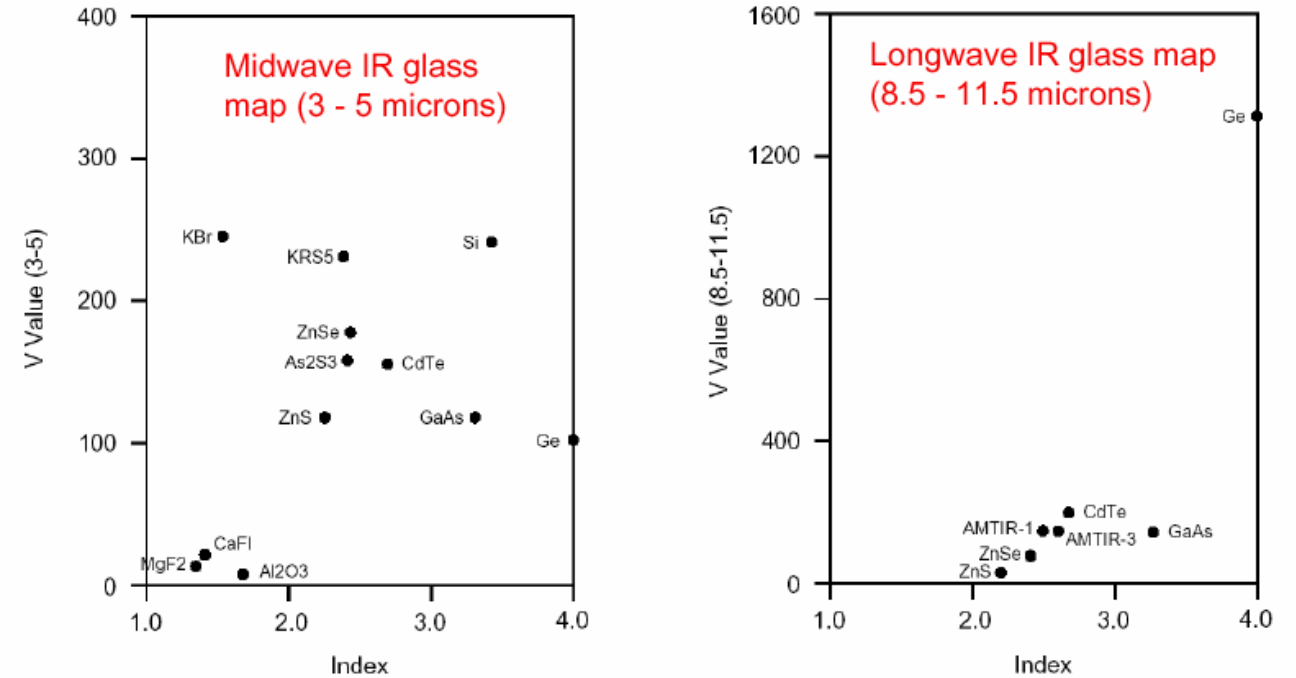

Figure 3: Familiar glass mapping for index vs. dispersion for the IR ranges

4 Mechanical tables

It's also very important to be able to define mechanically how these materials will perform in a system. The better we know the material properties the better we can predict its behavior.

Material	CTE (x 10^{-6}/℃)	Young's modulus E (Gpa)	Density ρ (g/cm^3)	Poisson's ratio ν	Thermal conductivity k (W/m℃)	Knoop hardness HK (kg/mm^2)
Germanium (Ge)	5.8	103.7	5.323	0.278	59.8	800
Silicon	2.55	131	2.329	0.279	159	1150
Gallium Arsenide (GaAs)	5.7	82.9	5.32	0.31	46.05	721
GASIR	17	17.9	4.4	0.28	0.28	155
AMTIR 1	12	22	4.4	0.266	1.4	170
AMTIR 3	13.5	21.4	4.7	0.26	1.3	150
Zinc Selenide (ZnSe)	7.57	70.3	5.27	0.29	16	105
Arsenic Trisufide (As_2S_3)	26.1	15.8	3.43	0.295	1	180
Thallium Bromoiodide (KRS5)	58	15.8	7.37	0.369	0.54	40.2
Zinc Sulfide (ZnS)	6.5	46	4.08	0.29	27.2	230
Sapphire	5.6(//) 5.0 (⊥)	400	3.97	0.27	23.1(//) 25.2 (⊥)	1370
Baruim Fluoride (BaF_2)	18.4	53.2	4.89	0.343	7.1	82
Calcium Fluoride (CaF_2)	18.9	96	3.18	0.29	9.71	160
Fused Silica (SiO_2)	0.58	73	2.202	0.17	1.35	500

Table 3: Mechanical properties of IR materials

From this data, we can combine some of the properties to give other useful information for system calculations such as vibration isolation and shock survival.

Material	Specific stiffness (E/ρ)
Germanium (Ge)	19.5
Silicon	56.2
Gallium Arsenide (GaAs)	15.6
GASIR	4.1
AMTIR 1	5.0
AMTIR 3	4.6
Zinc Selenide (ZnSe)	13.3
Arsenic Trisufide (As_2S_3)	4.6
Thallium Bromoiodide (KRS5)	2.1
Zinc Sulfide (ZnS)	11.3
Sapphire	100.8
Baruim Fluoride (BaF_2)	10.9
Calcium Fluoride (CaF_2)	30.2
Fused Silica (SiO_2)	33.2

Table 4: Specific stiffness of IR materials

Specific stiffness of materials is a very useful ratio (elasticity to density) that is repeated quite frequently in optomechanical analyses.

5 Conclusion

From this short list of materials, we see that there are limitations when designing in the infrared spectrum. But because of the wide range of properties available in this limited list, we do have enough variety to produce working systems. What is of importance is the availability of some of these materials and their associated costs. Some materials are very expensive when sold by weight, for example germanium and zinc selenide. Others can be relatively inexpensive to purchase but very expensive to machine, for example silicon and sapphire.

In conclusion, I have to stress that it is extremely important to understand what is required of the optical system. Once this is known, choosing the appropriate materials to design with becomes the next priority. This is where knowing and understanding the properties of the materials to be used becomes invaluable. The materials I've included in this report are only a few of the ones available. Chalcogenides have helped to give more material options but they can also be the cause of some difficulties, such as inclusions or flaws in the bulk material, inhomogeneities in the materials, nature of the materials in the mix (toxic, radioactive, water soluble, etc) and last but not least, the availability of the material in the size that is required in the design.

6 References

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