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Optical Materials for the Infrared

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ABSTRACT

Various optical, mechanical and thermal properties of old and new infrared materials are reviewed with attention to their application.

2. INTRODUCTION

The subject of optical materials for infrared instrumentation is a vast one. (Or maybe only half vast). It encompasses the usual materials that are used for lenses at both ambient temperatures and at lower and higher ones. It includes those materials that have or might be used for thin films and filters, mirror substrates and coatings, domes and windows, and even some non-linear elements. Some restrictions are necessary to keep the discussion of data and usage within reasonable bounds. Thus, there will be no discussion in this review of non-linear materials nor of the materials that are used for filters and films. Some of the materials discussed in the other contexts may be applicable for these.

There have been several compilations of data over the years. The "Blue Book" was published in 1959[1]. Data were compiled from it and updated for publication in several well known handbooks[2,3,4] and one textbook[5]. In addition, a recent review of the status of refractive index values has been presented[6]

3. OVERVIEW

The first table presents as much of an overview as can be entered in one figure. The table shows all the materials that are under any active (or even passive) consideration for employment in infrared instruments. It lists the chemical formula of the material (usually), its long and short wavelength cutoffs, refractive index, change in refractive index with temperature, Abbe numbers (or Vee values, describing reciprocal dispersion) in the 3 to 5 and 8 to 12 μm spectral regions, where appropriate, its temperature of melting, softening or glass formation, a rough estimate of its temperature of maximum usage, Knoop value of hardness, specific heat, thermal expansivity, thermal conductivity,Young's modulus, density, and water solubility. The data are representative in this summary chart. The cutoff wavelengths, for instance, are just an estimate based on transmission data for samples of different thicknesses. For more careful work, the reader should check on the data for the specific samples and thicknesses of interest. Other data are also representative. There are sometimes several values in the literature for a particular property. One of them was arbitrarily chosen for entry in the table, but the data are generally approximately correct.

The wavelengths are given in micrometers, shown as um in the table, since μm is hard to put on a spread sheet. Only three significant figures are given in this table for the refractive index, merely to indicate the need for antireflection coatings. Of course the refractive index is dimensionless. The change with temperature is represented as (1/n)(dn/dT) and is indicated as a relative change in parts per million, or, equivalently, the relative change in index per megakelvin (microchange per K). Abbe numbers are dimensionless. All temperatures in this report are given in kelvins, unless otherwise specified. Knoop values are reported as kilograms per square millimeter, indicating the area of an indentation for a given applied load of a diamond shaped indenter. Specific heat is given in the modern units of joules per kilogram per degree kelvin. Thermal expansion is given in the same units as the temperature coefficient of refractive index, a relative expansion per megadegree, or parts per million per kelvin. Thermal conductivity is given in the mks units of watts per meter per degree, and Young's modulus is given in gigapascals (giga newtons per square meter). Density is given as a specific gravity. Water solubility is given as the number of grams of solute in 100 cubic centimeters of water. Since the density of water is 1 g per cubic centimeter, this may be thought of as a percent.

Many of the values had to be converted from older units to bring them to a common, modern basis. The specific-heat conversion from calories per gram per kelvin to joules per kilogram per kelvin is 4187, as shown. That is, multiply the old unit by the factor to get the new unit. Similarly, thermal conductivity is converted by multiplying the old unit by 418.68. Young's modulus in pounds per square inch is converted to gigapascals by the factor 6.894757.

There are different applications for these materials, and the ensuing discussion (mercifully) divides the table by selecting those materials that make sense for each of the applications. Although it would be possible, no attempt is made here to give the reasons for the rejection of each and every material for the various uses. The reader might assume there are good reasons, or he might investigate for himself.

Figure 1 is a plot of the approximate transmission regions of these many materials.

4. DOMES FOR THE MIDDLE INFRARED

The middle infrared is here defined as the region that approximates 3 to 5 µm. The main applications are domes for relatively high speed missiles, and the main problems are to obtain transparent materials that have good high-temperature properties and good resistance to rain and other damage. Little attention is paid to issues of refractive index and dispersion, but high priority is assigned to high-temperature operation, hardness (to avoid rain erosion) and other, similar mechanical and thermal characteristics.

Perhaps the most stressing application is the hypersonic missile, travelling at speeds of approximately mach 10. In such a case, not only does the flow become heated to temperatures of about 5000K, but the air breaks down, and there is even some question as to what temperature means. Such windows (not domes) must be recessed, cooled and protected. Even so, about the only material that has proven reasonably effective is sapphire, Al_2O_3. Table 1A is the same as Table 1, but the materials appropriate for merely supersonic applications have been highlighted. They are listed separately in Table 2. Figure 2 is a plot of the temperature of the flow field as a function of mach number. A number of assumptions have been made, but it is also representative of the temperatures to be encountered[2]. It is clear that one must be able to withstand temperatures approaching 555K (1000R) for speeds up to mach 4. Figure 3 shows those materials that have transparency in the 3 to 5 µm region and their melting, softening or glass formation. The prime candidates here are fused silica, magnesium oxide, magnesium fluoride, spinel, alon, yttria, diamond and several special glasses. They all transmit in the region. Although diamond is the best, it is also the smallest, and no one has yet made a diamond window of the size that is needed. The special fluoride glasses might be used, but their melting temperatures are rather marginal. The rest of the considerations are based on the stresses generated in the materials and their ability to withstand them. For this the thermal conductivity, specific heat, thermal expansion and Young's modulus are important. An attempt was made to calculate a simple figure of merit, but the data are insufficient. Clearly, the higher the thermal conductivity, the better the window will transfer the heat to a sink, that may be its mount. The higher the specific heat, the lower will be the temperature rise in the window. The smaller the expansion coefficient, the less will be the strain on the window, and the higher the modulus, the more it can withstand such strain. The evaluation may be made to some extent by reference to the values in Table 2.

Green et al[7] report on the comparative abilities of spinel, quartz, calcium aluminate glass and sapphire to withstand sandblasting, ultraviolet radiation and chemical attack. The most pertinent curve for the sandblasting, recreation sand about 30 cm away at 10 psi, shows that spinel is at first worse than quartz, and then better. No data were shown on the reduction of infrared transmission as a result of ultraviolet illumination, but the calcium aluminate glass lost about 35% of its transmission when exposed to sunlight for 2 hours, and spinel was unaffected after 244 hours. At 4µm spinel was affected only by 100 hours of immersion in sulfuric acid at 373K! Domes can currently be made up to about 7.5cm in most curvatures up to about 170° arcs.

It is, of course, possible to use materials that operate in the longer wavelength regions, but they generally have lower degradation temperatures.

5. WINDOWS FOR THE MIDDLE INFRARED

This category, windows rather than domes, represents a more benign environment for the same spectral region. Windows are generally thought to be those optical materials that protect an imaging device or a tracker. They do not travel at speeds in excess of mach one. They are in planes and tanks and trucks. Here the maximum temperature is more like 500K than 1000K. Certainly the materials that can be used for domes can be used for windows, but others can also be used, and these might have advantages in cost and other factors. Table 3 shows some of the materials that are applicable here in the same highlighted fashion as before, and Table 3A is the abbreviated version.

6. WINDOWS FOR THE LONG WAVE INFRARED

The long-wave infrared (LWIR) is defined here as the 8 to 12 μm region in accordance with common custom. The Far Infrared indicates still longer wavelengths. The temperature considerations are the same, but the issue of transparency out to 12μm is now encountered. The materials of choice have usually been germanium, silicon, zinc sulfide and zinc selenide. Although some systems now operate out to 24μm in space, when they do there is no atmosphere, and a window is not needed. When they are in the atmosphere, the atmospheric transmission cuts off the useful range of the system at about 12μm: Table 4 shows the highlights, and Table 4A is the abbreviated version, after the selection. The highlights in Table 4A indicate the reasons that most of these materials are not entirely acceptable. The chalcogenide glasses all have cutoffs that may be a little marginal, but in some applications are all right. Barium fluoride is not acceptable for the band, but it makes a fine window, especially for laboratory use, that passes both HeNe and CO_2 laser wavelengths. Diamond is, of course, too small, the cadmium compounds are not very well known, although they have some interesting characteristics. This is true as well of the gallium and indium compounds. Cesium iodide and bromide are far too water soluble, as are the potassium compounds. So is salt. KRS-5 has a tendency to cold flow and slump, but can be use for less critical applications. Selenium and its arsenic-modified version both have too low a melting temperature. The two thallium compounds, which of course make up KRS-5 have similar characteristics, and can be used in some applications.

The remaining stars are germanium, Irtrans 1 and 2, silicon and zinc sulfide and selenide. Care must be taken with these. Germanium has the unfortunate property that it becomes opaque at a temperature of about 373K

(100C) as a result of the thermal activation of carriers from the valence band to the conduction band. The energy gap of germanium is about 0.7 eV, corresponding to its cuton wavelength of 1.8μm. Silicon follows the same laws of physics, but has an energy gap of 1eV (1.2μm). Thus its critical temperature is about 673K (300C). The zinc compound have still larger energy gaps of about 0.5eV and therefore higher critical temperatures. The development of diamond coatings for some of these materials is one of the most exciting of the recent developments. Two complete SPIE Proceedings [8,9] have been dedicated to these developments. Unfortunately, the general state of the art seems to be that the films are still too granular to allow low scatter (≈10μm). They have been applied to systems in at least one case.

7. LENS MATERIALS

These materials are usually more protected than the windows and domes that are discussed above. Although the mechanical and thermal properties are still important, consideration of the refractive index and its change with both wavelength and temperature become the dominant concerns. The details of these data, which can be excruciating difficult to measure (or even obtain from the literature), have been compiled in the references cited above. Here it seems appropriate to make more general comparisons. Figure 1 above already indicates the spectral range of transparency, and all the materials listed here have good transmittance in the 8-12μm region. For the lenses, three parameters are important. These are the refractive index that determines the lens power and the requirement for antireflection coatings; the dispersion, which determines the amount of chromatic aberration and the need for its correction; and the change of refractive index with temperature, which determines the need for athermalization. The refractive index and the dispersion are shown in Figures 4 and 5. These are what may be called Abbe plots. The refractive index is plotted as a function of the reciprocal dispersion, or η or V value. The definition, rather than being in terms of special visible lines, is given in terms of the maximum, minimum and middle values in the 3-5μm and 8-12μm regions.

One of the most outstanding materials is certainly germanium, with its high refractive index and concomitantly high optical power and its low dispersion (high reciprocal dispersion) in both spectral regions. Surely silicon is a close second, and there can be no question that these two materials have been those of choice for most refractive optical designs. However, the use of the chalcogenide glasses is coming on strong. Their characterization is less complete, and perhaps less complicated. The performance of germanium and silicon is importantly tied to its purity. Although the refractive index does not change in any significant way, the transmission does. There has also long been the question of *mono versus poly*. This dispute arises from the small angle scatter that can occur in polycrystalline germanium as a result of the boundaries. On the other hand, the single crystal material is more expensive. The controversy has not raged in the same way for silicon.

8. SCATTERING

The scattering of these materials is important in some applications. The issue is not so much the relatively small loss of light by the "outscattering", but rather the introduction of undesirable background by inscattering. Thus, a few of the data on scattering are summarized here. The data are presented in terms of the bidirectional reflectivity, sometimes referred to as BTDF. Figure 6 shows limited data at 3.39μm on several materials[10]. Data are scarce[10,11].

9. REFERENCES

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Table 1 Optical Materials for the Infrared

Material	Wave Band um	um	n	dn/dT 1/MK	V '3-5	V '8-12	Tmelt K	Tmax K	Knoop kg/mm2	Specific Heat J/Kg/K 4187	Thermal Expansion 1/MK	Thermal Conductivity W/m/K 418.68	Youngs Modulus GPa 6.894757	Density	Water Solubilit
ABCZT	0.3	7					703		295		16.6			4	
ABCY	0.3	7					651		360		16.5			3.95	
Amtir	1	11						473	150						
TI 1173	1	11						473	150						
TI1120	1	11						473	150						
IRG100	1	11	2.6	56	197	105		473	150		15		22	4.7	
Ag	0	0								234					0
AgCl	0.4	20	1.98	-61	275	54	731	473	9.5	355	30		20	5.589	0.0001
Al							933			913					0
AlON	0.18	5					2303		1370	754	7.8	25	345	3.98	0
ALO.	0.2	7					2473		1912			13	288		
As2S3	0.6	9					483		109				16	3.198	0
BaF2	0.18	10					1553		82			12	53	4.83	0.17
BaTiO3	0.2	7												5.9	
C	0.2	80					3775		8820	904		14235			0
CaAl2O3	0.4	5					1073		608		8.2	1		3.12	
CaCO3	0.3	2.5					1612			892			76	2.71	0.0014
CaF2	0.16	7					1633			854		39	76	3.179	0.0017
CdF2	0.5	10												6.382	
CdS	0.6	14					1560		80	369		16		4.82	0
CdSe	0.5	15							90						0
CdTe	0.5	18	2.68	98	189	150	1315	573	56	79	6	6	36	5.854	0
CsBr	0.3	32	1.66	-79	529	132	909	673	19.5	2638	48	1	16	4.44	124.3
CsI	0.2	42	1.74	-90	577	234	894	673		201	50	1	5	4.526	44
GaAs	1	15	3.28	150	174	107	1511	523	721		6	52	84	5.3161	0
GaSb	2	14?					993		469			44	63		0
Ge	1.8	14	4	396	120	1700	1210	353	176	310	6	59	103	5.327	0
InAs	4	14?					1215		330	3				5.66	0
InP	1	14							430					4.8	
InSb	6	12					796		225	97		36	43	5.78	0
Irtran 1	1	6										15	114	3.18	0
Irtran2	1	13										15	97	4.09	0
Irtran3	0.4	9										8	97	3.18	0
Irtran4	0.5	22										13	69	5.27	0
Irtran5	0.4	9										44	331	3.58	0.00062
KBr	0.3	25	1.53	-40	331	1700	1003	573	5.9	1038	41	3	27	2.75	53.48
KCl	0.3	15					1049		9.3	678		7	30	1.984	34.7
KI	0.4	30					996			3056		2	32	3.13	127.5
KRS-5	0.5	35	2.37	-235	278	165	688	473	40	0	58	1	16	7.4	0.05
LiF	0.12	7					1143		113	1562		11	65	2.639	0.27
MgO	0.3	7					3073		692	875		59	249	3.567	0
Spinel	0.3	4.5					2303		1140	126		14		3.61	0
NaCl	0.3	15	1.5	-25	133	19	1074	673	18.2	854	44	6	40	2.164	35.7
NaF	0.2	8								0				2.79	4.22
Se	1	20					308			285		1		4.82	0
Se(As)	1	12					345			0		1		2.648	0
Si	1.2	14					1693		1000	741		163	131		0
SiO2	0.2	3.5					1743		741	787		11	76	2.202	0
SrTiO3	0.4	4					2353		595					5.122	0
Te	3	8					723			202		6		6.24	0
TiO2	0.4	4.5					2093			712		13		4.25	0
TlBr	0.4	26					733		11.9	188		1	30	7.453	0.05
TlCl	0.4	20					703		12.8	218		1	32	7.018	0.32
Y2O3	0.25	6					2640			1846	0.001693	57	1193	5.024	
Y2O3:La	0.25	6					2325			1813	0.001716	22	1172	5.14	
ZBLAN	0.3	7					535		221		17.5		0	3.95	
ZnS	1	14	2.23	46	153	23		673	178	1964	7	17	74	4.09	0.0001
ZnSe	0.5	22	2.42	57	229	58		523	137	1419	7	18	67	5.27	

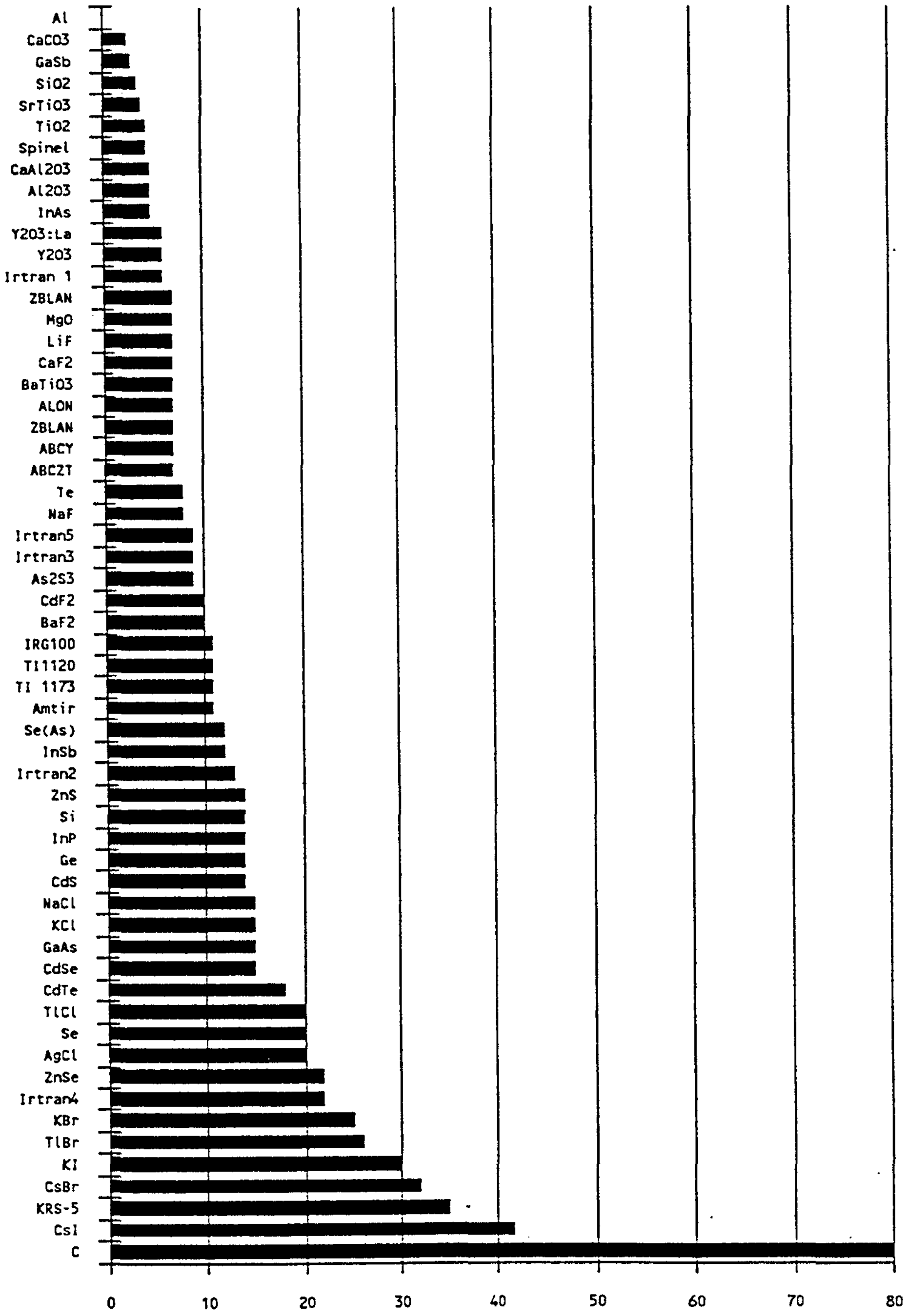

Figure 1. Transmission of Infrared Materials

Table 1A Highlighted Materials for Mid IR Domes

Material	Wave Band		n	dn/dT	V '3-5	V '8-12	Tmelt	Tmax	Knoop	Specific Heat	Thermal Expansion	Thermal Conductivity	Youngs Modulus	Density	Water Solubilit
	um	um		1/MK			K	K	kg/mm2	J/Kg/K	1/MK	W/m/K	GPa		
										4187		418.68	6.894757		
ABCZT	0.3	7					703		295		16.6			4	
ABCT	0.3	7					651		360		16.5			3.95	
Amtir	1	11						473	150						
TI 1173	1	11						473	150						
TI1120	1	11						473	150						
IRG100	1	11	2.6	56	197	105		473	150		15		22	4.7	
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Al2O3	0.18	5					2303		1370	754	7.8	25	345	3.98	0
ALON	0.2	7					2473		1912			13	288		
As2S3	0.6	9					3		109				16	3.198	0
BaF2	0.18	10					1553		82			12	53	4.83	0.17
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C	0.2	80					3775		8820	904		14235			0
CaAl2O3	0.4	5					1073		608		8.2	1		3.12	
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CdSe	0.5	15							90						0
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CsI	0.2	42	1.74	-90	577	234	894	673		201	50	1	5	4.526	44
GaAs	1	15	3.28	150	174	107	1511	523	721		6	52	84	5.3161	0
GaSb	2	14?					993		469			44	63		0
Ge	1.8	14	4	396	300	1700	1210	353	176	310	6	59	103	5.327	0
InAs	4	14?					1215		330	3				5.66	0
InP	1	14					1		430					4.8	
InSb	6	12					796		225	97		36	43	5.78	0
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Se	1	20					308			285		1		4.82	0
Se(As)	1	12					345			0		1		2.648	0
Si	1.2	14					1693		1000	741		163	131		0
SiO2	0.2	3.5					1743		741	787		11	76	2.202	0
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ZBLAN	0.3	7					535		221		17.5		0	3.95	
ZnS	1	14	2.23	46	153	23		673	178	1964	7	17	74	4.09	0.0001
ZnSe	0.5	22	2.42	57	229	58		523	137	1419	7	18	67	5.27	

Table 2 Materials for Mid IR Domes

Material	Wave Band		Tmelt	Tmax	Knoop	Specific Heat	Thermal Expansion	Thermal Conductivity	Youngs Modulus	Density
	um	um	K	K	kg/mm2	J/Kg/K	1/MK	W/m/K	GPa	
						4187		418.68	6.894757	
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ALON	0.2	7	2473		1912			13	288	
C	0.2	80	3775		8820	904		14235		
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Y2O3:La	0.25	6	2325			1813	0.001716	22	1172	5.14

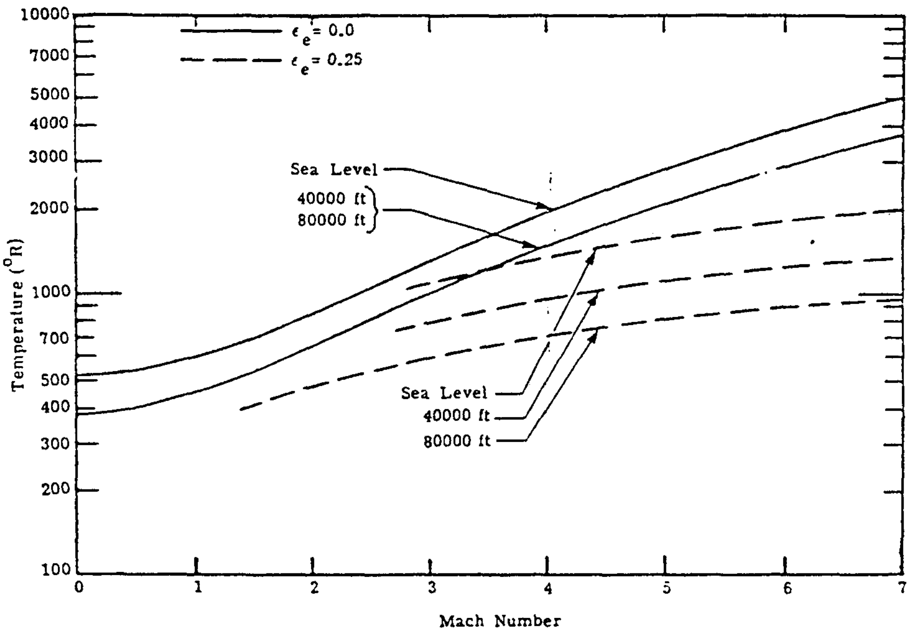

Figure 2. Temperature of Flow Field

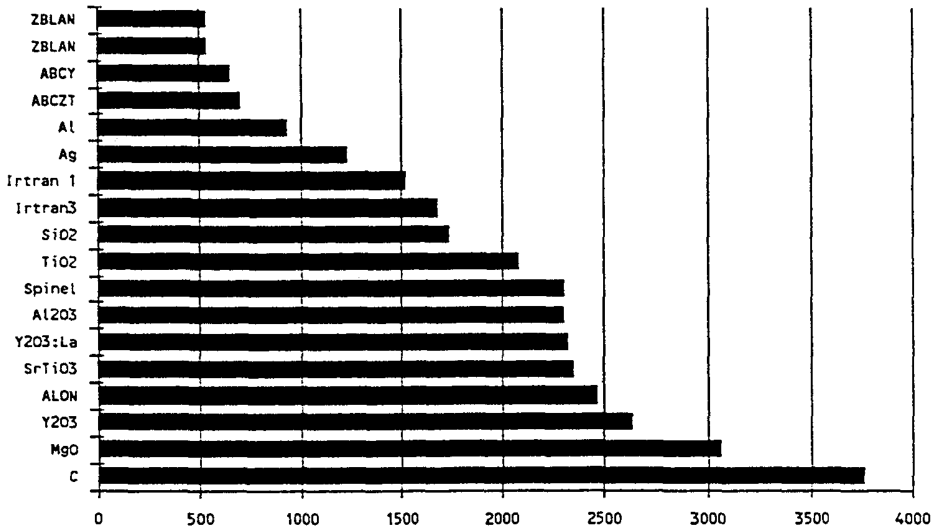

Figure 3. Temperatures of Mid Infrared Dome Materials

Table 3 Highlighted Materials for Mid IR Windows

Material	Wave Band um	um	n	dn/dT 1/MK	V '3-5	V '8-12	Tmelt K	Tmax K	Knoop kg/mm2	Specific Heat J/Kg/K	Thermal Expansion 1/MK	Thermal Conductivity W/m/K	Youngs Modulus GPa	Density	Water Solubilit
										4187		418.68	6.894757		
ABCZT	0.3	7					703		295		16.6			4	
ABCY	0.3	7					651		360		16.5			3.95	
Amtir	1	11						473	150						
TI 1173	1	11						473	150						
TI1120	1	11						473	150						
IRG100	1	11	2.6	56	197	105		473	150		15		22	4.7	
Ag	0	0					1			234					0
AgCl	0.4	20	1.98	-61	275	54	731	473	9.5	355	30		20	5.589	0.0001
Al							933			913					0
[illegible]	0.18	5					2303		1370	754	7.8	[illegible]	345	3.98	0
ALON	0.2	7					2473		1912			[illegible]	288		
As2S3	0.6	9					483		109				16	3.198	0
BaF2	0.18	10					1553		82			12	53	4.83	0.17
BaTiO3	0.2	7												5.9	
C	0.2	80					3775		8820	904		14235			0
CaAl2O3	0.4	5					1073		608		8.2	1		3.12	
CaCO3	0.3	2.5					1612			892			76	2.71	0.0014
CaF2	0.16	7					1633			854		39	76	3.179	0.0017
CdF2	0.5	10												6.382	
CdS	0.6	14					1560		80	369		16		4.82	0
CdSe	0.5	15							90						0
CdTe	0.5	18	2.68	98	189	150	1315	573	56	79	6	6	36	5.854	0
CsBr	0.3	32	1.66	-79	529	132	909	673	19.5	2638	48	1	16	4.44	124.3
CsI	0.2	42	1.74	-90	577	234	894	673		201	50	1	5	4.526	44
GaAs	1	15	3.28	150	174	107	1511	523	721		6	52	84	5.3161	0
GaSb	2	147					993		469			44	63		0
Ge	1.8	14	4	396	300	1700	1210	353	176	310	6	59	103	5.327	0
InAs	4	147					1215		330	3				5.66	0
InP	1	14					1		430					4.8	
InSb	6	12					796		225	97		36	43	5.78	0
Irtran 1	1	6										15	114	3.18	0
Irtran2	1	13										15	97	4.09	0
Irtran3	0.4	9										8	97	3.18	0
Irtran4	0.5	22										13	69	5.27	0
Irtran6	0.4	9										44	331	3.58	0.00062
KBr	0.3	25	1.53	-40	331	62	1003	573	5.9	1038	41	3	27	2.75	53.48
KCl	0.3	15					1049		9.3	678		7	30	1.984	34.7
KI	0.4	30					996			3056		2	32	3.13	127.5
KRS-5	0.5	35	2.37	-235	278	165	688	473	40	0	58	1	16	7.4	0.05
LiF	0.12	7					1143		113	1562		11	65	2.639	0.27
MgO	0.3	7					3073		692	875		59	249	3.567	0
Spinel	0.3	4.5					2303		1140	126		14		3.61	0
NaCl	0.3	15	1.5	-25	133	19	1074	673	18.2	854	44	6	40	2.164	35.7
NaF	0.2	8								0				2.79	4.22
Se	1	20					308			285		1		4.82	0
Se(As)	1	12					345			0		1		2.648	0
Si	1.2	14					1693		1000	741		163	131		0
SiO2	0.2	3.5					1743		741	787		11	76	2.202	0
SrTiO3	0.4	4					2353		595					5.122	0
Te	3	8					723			202		6		6.24	0
TiO2	0.4	4.5					2093			712		13		4.25	0
TlBr	0.4	26					733		11.9	188		1	30	7.453	0.05
TlCl	0.4	20					703		12.8	218		1	32	7.018	0.32
Y2O3	0.25	6					2640			1846	0.001693	57	1193	5.024	
Y2O3:La	0.25	6					2325			1813	0.001716	22	1172	5.14	
ZBLAN	0.3	7					535		221		17.5		0	3.95	
ZnS	1	14	2.23	46	153	23		673	178	1964	7	17	74	4.09	0.0001
ZnSe	0.5	22	2.42	57	229	58		523	137	1419	7	18	67	5.27	

Table 3A Materials for Mid IR Windows

Material	Wave Band		n	dn/dT	V 3-5	V 8-12	Tmelt	Tmax	Knoop	Specific Heat	Thermal Expansion	Thermal Conductivity	Youngs Modulus	Density	Water Solubilit
	um	um		1/MK			K	K	kg/mm2	J/Kg/K	1/MK	W/m/K	GPa		
										4187		418.68	6.894757		
ABCZT	0.3	7					703		295		16.6			4	
ABCY	0.3	7					651		360		16.5			3.95	
Ag	0	0					1			234					0
Al							933			913					0
Al2O3	0.18	5					2303		1370	754	7.8	25	345	3.98	0
ALON	0.2	7					2473		1912			13	288		
C	0.2	80					3775		8820	904		14235			0
CaF2	0.16	7					16[illegible]			854		39	76	3.179	0.0017
Irtran 1	1	6										15	114	3.18	0
Irtran2	1	13										15	97	4.09	0
Irtran3	0.4	9										8	97	3.18	0
MgO	0.3	7					3073		692	875		59	249	3.567	0
Spinel	0.3	4.5					2303		1140	126		14		3.61	0
SiO2	0.2	3.5					1743		741	787		11	76	2.202	0
SrTiO3	0.4	4					2353		595					5.122	0
TiO2	0.4	4.5					2093			712		13		4.25	0
Y2O3	0.25	6					2640			1846	0.001693	57	1193	5.024	
Y2O3:La	0.25	6					2325			1813	0.001716	22	1172	5.14	
ZBLAN	0.3	7					535		221		17.5		0	3.95	

Table 4 LWIR Window Candidates

Material	Wave Band		n	dn/dT	V 3-5	V 8-12	Tmelt	Tmax	Knoop	Specific Heat	Thermal Expansion	Thermal Conductivity	Youngs Modulus	Density	Water Solubilit
	um	um		1/MK			K	K	kg/mm2	J/Kg/K	1/MK	W/m/K	GPa		
										4187		418.68	6.894757		
ABCZT	0.3	7					703		295		16.6			4	
ABCY	0.3	7					651		360		16.5			3.95	
Amtir	1	11						473	150						
TI 1173	1	11						473	150						
TI1120	1	11						473	150						
IRG100	1	11	2.6	56	197	105		473	150		15		22	4.7	
Ag	0	0					1			234					0
AgCl	0.4	20	1.98	-61	275	54	731	473	9.5	355	30		20	5.589	0.0001
A							933			913					0
Al2O3	0.18	5					2303		1370	754	7.8	25	345	3.98	0
ALON	0.2	7					2473		1912			13	288		
As2S3	0.6	9					483		109				16	3.198	0
BaF2	0.18	10					1553		82			12	53	4.83	0.17
BaTiO3	0.2	7												5.9	
C	0.2	80					3775		8820	904		14235			0
CaAl2O3	0.4	5					1073		608		8.2	1		3.12	
CaCO3	0.3	2.5					1612			892			76	2.71	0.0014
CaF2	0.16	7					1633			854		39	76	3.179	0.0017
CdF2	0.5	10												6.382	
CdS	0.6	14					1560		80	369		16		4.82	0
CdSe	0.5	15							90						0
CdTe	0.5	18	2.68	98	189	150	1315	573	56	79	6	6	36	5.854	0
CsBr	0.3	32	1.66	-79	529	132	909	673	19.5	2638	48	1	16	4.44	124.3
CsI	0.2	42	1.74	-90	577	234	894	673		201	50	1	5	4.526	44
GaAs	1	15	3.28	150	174	107	1511	523	721		6	52	84	5.3161	0
GaSb	2	147					993		469			44	63		0
Ge	1.8	14	4	396	120	1700	1210	353	176	310	6	59	103	5.327	0
InAs	4	14?					1215		330	3				5.66	0
InP	1	14					1		430					4.8	
InSb	6	12					796		225	97		36	43	5.78	0
Irtran 1	1	6										15	114	3.18	0
Irtran2	1	13										15	97	4.09	0
Irtran3	0.4	9										8	97	3.18	0
Irtran4	0.5	22										13	69	5.27	0
Irtran5	0.4	9										44	331	3.58	0.00062
KBr	0.3	25	1.53	-40	331	1700	1003	573	5.9	1038	41	3	27	2.75	53.48
KCl	0.3	15					1049		9.3	678		7	30	1.984	34.7
KI	0.4	30					996			3056		2	32	3.13	127.5
KRS-5	0.5	35	2.37	-235	278	165	688	673	40	0	58	1	16	7.4	0.05
LiF	0.12	7					1143		113	1562		11	65	2.639	0.27
MgO	0.3	7					3073		692	875		59	249	3.567	0
Spinel	0.3	4.5					2303		1140	126		14		3.61	0
NaCl	0.3	15	1.5	-25	133	19	1074	673	18.2	854	44	6	40	2.164	35.7
NaF	0.2	8								0				2.79	4.22
Se	1	20					308			285		1		4.82	0
Se(As)	1	12					345			0		1		2.648	0
Si	1.2	14					1693		1000	741		163	131		0
SiO2	0.2	3.5					1743		741	787		11	76	2.202	0
SrTiO3	0.4	4					2353		595					5.122	0
Te	3	8					723			202		6		6.24	0
TiO2	0.4	4.5					2093			712		13		4.25	0
TlBr	0.4	26					733		11.9	188		1	30	7.453	0.05
TlCl	0.4	20					703		12.8	218		1	32	7.018	0.32
Y2O3	0.25	6					2640			1846	0.001693	57	1193	5.024	
Y2O3:La	0.25	6					2325			1813	0.001716	22	1172	5.14	
ZBLAN	0.3	7					535		221		17.5		0	3.95	
ZnS	1	14	2.23	46	153	23		673	178	1964	7	17	74	4.09	0.0001
ZnSe	0.5	22	2.42	57	229	58		523	137	1419	7	18	67	5.27	

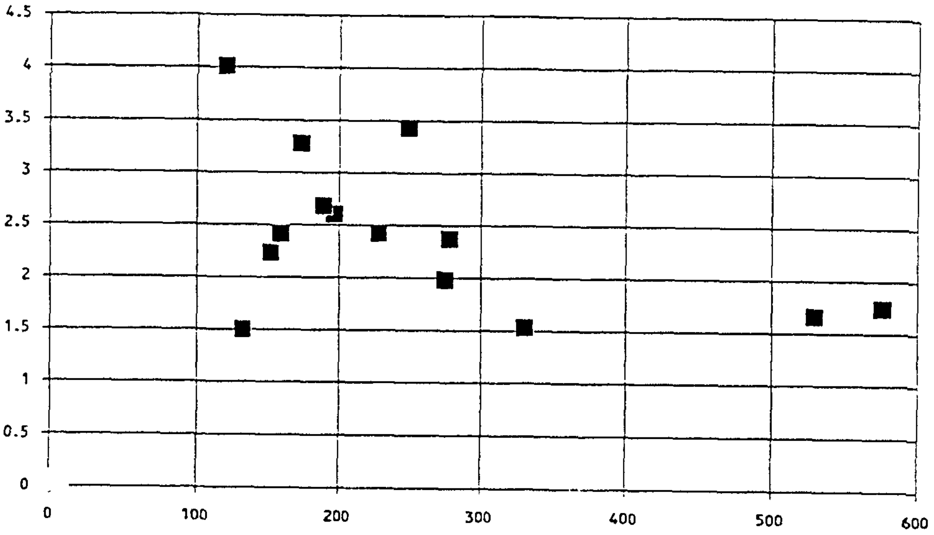

Figure 4 Abbe chart for 3-5 micrometers1

Table 4A. A Selection of LWIR Materials

Material	Wave Band		n	Tmelt	Tmax	Knoop	Specific Heat	Thermal Expansion	Thermal Conductivity	Youngs Modulus	Water Solubility	Other
	um	um		K	K	kg/mm2	J/Kg/K	1/MK	W/m/K	GPa		
							4187		418.68	6.8947572		
Amtir	1	11			473	150						
TI 1173	1	11			473	150						
TI1120	1	11			473	150						
IRG100	1	11	2.6		473	150		15		22		
BaF2	0.18	10		1553		82			12	53	0.17	Lab use
C	0.2	80		3775		8820	904		14235		0	Size
CdS	0.6	14		1560		80	369		16		0	?!
CdSe	0.5	15				90					0	?!
CdTe	0.5	18	2.68	1315	573	56	79	6	6	36	0	?1
CsBr	0.3	32	1.66	909	673	19.5	2638	48	1	16	124.3	
CsI	0.2	42	1.74	894	673		201	50	1	5	44	
GaAs	1	15	3.28	1511	523	721		6	52	84	0	?
GaSb	2	147		993		469			44	63	0	?
Ge	1.8	14	4	1210	353	176	310	6	59	103	0	
InAs	4	147		1215		330	3				0	?
InP	1	14		1		430						?
Irtran2	1	13							15	97	0	
Irtran4	0.5	22							13	69	0	
KBr	0.3	25	1.53	1003	573	5.9	1038	41	3	27	53.48	
KCl	0.3	15		1049		9.3	678		7	30	34.7	
KI	0.4	30		996			3056		2	32	127.5	
KRS-5	0.5	35	2.37	688	473	40	0	58	1	16	0.05	Slumps
NaCl	0.3	15	1.5	1074	673	18.2	854	44	6	40	35.7	
Se	1	20		308			285		1		0	
Se(As)	1	12		345			0		1		0	
Si	1.2	14		1693		1000	741		163	131	0	
TlBr	0.4	26		733		11.9	188		1	30	0.05	
TlCl	0.4	20		703		12.8	218		1	32	0.32	
ZnS	1	14	2.23		673	178	1964	7	17	74	0.0001	
ZnSe	0.5	22	2.42		523	137	1419	7	18	67		

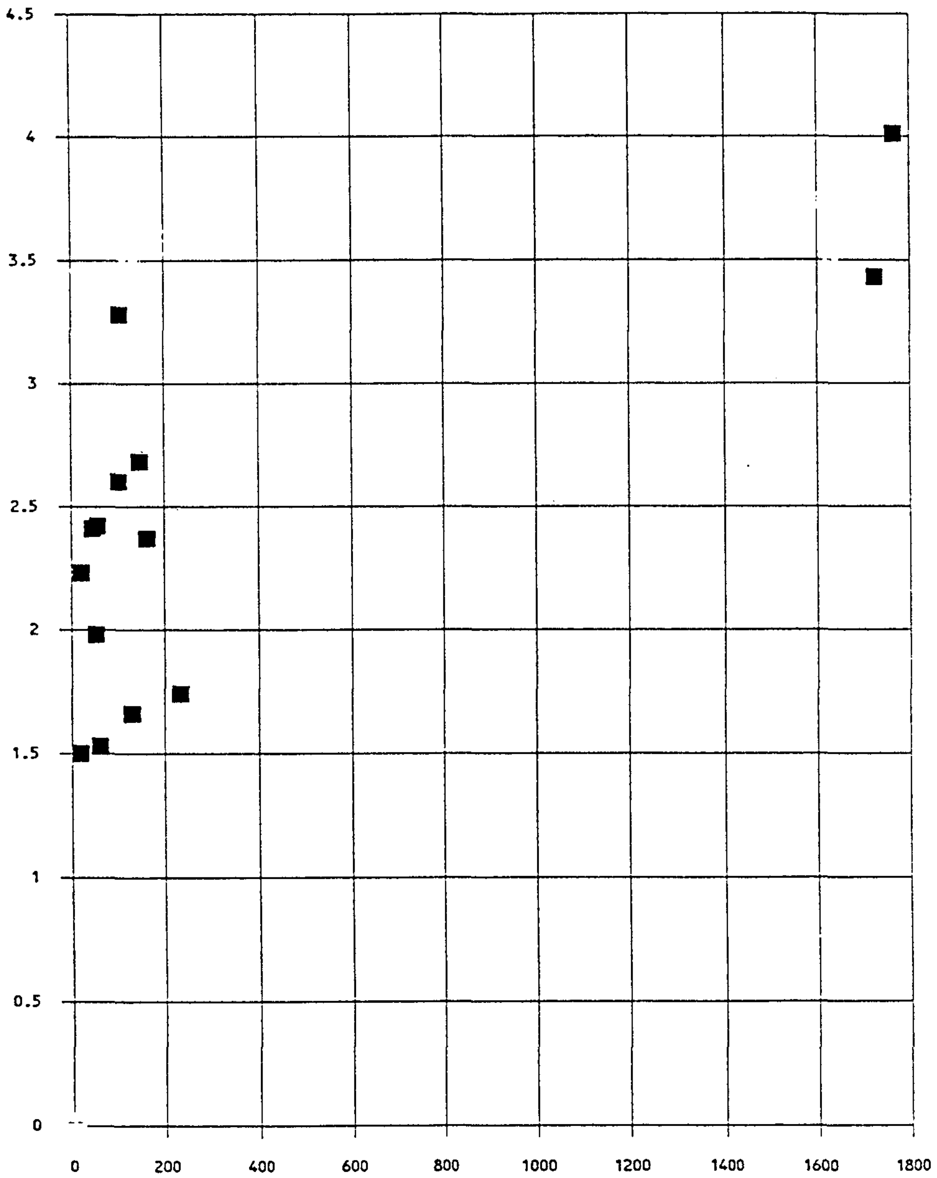

Figure 5. Abbe plot for 8-12 micrometers