

Chapter 3

Unique Features of the Infrared Region

3.1 Optical Materials

3.1.1 Materials for the infrared

A large number of optical materials transmit in the infrared region of the spectrum. However, the list of materials is quite limited when one considers physical characteristics, workability, and cost. Table 3.1¹ indicates the materials most commonly used in infrared zoom-lens systems for the 3- to 5- μm and 8- to 12- μm regions. It is apparent that indices of refraction are higher than they are for optical materials in the visible spectrum. This is an advantage in the correction of third-order and higher-order aberrations. For example, with a lens shaped for minimum spherical aberration, the angular spherical aberration β_{SPH} for an object at infinity can be expressed by

$$\beta_{SPH} = \frac{n(4n-1)}{128(n-1)^2(n+2)(F^3)}, \quad (3.1)$$

where

n = index of refraction and

$$F = \frac{f}{d}, \text{ or } \frac{\text{focal length}}{\text{diameter}}.$$

The variation with a refractive index can readily be seen by tabulating β for an $f/1$ lens as an example in Table 3.1. The advantage of using a high-index material like silicon or germanium is quite apparent from these calculations.

Table 3.1 Variation of spherical aberration with a refractive index.

$f/\#$	n	β
1.0	4.0	0.008681
1.0	3.0	0.012891
1.0	2.0	0.027344

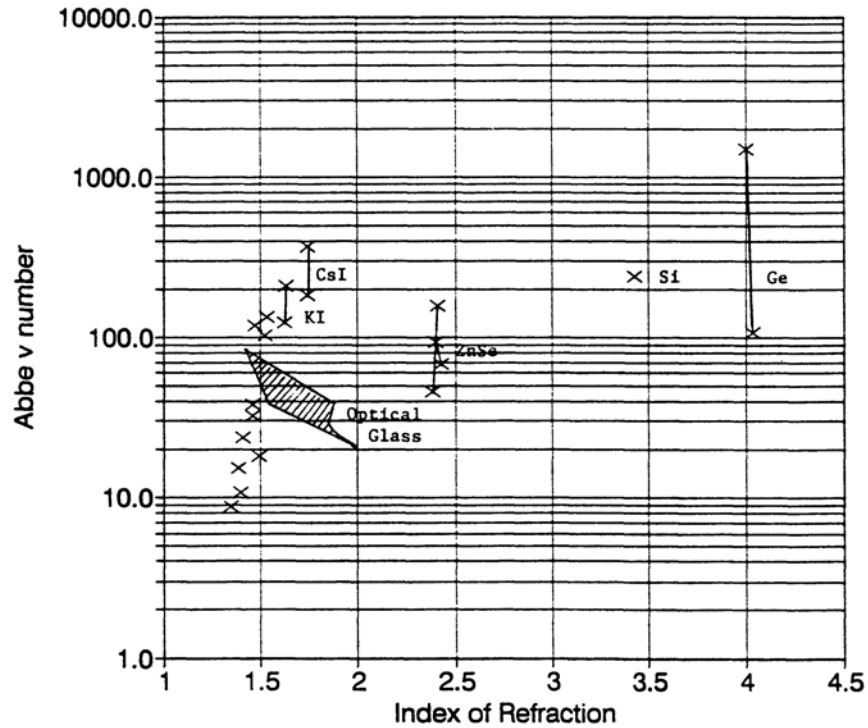


Figure 3.1 V value versus index of refraction for several of the more commonly used infrared materials.²

Also, infrared materials tend to have low dispersion, which corresponds to a high V number. Figure 3.1 presents the V value versus the index of refraction for several of the more commonly used infrared materials.² The hatched area indicates the more limited range of V values and refractive indices as compared with visible materials. However, one should keep in mind that the Schott catalog alone contains some 200 optical glasses within the hatched area;³ in fact, the number of available glasses in the visual region is more than one order of magnitude greater than in the infrared.

Germanium is less expensive than zinc selenide or zinc sulfide. Since silicon has become an order of magnitude less expensive than germanium, its use in infrared zoom lens systems has greatly increased in recent years. This development, in turn, has helped caused a shift from the 8- to 12- μm to the 3- to 5- μm region. Another factor is the availability of detectors such as InSb which work well in the 3- to 5- μm waveband.

In Table 3.2, V is defined as:

$$V_{3-5\mu\text{m}} = \frac{n_{4\mu\text{m}} - 1}{n_{3\mu\text{m}} - n_{5\mu\text{m}}}, \quad V_{8-12\mu\text{m}} = \frac{n_{1\mu\text{m}} - 1}{n_{8\mu\text{m}} - n_{1\mu\text{m}}}. \quad (3.2)$$

Table 3.2 Refractive index data for infrared materials.

Material	Zinc sulfide	Zinc selenide	Silicon	Germanium	Calcium fluoride
3 μm	2.2570	2.4376	3.4320	4.0452	1.4179
4 μm	2.2520	2.4331	3.4255	4.0243	1.4097
5 μm	2.2460	2.4295	3.4223	4.0161	1.3990
V	114	177	250	107	22
8 μm	2.2229	2.4173	3.4184	4.0051	--
10 μm	2.2005	2.4065	3.4179	4.0032	--
12 μm	2.1704	2.3930	3.4157	4.0023	--
V	23	58	896	1073	--
dn/dt	0.000043	0.000060	0.00015	0.000396	0.000011
density	4.09	5.27	2.33	5.33	3.18

Since many infrared components require aspheric or diffractive surfaces, diamond turning is often the method of choice for the fabrication of these surfaces that are so difficult to fabricate by traditional methods. Among other methods, reactive ion etching has been successfully utilized to transfer a binary optic diffractive pattern into the substrate.⁴

3.1.2 Calculation of index of refraction

The calculation of refractive index data may be accomplished through the use of general polynomials to provide interpolation at infrared wavelengths of interest for purposes of optical design and analysis. Several forms of general polynomials are available for use with infrared materials.

For their optical glasses Schott uses:

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8}, \quad (3.3)$$

which provides a worst-case fit of the refractive index to within ± 0.000005 . For infrared materials, Barr & Stroud⁵ used a modified version of the Schott formula. The data for infrared materials require additional positive terms. The full expansion is:

$$n^2 = C_{.8}\lambda^{-8} + C_{.6}\lambda^{-6} + C_{.4}\lambda^{-4} + C_{.2}\lambda^{-2} + C_0 + C_2\lambda^2 + C_4\lambda^4 + C_6\lambda^6. \quad (3.4)$$

A least-squares technique is applied to form a set of linear equations to solve to obtain the required coefficients. The least-squares fit process allows an estimation of error by computing the fit error. This process is dependent on using more data points than polynomial coefficients. The rms refractive index error

ranges from 0.00008 for germanium in the 8- to 13- μm range to 0.00002 for zinc sulfide.

Another commonly used formula in the infrared is the Sellmeier equation,

$$n^2 - 1 = \sum_{k=1}^m \frac{A_k \lambda^2}{(\lambda^2 - B_k^2)}. \quad (3.5)$$

For example, the Optical Research Associates CODE V optics program uses this equation in its special materials catalog for infrared materials. The number of terms varies from two to five, depending on the material. Most materials use three terms.⁶ The acceptable level of fit accuracy for inclusion in the CODE V special catalog is based on the optical path difference (OPD) errors that can be expected due to departures from measured data. The criterion chosen is that the induced chromatic effect, ΔOPD , be less than $1/10\lambda$ for a $f/1.5$ singlet of 200-mm diameter in any one of three spectral bands: 8 to 12, 3 to 5, and 0.4 to 0.7 μm . The result of imposing these criteria is that in certain cases, the same material is fitted for two spectral ranges and both fits are included in the special catalog using different names.⁷ Some infrared zoom lens applications may require tighter criteria. For example, the Pilkington "Dezir" compact infrared zoom telescope has an entrance lens that has a diameter somewhat in excess of 200 mm and operates at approximately $f/1.0$.⁸

3.2 Thermal Compensation

3.2.1 Focus shift with temperature

Focus shift with temperature is a significant problem in the infrared region. The change in refractive index with temperature, dn/dt , is presented in Table 3.1 for the listed materials. Germanium, in particular, has a very high dn/dt . For a thin lens the change in focal length with temperature can be expressed as¹

$$df = \left[\frac{f}{(n-1)} \right] \left(\frac{dn}{dt} \right) dt. \quad (3.6)$$

For a system with a 100-mm focal length and a 40° C temperature range, the focal shift is 0.527 mm for germanium. This would exceed the Rayleigh limit for acceptable performance of 0.400 mm for an $f/5$ system in the 3- to 5- μm spectral region and of 0.490 for $f/3.5$ systems in the 8- to 12- μm region.

3.2.2 Athermalization

Athermalization is the correction of this effect of focus shift with temperature. There are several mechanical and optical methods, active and passive, available to accomplish athermalization. It is possible to solve for achromatism and

athermalization at the same time with three infrared materials by solving the following simultaneous equations:⁹

$$\text{Total power} \quad \sum_{i=1}^J k_i = k. \quad (3.7)$$

$$\text{Achromatism} \quad \sum_{i=1}^J \frac{k_i}{V_i} = 0. \quad (3.8)$$

$$\text{Athermalization} \quad \left(\frac{1 + dl}{dt \cdot \Delta t} \right) \sum_{i=1}^J \left(\frac{dk}{dt} \right)_i + \frac{dl}{dt} \cdot k = 0, \quad (3.9)$$

where dl/dt is the coefficient of expansion of the mounting material.

The above equations can be used to derive an achromatic, athermal hybrid doublet with only two materials if a diffractive surface is considered to be the third material.

3.2.3 Athermalization methods

There are several mechanical and optical methods available to accomplish athermalization:

- (1) *Mechanical passive*: The basic principle behind this approach is to passively modify the axial position of a lens or lens group in order to compensate for the image shift caused by temperature change. This movement is achieved by natural expansion or contraction of mechanical components. (However, for germanium this type of correction by such metals as aluminum does not provide sufficient movement.)
- (2) *Mechanical active*: A lens or lenses are moved axially either manually or, preferably, by electromechanical means. Typically, temperature sensors feed information to actuate motors which drive the athermalizing elements to the required positions. This is particularly useful in zoom lenses where the required athermalization movements differ with magnification change.
- (3) *Optical passive*: It is possible to select a combination of optical materials that will minimize focus shift over a limited temperature range. For simultaneous correction of achromatism and athermalization at least three optical materials are required (refer to Sec. 3.2.2). By solving the basic equations for power, achromatism and athermalization, the relative power for each material can be derived. The use of zinc selenide, zinc sulfide, and germanium is one such combination.
- (4) *Optomechanical*: Optics with reduced temperature sensitivity can be compensated by small passive or active mechanical movements.
- (5) *Passive-active mechanical*: Passive mechanical means are combined with small active movements to minimize temperature effects.

- (6) *Reflective optics*: A single spherical mirror, if fabricated from the same material that separates the mirror from the focal plane, is in effect self-athermalized. A uniform temperature soak will cause a uniform expansion or contraction without any induced defocus.

Illustrations of the use of these techniques may be found in Figs. 6.17, 6.23, and 6.30.

The use of materials such as zinc sulfide and zinc selenide in combination with germanium makes it possible to provide some passive optical athermalization. Hybrid passive/active mechanical athermalization techniques are also being utilized. The most common arrangement involves the additional movement of lens elements which move for other reasons, such as zooming. These movements are either real time computed or calculated from look-up tables, and the whole process involves carefully selected temperature sensors as part of a closed-loop system.

3.3 Cold Stop and Cold Shield

The cold stop is an aperture or baffle which prevents the detector from looking at any extraneous stray radiation. If it is not the aperture stop of the system, it is a cold shield.

3.4 Narcissus

Narcissus is a change through scan or across the format resulting from radiation reflected from lens surfaces back into the detector/dewar assembly. The large temperature differential between the 300 K ambient temperature and the 77 K cooled detector temperature provides the potential for a large spurious signal.

3.4.1 Types of retroreflections

Narcissus consists of two components:

- (1) pedestal level at the center of scan, and
- (2) variation of the pedestal level with scan.

Mechanisms which create large pedestal levels are as follows:

- (1) A refractive surface is at or near an intermediate image plane ($y = 0$), where y is the paraxial marginal ray height at the offending surface.
- (2) The marginal axial ray is normal or nearly normal to a refractive surface ($ni = 0$), where n is the refractive index and i is the angle of incidence of the marginal ray following this surface.

These two types of retroreflections are shown in Fig. 3.2.¹⁰

3.4.2 Reduction techniques

Narcissus reduction techniques include improved multilayer antireflection coatings on the offending lens surfaces and optical designer-controlled methods.

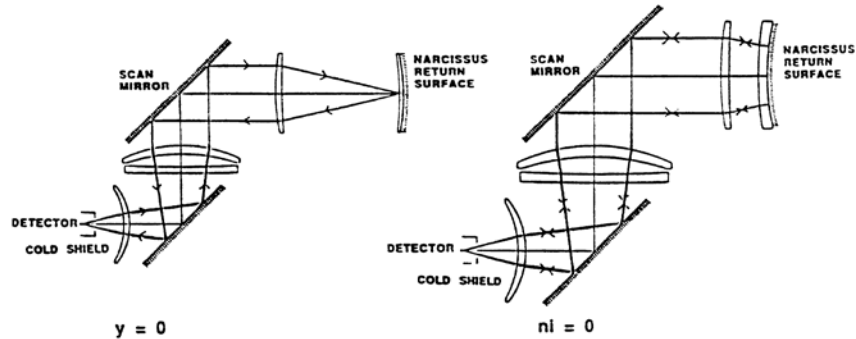


Figure 3.2 Two types of retroreflections.¹⁰

In the latter technique, the optical designer introduces baffles into the design in order to reduce the solid angular subtense of the cold signal and/or controls the position and shape of offending surfaces during the optical design process. Controls based on paraxial quantities at each surface can be highly effective in reducing total narcissus and/or variation with scan.

The paraxial quantity y_{ni} is one measure of narcissus that can be controlled. In general, increasing y_{ni} at a surface reduces the overall pedestal signal by defocusing the reflected bundle so that it can be clipped by existing apertures or the cold stop itself. Unfortunately, lens curvature changes which increase ni at a surface usually increase third-order spherical aberration and coma contributions at that surface. These aberrations may be balanced by contributions of opposite sign from other lens elements in the system or may require the introduction of an aspheric surface.

3.5 Glass Substitution

Optimization of glasses is handled differently than other lens data because there does not exist a continuum of glasses on the glass map. This is particularly true in the infrared region of the wavelength spectrum where the number of available glasses is very limited.

Glass substitution is a very effective method for choosing glasses in the infrared. The glass types are directly altered from a previously stored substitute list, and then the optical system is reoptimized while seeking a better solution. By selecting substitute glasses with a similar refractive index, the first-order characteristics of the optical system are maintained before reoptimization. This means that the principal planes of each altered lens are spatially maintained when bending the lens or when shifting the lenses proximate to the altered lens to maintain the proper distance between principal planes, or when bending and shifting simultaneously in combination. For further discussion of computer optimization, refer to Sec. 4.13.

This substitution feature was utilized to achieve passive athermalization of the all-germanium 3:1 zoom lens solution described in detail in Sec. 6.1.2.¹¹ Optical materials were selected during optimization with a lower dn/dt than germanium. Various optical materials such as GaAs and AMTIR-1 were inserted with similar refractive index as germanium. Table 3.3 shows the optical materials selected during the design process. Table 3.4 presents the optical properties of these materials.

Table 3.3 Optical materials selected during the design process.

	System #1	System #2	System #3	System #4
Lens 1	GE	GE	GE	GE
Lens 2	GE	GE	GE	GE
Lens 3	GE	GaAs	GaAs	GaAs
Lens 4	GE	CdSe	CdSe	AMTIR-1
Lens 5	GE	GE	GE	GE
Lens 6	GE	ZNGEP2	GaAs	GaAs

Table 3.4 Optical properties of materials selected during the design process.

	$N(10.0 \mu\text{m})$	$V(8 \text{ to } 12 \mu\text{m})$	dn/dt	CTE($\times 10\text{E-}6$)
GE	4.0031	1007	.000396	5.9
GaAs	3.2781	106	.000150	5.0
ZNGEP2	3.0791	49	.000003	--
AMTIR1	2.4975	113	.000076	12.0
CdSe	2.4292	84	.000135	4.9

The final passive solution contains one conic and one diffractive surface. It is about 20% longer than the starting solution. Performance over the zoom range and temperature range from 0 to 40° C is comparable to performance achieved by active compensation.

3.6 References

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