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Choosing a Material for Use in the Infrared

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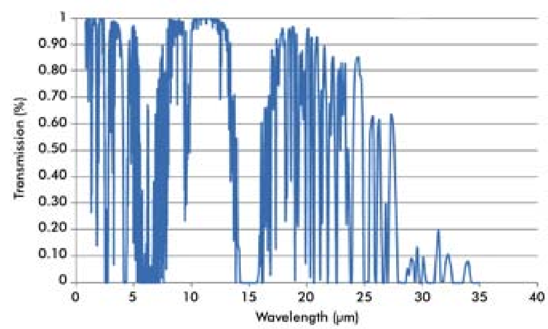
Creators of infrared systems often encounter difficulty when trying to select the proper materials for their optical designs. Part of the challenge is gathering information on the physical properties of IR materials. The other part is understanding the importance of those properties to an IR system design.

Zinc selenide IR aspheric lenses from Edmund Optics are uncoated and provide diffraction-limited focusing performance over a spectral range of 0.6 to 18.0 µm.

The IR region of the electromagnetic spectrum spans 780 nm to 1000 µm. Although the entire IR region is rather large, not all regions are considered usable because of significant atmospheric absorption bands. Still, there are many applications for the usable IR regions, ranging from missile guidance systems to thermal imaging and from meteorology to medical procedures. Each uses different portions of the IR bands based on specific needs. The optical materials for these applications also will be different, so developers must examine the properties of these materials based on their systems' needs.



Atmospheric absorption makes sections of the IR spectrum unusable for many applications. The data used here was produced using the program IRTRANS4 and obtained from the UKIRT (UK Infrared Telescope) website.

Optical properties

Perhaps the most important material properties for a designer to consider are the optical ones, including the transmission range, which describes the wavelengths that the material can transmit. Transmission range information, however – such as that included in Table 1 – considers only whether some specific fraction of the incident energy is submitted, not whether the material will completely transmit the incident energy. To better understand the material's ability to transmit it completely, look at a complete transmission curve, which can be found in the manufacturer's or supplier's product information.

Table 1.
General material properties for common IR materials.

	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+	–

Another important quality is the refractive index (n), which dictates a material's ability to control and manipulate light. The ratio of the speed of light in a vacuum to the speed of light in a different material, the refractive index is a function of both the light's wavelength and the temperature of the material being considered. Typically, materials designed for use in the infrared have higher n values, which allows for better correction of third- and higher-order aberrations.[1]

A third and very important optical property is dispersion, the derivative of the material's refractive index with respect to wavelength, or how the index of refraction changes as the wavelength changes. For transparent materials, dispersion is typically a negative value.

Dispersive properties of a material can be a benefit or a drawback. The prism in a spectrometer, for instance, needs dispersion to separate wavelengths. In lenses, however, having large amounts of angular dispersion will cause chromatic aberrations and should be avoided. Thus, dispersion must be considered based on the optic's end use.

At top Edmund Optics' germanium windows are available uncoated or with two antireflection coating options: 3 to 12 µm for mid-IR or broadband multispectral applications, or 8 to 12 µm for thermal imaging applications. Below, the company's mid-wave IR achromatic lenses are suitable components for applications in Fourier transform IR spectroscopy and mid-wave IR thermal imaging, and for use with tunable quantum cascade lasers.

As a result of the index of refraction being wavelength- and, thus, frequency-dependent, the material's molecular structure also can affect optical performance. Consider the case where the material has a crystalline structure that is anisotropic (directionally dependent). In this case, the material will cause light to experience double refraction, a process in which incident light is split into two refracted beams. One beam is known as the ordinary beam because it correctly obeys the law of refraction; the other is referred to as the extraordinary ray because it is refracted despite having a perpendicular incidence. A material that experiences double refraction is considered to be birefringent. Birefringence is measured as the difference in the index of refraction between the extraordinary rays and the ordinary rays.[2]

Thermal properties

A common misconception for the IR region of the electromagnetic spectrum is that these wavelengths transport heat; consequently, they are sometimes referred to, incorrectly, as "heat waves." In reality, the frequencies of IR wavelengths either cause the vibrational modes of certain molecules to become excited or the molecules themselves to rotate. Many materials that absorb the IR also have rotational or vibrational resonances in these wavelengths. It is these resonances that cause the materials to become hot.

Because most materials that work well optically in the IR do not have 100 percent transmission and, consequently, absorb the IR, their vibrational or rotational resonances can be excited, causing temperature changes within the material. Thus, it is important to consider the thermal properties when choosing an IR material.[3] Table 2 shows the thermal properties of some common IR optical materials.

Table 2.
Thermal properties for common IR materials.

	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

The thermal conductivity (k) of a material describes how well thermal energy is transmitted through it. Thermal conductivity is the measure of heat that successfully passes through a unit thickness of material in a direction normal to a surface of unit area resulting from a unit temperature gradient. The thermal conductivity can be used to predict the amount of energy lost as light passes through the system. As with refraction, thermal conductivity can be bidirectional, as determined by the crystalline structure of the material.

If a material does not have unit thermal conductivity, some of the energy is absorbed, and heat is created. As the heat is applied and absorbed by the material, the internal temperature changes. The rate at which the temperature changes depends on the material. The specific heat capacity (c) is defined as the heat necessary to raise the temperature of a unit of mass of the substance by 1 °C. While the definition of specific heat capacity is uniform regardless of the material being tested, when comparing materials, it is easier to look at specific heat directly. The specific heat of a material is the ratio of the material's specific heat capacity to the specific heat capacity of water.

If the material undergoes changes in temperature, the material properties can change significantly. This can cause significant alterations in the optical properties. When a material is heated, through the absorption of vibrational or rotational energy, the dimensions can change. The characterization of this dimensional change is referred to as the material's coefficient of thermal expansion. The dimensional fluctuation of a material is one of the leading causes of focal plane shifts for IR imaging systems; in most cases, this can be accounted for through athermalization.[1]

Similar to the coefficient of thermal expansion, which simply accounts for changes resulting from gradual temperature variations, it is important to consider a material's thermal stability, which is the measure of a material's ability to resist sharp or sudden changes in temperature without catastrophic material failure. One last thermal property to consider when choosing an IR material is the melting point, the temperature where a material changes physical states (for example, from solid to liquid).

Mechanical properties

Because the environmental conditions of IR components are dependent upon the end use, it is important to be cognizant of how the materials will behave given some more rugged applications. In many cases, the mechanical properties can serve as great decision points when the optical performances are similar. Table 3 summarizes key mechanical properties for common IR materials.

Table 3.
Mechanical properties for common IR materials.

	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

One important mechanical property is the specific gravity of the material. Sometimes called relative density, it is the ratio of the material's density to the density of water. Although specific gravity is a unitless number, numerically it is equivalent to the density when using metric units. As such, the specific gravity is listed instead of the density in Table 3.

When making considerations around the ruggedness of a material, look at the material's hardness. There are several standard tests for hardness. Here the Knoop hardness test is considered. The Knoop number is calculated by measuring the indentation made on the surface of the test material after pressing a pyramidal diamond point with a given load. The Knoop number for materials can vary from small values for soft materials (4 kg/mm^2 for potassium bromide) to high values for hard materials (7000 kg/mm^2 for diamond).

One final mechanical property to consider when choosing a material for IR optics is the Young's modulus, or the measure of the stiffness of the material. Dealing specifically with elastic deformations, Young's modulus is the ratio of the stress (force per unit area perpendicular to the force) to the strain, or the resulting fractional stretching (or compressing) of the material.

Material comparison

The wide variety of optical, thermal and mechanical properties used to evaluate the fit for a material to be used in an optical design ultimately means that the designer must perform a trade-off study. Unfortunately, the lack of a single IR material reference guide can make this study difficult. Many designers have found a temporary solution by keeping handbooks and reference guides on their desks, with pages for their favorite IR materials bookmarked. Housing all this information in one location will help designers focus on optical design rather than on researching material properties.

Meet the author

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