Field Guide to

Infrared Optical Materials

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Field Guide to Infrared Optical Materials

The authors' purpose in writing the *Field Guide to Infrared Optical Materials* was to create a concise, efficient reference for the quick analysis of commonly used infrared optical materials to aid in their review for selection. The emphasis has been placed on practicality. The collection of materials is based on the authors' experience of which materials, processes, and procedures are commonly used in the industry today. There are certainly many other infrared optical materials available on the market and there are much more detailed and comprehensive references for this sort of information. The authors would suggest the excellent references by Klocek, Weber, and Wolfe, or any of the other books listed in the bibliography. It is also highly recommended that, prior to final selection of a material, a detailed study is undertaken and direct contact is made with the specific material manufacturer for any required material properties (see **disclaimer**).

The authors would like to thank the following individuals for their assistance in writing this guide: Matthew Brown, Jacklyn Novak, Dr. Bill Moreshead, and Erik Stover at M3 Measurement Solutions and John Burnett at NIST for assistance with the page on measurement of the index of refraction. A special thanks to Jeff Richling and Myeong Nam for their substantial help with the coating section and to Pavel Reshidko and Ran Carmeli at RP Optical for the excellent images. This work would not have been possible without the support of the exceptional team at LightPath Technologies and ISP Optics.

This guide is dedicated to my family: Lauren, Carter, Cooper, and Holden. I could never have imagined to be so lucky to have a family like this! A.S.

This guide is dedicated to my family: Erenn, Donna, Boris, David, and Daniel. Love you all. M.L.

Alan Symmons
Mark Lifshotz
July 2021

Infrared Optics

Infrared (IR) technology started its life in predominantly military applications and transitioned into commercial and industrial applications starting in the 1990s. Although the technology was initially very expensive, system costs have reduced rapidly. During this same period, IR **crystal growth** processes improved significantly: materials have become more uniform with fewer internal defects. As processes improved, demand has increased and material prices have gone down. Advancing detector/camera manufacturing technologies (smaller pixels, larger format, lower price) led to an applications boom. Infrared technology has quickly become one of the major optical technologies of contemporary life.

Commercial **applications of infrared optics** have blossomed (see next page). This commercialization has driven market growth and helped drive down the cost of **LWIR** uncooled cameras and, at the same time, has driven demand for low-cost lenses. The optics and therefore the optical materials have become a significantly greater percentage of the bill of material of an optical system. The fast growth of the IR market led to the necessity to develop fast and cost-effective, but reliable, fabrication and coating processes while maintaining tight tolerances and high precision. Machinery and metrology equipment have made significant advancements; today it is hard to imagine an IR system without aspheric/diffractive surfaces, something unheard of only a few decades prior. **Single-point diamond turning** from state-of-the-art equipment has become the workhorse of IR optical fabrication, while **CNC grinding and polishing** machines have become more and more popular for IR crystal fabrication and IR coating technologies have improved. Chalcogenide glasses have been developed and **precision glass molding** has been optimized for these glasses.

Today's **SWIR**, **MWIR**, **LWIR**, and multispectral technologies cover a wide spectrum of applications and continue to rapidly expand throughout many industries and applications, both military and commercial.

LWIR

Long-wave infrared (LWIR) light is typically defined as light in the 8.0–12.0 μm wavelength range, and sometimes from 5.0 to 14.0 μm. In the LWIR band there is comparatively more radiation emitted from terrestrial objects compared to the MWIR band. LWIR is the most used waveband for **thermal imaging** as it provides the best overall combination of cost, quality, and availability. The LWIR region has the lowest number of available materials.

Applications in the LWIR

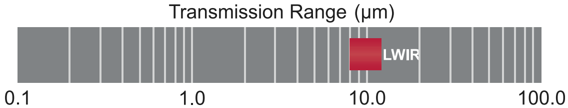
- Short- and long-range surveillance
- Thermography
- Spectroscopy
- Laser imaging
- Automotive night vision & ADAS
- Fire fighting
- Targeting and fire control
- Night vision & thermal weapon sights (TWS)

Common Materials for LWIR Applications

- Ge, chalcogenide glasses, ZnSe, ZnS, GaAs, CdTe, KBr, KCl, NaCl, KRS-5, CsI

Common Detectors for LWIR Applications

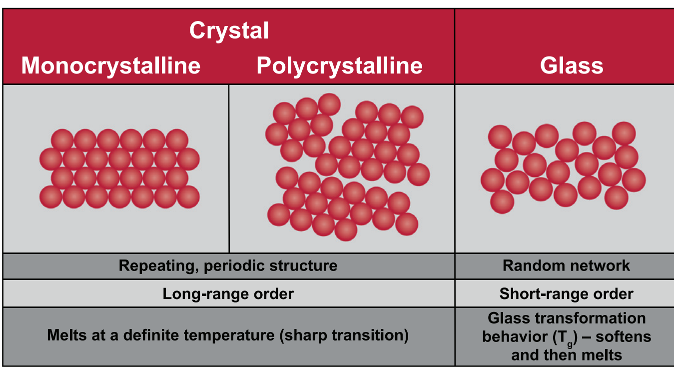
- Microbolometers, typically a-Si (silicon) or VO*x* (vanadium oxide) based
  - 7–14 μm, uncooled
- Mercury cadmium telluride (HgCdTe, or MCT)
  - 8–10 μm, cooled
- Quantum-well infrared photodetectors (QWIPs)
  - Shorter band, typically 1 μm wide, cooled



Crystal versus Glass

Infrared optical materials are either optical crystals or glasses. IR optical crystals are crystalline materials with either a **monocrystalline** or **polycrystalline structure**. They are a hard solid and, when they reach a certain temperature, they melt into a liquid with an abrupt solid-to-liquid transition. Crystalline materials have high hardness and strength, especially at high temperatures, high **thermal conductivity**, and low scatter. IR optical crystals are manufactured by a number of different **crystal growth** processes.

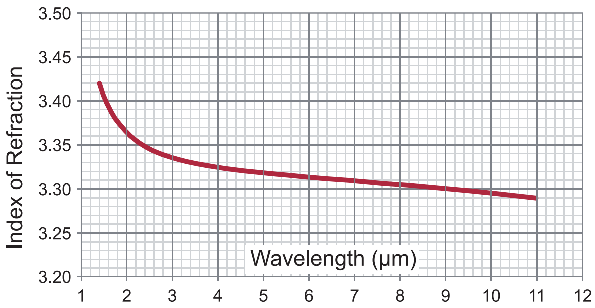
Crystalline materials are differentiated from amorphous materials by their structural or **crystallographic order**. Crystalline structures have long-range periodic orders, whereas amorphous materials (glass) have short-range random orders. The periodic structure of crystalline materials defines their **crystallographic properties**.



Glasses have many advantages over crystals. Manufacturing is comparatively easy in comparison and lends itself to mass production. Since glasses soften before they melt, they can be molded. Unfortunately, most glasses do not transmit far into the IR spectrum; silicates, phosphates, and borates are limited to ~3 µm. Oxygen-containing glasses are limited to ~6 µm (e.g., germanium dioxide) because oxygen bonds with other elements above this wavelength, preventing any further transmission. Oxygen-free glasses such as chalcogenides are required for transmission beyond 6 µm. **Chalcogenide glass** can transmit far into the IR spectrum.

Gallium Arsenide, GaAs (cont.)

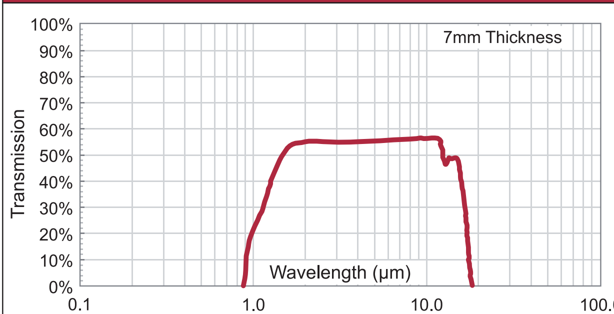
Index of Refraction over Wavelength



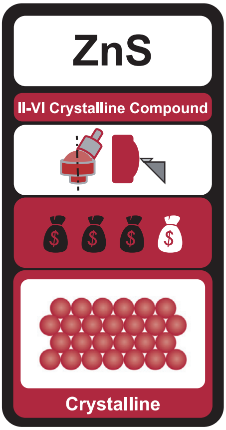
Gallium Arsenide

Sellmeier (RT)		λ (μm)	Index	λ (μm)	Transmission (7mm Thick)
A	3.5	1.40	3.4192	0.88	0.0%
B_1	7.4969	1.95	3.3668	1.92	55.0%
C_1	0.1666	2.50	3.3457	2.95	55.0%
B_2	1.9347	3.05	3.3347	3.99	55.2%
C_2	1,381.61	3.60	3.3281	5.03	55.5%
B_3	0.0	4.15	3.3235	6.07	55.6%
C_3	0.0	4.70	3.3200	7.10	56.1%
B_4	0.0	5.25	3.3171	8.14	56.4%
C_4	0.0	5.80	3.3145	9.18	56.5%
B_5	0.0	6.35	3.3121	10.21	56.5%
C_5	0.0	6.90	3.3097	11.25	56.6%
B_6	0.0	7.45	3.3073	12.29	55.4%
C_6	0.0	8.00	3.3049	13.32	46.4%
B_7	0.0	8.55	3.3024	14.36	48.5%
C_7	0.0	9.10	3.2998	15.40	47.9%
Min. Range	1.40	9.65	3.2970	16.44	34.8%
Max. Range	11.00	10.20	3.2941	17.47	16.4%
Reference	[Kachare 1976]	11.00	3.2896	18.51	0.0%

Transmission over Wavelength



Zinc Sulfide, ZnS (cont.)



Zinc sulfide (ZnS) is a **II-VI crystalline compound**. It is a polycrystalline material. As an optical IR material, it was originally produced as a hot-pressed material (**Irtran materials**, Irtran 2). **Hot pressing** was replaced by **CVD** due to the superior quality of CVD materials, although sintered and single-crystal materials are still available. CVD ZnS is primarily available in standard FLIR grade but is also available in clear, elemental, and red grades. ZnS is considered a medium-refractive-index material ($n = \sim 2.1–2.4$). It has good **transmission** in the LWIR.

- High transmission from 8 to 12 μm
- Hard, durable

- Limited applications for LWIR
- Expensive

ZnS has higher tensile strength, better abrasion resistance, and superior chemical resistance compared to ZnSe, but its popularity has largely decreased in favor of the latter. Zinc sulfide is, however, a common choice for IR windows due to its mechanical durability, exceptional fracture strength, excellent performance at elevated temperatures, and IR transmission. ZnS has a lower cost relative to ZnSe and ZnS clear grade.

Size Limitation
- 10” diameter
- Shaped dome blanks

Fabrication Method
CVD

Available Grade
Infrared grade

Main Applications
- Missile domes
- Cover windows for aircraft

Alkaline Earth Halides or Fluorides (cont.)

All **fluorides** are considered low-refractive-index materials (n = 1.3–1.45). The alkaline earth halides possess very high **Abbe numbers**, ranging between 80 and 110. Low-spectral-**dispersion** (high Abbe number) materials like the fluoride crystals can be used in imaging systems to reduce **chromatic aberration**.

Fluorides Abbe Number	
BaF_2	81.78
CaF_2	95.31
LiF	97.29
MgF_2	106.22

All fluorides are soft and brittle in comparison to **semiconductors** and are soluble in water to a certain degree. The latter property limits the use of optics made from fluoride crystals in high-humidity-environment applications.

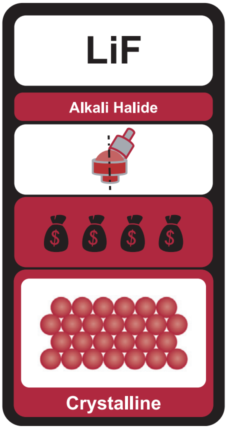
All fluoride crystals exhibit low resistance to temperature changes or low **thermal stability**, the ability of the material to withstand a rapid change in temperature (**thermal shock**). CaF_2 and especially BaF_2 are the most sensitive fluorides, particularly when the material is cooled. The materials will cleave along their preferred crystal planes when certain temperature gradients are exceeded. This is an important consideration from an application standpoint and for fabrication (at the cutting, grinding, and polishing stages). CaF_2 and BaF_2 also exhibit relatively high coefficients of thermal expansion, which also needs to be taken into consideration from an application viewpoint.

Main Characteristics

- Visible transmission
- High transmission
- Low refractive index
- Soft and brittle
- Low thermal stability

CaF_2 is the most popular fluoride crystal for the IR due to its excellent optical properties, high **transmission** through the **MWIR**, and relatively low price for small-size optics. This material is readily available around the world.

Lithium Fluoride, LiF (cont.)



Lithium fluoride (LiF) is available in monocrystalline form. It is available in VUV and IR grades. Due to its high **transmission** at lower wavelengths, it is used primarily in UV applications. It is the best VUV transmitter available.

LiF has the lowest index of refraction of all IR materials, although it is not a very popular material for IR applications. It is usually produced for deep-UV applications by the **Stockbarger** technique. LiF IR grade is grown in open air by the **Kyropoulos** method. Lithium fluoride is a relatively soft material. It is sensitive to **thermal shock** and, while largely insoluble in water, does degrade by atmospheric moisture at temperatures greater than 400 °C. Lithium fluoride's use in IR applications is limited by its high price, size limitations, and difficulty to polish, as it cleaves very easily.

↑
- Transmits UV–VIS–MWIR
- Lowest index of refraction of the fluorides

↓
- Soft, brittle
- Most-expensive fluoride

Steep radii can lead to surface tearing. Diamond turning is not feasible due to its high **cleavability**. Lithium fluoride can devitrify if exposed to UV light for extended periods.

Size Limitation
~100 mm

Main Applications
- Astronomy
- SWIR lenses
- X-ray monochromator plates

Fabrication Methods
- Stockbarger
- Kyropoulos

Available Grades
- Vacuum-UV grade
- Infrared grade

Sapphire, Al_2O_3

Sapphire

Crystallographic Properties

Property	Value
Syngony	Hexagonal
Symmetry Class	R–3c
Lattice Constants	a = 4.758; c = 12.991
Cleavability	None

Mechanical Properties

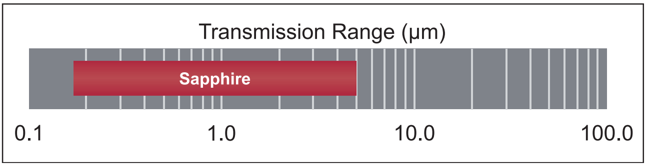
Property	Value
Density, ρ	3.98 g/cm^3
Knoop Hardness	1,762.5 kg/mm^2
Poisson's Ratio, *v*	0.23
Young's Modulus, *E*	345.0 GPa
Shear Modulus, *G*	148 GPa
Solubility	0.000098 g/100g H_2O (°C)

Thermal Properties

Property	Value
Thermal Linear Expansion, α	8.4 × 10^{-6}/K
Thermal Conductivity, *k*	27.21 W/(m•K)
Specific Heat Capacity, C_p	0.7744 J/(g•K)
Melting Point, T_m	2,040 °C

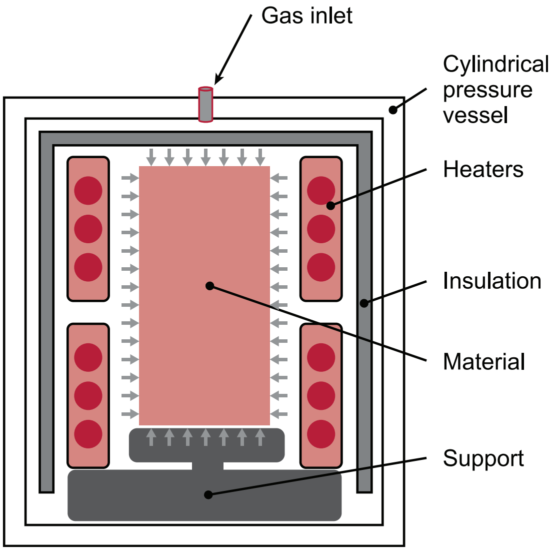
Optical Properties

Property	Value
Refractive Index, n_o	1.7377 @ 2.0 μm (24°C)
Refractive Index, n_e	1.7299 @ 2.0 μm (24°C)
Absorption Coefficient, *A*	3.00E–04 cm^{-1} at 2.4 μm
dn/*dT*	13.1 (10^{-6}/°C) at 546 nm
Transmission Range	0.17–5 μm



Hot Isostatic Pressing

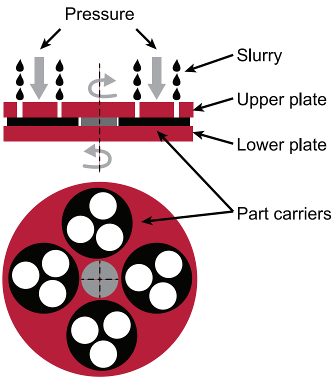
Hot isostatic pressing (HIP) is the most commonly applied sintering technique for consolidation of optical materials. In contrast to the uniaxial load of **hot pressing**, HIP employs an isostatic gas pressure, providing compression from all directions for further densification. The approach that combines HIP with other **sintering** methods is a common way to fabricate optical materials. The powders may be partially sintered prior to hot isostatic pressing the material. This effectively removes any surface-connected porosity.



Hot isostatic pressing is used for modifying the properties of orange-yellow, translucent, standard zinc sulfide to create water-clear, colorless, multispectral ZnS, or **zinc sulfide clear grade**. This property modification was accidentally discovered by C. B. Willingham at **Raytheon** in 1979. The HIP process effectively removes the color from ZnS, removes the Zn–H absorption band at 6.2 µm, converts most of the residual **hexagonal phase** to **cubic phase**, and collapses the residual pores.

Double-Side Polishing

Double-side polishing (DSP) is a cost-effective technique for polishing IR windows. DSP is especially appropriate for thin IR windows for commercial applications with good parallelism (30–60 arcsec) and a flatness of a few fringes. There is no blocking or polishing pitch; the windows are freely "floating" inside a plastic carrier disc sandwiched between two round, flat, aluminum or stainless-steel plates rotating in opposite directions. DSP uses planetary action that suspends particles in a liquid to abrade windows evenly from both surfaces. The self-adhesive lapping pads are glued to the top and bottom plates, and a slurry is continuously added in precise amounts to control the removal rate and the surface finish. Windows made from water-soluble materials like KBr and NaCl, as well as **semiconductor** and fluoride crystals, are routinely made by DSP. DSP can be used for parts up to 650 mm in diameter and down to 0.10 mm of thickness. DSP induces less thermal distortion, fewer surface imperfections, and less edge chipping than conventional polishing.



Applications: Quantum Cascade Lasers

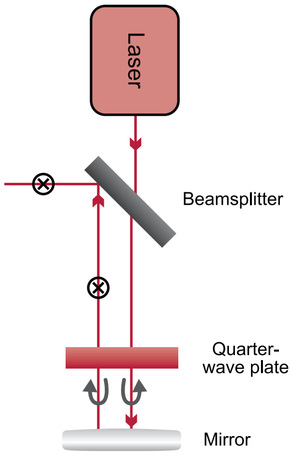
A **quantum cascade laser** (QCL) is a **semiconductor** laser that emits in the **MWIR** to the far IR. QCLs operate at room temperature and have high tuning ranges and high-power output. These properties make QCLs ideal for spectroscopic applications such as **remote sensing** of gases, remote sensing of pollutants, and security.

QCLs operate with narrow linewidths from 4 to 11 μm:

- QCL manufacturers package several QCL beams into a single unit that can produce multiple wavelengths.
- QCL manufacturers attempt to combine beams in their products (e.g., a gas sensor).
- Combining these beams requires dichroic mirrors with sharp cutoffs or precise optics that overlap beams that are "close enough."

A solution would be to use optical isolators:

- Light passes through a linear polarizer.
- The light is made circularly polarized by a quarter-wave plate (QWP).
- The reflected light is further retarded to 90 deg from the original, which is equivalent to a half-wave plate at 45 deg.
- The polarizer blocks the reflected light.



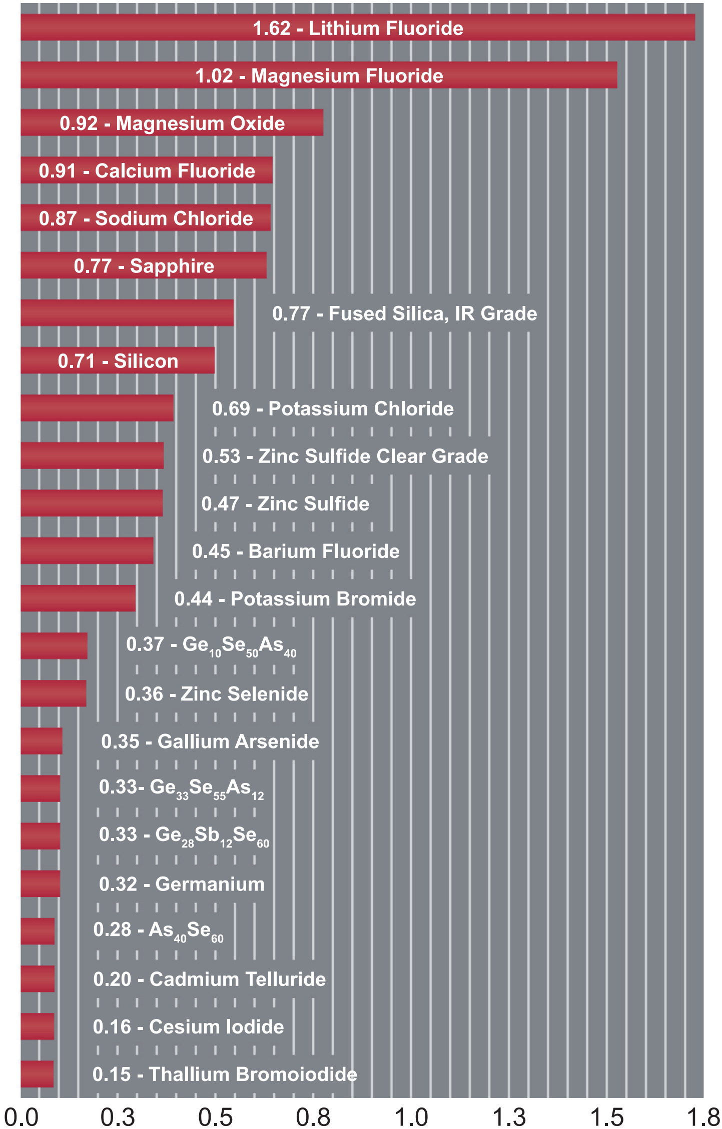
IR material selection for QCL applications is largely based on the wavelength(s) of light for the application. As the lenses are typically single-element collimating lenses positioned close to the laser, small-diameter single-element **aspheric lenses** are commonly used and are available from optics catalogs. The materials are primarily **Ge** or molded **ChGs**.

Appendix A: Material Property Comparisons (cont.)

Specific Heat Capacity, C_p

[J/(g·K)]

(highest to lowest)



Alan Symmons is the Executive Vice President, Infrared, Optics and Lasers at Vital Materials Co. Ltd., a market leader in global functional materials. The Infrared business unit of Vital Materials is engaged in the research and development, production, sales, and recovery of infrared materials and optics for laser and thermal imaging systems. Prior to joining Vital, Alan was employed at LightPath Technologies from 2006 through 2019, servings in various executive positions in product development, engineering, and operations, and ultimately serving as Chief Operating Officer.

Alan has over 20 years of experience in the high-volume manufacture of optical components and assemblies in both the visible and infrared spectrums. He is the co-author of the *Field Guide to Molded Optics* and *Molded Optics: Design thru Manufacture* and has published more than 20 papers in the field. He is a Fellow of SPIE. Alan has a Bachelor of Science in Mechanical Engineering from Rensselaer Polytechnic Institute and a Master's degree in Business Administration from the University of Arizona.

Since 2020, **Mark Lifshotz** has been leading Strategic Business Development at LightPath Technologies, a fully integrated manufacturer and supplier of visible and infrared optical components and sub-systems. For more than 23 years, Mark Lifshotz was CEO of ISP Optics Corporation, the company he co-founded in 1993. Under his leadership, ISP Optics grew into an international, multimillion-dollar company and became a recognized world leader in infrared optics manufacturing. In 2016 ISP Optics Corporation was acquired by LightPath Technologies. Mark Lifshotz also co-founded UAV Factory, the fixed-wing UAVs global vertical manufacturer. He has published several papers and patents in the field of optics and has a Master's degree in optics from the University of Latvia.