FRESNEL LENSES FOR INFRARED WAVELENGTHS

Fresnel Technologies, Inc. manufactures thin Fresnel lenses and lens arrays from the plastics of its POLY IR® series for use far into the infrared. These inexpensive lenses and lens arrays make excellent collecting optics for a variety of infrared detectors, and some POLY IR® material types are admirably suited to pyroelectric detectors with germanium or silicon windows. The lenses and lens arrays are thin enough and the POLY IR® materials good enough that transmission losses due to absorption in the material can be as low as 10% between 8 and 14 μm, the spectral region of interest in passive infrared applications.

Fresnel Technologies, Inc. has many years experience in making infrared lenses and lens arrays from POLY IR® materials, and invites your inquiry. Available focal lengths range from 5 mm to 600 mm and apertures to f/0.5.

The Fresnel Lens

It was recognized centuries ago that in a conventional lens, the contour of the refracting surface is the important parameter. The bulk of material between the refracting surfaces has only the effect of increasing absorption losses on the optical properties of the lens. In a Fresnel (point focus) lens (of positive focal length) this bulk of material has been reduced by the extraction of a stack of disks of material with decreasing diameters. (Positive focal length Fresnel lenses are almost universally plano–convex.) The contour of the curved surface is thus approximated by right circular cylindrical portions, which do not contribute to the lens' optical properties, intersected by conical (or, often, toroidal) portions called "grooves." Near the center of the lens, these inclined surfaces or "grooves" are nearly parallel to the plane face; toward the outside edge, the inclined surfaces become extremely steep, especially for lenses of low f–number.

The first Fresnel lenses were cut and polished in glass—an expensive process, and one limited to a few large grooves. Computer–controlled equipment and diamond cutting tools have made it possible to cut master tooling of excellent accuracy and optical surface finish. Contemporary plastics and molding techniques have made possible the faithful reproduction of this tooling in materials with excellent optical properties.

Advantages of the Fresnel Lens in the Infrared

Excellent infrared–transmitting materials exist, such as germanium in the 8 to 14 μm region. However, these materials are inherently expensive, and lenses must be made from them by conventional grinding and polishing techniques. Some plastics materials have reasonably small absorption in portions of the infrared spectrum, but not small enough to be made into practical conventional lenses. Lenses made from these plastics materials are generally limited to thicknesses of 1 mm or so (and preferably far less). This thickness restriction limits conventional lenses made from these plastics materials to high f–numbers (small aperture relative to the focal length). Even at high f–numbers, the thickness variation across a conventional lens can lead to a large variation in transmittance through the lens; absorption is highest for rays passing through the center of the lens (for positive focal lengths) and for rays traversing the lens at steep angles to the optical axis.

Fresnel lenses can be made extremely thin; some Fresnel Technologies, Inc. Fresnel lenses are made as thin as 0.005" (0.13 mm). Furthermore, lens thickness remains substantially constant across the lens. Apertures as large as f/0.5 can be used with little absorption loss (although thicknesses greater than 0.005" are generally needed for such small f–numbers) and the absorption loss also remains essentially constant across the lens.

The very large refractive index of such infrared materials as germanium leads either to substantial reflection losses or to the need for expensive antireflective coatings. POLY IR® materials have refractive indices of approximately 1.5, leading only to about 10% loss due to reflection at normal incidence even without coatings.

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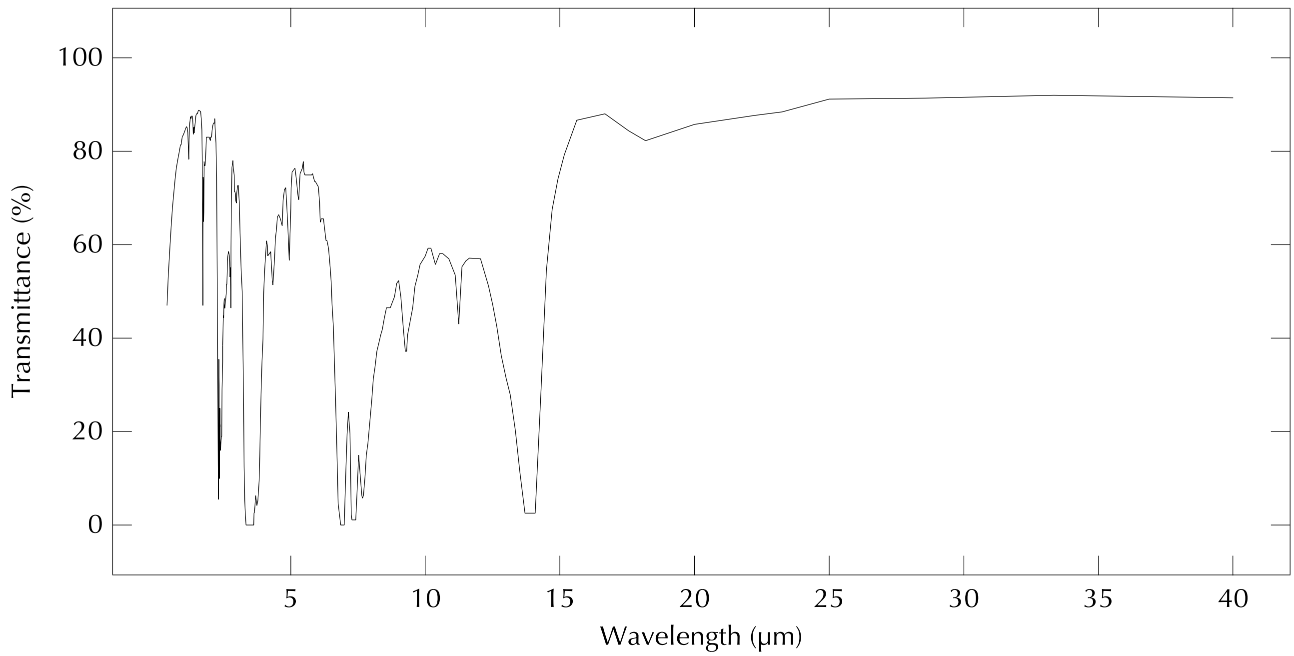

Figure 1. Transmittance of POLY IR® 1 material as a function of wavelength, including the visible and near–infrared portions of the spectrum. Sample thickness 0.38 mm (0.015" nominal).

LODIFF® lenses

A new lens has been developed by Fresnel Technologies, Inc. which has greatly improved optical properties. The LODIFF® lens has several unique characteristics that minimize optical aberrations: a totally aspheric surface, an aperiodic groove structure and constant depth grooves. These all combine to give the LODIFF® lens greatly improved performance over that of a conventional Fresnel lens, especially well into the infrared. Diffraction, transmittance, scattering, and imaging ability have all been improved. The development of the LODIFF® lens has been made possible by new techniques in computer–controlled diamond machining technology.

The conventional Fresnel lens has a constant number of grooves per unit radius. The LODIFF® lens, however, has a varying number of grooves per unit radius, with the number of grooves increasing toward the edge. This is done by keeping the depth of each groove constant. Thus in the center of a LODIFF® lens, there are very few grooves. This reduction in the number of grooves directly reduces the amount of scattering and diffraction into undesired directions. Groove reduction for a typical LODIFF® lens is estimated to be approximately 25%. This translates into an increase in the transmittance for the lens, because of the reduction of scattering.

The aspheric surface of the LODIFF® lens also plays a large role in reducing the aberrations caused by the lens, since a conventional Fresnel lens' grooves are actually conical. This conical groove shape leads to some of the light being refracted into a slightly incorrect direction, and thus to an increase in minimum spot size and increased aberrations. With the aspherical surface, however, all of the light is refracted in the desired direction, resulting in a smaller minimum spot size and therefore better image quality.

The LODIFF® lens is covered under U. S. patent Re. 35,534.

POLY IR® Materials

Fresnel Technologies, Inc. presently produces infrared–transmitting Fresnel lenses in seven materials: POLY IR® 1, 2, 3, 4, 5, 6 and 7. Each has its own domain of applicability. POLY IR® 1 material is an early attempt at a material for the 8 to 14 µm passive infrared range, and is no longer recommended for that use. However, it is superior to some other POLY IR® materials at shorter wavelengths, and may therefore be of some interest in applications other than passive infrared detection (and especially in multispectral applications). POLY IR® 2, 4, and 7 materials are recommended for use in the 8 to 14 µm passive infrared region. POLY IR® 3 material offers superior performance and a practically flat spectrum for wavelengths longer than 12 µm. POLY IR® 5 material transmits well through the visible region to about 4.2 µm. POLY IR® 5 material contains no hydrogen, and so is free from the strong 3.4 µm absorption characteristic of hydrocarbons (and present in all our other materials). POLY IR® 6 material is a visible light filtering, infrared–transmitting material with a sharp cutoff in transmittance at about 780 nm.

POLY IR® 1

POLY IR® 1 infrared–transmitting material is a soft, flexible, whitish plastic. Its primary characteristics are reasonable transmittance in the 8 to 14 µm region, low index of refraction (and hence small reflection loss), and extremely low price. POLY IR® 1 is not ultraviolet stabilized, and must therefore be protected from the sun's rays. The transmittance

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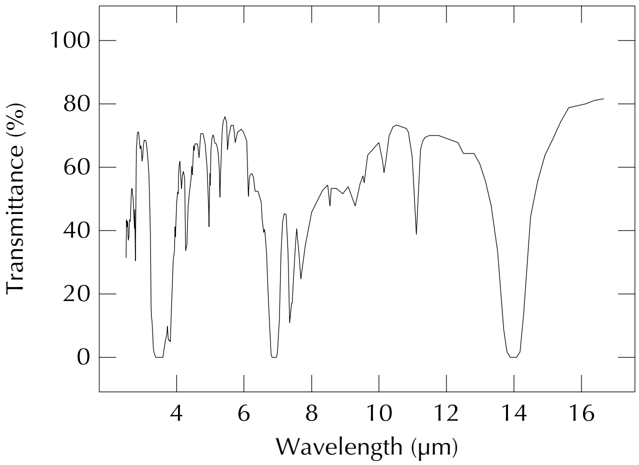

Figure 2. Transmittance of POLY IR® 2 material as a function of wavelength. Sample thickness = 0.38 mm (0.015" nominal).

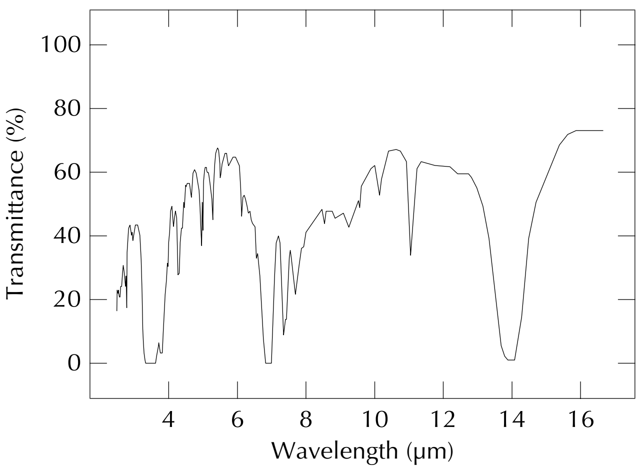

Figure 3. Transmittance of white POLY IR® 4 material as a function of wavelength. Sample thickness = 0.38 mm (0.015" nominal).

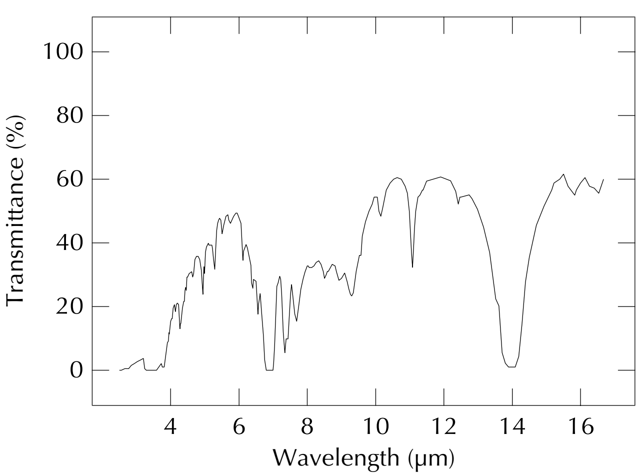

Figure 4. Transmittance of white POLY IR® 7 material as a function of wavelength. Sample thickness = 0.39 mm (0.015" nominal).

of POLY IR® 1 material between 0.4 and 40 μm is shown in Figure 1 for a nominal thickness of 0.015" (0.38 mm).

POLY IR® materials suitable for passive infrared use

The maximum contrast in emitted infrared radiation between a warm body (a human or a warm–blooded animal, for example) and the slightly cooler background normally found indoors or out occurs in the 8 to 14 μm region. This is the basis for many clever consumer electronics devices, from convenience lighting to security systems. Inherent properties of the pyroelectric detectors used in these devices produce maximum signals for warm bodies moving against the background; proper lens array design can further enhance these signals. These passive infrared devices, so called because the natural infrared emission from warm bodies is used (rather than radiation from artificial sources), constitute a very important class of Fresnel lens applications.

POLY IR® 2

POLY IR® 2 infrared–transmitting material is also a flexible, whitish plastic, but is substantially harder and more rigid than POLY IR® 1. It presently offers the least absorption loss in the 8 to 14 μm region of any of the POLY IR® materials. POLY IR® 2 material is ultraviolet stabilized, and has a lifetime of several years in full sun. The transmittance of POLY IR® 2 material between 2.5 and 16 μm is shown in Figure 2 for a nominal thickness of 0.015" (0.38 mm).

POLY IR® 4

POLY IR® 4 material is a pigmented version of POLY IR® 2 material. The pigmentation is not specifically intended as a filter for visible light, but rather as an aid in ultraviolet stabilization and for appearance. POLY IR® 4 material is available in a variety of colors and thicknesses. POLY IR® 4 material is ultraviolet stabilized, and has a lifetime of several years in full sun. There is no increase in transmission loss in the 8 to 14 μm region over that exhibited by POLY IR® 2 material for white POLY IR® 4 material, and minimal increases for the other colors. The transmittance of white POLY IR® 4 material between 2.5 and 16 μm is shown in Figure 3 for a nominal thickness of 0.015" (0.38 mm).

POLY IR® 7

POLY IR® 7 material is also a pigmented version of POLY IR® 2 material, but it is pigmented to reduce false alarms due to "white light." It is very effective in doing so, but shows an increased transmission loss in the 8 to 14 μm region of about 15 percent over POLY IR® 2 material or white POLY IR® 4 material. POLY IR® 7 material is available in a variety of colors and thicknesses. POLY IR® 7 material is not ultraviolet stabilized, and has an extremely short life outdoors (and an unacceptably short life in areas where sunlight entering windows or doors illuminates it). Dark grey POLY IR® 7 material has been used in some limited outdoor applications, but we do not recommend it. The transmittance of white POLY IR® 7 material between 2.5 and 16 μm is shown in Figure 4 for a nominal thickness of 0.015" (0.39 mm).

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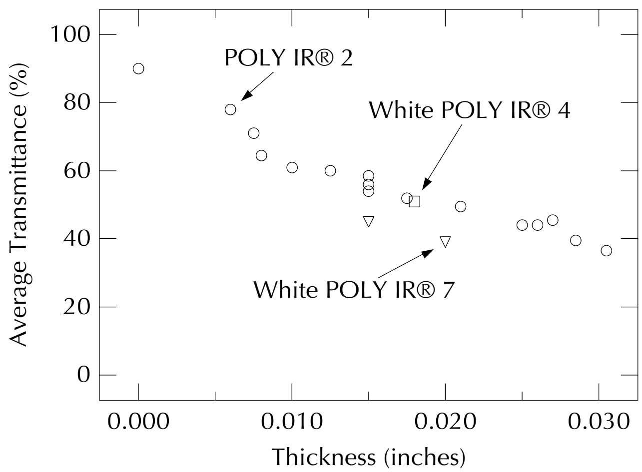

Figure 5. Average transmittance in the 8 to 14 µm region of POLY IR® 2, 4, and 7 materials as a function of their thickness.

Figure 5 shows the transmittance of POLY IR® 2, 4, and 7 materials in the 8 to 14 µm region as a function of their thickness.

POLY IR® materials for other applications

POLY IR® 3
POLY IR® 3 infrared–transmitting material offers superior performance at wavelengths beyond 12 µm. The spectrum of POLY IR® 3 material is practically flat for wavelengths longer than 12 µm. POLY IR® 3 material is not ultraviolet stabilized. The transmittance of POLY IR® 3 material between 0.4 and 16 µm is shown in Figure 6 for a nominal thickness of 0.020" (0.52 mm). Significant transmittance of POLY IR® 3 material in the 8 to 14 µm region occurs for wavelengths greater than 12 µm; the transmittance there is virtually independent of thickness.

POLY IR® 5
POLY IR® 5 material contains no hydrogen, and so is free from the strong 3.4 µm absorption found in all hydrocarbon plastics materials. POLY IR® 5 material is suitable, for instance, for process monitoring at about 3.4 µm; it is clear in the visible as well. POLY IR® 5 material is ultraviolet stable. The transmittance of POLY IR® 5 material between 0.4 and 16 µm is shown in Figure 7 for a nominal thickness of 0.030" (0.81 mm).

POLY IR® 6
POLY IR® 6 material is a visible light filtering, infrared–transmitting plastic. The spectrum of POLY IR® 6 material has a sharp cutoff at a wavelength of about 780 nm; the material appears virtually black in visible light. The transmittance of POLY IR® 6 material between 0.3 and 2.2 µm is shown in Figure 8 for a nominal thickness of 1/8" (2.8 mm).

Physical and chemical properties of interest for all seven POLY IR® materials are listed in the table on the back page.

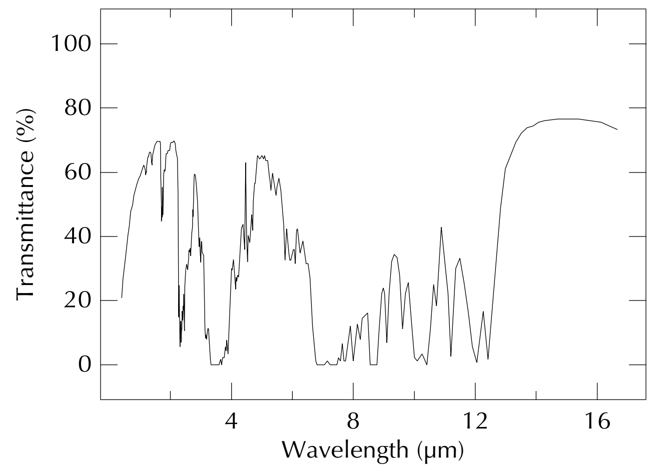

Figure 6. Transmittance of POLY IR® 3 material as a function of wavelength. Sample thickness = 0.52 mm (0.020" nominal).

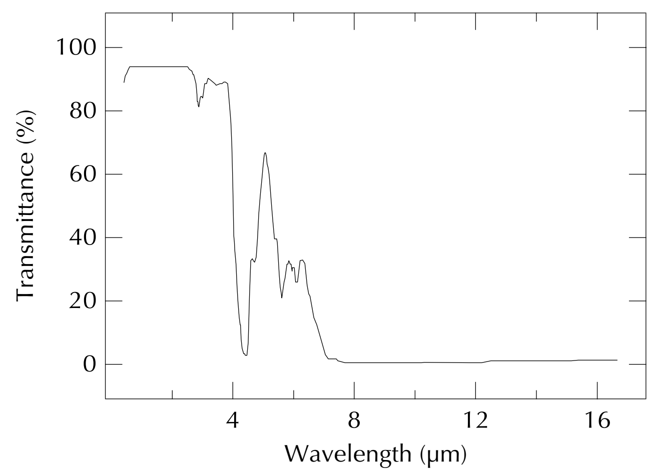

Figure 7. Transmittance of POLY IR® 5 material as a function of wavelength. Sample thickness = 0.81 mm (0.030" nominal).

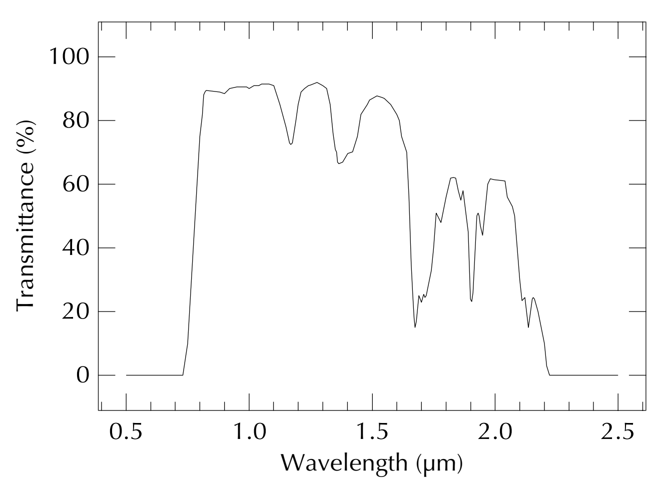

Figure 8. Transmittance of POLY IR® 6 material as a function of wavelength. Sample thickness = 2.8 mm (1/8" nominal).

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Available Fresnel Lens Types

Fresnel Technologies, Inc. has the largest catalog of standard Fresnel lens types in the industry. A copy of the most recent catalog is included with this brochure. Most lenses in our catalog can be produced satisfactorily from most POLY IR® materials. Exceptions include those which must be made with substantial thickness, i.e., lenses with a coarse groove pattern and a low f–number, such as #18.2 and #53, and our 11" (280 mm) square types which use molds unsuitable for the materials in this brochure. Lens arrays which are made up of sizable conventional lenses, such as #200 and #300, also cannot be satisfactorily made from POLY IR® materials.

The cataloged focal lengths apply to a refractive index of 1.49. The focal lengths of POLY IR® material lenses in the infrared are obtained by multiplying by (1.49 – 1)/(n – 1), where n is the refractive index listed in the table of properties on the back page of this brochure.

POLY IR® Lens Design Tradeoffs

The design of an infrared–transmitting Fresnel lens involves many complex considerations. A few hints follow.

The grooved side of a Fresnel lens should face the longer conjugate (away from the detector when used to collect radiation). If the smooth side needs to face the longer conjugate for some nonoptical reason, the maximum aperture of the lens should be f/1. In this case, total internal reflection keeps all radiation from the area of the lens past f/1 from reaching the image. Even when the grooves face the longer conjugate, the portion of the lens past f/1 contributes a diminished amount and there is no significant contribution past f/0.5.

Conjugates

The two points, one on either side of a positive focal length lens, at which light is focused are called "conjugates." Nearly all the conventional Fresnel lenses in the Fresnel Technologies, Inc. catalog are correct for the case of conjugates of the focal length and infinity, with the grooved side toward the infinite conjugate. The conjugates are listed among the lens specifications in the catalog. In the case of LODIFF® lenses, the lenses listed in the catalog are all correct for conjugates of the focal length and infinity, but are about evenly divided between having the infinite conjugate on the grooved side and having the infinite conjugate on the smooth side. There are many cases which require conjugates other than the focal length and infinity—copy lenses, relay lenses, field lenses, and condenser lenses are common examples. In these cases both of the foci are at finite distances from the lens; hence the term "finite conjugates." Several of our Fresnel lenses are correct for finite conjugates in the ratio 3:1, with the grooved side toward the longer conjugate. The values of the conjugates for a given focal length f may be determined from the equation $1/f = 1/i + 1/o$ (where i and o are the image and object distances, i.e. the conjugates), and are found to be 4f and 4f/3 for the conjugate ratio 3:1. Even though a lens may be designed for conjugates in the ratio 3:1, it can be used at other finite conjugate ratios as well. The error introduced is usually reasonably small.

The thinnest possible POLY IR® material should be used, to maximize transmittance. Unfortunately, there are restrictions on the thickness of the material brought about by the nature of the lens chosen. A lens with a large groove density can be made from thin material, because there is little relief to the grooves. However, a large groove density can lead to diffraction problems. As a general rule, 125 grooves per inch should be the maximum groove density for lenses used in the 8 to 14 μm region.

Fresnel lenses with a large f–number can also be made thin, because the central region of a lens has a surface contour which is relatively flat. Unfortunately, most users of infrared–transmitting lenses prefer lenses with low f–numbers, since they collect radiation most effectively. The data of Figure 5 can be used to determine if there is an advantage to reducing the thickness of a lens to the next thinner POLY IR® material by reducing its diameter.

We have also found that diffraction losses for wavelengths longer than 8 μm become extreme for focal lengths longer than about 6" (150 mm). We do not recommend such long focal lengths for application at 8 μm and beyond; they are successful, however, in shorter wavelength applications such as those for which POLY IR® 5 material is suited.

Special Services

Fresnel Technologies, Inc. discourages the production of new focal length lenses, i.e., those not presently cataloged. However, we will be pleased to produce lens arrays of any desired complexity from cataloged masters, as well as tooling to produce standard types most economically for quantity orders.

Fresnel Technologies, Inc. will be pleased to assist you in selecting the best lens and material for your application. Please call or write to discuss your needs.

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Properties of POLY IR® Materials

	POLY IR® 1	POLY IR® 2	POLY IR® 3	POLY IR® 4	POLY IR® 5	POLY IR® 6	POLY IR® 7
Index of refraction visible (sodium D line)	1.52	1.53	1.50	1.53	1.425	1.49 at 1 μm	1.53
8–14 μm	1.53	1.54	—	1.54	—	—	1.54
beyond 15 μm	1.48	1.48	1.50	1.48	—	—	1.48
Tensile modulus 10^3 PSI	14–38	60–180	165–225	60–180	150–300	350–450	60–180
Flexural modulus 10^3 PSI	8–60	100–260	170–250	100–260	170–250	390–470	100–260
Hardness	D40–50 (Shore)	D60–70 (Shore)	R85–110 (Rockwell)	D60–70 (Shore)	R80 (Rockwell)	M80–100 (Rockwell)	D60–70 (Shore)
Thermal expansion 10^{-5}/°C	10–20	11–13	6–10	11–13	4.5–7	5–9	11–13
Service temperature, °C	65	100	120	100	70*	80	100
Effect of sunlight	crazes rapidly	none	crazes rapidly	slight	none	none	crazes rapidly
Effect of weak acids	little	very little	none	very little	none	none	very little
Effect of strong acids	attacked by oxidizing acids	attacked by oxidizing acids	attacked slowly by oxidizing acids	attacked by oxidizing acids	none	attacked by conc. oxidizing acids	attacked by oxidizing acids
Effect of weak alkalies	little	very little	none	very little	none	none	very little
Effect of strong alkalies	little	very little	very little	very little	none	attacked	very little
Effect of organic solvents	little	little below 60°C	little below 80°C	little below 60°C	slight	sol. in ketones, esters, and some hydrocarbons	little below 60°C

* POLY IR® 5 material becomes flexurally weak above 70° C, i.e., its heat deflection temperature is very low even for the small stresses normally encountered in mounted lenses. Unless you take special precautions to avoid such stresses, we do not recommend that POLY IR® 5 material be used above 70° C even though its other properties, both physical and optical, are good to 135° C. POLY IR® 5 is a very frustrating material: one with good high-temperature properties which cannot be used at high temperatures.

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