Critical Review Vol. CR43, Optomechanical Design, ed. P.R. Yoder, Jr. (July 1992) Copyright SPIE

What's Different about Ultraviolet and Infrared Optics?

R. Barry Johnson
Center for Applied Optics
University of Alabama in Huntsville
Huntsville, Alabama 35899

Abstract

The design and fabrication of components comprising ultraviolet and infrared optical systems require the same general engineering considerations to be given. In actuality, a variety of significant differences exist in the magnitude of considerations for optical systems in these two spectral regions. Among these are the optical materials available for use, surface finish, mechanical and optical fabrication techniques, housing and mounting methods, alignment and test, and cost. This paper contrasts and compares the practical issues facing the designer, fabricator, and assembler dealing with optical systems for the ultraviolet and infrared spectrums.

1 Introduction

The design and fabrication of components comprising ultraviolet and infrared optical systems require the same general engineering considerations to be given. So what's different about UV and IR optics from a practical point of view? The objective of this paper is to address this question.

In actuality, a variety of significant differences exist in the magnitude of considerations for optical systems in these two spectral regions. Among these are the optical materials available for use, surface finish, mechanical and optical fabrication techniques, housing and mounting methods, alignment and test, and cost. In the following sections, these considerations will be explored.

2 Optical Materials

The UV spectrum can be divided into several portions, viz., 400–300 nm (near ultraviolet), 300–200 nm (far ultraviolet), and $<$ 200 nm (deep ultraviolet). In a like manner, the infrared spectrum can be segmented into different parts, viz., 0.7–3 μm (near infrared), 3–6 μm (middle infrared), 6–15 μm (far infrared), and > 15 μm (extreme infrared). The most obvious point is the large difference in the wavelengths — a wavelength ratio of about 10 for the middle-infrared to the near-ultraviolet spectrums exemplifies this point.

The number of optical materials available for the different portions of the spectrum varies greatly with the smallest number being in the ultraviolet and the greatest being in the visible. The visible and near-infrared regions are dominated by glasses whereas crystalline materials dominate the other spectral regions. Figure 1 illustrates the approximate number of optical materials available as a function of wavelength.[1] It is evident that the richness in materials falls off rapidly for wavelengths < 300 nm and > 10 μm. In this sense, infrared and ultraviolet optical systems share the same limitation. However, the range of refractive index and the maximum value are much lower for the ultraviolet than for the infrared. This is graphically illustrated in Fig. 2 which shows the approximate upper and lower boundaries for the refractive index as a function of wavelength.[1] The lesser upper values of refractive index for ultraviolet materials tend to require more lens elements than for an equivalent infrared lens system. On the other hand, the lower refractive index produces less surface reflection losses for the ultraviolet optics; but, coatings become more difficult as the wavelength shortens. A rather significant difference between ultraviolet and infrared materials is the dispersion. Figure 3 illustrates the approximate upper and lower boundaries of the dispersion ($\frac{dn}{d\lambda}$) as a function of wavelength.[1] It is readily apparent that ultraviolet materials are much more dispersive than infrared materials.

Fused or synthetic silica is the most commonly used glass for wavelengths greater than 170 nm. Other commonly-used UV-materials include calcium fluoride, lithium fluoride, and magnesium fluoride. Significant research and development of fluorocrown glasses with relatively low refractive indices and dispersions have occurred during the past few years. Examples of such glasses are the Schott Ultran series of ultraviolet glasses. These glasses provide an alternative to the crystalline materials typically used to chromatically correct lens systems incorporating silica.

A problem suffered by ultraviolet materials, and to a much lesser degree by infrared materials, is solarization. This is a serious problem faced by designers of lenses to be used in microlithography applications. In the infrared, internal absorption is often the limiting factor when refractive ma-

---

[1] Figure prepared by Dr. Chen Feng of the Center for Applied Optics at the University of Alabam in Huntsville.

terial is used for high-power infrared laser optics.

A modest variety of materials are available for use in the infrared spectrum. Most popular of the crystalline materials are germanium, silicon, sapphire, and CVD-processed zinc selenide and zinc sulfide. Several special glasses have been developed with the chalcogenides being somewhat more useful. Others include calcium aluminate glasses, germanate glasses, metal fluorides and oxides. Several of these materials can be used together to form color corrected lens systems.

3 Structural Materials

Generally speaking, the structural materials used for both ultraviolet and infrared optical systems are the same. The principal difference is that the precision and dimensional stability requirements for ultraviolet systems are much more exacting than for infrared systems. The reason is basically due to the large ratio in wavelengths between these two spectrums.

Selection of the structural materials is affected by the coefficient of thermal expansion (CTE) of the optical materials. The value of the CTE for the optical materials varies from almost zero to over $50 \cdot 10^{-6}/^oC$. CTE values for popular optical materials used in the ultraviolet or infrared spectrums are fused silica $(0.5 \cdot 10^{-6}/^oC)$, silicon $(4.2 \cdot 10^{-6}/^oC)$, germanium $(6.1 \cdot 10^{-6}/^oC)$, sapphire $(6.7^p \cdot 10^{-6}/^oC$ and $5^s \cdot 10^{-6}/^oC)$, zinc selenide $(7.8 \cdot 10^{-6}/^oC)$, chalcogenides (e.g., AMTIR-1, $13 \cdot 10^{-6}/^oC$), calcium fluoride $(24 \cdot 10^{-6}/^oC)$, and lithium fluoride $(37 \cdot 10^{-6}/^oC)$[2]. The CTE for structural materials ranges from about $2 \cdot 10^{-6}/^oC$ to over $25 \cdot 10^{-6}/^oC$. Four commonly used materials and their CTE values are 6061 aluminum $(23.6 \cdot 10^{-6}/^oC)$, 17-4 PH stainless steel $(10.8 \cdot 10^{-6}/^oC)$, Invar $(0.9 \cdot 10^{-6}/^oC)$, and titanium $(8.6 \cdot 10^{-6}/^oC)$.

In addition to the CTE of the structural materials, the refractive index of the optical materials varies as a function of temperature. For example, the temperature coefficient of refractive index (TCRI) is $6.7 \cdot 10^{-5}/^oC$ for germanium, $3.9 \cdot 10^{-5}/^oC$ for silicon, $-1.6 \cdot 10^{-5}/^oC$ for lithium fluoride, and $-9 \cdot 10^{-5}/^oC$ for calcium fluoride. As the temperature of an optical system varies, the optical designer faces a significant challenge to maintain the focal length and focus as a consequence of the differences in CTE and TCRI of the materials comprising the optical system. Generally, maintaining focus is the only objective although holding the value of the focal length can be of importance in certain applications.

---

[2] W. L Wolfe, *Handbook of Military Infrared Technology*, Office of Naval Research, Washington (1965).

Over the years, much effort has been expended to create designs that achieve these objectives. In general, passive techniques are employed for infrared optics while active means are often needed for high precision ultraviolet optics. As can be readily shown[3] the combined effects of CTE (α) and TCRI ($\frac{\partial n}{\partial T}$) cause a defocus ($\delta$) for a single lens with a focal length of f in a housing of overall length L of

$$\delta = \left[-\frac{f}{n-1}\frac{\partial n}{\partial T} + \alpha f + \alpha L \right] \Delta T.$$

Passive techniques usually involve the use of materials with high thermal expansion coefficients arranged in a manner such that the focal shift is eliminated. In practice, this is difficult to attain in the infrared and almost impossible in the ultraviolet. Recalling that for a lens with a numerical aperture of NA the Rayleigh criterion for resolution ($\mathcal{R}$) is

$$\mathcal{R} = \frac{0.61\lambda}{NA}$$

and that the Rayleigh depth of focus ($\mathcal{D}$) is given by

$$\mathcal{D} = \frac{\pm\lambda}{2(NA)^2},$$

the strong influence of wavelength is evident. Since ultraviolet microlithographic lenses and infrared lenses often have F/#'s near unity, the resolution and depth of focus differences are due to wavelength. For example, if the $NA = 0.48$, then $\mathcal{R} = 0.61\ \mu m$ and $\mathcal{D} = \pm 0.71\ \mu m$ for an ultraviolet lens[4] operating at $0.365\ \mu m$ and $\mathcal{R} = 12.7\ \mu m$ and $\mathcal{D} = \pm 21.7\ \mu m$ for an infrared lens operating at $10\ \mu m$. Clearly, the focus stability requirement with temperature changes is about 30 times tighter for the ultraviolet optics than the infrared optics. Consequently, the engineering demands for a passive optomechanical design to maintain focus for an ultraviolet lens system is very difficult to achieve (if not impossible) over a reasonable temperature range. On the other hand, infrared optical systems with passive thermal compensation can and have been designed and constructed[5] although substantial attention to the CTE and TCRI of the materials must be given.

High-performance ultraviolet lenses require that they be operated within a very narrow temperature range or that some form of active mechanical

---

[3] J. M. Lloyd, *Thermal Imaging Systems*, Plenum Press, New York, pp 257–267 (1975)

[4] The resolution for a microlithographic lens includes a multiplicative factor that expresses the process dependent aspect of the lithographic process A typical value of 0.8 was used in this case.

[5] P. J. Rogers, "Athermalization of IR Optical Systems," Proc SPIE, Vol CR38, pp.69–94 (1991).

athermalization be used.[6] Active means include the use of temperature sensors that provide input for the computation of mechanical compensation. This is often implemented by motors, piezo-electric, etc., devices. It should be noted that infrared optics sometimes include active athermalization although the accuracy of the movements is much less demanding than for the ultraviolet case.

4 Lens Configurations

Both ultraviolet and infrared optical systems share several common features, viz., the use of all-reflective optics, catadioptric optics, and relatively few optical elements. Figure 4 shows the configuration of a catadioptric objective lens for an infrared scanner along with the "eyelens," scanner, and imaging lens.[7] The next figure illustrates an ultraviolet catadioptric microscope objective of the basic Schwarzschild class.[8] Figure 6 contains a rendering of a five-element ultraviolet lens used in the 0.2–0.4 μm spectrum.[9] The lens is made of CaF_2 and quartz, has a focal length of 5.0 inches, the F/# is 4.0, and the total field of view is 10 degrees. In general, infrared optics have a much larger field-of-view than ultraviolet optics whereas ultraviolet optics have a much tighter tolerance on field flatness and distortion.

An example of an athermalized infrared zoom lens with a magnification range of 3.5–20 power is shown in Fig. 7.[10] This lens is made of germanium, zinc selenide, and zinc sulfide. Athermalization is accomplished by combining lens groups that are each athermalized about the central movable elements that are used for the zoom function. The elements comprising the first and third lens groups shown in Fig. 7 are made of germanium, zinc selenide, zinc selenide, and zinc sulfide. Specific details of how to realize passive athemalization is taught in the patent. Unfortunately, this type of passive athermalization is not viable for ultraviolet optics due to the lack of appropriate optical materials.

A typical projection optical system for submicron lithography is illustrated in Fig. 8.[11] The complexity of the optical system is similar to that of the more sophisticated infrared optical systems. The fabrication and alignment precision required by the intermediate and wafer triplet assemblies is far bet-

---

[6] A. Ahmad, "High Resonance Adjustable Mirror Mounts," Proc. SPIE, Vol 1167, pp 313–317 (1989).

[7] U.S. Patent 4,432,596 (1984)

[8] J. R. Benford, "Microscope Objectives," in *Applied Optics and Optical Engineering*, R. Kingslake Ed., Academic Press, New York, pp. 172–174 (1965).

[9] Adapted from M. Laikin, *Lens Design*, Marcel Dekker, New York, pp. 198–199 (1991).

[10] U.S. Patent 4,679,891 (1987).

[11] Private communication from A. Ahmad.

ter than for infrared optical systems. The wafer triplet assembly is shown in its housing in Fig. 9. The tolerances are so exacting that the housing must be diamond turned and the alignment of the elements is accomplished on an air bearing table. Each optical element is carefully measured in order that the housing can be modified to compensate for optical fabrication errors. Tolerances can be as small as 0.5 μm. Infrared optical systems rarely have housing related mechanical tolerances tighter than 10 μm. Consequently, the effort to construct and align these optical systems is significantly greater for ultraviolet optics. Yoder[12] and Ahmad[6,13] have discussed many of the issues concerning design, fabrication, and alignment of mechanical systems for optics.

The use of binary or diffractive optical surfaces for infrared optical systems is gaining popularity.[14] Although the performance is adequate in the infrared spectrum, this surface form cannot be used in the ultraviolet due to material and fabrication limitations.

5 Coatings

Effective coatings for antireflection, bandpass, etc. require that appropriate materials be available from which coatings can be constructed. The number of materials available for coatings in the ultraviolet and infrared spectrums is limited to approximately the same number as can be used to construct lenses. Even with this limitation, coating designers and engineers have been able to produce excellent coatings throughout the infrared spectrum and over much of the ultraviolet spectrum. Although almost any functional coating type can be realized in the infrared, in the ultraviolet spectrum antireflective coatings are not available for wavelengths below about 250 nm. In this spectral region, only bandpass filters can be made, but with great difficulty and expense. Special fabrication techniques have been developed in order to make even these filters with adequate transmission and out-of-band rejection.

Reflective coatings in the infrared are relatively straightforward and typically use gold, aluminum, or enhanced silver. In the ultraviolet, the reflectivity of useful coating materials, such as UV-enhanced aluminum, is limited to wavelength greater than 150 nm.[15] Special coating stacks can be designed

---

[12] P. R. Yoder, Jr., *Opto-Mechanical Systems Design*, Marcel Dekker, New York (1986).

[13] A. Ahmad, "Fabrication techniques for high-resolution lens assemblies," Proc. SPIE, Vol. 1335, pp.194–198 (1990).

[14] M. J. Riedl and J. T. McCann, "Analysis and Performance Limits of Diamond Turned Diffractive Lenses for the 3– and 8–12 Micrometer Regions," Proc. SPIE, Vol CR38, pp.153–163 (1991)

[15] S. Musikant, *Optical Materials*, Marcel Dekker, New York, pp. 194–197 (1985)

that yield a reflective surface over a very narrow spectrum in the far and deep ultraviolet spectrums.

6 Fabrication and Test

Fabrication of the optical elements used in the ultraviolet and infrared spectrums is typically accomplished using conventional grinding and polishing techniques. Infrared optics are being made on an increasing basis by diamond-turning methods; however, the as-turned surface quality is simply inadequate for ultraviolet applications. In some cases, diamond turning is used to prepare the base substrate for an ultraviolet mirror that will be subjected to additional processing. For example, an aluminum substrate might be diamond turned, then overcoated with nickel, diamond turned again, and then post polished to remove the residual machining marks and surface roughness. An appropriate reflective coating is then deposited. This process provides a means to attain surfaces that have low light-scattering properties. Figure 10 presents the theoretically predicted levels of scattered light as a function of surface roughness and wavelengths covering both the ultraviolet and infrared regions.[16] Typical types of surface polish are indicated by the dashed lines. As can be seen from the figure, the relationship between surface roughness and wavelength for a constant amount of scattered light is directly proportional. This implication is that ultraviolet optical surfaces require greater care and quality than is necessary for infrared optical surfaces. Cost and schedule seem to grow exponentially with decreasing surface roughness.

Because of the very high quality surfaces needed for ultraviolet optics, conventional polishing methods are essentially the only option. The fundamental surface figure requirements are about the same for both ultraviolet and infrared optics, e.g., $\frac{\lambda}{4}$; however, the physical scale is extremely different. At 365 nm, the physical displacement is 91 nm while at 10 μm the displacement is 2,500 nm! Testing of surface figure is more difficult for ultraviolet optics since the wavelength of the light used in a typical surface measuring interferometer is about two or so times greater. This means that the fringe sensitivity is reduced by the wavelength ratio. The converse is true for infrared optics, i.e., testing of the surface is much easier. In a like manner, the same is true for system level testing (resolution, MTF, etc.).

Measurement of scattered flux from the surface of the optics or from the entire lens assembly is significantly more challenging for ultraviolet optics than for infrared optics. One of the most basic problem in testing ultraviolet optics is that as the wavelength shortens, the atmospheric absorption

---

[16] H. Bennett, "Optical properties of optical materials," Opt Eng. **17**(5) (1978).

dramatically increases to such a degree that measurements must be made in a vacuum environment. Although a number of facilities exist that can measure infrared optics, by comparison, very few are available for testing ultraviolet optics. For example, to the author's knowledge, quality measurement of the scattered flux in the deep ultraviolet from a surface can be measured only at NASA Marshall Space Flight Center.

The parts comprising mounts and housings for the optical systems typically are fabricated by standard machine shop equipment. In order to achieve the highest performance levels for ultraviolet optics, the parts must often be hand lapped and/or diamond turned. For example, improvements in microlithographic lens design and manufacturing methods have produced improvements in the number of pixels per image field of over an order of magnitude during the past decade.[17] Although the precision required for infrared optics is lower, diamond-turned mechanical components are used as a means to reduce overall fabrication and alignment costs.

7 Conclusions

Ultraviolet and infrared optics share many common features and characteristics while at the same time having a number of practical differences. For the most part, these differences can be directly related to the large difference in wavelength between the two optical spectrums and the environments in which they operate. The most exacting ultraviolet applications requires that the optical system be maintained within a very narrow temperature range in a clean room whereas a precision military FLIR *must* operate over a broad temperature range in often hostile environments. Another interesting difference is that polarization and partial coherence are of little importance in infrared optics, but are often of great significance in the ultraviolet. For example, the partial coherence specified for the Zeiss 10-78-65 lens for i-line microlithography is 0.61. Also, ultraviolet optical systems do not suffer the narcissus problem that many infrared system must address.[18]

Continued interest and application of the ultraviolet spectrum will result in further improvement of fabrication, alignment, and test methods and techniques. Optics for the infrared will reap the benefit of these developments — but the differences will remain.

---

[17] W. H. Arnold, A. Minvielle, K Phan, B. Singh, and M. Templeton, "0.5 Micron Photolithography using High Numerical Aperture I-Line Wafer Steppers," Proc. SPIE, Vol. 1264, pp. 127–142 (1990)

[18] E. Ford and D. Hasenauer, "Narcissus in current generation FLIR systems," Proc. SPIE, Vol. CR38, pp. 95–119 (1991).

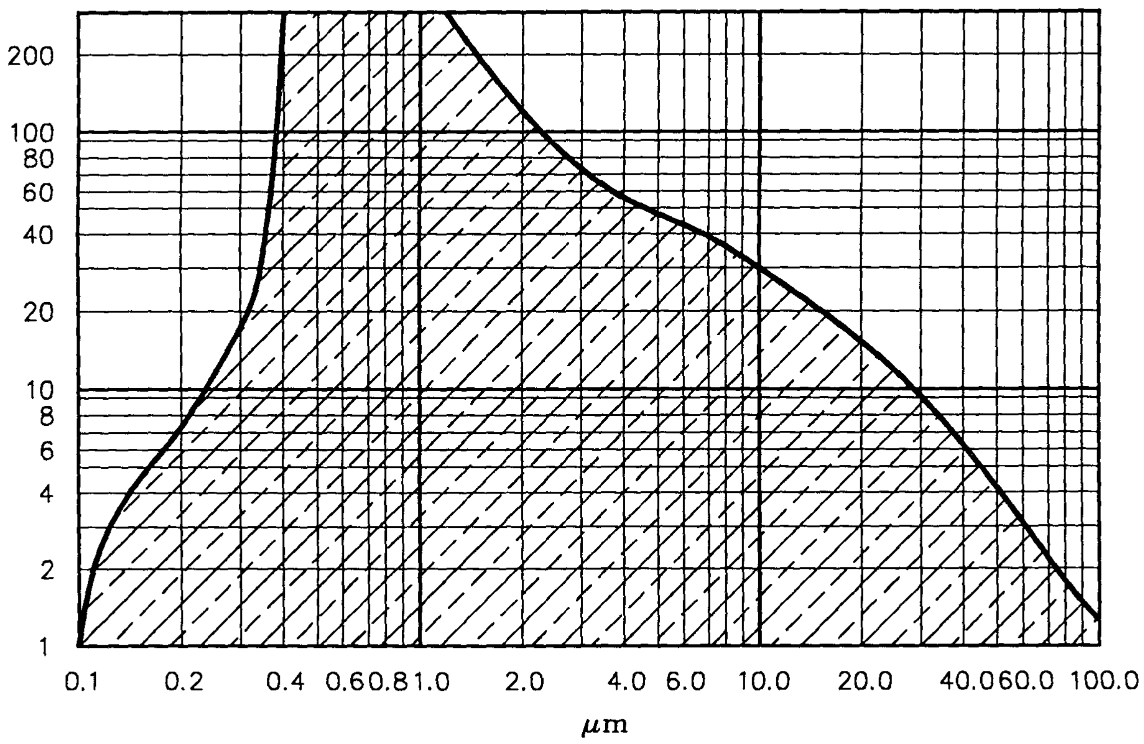

Figure 1. Approximate distribution of optical materials available at wavelengths from the ultraviolet to infrared spectrums.

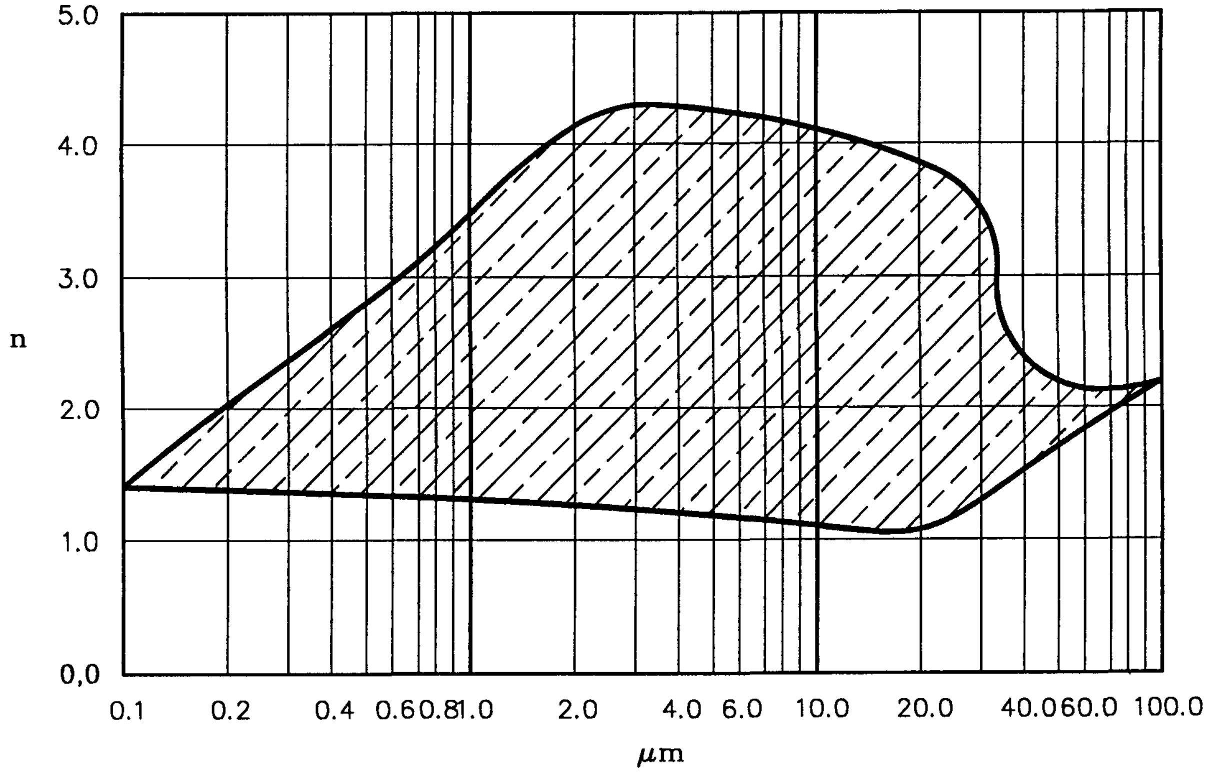

Figure 2. Approximate upper and lower boundaries of the refractive index of optical materials as a function of wavelength.

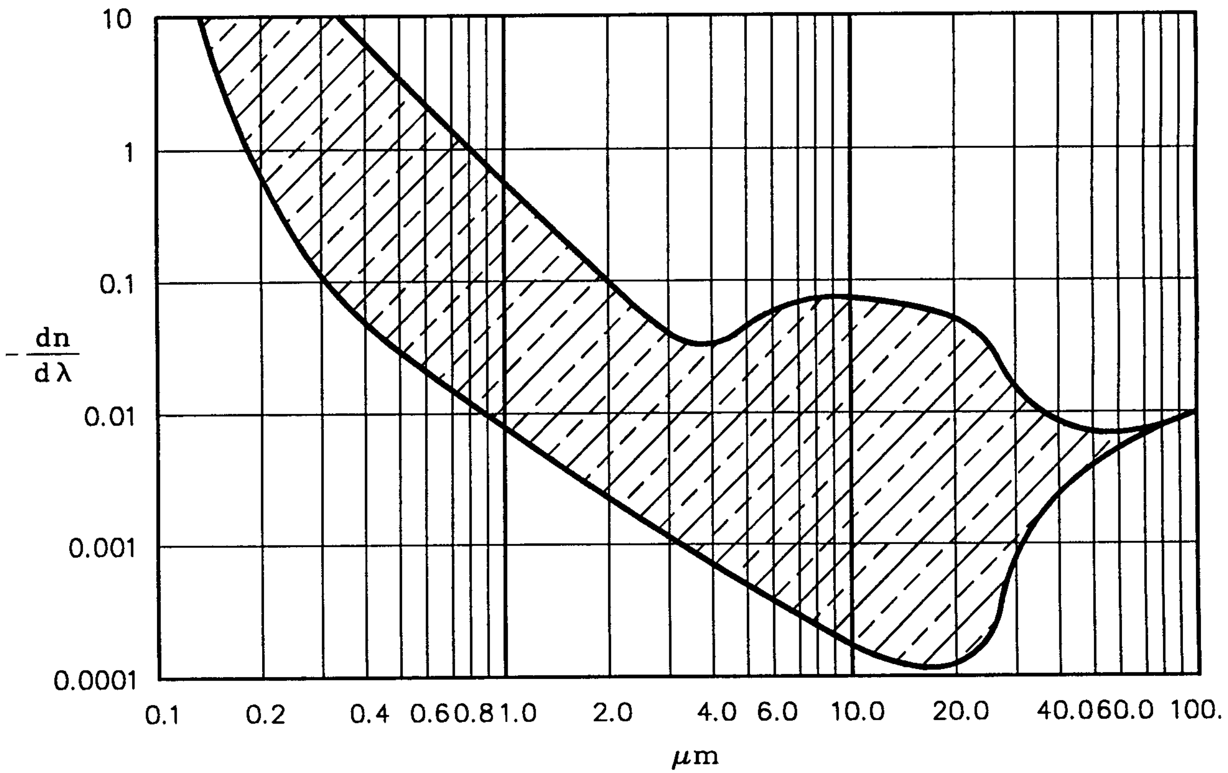

Figure 3. Approximate upper and lower boundaries of the dispersion of optical materials as a function of wavelength.

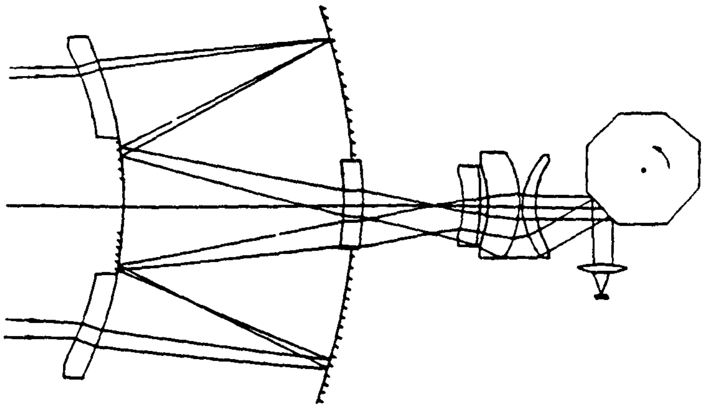

Figure 4. Catadioptric optical system for an infrared scanner.

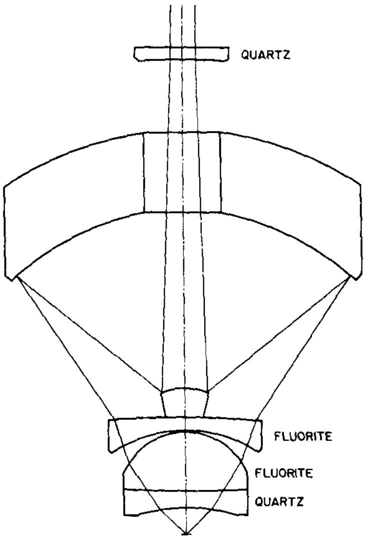

Figure 5. Ultraviolet catadioptric microscope objective.

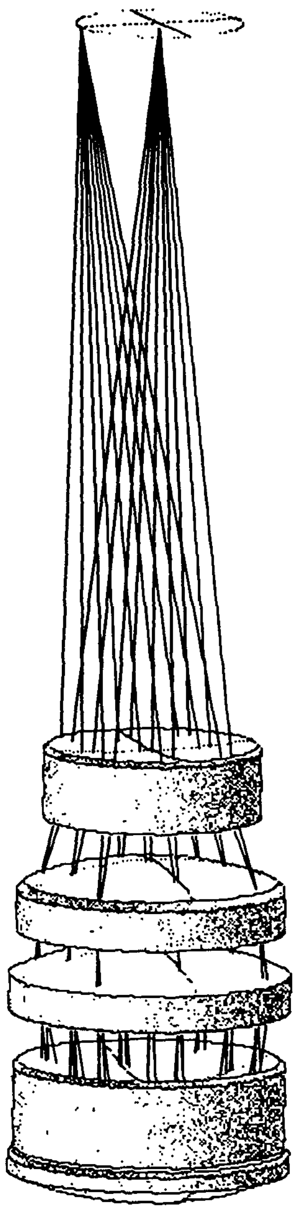

Figure 6. F/4 ultraviolet lens for use in the 0.2–0.4 μm spectrum.

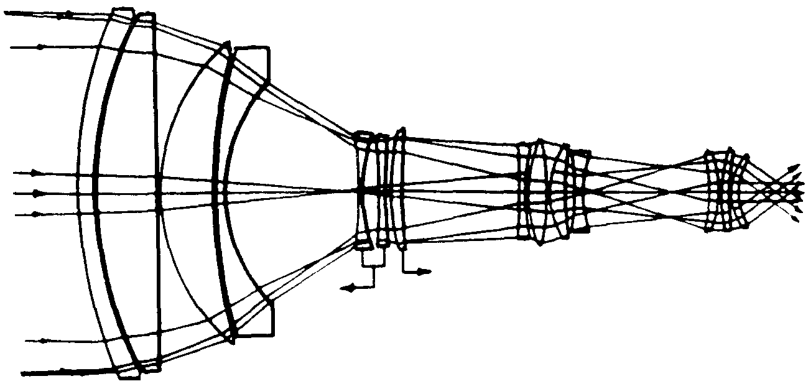

Figure 7. Athermalized infrared zoom lens.

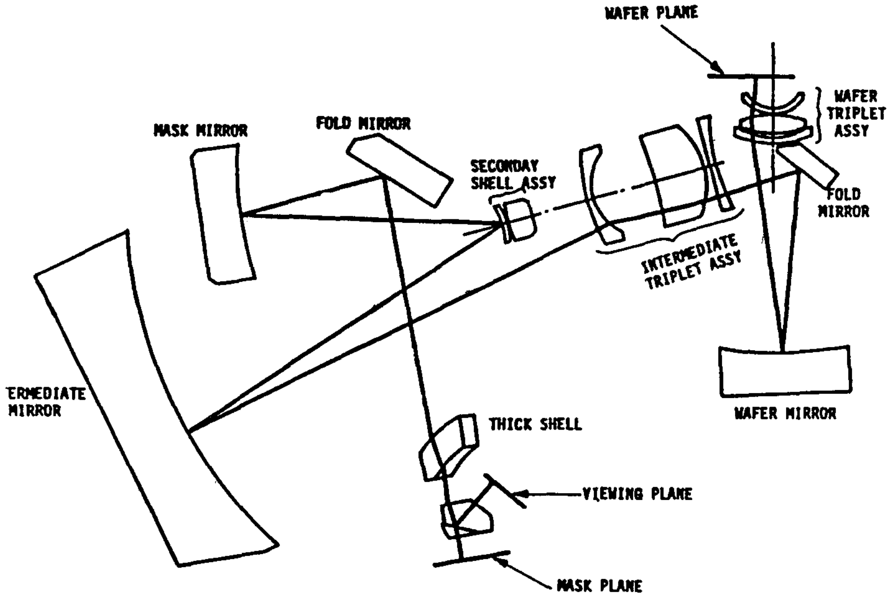

Figure 8. Projection optical system for submicron lithography.

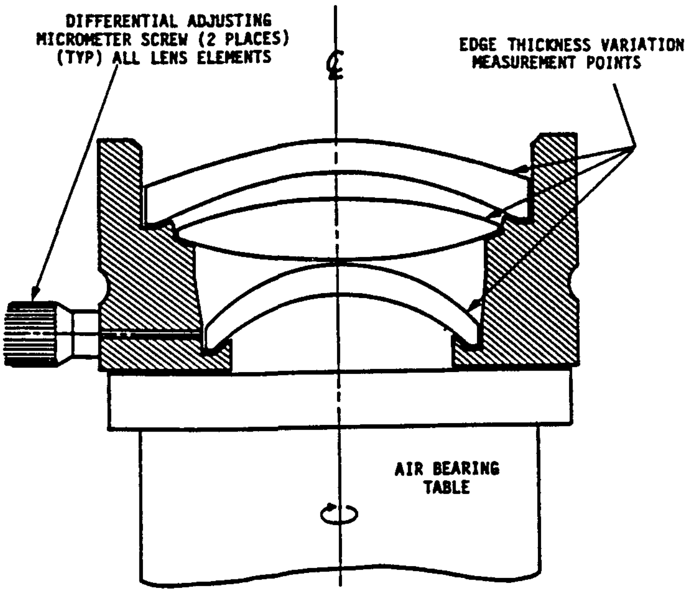

Figure 9. Wafer triplet assembly and housing for the projection optical system for submicron lithography shown in Fig. 8.

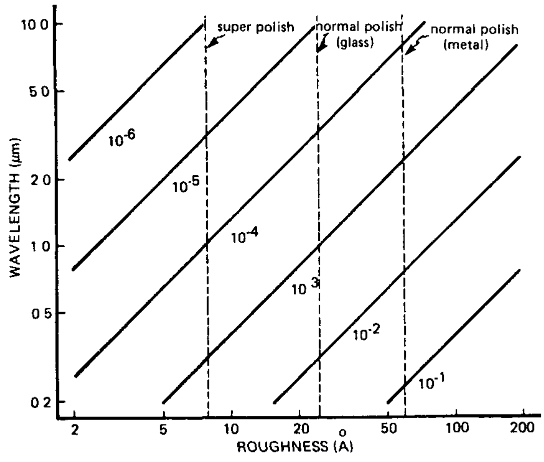

Figure 10. Theoretically predicted levels of scattered light as a function of surface roughness and wavelength covering both the ultraviolet and infrared regions.