Selection of Materials for UV Optics

James Johnson

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Abstract

Ultraviolet technology is seeing an increase in demand with many industries needing the ability to use non-x-ray short wavelengths. Key industries include lithography where writing smaller traces is the key to staying viable. When considering the design of ultraviolet optics, the materials available are far fewer than for the visible range. This makes the selection trade offs for each material that much more important. The goal here is to explore the issues facing UV materials and take a closer look at Fused Silica, Calcium Fluoride, Magnesium Fluoride, Sapphire and Aluminum as suitable choices.

1 Ultraviolet considerations

Ultraviolet light is considered any wavelength from 300 *nm* down to 10 *nm*. This is very energetic light. It can be shown that

$$E = \hbar\omega = \frac{2\pi\hbar c}{\lambda} \tag{1}$$

For a material to be considered transparent, there cannot be an atomic absorption resonance at the desired wavelength. The difficulty in finding acceptable UV transparent materials for refractive optics is due to the high energy of the photons. Few materials have a large enough energy gap to avoid any absorption.

Absorption follows the Beer-Lambert Law of exponential decay based on the length of material the light passes through.

$$I = I_0 e^{-\alpha L} \tag{2}$$

where α is the absorption coefficient per unit length and L is the total length of the material. Longer materials will see more attenuation. This also makes it possible to use very thin lenses to make UV optics. Candidate materials for Transmissive UV optics include Fused Silica, Quartz, Vycor, some formulations of Pyrex, Sapphire and a variety of fluoride compounds.

High absorption also results in another effect due to UV: damage. UV photons can have enough energy to ionize an atom or change its chemical structure. This process, known as solarization, results in a decreased transmission and a change in color of the substrate material.

Scattering is another problem for producing UV optics. Where a 5% surface height error is acceptable for a visible wavelength surface($\lambda/10 \approx 50nm$), well within a reasonable manufacturing range. The same height error for UV light is closer to 25%. Rayleigh scattering increases at $1/\lambda^4$ leading to much larger effects in the UV. Height errors must be very tightly controlled for good optics.

2 Choosing A Material

The system's operating wavelength will be the primary deciding factor in choosing a material. Most materials will have a sharp cutoff wavelength, where absorption begins, and how far into the UV the cutoff goes depends on the material type and purity. The materials may also have smaller absorption dips which can limit operation at specific wavelengths. Even if the material is transmissive, it may not see more than 50% at that wavelength.

Cost is the other major consideration in the material choice. The largest bandwidths tend to be only possible in the more exotic(and expensive) materials. Their costs come from more expensive physical medium as well as the increased difficulties in polishing. All UV optics must go through traditional polishing, but more brittle or soft materials need softer laps to keep the scratch/dig below $\lambda/10$. Other aspects to consider are the damage threshold and durability, if working with intense UV sources or lasers. Durability directly relates to the lifetime of the optics and can increase to operating costs of a system when materials can have a maximum 20 hours before performance begins to drop.

3 Fused Silica

Fused Silica, also known by trade names Suprasil, Spectrosil, Lithosil, etc., is the most common of the UV grade transmissive materials. It is very popular due to cheap production, as it is made from sand, very good thermal dimensional stability, and its durability.

Fused Silica can operate down to 190 nm and all through the visible spectrum, though most grades have a UV cutoff around 200 nm.

Parts made out of fused silica will be smaller than 100 mm due to the difficulty finding blanks of that size or larger of the UV grade. Fused silica

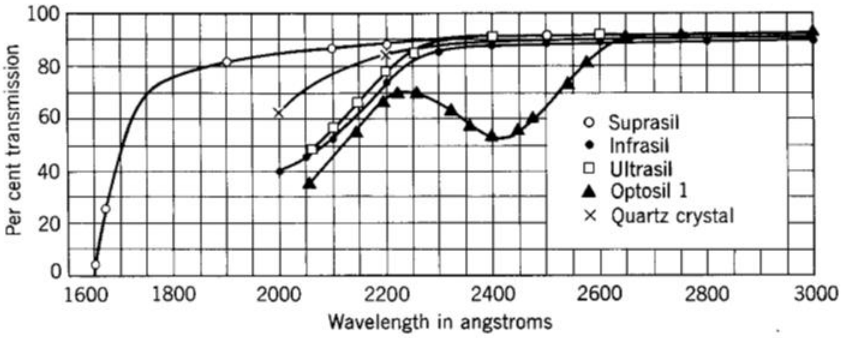

Figure 1: Spectral Transmission for Various Grades of Fused Silica[Koller]

does have an absorption dip around $240nm$. This makes it a poor choice for sources operating in this region, as well as any operating below its cutoff at 190 nm.

Additionally, long exposure to strong ultraviolet light will disrupt the internal structure of the glass. This results in compaction, a shrinking of the glass, potentially changing the shape of the lens.

4 Calcium Fluoride

Fluorides have a much lower cutoff wavelength than fused silica making them ideal for sources where it no longer works. This fact makes Calcium Fluoride the second most common UV material. It operates from 130 nm to nearly 10 μm. The material also has a low index of refraction($n \approx 1.46$) in the UV, making it a very good choice as an AR coating material.

Most fluorides are hygroscopic, meaning they absorb water from the atmosphere. This will result in a slow decrease in UV performance over time when exposed to the atmosphere. The decrease is a result of two factors. First, the water will absorb the UV light. Second, the absorption will cause a change in volume leading to stresses and potential changes in shape.

CaF_2 is a soft, brittle material. It will chip easily during polishing, making it much harder to tolerance surface roughness and curvature together. It also requires extensive cleanings between lapping. This is because particles from the lapping process can become trapped and rebonded to the surface creating increased scattering sites and decreasing overall performance. Subsurface scattering has been well studied and most commercial products will work to minimize these defects.

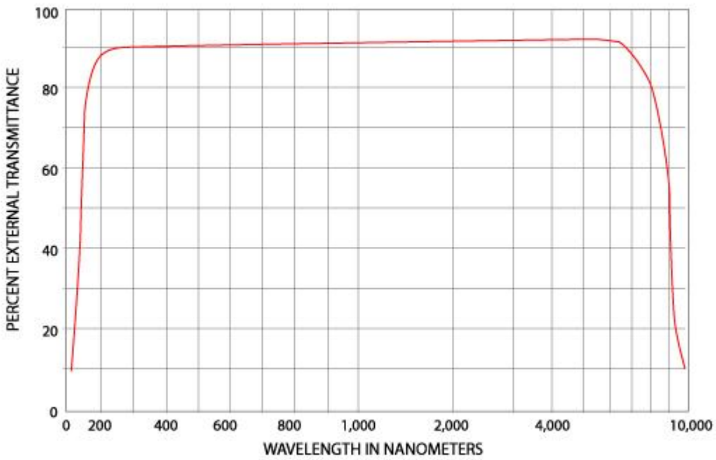

Figure 2: Spectral Transmission for Calcium Fluoride[Courtesy Melles-Griot]

5 Magnesium Fluoride

Like Calcium Fluoride, Magnesium Fluoride(MgF_2), has an increased spectral range over fused silica. It is also the most common single layer AR coating film available($n \approx 1.38$). It isn't quite as transmissive as CaF_2, but its performance isn't affected by water.

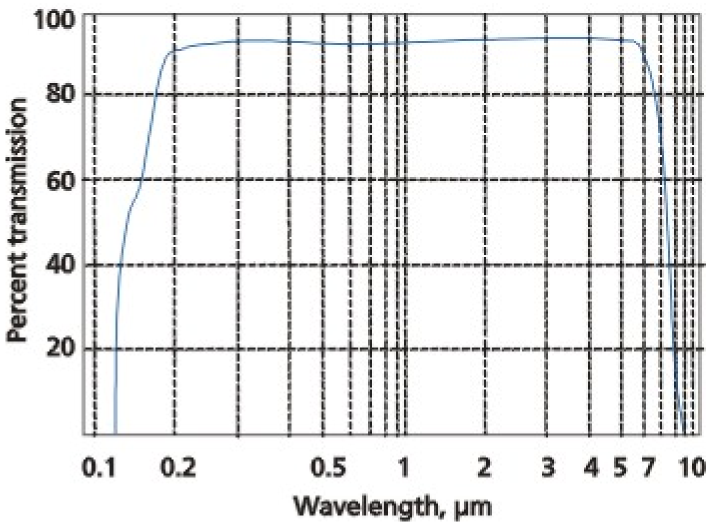

Figure 3: Spectral Transmission for Magnesium Fluoride[Courtesy Eksma Optics]

Fluorides are the most effective as thin-films for very short wavelengths due to their spectral ranges. However, the deposition process makes their application onto surfaces very difficult. It requires high heats to deposit the materials. As the material cools, the material stresses through tension. These net forces can end up distorting the optic.

6 Sapphire

Sapphire is an amazing optical material with many applications from the UV to the IR. It is the one of the hardest substances known, behind diamond. Sapphire makes for excellent windows and can have diameters over 200 mm in size. Its UV cutoff approaches 142.5 nm. Sapphire is very stable, and stain and chemical resistant; not even HF can etch the surface.

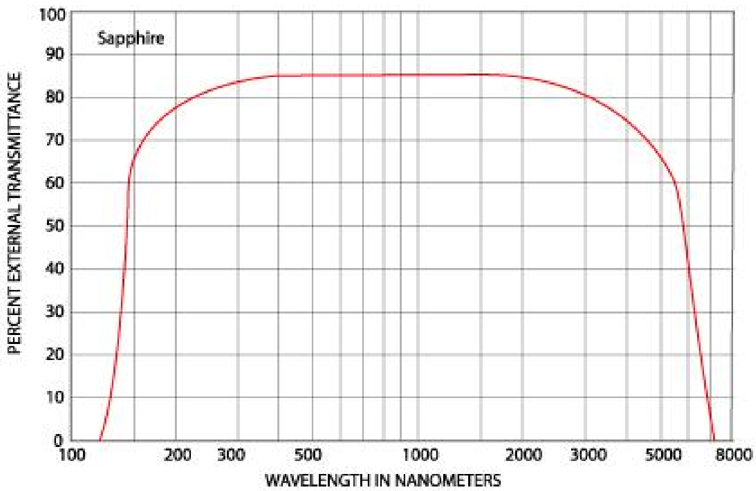

Figure 4: Spectral Transmission for Sapphire[Courtesy Melles-Griot]

Sapphire's big drawback is in its cost. High quality sapphire blanks must be grown, and it is extremely difficult to figure and polish due to its hardness. Depending on the slurry, it can take a week just to remove a few nanometers of material.

7 Feature Comparison Summary

	Pros	Cons
Fused Silica	Cheap Thermally stable	Cutoff at $200nm$ Compaction at high intensities
$\mathbf{CaF_2}$	Cutoff at $123nm$ Resistance to Fluorine corrosion	Brittle Hygroscopic
$\mathbf{MgF_2}$	Similar spectral range as CaF_2 Doesn't absorb water	Transmission less than CaF_2 Brittle
Sapphire	Range to $142.5nm$ Hard/Durable	Expensive Difficult to polish

Conclusions

There are a variety of materials that are suitable for UV optics ranging from cheap and efficient to expensive with outstanding performance. Choosing the right material depends on the source spectrum and budget. As with any material, the thickness will affect the total performance based on the residual absorptions, but these will fit most UV optics needs.

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