Using GRADIUM® glass lenses in High Power Lasers: Tips and Tricks

1 *Why use GRADIUM® lenses?*

GRADIUM® lenses have been used successfully in high power laser systems since their initial application in a 1.6 kW Nd:YAG at Argonne National Laboratory in 1996[1]. Since that time, GRADIUM® lenses have been used in a wide variety of industrial and research applications, ranging from 100W welding systems to multikilowatt cutting applications to specialized high power beam delivery, such as the use of a GPX-80-125 by the US Air Force Research Laboratory at Kirtland AFB, NM to launch a 25 x 25 mm beam with 5.3 kW of 1.3 µm laser power into a fiber[2]. Many of the world's leading laser manufacturers and systems integrators–after extensive qualification testing–use GRADIUM® lenses in their products.

Why have these manufacturers and systems integrators chosen GRADIUM® lenses for use in their products? The answer can be distilled to two words: **performance** and **reliability**.

Performance: GRADIUM® lenses provide the best possible performance from a given laser system. Over the last few years, beam quality from high power lasers has improved, particularly with the use of laser diodes as laser sources or pump sources. Diodes have made it possible to increase brightness without the thermal management problems common to older technologies, such as flashlamps, which had significant quantities of wasted energy. The improved beam quality makes smaller focused spots possible.

Welding and cutting processes have threshold limits which are appropriately expressed in terms of irradiance (Watts of power per unit area). Because the irradiance scales inversely with the beam area, it is important to get the smallest possible spot on the workpiece. For example, a 10% reduction in spot size (Figure 1) translates into a 19% reduction in total power required to maintain the same irradiance level on the workpiece. This efficiency can be leveraged to increase processing speed or to lower the laser power (thus reducing the electrical power consumption–wall plug efficiency is typically 20% or less–and increasing the lifetime of the laser components).

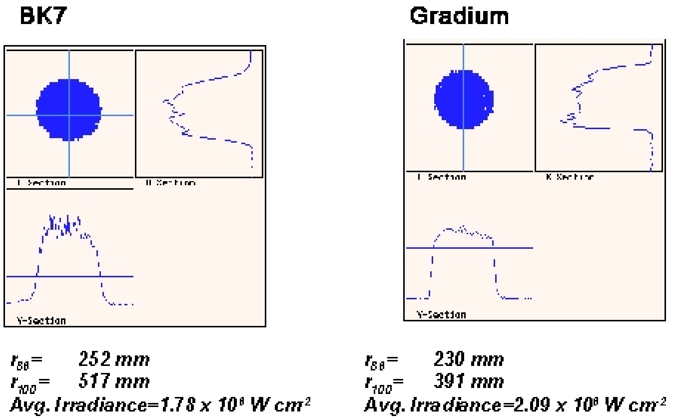

Figure 1: Cross-sectional irradiance profiles of focused spots from imaging the 1000 µm step-index fiber with pairs of BK7 and GRADIUM singlets (magnification of 0.5). The reduced aberration from the GRADIUM lenses is evident in the sharper, more "top-hat" profile. Reproduced from Ref. 1. Copyright 1997, Optical Society of America.

The effect of GRADIUM® lenses is understood from a simple model. The spot size on the workpiece is determined by the optical demagnification of the source due to the idealized beam delivery system plus some blur due to the quality of the optics used in the beam delivery system (cf. Figure 2). The purpose of GRADIUM® lenses is to make this blur term as small as possible. The overall impact of GRADIUM® lenses increases as the spot size decreases, typically due to improved beam quality or higher demagnification levels[1,3].

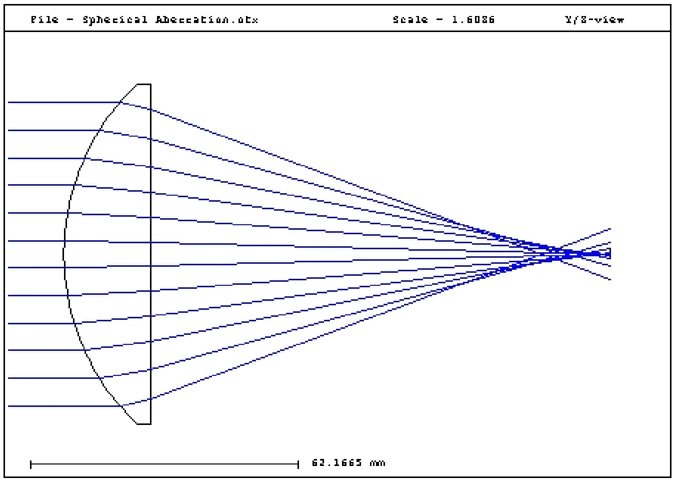

Figure 2: The dominant aberration in laser beam delivery systems is spherical aberation, which causes the light rays at the edge of the lens to be misaimed with respect to the rays at the center of the lens. This aberration results in a larger focused spot, as illustrated in Figure 1. The use of GRADIUM ® lenses effectively eliminates this aberration.

Reliability: Simpler configurations offer fewer points of failure. There are other means to achieve the same levels of optical quality. However, these solutions typically involve using more glass surfaces. If an optical adhesive is in the beam path, it typically has a low damage threshold. Also, even with high quality anti-reflection coatings, each glass surface increases the power reflected to someplace other than the work piece. Sometimes these reflections, often called ghosts, can have enough power to cause damage within the beam delivery system. A ghost focus is illustrated in Figure 3.

The purpose of this white paper is to familiarize the high power laser user with the best practices and precautions necessary in order to successfully and reliably use GRADIUM® lenses in real-world laser applications.

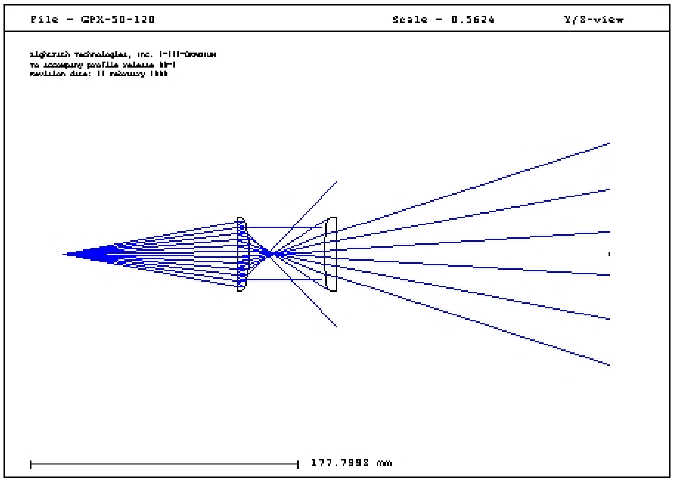

Figure 3: An example of a ghost focus in a beam delivery system caused by reflections from the lens surfaces. Ghost focus problems are avoided by using good coatings and by making sure that the focus is not incident on another lens, the fiber, or any other sensitive location.

2 *Understanding glass properties*

Glasses are, by their nature, hard yet brittle materials and are electrical and thermal insulators. While considered transparent, some of the light passing through the glass is absorbed and converted to heat. For most applications, these properties are academic curiosities; however, in multi-kilowatt lasers, the heat becomes significant and can lead to several failure modes unless the lens is properly used. The changes experienced by the lens are appropriately understood in terms of the localized light flux, the irradiance, expressed in terms of power/area, not the total power.

In the table below, GRADIUM glass is compared to two other commonly used glasses: BK7 (very inexpensive and frequently used) and silica (which has unusual thermal stability).

	CTE ($x10^{-6}$ K^{-1})	Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific Heat ($J \cdot g^{-1} \cdot K^{-1}$)	Heat capacity per unit volume ($J \cdot cm^{-3} \cdot K^{-1}$)	Softening point (°C)
GRADIUM	8.25 (avg.)	0.7 (avg.)	0.410 (avg.)	1.81 (avg.)	~500
Silica	0.55	1.38	0.740	1.63	1600
BK7	7.1	1.114	0.858	2.15	719

The differences between the glasses are due to the dopants added to the raw silica to generate the desired optical properties. Silica has a very low refractive index (n=1.46) as does BK7 (n=1.52). These low refractive indices means that the lenses tend to be more strongly curved, resulting in increased spherical aberration. GRADIUM® glass is essentially silica which has been doped with lead oxide; the lead oxide concentration varies within the glass to create the high refractive index (n ranges between 1.65 and 1.8 through the profile) and the refractive index gradient (which corrects the spherical aberration). These glasses are shown in Figure 4, a glass map, which plots the glasses refractive index versus dispersion (lower values on the horizontal axis mean that optical properties change more with wavelength).

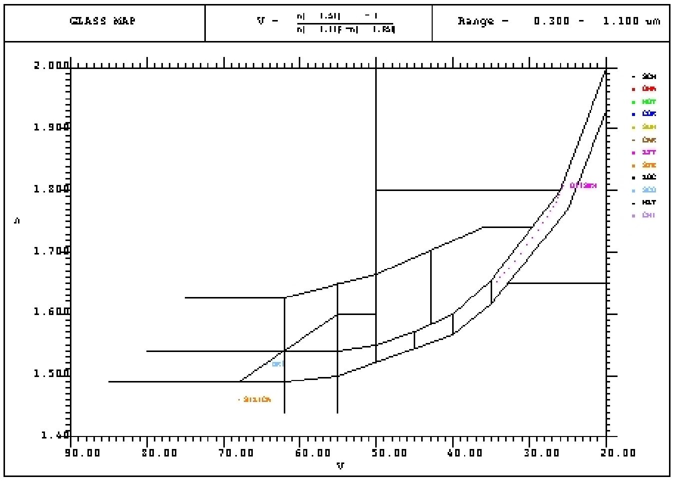

Figure 4: Glass map showing the relative dispersion and refractive index of the different glasses.

The various dopants also affect mechanical properties such as the coefficient of thermal expansion (CTE), conductivity, density, softening temperature, etc. The properties shown for GRADIUM® and BK7 are representative of the range seen for almost all commonly used optical glasses. The addition of lead oxide tends to make a glass with a low softening temperature and which is relatively soft. Understanding these properties allows appropriate precautions to be taken when handling the lenses. The antireflection coatings on the lenses are applied in a vacuum at a temperature of 300° C. Thus, on **any** lens made of **any** glass, a service temperature in excess of approximately 200° C is undesirable in order to protect the coatings.

One critical properties affected by the dopants added to the silica to make optical glass is the transmission versus wavelength of the glass. Some glasses have just two or three dopants; some have a great many. Thus even within a glass family, some glasses will be suitable for high power lasers and some will not, often because of trace amounts of a specific dopant. Glass manufacturers provide transmission data on their products; however, sometimes the samples are too thin to show any differences in the NIR wavelengths. Transmission results for a 14.7 mm thick GRADIUM® sample are presented in Figure 5[4]. The linear increase in transmission around 800-1000 nm is due to a calibration error between different lamps in the spectrophotometer. However, this graph can be used to estimate internal absorption. Even though the absorption is small, in a high power laser, the result can still be a significant amount of absorbed energy.

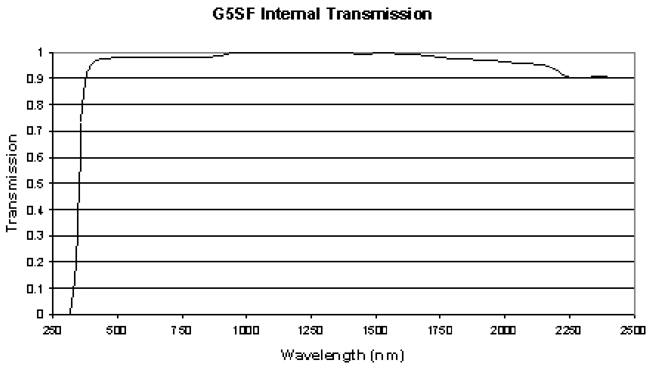

Figure 5: Internal transmission data for 14.7 mm of G5SF. Data courtesy of Juan Ochoa, MIT-Lincoln Lab.

3 *Known lens failure modes: how to keep them from happening to you*

3.1 *Stress fractures*

Because glass is a brittle material, when the stress at any point becomes too large, it is relieved by cracking. The cracks tend to propagate significant distances before the stress is relieved. This behavior is exemplified by fiber cleaving and the spread of a crack across a windshield. It comes, therefore, as no surprise, that stress fractures almost always split a lens. The cracks are the full thickness of the lens and originate, usually, at the edge of the lens, as illustrated in Figure 6. There two primary causes for these fractures: (a) chipped or damaged lens surfaces and (b) improper mounting resulting in a stressed lens.

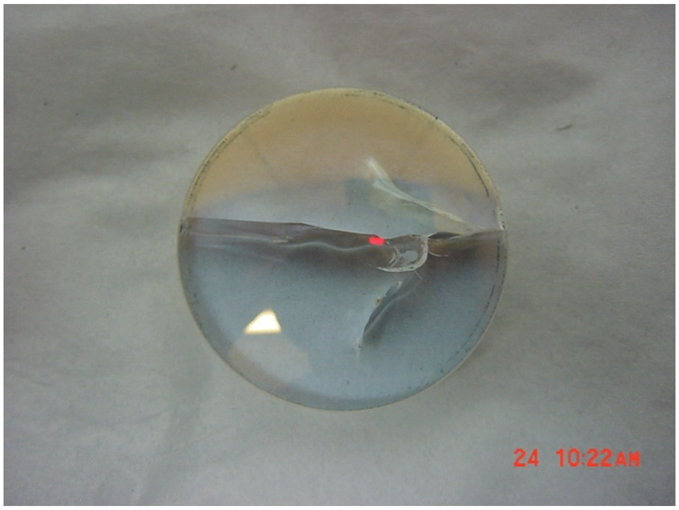

Figure 6: Example of a lens with a stress fracture.

Chips and other lens damage are remedied through careful lens handling. When the lens arrives from LightPath, it has been inspected for damage. The edges of the lens have been beveled or chamfered to eliminate fracture sites from the edge of the lens. However, the user should take care not to damage the lens by dropping it, pushing it into a mount when it is cocked sideways, or using any sort of retaining ring configuration that will cut or scratch the lens. Any of these problems could create a fracture site when the lens is subjected to heat from the laser.

Proper mounting is the other key to avoiding this problem. Because of the expansion of the glass when it heats up, do not think of the glass as a solid object to be mounted securely. Remember that it is a hard–yet brittle–object that will need the ability to expand and contract without damage. The lens should be mounted securely enough to stay in place (for example, to withstand the forces applied during robot motion). Lens mounting is not the place to demonstrate brute strength.

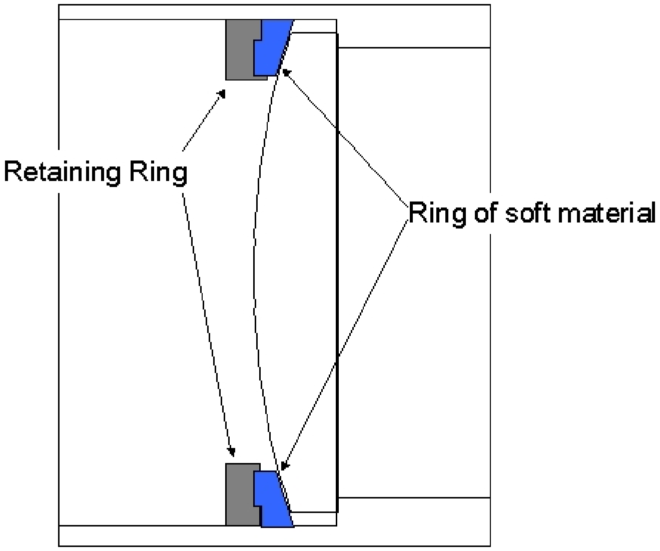

Figure 7: Example of a proper lens mounting design.

When mounting, the retaining ring should be tightened only enough to hold the lens in place. A ring of soft material should be placed on the convex surface to protect it from damage and to provide a means for the lens to expand and contract without coming loose. The choice of material depends upon other issues in the beam delivery system; however, rubber o-rings, Teflon, or indium wire are representative of suitable materials. Indium wire is ductile and has been used for many years in high power CO_2 lasers to protect the lens and to promote good heat conduction from the lens to the welding head.

Figure 7 exemplifies the key points of an appropriate mounting procedure. The plano side of the lens is in contact with the metal of the lens mount in order to provide a path for conduction of heat from the lens into the lens mount (the mount should be cooled and capable of dissipating far more heat than the lens could absorb). Note that there is a gap between the side of the lens and the lens mount to allow for expansion. The convex surface is contacted by a soft material. Note that the soft material ring contacts the lens on a tangent to the convex surface; no metal can contact or damage the convex lens surface. It is generally best to design the retaining rings so that the lens is centered, or positioned in the mount, by the rings. Edge centering, *i.e.* putting the lens in a mount with very little lens OD-to-mount ID clearance is usually a bad idea, as it is more likely to cause lens damage when the lens is installed or not allow sufficient room for expansion. Texts are available to provide a more general discussion of lens mounting techniques[5].

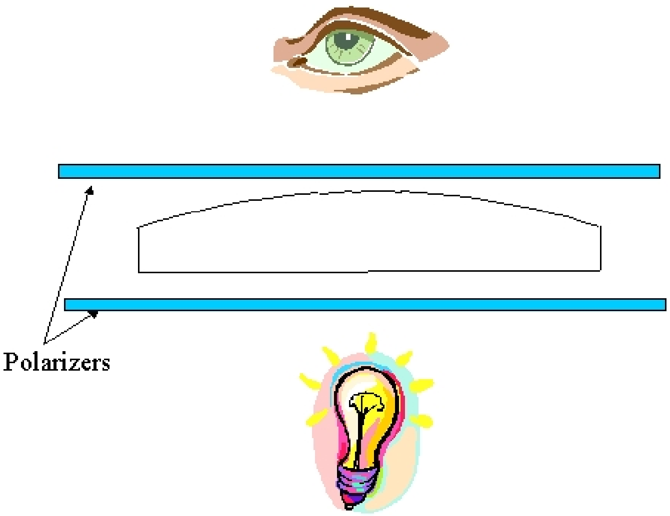

Figure 8: Conceptual layout of a pair of crosssed polarizers used to detect stress in a mounted lens. Polarizer sheets or polarizing filters for a camera are convenient to use.

A simple, inexpensive test for a stressed lens involves a white light source and crossed polarizers, as illustrated in Figure 8. The polarizers should be rotated so that, with nothing between them, no light is transmitted. With the lens/lens assembly between the polarizers, if colored fringes are observed, then the lens is stressed at the location of the fringes. This is the location of a potential problem.

3.2 *Localized melting and related cracking*

Figure 9: An example of a fracture due to contamination on the lens surface.

Another common failure mode is due to poor cleanliness. The lens should be kept clean at all times. Cover glasses should be used to protect the side of the lens near the workpiece from spatter. If a contaminant is on the surface of the lens, the contaminant will absorb heat from the laser beam far more rapidly than the lens and reach a high temperature. Considering the table of materials properties in §2, we note that GRADIUM® glass has a relatively low softening temperature. Thus a hot contaminant can quickly raise a small portion of the lens to its melting temperature. The result is either a melted spot or a fracture–often in the lens surface–originating from the location of the impurity. Since the area near the center of the laser beam tends to have the highest power levels, this is the area where this damage is most likely to occur. This type of damage is illustrated in Figure 9.

The fix for this problem is care in handling the lens, use of protective cover glasses, and making sure that any air from purge lines does not carry contaminants to deposit on the lens. When this is done, GRADIUM® lenses provide a long service life, as has been demonstrated in large industrial applications.

3.3 *Thermal overload*

One of the key issues in optics for high power lasers is stability and durability when subjected to high average power. This is determined by the absorption, the thermal conductivity, and the thermal expansion. Some common materials work well; others do not (sometimes it is surprising which ones do not do well). To gain some understanding of the performance of GRADIUM® glass in a realistic setting, windows made from three different GRADIUM® profiles as well as silica and BK7 were placed in a collimated 1.5 kW CW Nd:YAG laser beam[3].

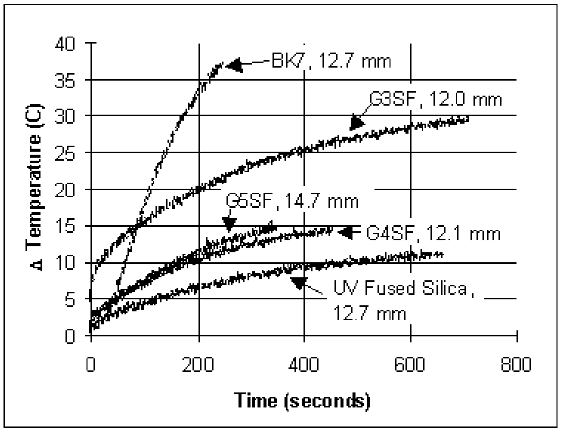

Figure 10: Temperature-time traces for 38 mm diameter AR-coated windows made from fused silica, BK7, and three GRADIUM® materials. The thickness of the windows ranged from 12.0 to 14.7 mm. The incident power was 1500 W (CW, λ=1064 nm). Reproduced from Ref. 3. Copyright 1997, Optical Society of America.

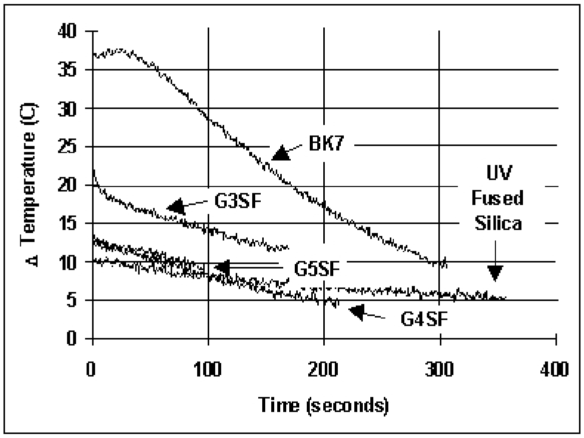

Figure 11: Temperature-time traces for the windows shown in Figure 6 after the laser shutter was closed and the windows began to cool. Reproduced from Ref. 3. Copyright 1997, Optical Society of America.

The windows were AR coated at 1046 nm. The window thicknesses were in the 12-15 mm range. The temperature on the edge of the windows was monitored with a surface-mount thermocouple for a period of 4-11 minutes, depending upon the sample. The temperature was monitored as the windows heated up as the shutter was opened (Figure 10) and as they cooled down when the shutter was closed (Figure 11). The experiment showed that silica, a material commonly used for temperature sensitive applications, heated least. The excellent thermal performance of fused silica is apparent from the plot, showing only approximately a 11° C temperature rise after 10 minutes of exposure. At 4 minutes exposure, BK7, one of the most widely used glasses, had already experienced a 40° C temperature rise so the test was discontinued. BK7 is clearly a poor choice for high power lasers. The GRADIUM® materials did well in this test; G4SF and G5SF would have been at about 16-20° C temperature rise at 10 minutes and G3SF experienced a 28° C temperature rise. The differences in the performance of the GRADIUM® materials is due to the different thicknesses of the windows and the differences in base glass composition when the profiles are made. Sometimes glasses from the same glass family perform quite differently.

These tests provide a reasonable basis for estimating the temperature increases that might be experienced by a GRADIUM® lens in a laser beam; the estimation will need to compensate for the power level and the thickness of the lens versus the windows that were used in the experiment. The effect of wavelength on the absorption (Figure 5) will also need to be considered, as the peak transmission occurs in the 1-1.3μm range.

Of course, the temperature profile across the lens would be different than the temperature at the edge. The localized temperature profile will reflect the localized irradiance profile. Higher temperatures will be experienced at the center of the lens than at the edges due to the typical laser beam profile and the fact that the heat sink is at the edge of the lens.

There is clearly a point at which heat is deposited faster than it can be conducted away from the lens. When this happens, the lens will soften and melt. When the region that this happens is small because of a contaminant, a failure of the type discussed in §3.2 occurs. The exact onset of this condition is determined by the absorption of the material, heat capacity per unit volume, and the softening temperature.

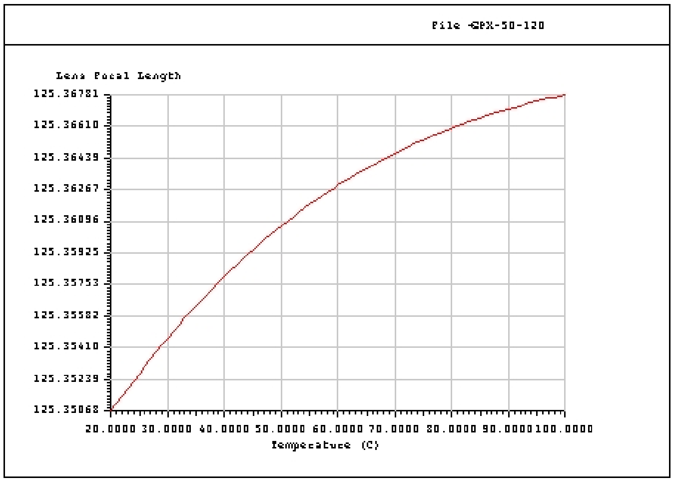

Figure 12: Change in EFL for a GPX-50-120 with temperature. The change (magnitude and direction) is dependent upon temperature and wavelength.

As a general rule, larger diameter lenses are preferred for use with higher beam powers. The larger beam will reduce the size of the irradiance gradient and the maximum irradiance; this general comment applies to all lasers and is the same reason that the optics on the ultra-high power National Ignition Facility lasers are very large.

The other effect that will be observed with temperature is some change in the focal length. As the lens heats, the thickness increases, the radius of curvature increases and the refractive index changes. All of these effects act together to produce some variation in the focal length (which translates into spot size errors as the beam moves in and out of focus). Using a GPX-50-120 operating at 1064 nm as an example, the calculated effect over a 20-100° C temperature range is shown in Figure 12. In this case the temperature is assumed to be the same at all points on the lens. Of course, since the temperature is a function of the irradiance, that is not exactly what happens; the final result is due to a range of temperature variations and focal shifts on the lens. Perhaps this could be modeled by a very complex finite element analysis. Certainly the radius of curvature will vary across the lens; some complex aspheric surface is the likely result.

In order to gain some understanding of the effect, a GPX-50-120, which is diffraction limited, was analyzed at room temperature (where the laser would likely be set up) and also with a temperature profile across the lens. The wavelength was 1064 nm. The temperature profile was realized by dividing the lens into a series of annular regions, with each annulus at a temperature between 40 and 100° C, as shown in Figure 13. The increase in spot size is what is expected to be the change on the spot size in a real application.

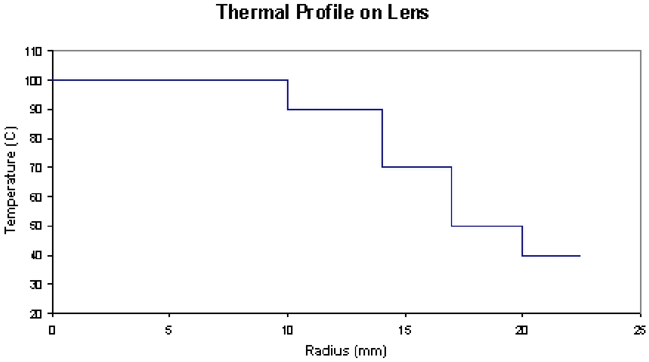

Figure 13: Thermal profile used in simulation. The clear aperture radius is 22.5 mm.

The observed effects are shown compared to the lens at room temperature in Figure 14 and Figure 15. The spot size increases with the thermal gradient; part of the effect is due to the focus shift (about 14 microns), part is due to the changes in the lens geometry. Note also that the wavefront has changed from the smooth, third order spherical pattern before heating to something with a more complex shape. The increased complexity increases the actual spot size. The effects that are seen

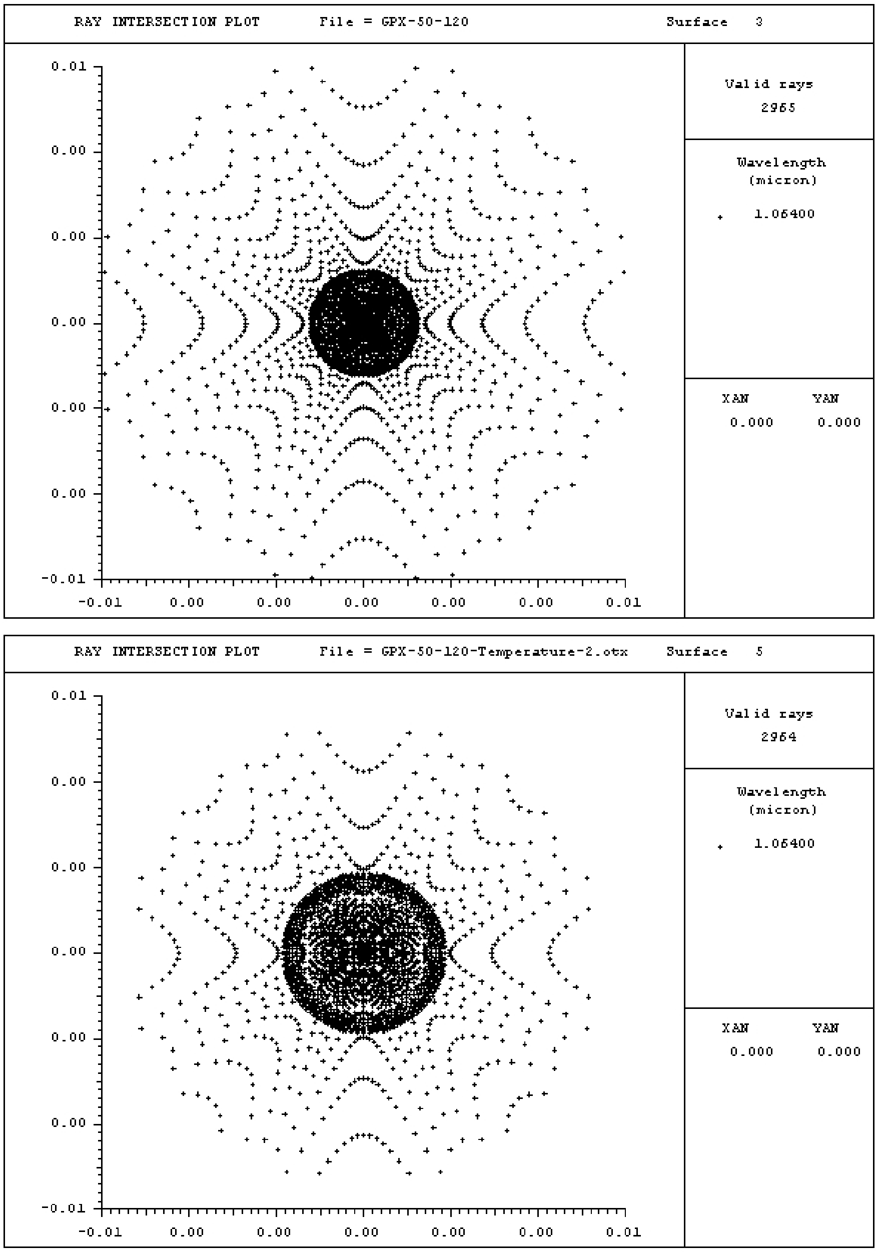

Figure 14: Focused spot from a point source for a GPX-50-120 at room temperature (20° C, top figure), and with the temperature profile of Figure 13 (bottom figure). The back focal length was not varied from the room temperature value. The box scale is 15 microns across.

are not very large, although there might be some practical impact on a process that was running too near the process limits.

3.4 *Irradiance overload*

If the irradiance level is too high, we see a failure mode in which the surface of the glass fails. This failure mode is typically associated with pulsed lasers, because of the tendency to have very high peak

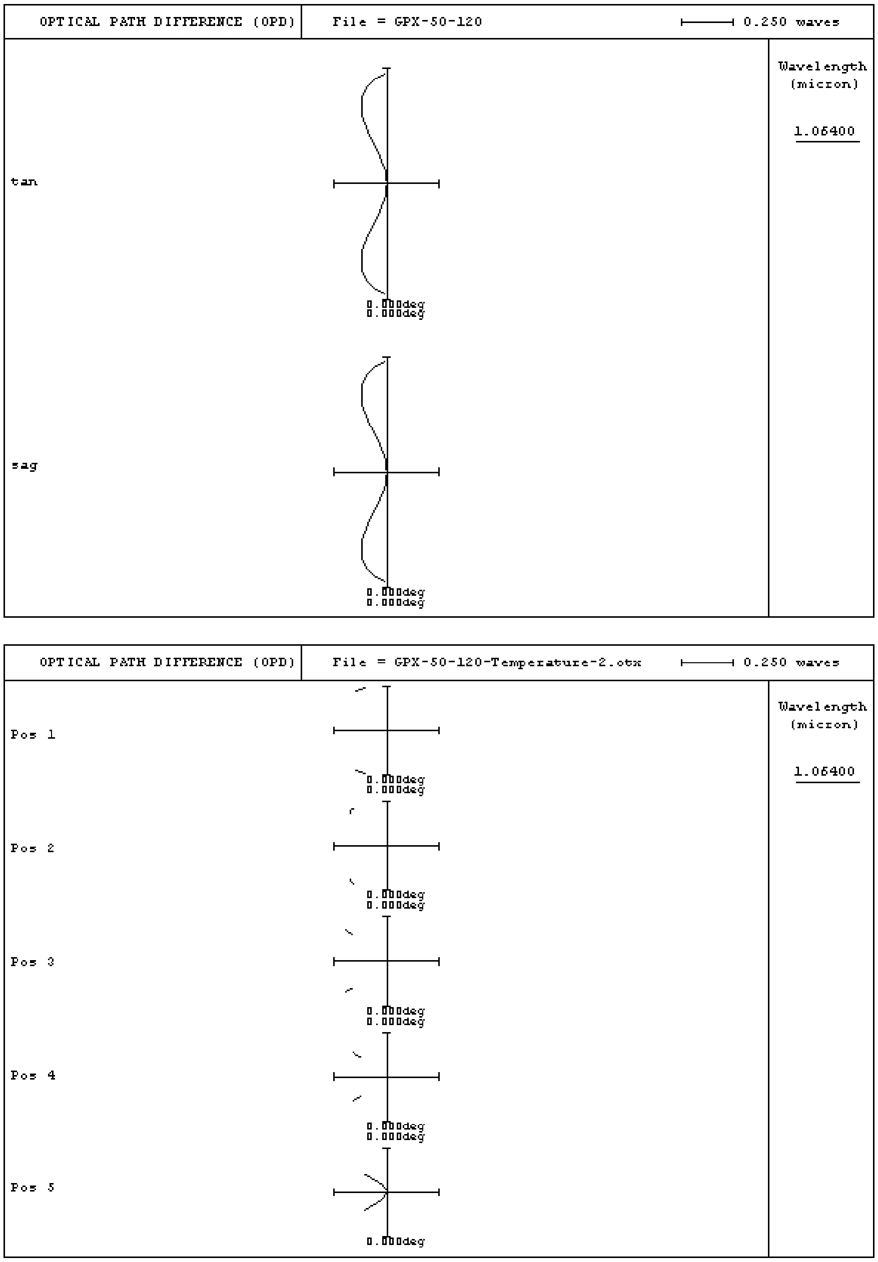

Figure 15: Wavefront error of GPX-50-120 at room temperature (20° C, top figure), and with the temperature profile of Figure 13 (bottom figure). The back focal length was not varied from the room temperature value. The scale is 0.25λ.

power levels. In order to avoid this failure mode, peak irradiances must be controlled either through control of the laser parameters or by using larger beam diameters.

The specific damage threshold values are somewhat complicated to use, because the physics of the interaction is such that the damage threshold decreases, *i.e.* damage is more likely, as (a) wavelength decreases and (b) pulse duration decreases; the assumption is that the beam size and total energy throughput do not change. For this reason, results are presented for nanosecond pulses, as well as for the millisecond pulses more typically encountered in multi-kilowatt industrial lasers. Some years ago the University of Rochester tested some early GRADIUM® materials. Their results indicated a damage threshold of $\sim 4\times10^{9}$ W cm^{-2} (4-5 J cm^{-2} for a 1 ns pulse at 1053 nm and 3 J cm^{-2} for an 800 ps pulse at 351 nm)[6]. Based on the glass family, the Newport catalog indicated a damage threshold of 2×10^{8} W cm^{-2} (2 J cm^{-2} for a 10 ns pulse at 1.06 μm)[7]. For reference, when a lens with optical cement is used, the cement is good to around 700 W cm^{-2}.

High average power pulsed lasers typically generate millisecond pulses. Tests carried out at Argonne National Laboratory with 1-5 ms pulses (10-55 J per pulse) on a G3SF window indicate a damage threshold of $\geq 3.8\times10^{5}$ W cm^{-2}. The G3SF is capable of withstanding $\geq 1.5\times10^{6}$ W cm^{-2} if there are no surface flaws or impurities.

4 *Conclusions*

GRADIUM® glass lenses offer a convenient mechanism to extract the best possible performance from a laser systems. As most GRADIUM® lenses that are used in high power laser systems have modest optical speeds, between f/2 and f/4, they are generally diffraction-limited; laser system performance will be determined by the laser beam quality and the effects of the beam delivery system, such as excited fiber modes.

GRADIUM® glass lenses have been used in industrial laser applications for the last seven years. They have demonstrated compatibility with the harsh environment of a factory floor by delivering excellent performance and long service life to the end user. LightPath's goal in the preparation of this paper was to provide a means for customers and prospective customers to understand the best practices that have helped maximize the service life of the lenses. These practices, coupled with the ability to recognize common failure modes, will allow the user to recognize the source of a problem as it develops and fix it before it interferes with equipment availability.

5 *References*

1. Boyd V. Hunter and Keng H. Leong, "Improving fiber-optic laser beam delivery by incorporating GRADIUM optics," *Applied Optics*, **36**, pp. 2763-2769 (1997).
2. Shiv C. Dass, Kip R. Kendrick, Charles A. Helms and Vincent Valdez, "Fiber Optic Beam Homogenizer and Resonator Design for 5-kW Class Supersonic Chemical Oxygen-Iodine Laser (COIL)," *Proc. SPIE*, **4270-04**, pp. 29-36 (2001).

3. Boyd V. Hunter, Keng H. Leong, Paul G. Sanders, Carl B. Miller, James F. Golden, Robert D. Glesias and Patrick J. Laverty, "Improving Laser Beam Delivery by Incorporating Axial-Gradient Optics," *OSA Trends in Optics and Photonics Series*, **9**, pp. 17-22 (1997).
4. *GRADIUM GSF Glass Data Book*, LightPath Technologies, 1999.
5. Paul R. Yoder, Jr., *Mounting Lenses in Optical Instruments* (SPIE Press, 1995).
6. A. Schmid, University of Rochester memo dated 7 September 1994.
7. Newport catalog, p. 2.69 (1994)

6 ***Appendix: Optical Modeling Considerations***

A complete thermal model of a lens–particularly a GRADIUM® lens, requires that the program consider the changes in the glass properties over temperature. These properties include the expansion or contraction of the glass thickness, diameter and radius of curvature with temperature (CTE); the change of refractive index with temperature (dn/dT); and it must ensure that the portion of the glass profile used by the lens is not altered as the CTE calculations alter the mechanical dimensions of the lens.

Since GRADIUM® glass is not a homogeneous material, the CTE and dn/dT values change through the lens. Lens design programs are only able to consider CTE as a constant; thus only an average CTE is applied to the entire lens. A more sophisticated treatment would require a CAD model with finite element analysis. This would also be the approach required were the use desire a more accurate representation of the localized CTE variations experienced on the lens due to the different irradiance levels and heat flow experienced by a lens in a high power application.

The dn/dT calculation is less problematic, as it simply requires an offset be applied to the refractive index profile at each point on the profile. A model was developed which makes this calculation as a function of the refractive index at room temperature[4]. Typically, the effect of dn/dT offsets the CTE; in different temperature ranges, as the different factors change, one may dominate or they may approximately cancel each other.

To the best of our knowledge, any lens design program that supports GRADIUM® (e.g. CODE V®, OSLO®, ZEMAX®, OpTaliX®) also includes the CTE calculation. However, only OpTaliX®-PRO 5.04 or later supports the dn/dT and profile thickness corrections described above. Thus the modeling in this paper was done with OpTaliX®. (OpTaliX®-LPT, available from LightPath, does not include thermal modeling.)

In order to model a thermal gradient across a lens, the lens was divided into several annular zones. A raytrace was run through each zone with the lens set at a different temperature; the results were then overlayed to model the composite effect.