Designing a fiber-optic beam delivery system

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ABSTRACT

One of the advantages offered by visible and NIR lasers over CO and CO_2 lasers is that they can be delivered through optical fibers. Fiber–optic beam delivery is ideal when the beam must be delivered along a complex path or processing requires complicated manipulation of the beam delivery optics. Harnessing the power of a high–power laser requires that knowledgeable and prudent choices be made when selecting the laser and its beam delivery system. The purpose of this paper is to discuss a variety of issues important when designing a beam delivery system; data obtained with high power Nd:YAG lasers will be used as illustrative examples. (1) Multimode optical fibers are used for high–power applications. The fiber imposes, to varying degrees, a structure on the beam that is different from the laser output. Fibers degrade the beam quality, although the degree of degradation is dependent on the fiber length, diameter and type. Smaller fibers tend to produce less degradation to beam quality, but the minimum usable fiber size is limited by the quality of the laser beam, focusing optic and the numerical aperture of the fiber. (2) The performance of the beam delivery system is ultimately determined by the quality of the optics. Therefore, well-corrected optics are required to realize the best possible performance. Tests with both homogeneous and GRADIUM™ lenses provide insights into evaluating the benefits offered by improvements in the output optics from gradient–index, aspheric and multi–element lens systems. Additionally, these tests illustrate the origins of variable focused spot size and position with increasing laser power. (3) The physical hardware used in the beam delivery system will have several characteristics which enhance its functionality and ease of use, in addition to facilitating the use of advanced diagnostics and monitoring techniques.

Keywords: fiber–optics, lasers, beam delivery, GRADIUM, manufacturing.

1. INTRODUCTION

The quality of the beam delivery system is an important factor in the performance of the laser systems. With the exception of heat treatment (which *shapes* the beam),[1] the optical system is used to increase the beam irradiance by focusing the laser light into a small spot. The smallest possible spot size depends on the quality (often expressed in terms of M^2, the times-diffraction-limited multiplier) of the laser beam incident on the optics.[2]

There are two basic mechanisms for delivering the beam from the laser to the point of use: free-space delivery and fiber-optic delivery. Free-space delivery routes the beam exiting the laser with mirrors and lenses. This method of beam delivery

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has the important advantage of delivering the best possible beam quality. Fiber-optic delivery launches the laser beam into a flexible fiber. The flexibility of the fiber-optic delivery often offsets the poorer final beam quality.[3-4]

In order to realize the best possible performance from the laser system, well-corrected optics are required. Eliminating aberrations increases the energy available for useful work because less energy is below the threshold irradiance. Conventionally, well-corrected optics are produced by using doublets, triplets, or aspheres. Aspheres are typically difficult to make and are more costly to manufacture than optics using spherical surfaces. Therefore, manufacturers of high-power Nd:YAG laser systems have often used air-spaced or cemented doublets.

Since at least the 1970's, it has been recognized that a superior alternative to doublets or triplets would be the use of gradient-index materials.[5] The refractive-index gradient, coupled with an appropriate surface curvature, allows well-corrected optics to be produced using planar or spherical surfaces; the effect is analogous to a single-term asphere. These gradient-index optics perform at least as well as comparable conventional doublets and often provide diffraction-limited performance.

Over the last three years, Argonne National Laboratory and U.S. Laser Corporation have been systematically considering beam delivery improvements. Fibers, optics and diagnostics have been considered as a part of this work. Argonne, U.S. Laser, Unitek Miyachi Corporation and LightPath Technologies have collaborated in testing and evaluation of GRADIUM lenses, using both CW and pulsed Nd:YAG lasers. Both beam profiling and actual welding tests were conducted. The lenses used in testing at Argonne and U.S. Laser used custom GRADIUM lenses. Catalog lenses were used at Unitek Miyachi; the LightPath catalog lenses (diameters range from 5-50 mm, focal lengths from 12-200 mm) have been available only since Fall 1996. The prices of these lenses compare favorably with homogeneous singlets. Different BK7 and GRADIUM lens combinations allowed a range of aberration to be present in the optical system. Based on the information gleaned from these tests, some general guidelines are presented to help the user determine what level of benefit to expect from GRADIUM lenses (or other well-corrected optical systems).

The information presented in this paper represents a summary of our experience and is intended to be an exposition of the salient issues in designing a fiber-optic beam delivery system. This manuscript draws on previous work and publications as well as new, previously unreported data and an expansion of the material to reflect the broader scope of this paper.

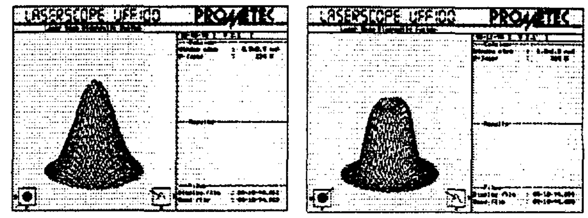
2. FIBER SELECTION

2.1 Fiber type

The optical fiber is a fundamentally quantized device capable of supporting only a discrete set of modes. These discrete modes, or eigenmodes, are determined uniquely by the fiber refractive index profile and geometry and can often be determined analytically.[6, 7, 8] Fiber modes can be separated into two general classes: radial and azimuthal (also called meridional and skew, respectively). Radial modes always go through the fiber's axis. Azimuthal modes do not pass through the fiber's axis; the rays propagate in a helical path. Unsupported modes exceed a specific maximum propagation angle and will either leak out of the fiber or be canceled/redistributed due to interference effects. A supported mode may be subjected to losses because of scattering from surface or inhomogeneities in the material. Introducing bends in the fiber locally perturbs the supported mode structure and may cause local mode mixing and losses. The fiber is capable of significantly modifying the properties of the laser beam; the final processing properties of a fiber-optic-delivered laser beam are determined by the fiber type, length, and propagation conditions.

The two fiber types differ in the constancy of the refractive index through the fiber. The commonly used step-index fiber has a constant refractive index in the core and an abrupt "step" transition to a different refractive index in the cladding. Total internal reflection in this fiber occurs at the core/cladding interface for all modes. When all modes are filled, the output profile (on the fiber face) will be the familiar "top-hat" distribution. This "top-hat" distribution provides a relatively homogeneous beam with a stable spot size.

A gradient-index (also called graded-index) fiber has a variable refractive index in the core. Typically, the variation of the refractive index is a parabolic function of the radius. The effect of this varying refractive index profile is that each mode is refracted gradually as it traverses the fiber. Each mode, therefore, has a unique mode radius. Except for the evanescent components, only the highest order mode reaches the core/cladding interface. The output profile (on the fiber face) resembles a Gaussian distribution and the peak intensity is often about five times higher than a step-index fiber of the same diameter. The size of the beam waist from this fiber varies as a function of the input beam power because a different set of modes are excited as the beam quality (a function of the power) changes. A gradient-index fiber provides the best possible output beam quality.



(a) Properly aligned beam launch. (b) Severely misaligned beam launch.

Figure 1. Focused beam profiles from an 800 μm gradient-index fiber for (a) a properly launched beam and (b) a severely misaligned beam.

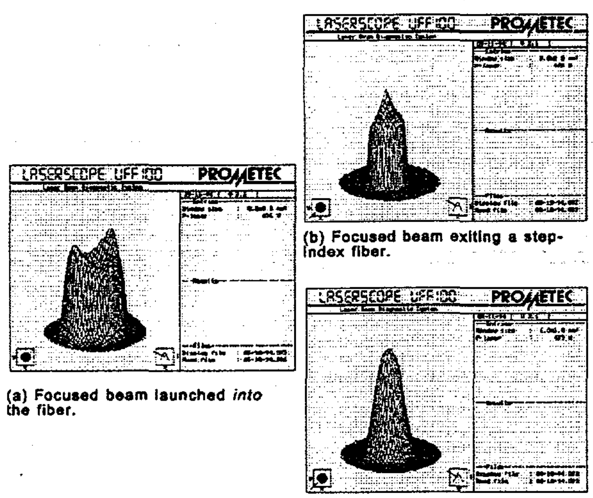
Misalignment of the fiber at the launch end preferentially induces azimuthal modes that appear as rings or crescents in the output. Collimating the output from the fiber makes the contributions from the higher angular momentum modes appear more distinctly as a crescent or ring. Figure 1 shows the focused spot profiles from a 3 m length of 800 μm gradient-index fiber when properly aligned and severely misaligned. These profiles dramatically illustrate the shift to azimuthal modes because of misalignment; the ring structure is so dominant that the Gaussian shape now resembles a D-mode.

2.2 Fiber length

The light launched into the fiber has some initial distribution determined by the laser. As the light propagates in the fiber, it is converted into modes supported by the fiber or it is lost and appears as leakage or heat. This conversion, however, requires a certain length of fiber to be effected. There are different length scales that must be considered: short, intermediate, and long.

A short fiber produces little modification to the input beam. This case is not of practical significance because the fiber is essentially a window. On the other hand, a long fiber causes the output to be independent of the input distribution.

Fiber lengths used in many applications fall into the intermediate category. The length scale of "intermediate" depends upon many factors, including launch conditions, input distribution, fiber inhomogeneities, and bends.[9, 10, 11] Some feel for the relevant length scale comes from the fact that if the launch optics focus the light into a spot much smaller than the fiber core, it will take 10 m to 1000 m to reach steady-state.[12] This transformation of the input by intermediate length fibers is illustrated with "before" and "after" beam intensity profiles taken with a 436 W CW Nd:YAG beam delivered through 800 μm fibers. Figure 2a shows the focused beam launched into the fiber. The distinctive double peak structure of the input beam is a common signature of the pumping method used in this laser. The fiber has significantly altered the beam profile and masks many properties of the source laser. Figure 2b shows the focused output from a step-index fiber. The focused beam profile is, subject to aberrations and magnification effects of the imaging lens, the profile on the fiber output face. The intermediate length of the fiber was not long enough to allow the formation of the top-hat profile expected for a long step-index fiber. Instead, a pointed top profile was produced. On other lasers, such as the 1600 W Electrox at Argonne, the expected "top hat" profile is realized. This variability in the output profile illustrates that even 10 m of fiber is often only in the intermediate length class. Figure 2c shows the output from the same laser after being modified by a gradient-index fiber.



(a) Focused beam launched *into* the fiber.

(b) Focused beam exiting a step-index fiber.

(c) Focused beam exiting a gradient-index fiber.

Figure 2. Focused beam profiles for the 436-439 W Nd:YAG laser beam (a) launched into the fibers and exiting the (b) step-index and (c) gradient-index 800 μm fibers.

2.3 Fiber core size

There are important limitations to selecting the appropriate (smallest) fiber size. Smaller fibers are preferred in order to get the best beam quality. However, the laser itself imposes constraints on the smallest fiber that can be used. The laser beam focused spot size has to be smaller than the fiber core to avoid heat effects and allow for the mechanical tolerances of the fiber-optic connectors. The laser's beam quality and the numerical aperture (NA) of the fiber constrain the focal length of the launch optics. Working from the equation for the focused spot size for an M^2-times-diffraction-limited beam, given the ratio of 86%-to-100% radii in the collimated beam exiting the laser is a, the ratio in the focused beam on the fiber face is b, and the desired fiber fill factor is c, the minimum fiber diameter, d, to be selected as a function of M^2, A, λ and the NA is given by

$$d = M^2 A \frac{2ab}{c} \frac{\lambda}{\pi \tan(\arcsin[NA])} \tag{1}$$

where A is the aberration multiplier of the optics (A=1 for a perfect lens) and λ is the wavelength. If a and b are 1.5 (reasonable based on our experience) and in the interest of conservative engineering, c is 0.8, λ=1.064 μm, NA=0.2 and M^2A=70, the minimum fiber diameter would be 650 μm; if M^2A=100, then the size increases to 930 μm. Consequently, most high average power Nd:YAG laser systems use 800 or 1000 μm fibers for beam delivery. However, if the performance of the laser (ratio of the 86% and 100% radii) is better than given by these conservative assumptions or a larger fill factor is used, the beam can be launched reliably into smaller fibers.

2.4 Fiber surface finish

The primary damage mechanism for fiber-delivered CW lasers in the kW power regime is heating in the connectors. If the fiber's input and output optics are properly designed, most of the connector heating comes from spurious reflections or refractions at the fiber end faces. The primary causes are the refractive index discontinuity at the fiber surface (Fresnel losses) and scattering from surface imperfections. The Fresnel losses can potentially be minimized by applying antireflection coatings to the fiber. The scattering can be reduced by optimizing the surface quality. In both cases, the fiber finishing technique is very important. It not only reduces the scattering losses but also affects the quality and adhesion of AR coatings. Properly finished fibers, together with good cleaning techniques, provide a surface to which AR coatings can adhere well. U. S. Laser has tested several AR coatings from different vendors and has found a direct correlation between the surface polish quality and the quality of the coating. With some effort, it is possible to get reliable, durable coatings. U. S. Laser has combined AR-coated fibers with proprietary injection optics to achieve >98% total transmission efficiency through the fiber-optic beam delivery system, including both injection and output collimation optics.

Several fiber samples were prepared and sent to an independent testing laboratory for surface evaluation. The samples were prepared using three different techniques: mechanical polish, cleaving and laser polishing. In addition, mechanical polishing was done by three different vendors to evaluate their respective capabilities. The sample fiber surfaces were evaluated with a Wyko interferometer. They were tested for RMS roughness and peak-to-valley surface figure error (deviation from a perfectly flat surface). The RMS roughness gives an indicator of microscopic roughness; the peak-to-valley surface figure error is an indicator of the macroscopic surface flatness. Both mechanical and laser polishing resulted in slightly aspheric convex fiber end faces. The results for 1000 μm core fibers are presented in Table 1. From this data, it appears that the high quality mechanical polish can provide both local smoothness and overall flatness for the optimum finish. The mechanical polish quality varied significantly among vendors A, B, and C. These variations are a direct function of each vendor's polishing techniques. Since polishing techniques are proprietary and are somewhat of an art, care

Technique		RMS Surface Roughness (nm)	Peak-to-Valley Surface Error (μm)
Mechanical Polish	Vendor A	0.4	3.3
	Vendor B	1.5	3.3
	Vendor C	1.7	4.1
Cleave		wavy	2.5
Laser Polish		0.3	4.1

Table 1. RMS surface roughness and average out-of-flatness results for the different polishing techniques and vendors. The fiber core diameter was 1000 μm.

must be taken to select vendors who can meet strict specifications. Overall, it was determined that laser polishing provides no particular advantages that cannot be achieved through less costly means. We found no vendors who could provide a repeatable cleave that was as good as a mechanical polish.

2.5 Connectors

A mechanically robust connector should perform well for repeatable precision reconnections and be rugged. However, high power applications impose stricter requirements on connector designs. For the beam input end, if the beam is launched properly with no undue heat effects, standard fiber-optic connectors can be effectively used. For example, the Electrox 1.6 kW pulsed Nd:YAG laser at Argonne National Laboratory has used a standard ST connector bored out for a 1 mm fiber core. On the other hand, the output end of the fiber is subject to more severe conditions with reflections from the workpiece in addition to frequent mechanical manipulation. The reflected laser energy incident on the epoxy, commonly used to hold the fiber core in the connector, may cause melting and vaporization that will affect the beam propagation out of the fiber end. The solution found in high power connectors is to use a well type ferrule connection that holds the fiber tip in air. The ferrule mass is also increased for improved thermal loads. Frequently, the last 20 to 30 cm length of the output end of the fiber is sheathed in a rigid casing to allow for handling ruggedness and to prevent bending of the fiber and maintain beam quality.

3. Optical Material Selection

3.1 Refractive Index and Mechanical Properties

One of the most important properties to be considered in designing an optical system is the selection of the materials from which the lenses will be made. In particular, the refractive index is important because it affects the curvatures of the surfaces required in order to effect the needed optical power. Higher indices allow less curvature to be used. For a homogeneous materials, higher indices improve the performance of the optics because less spherical aberration is produced because the deviation of a sphere from the ideal surface is reduced (the only significant aberration in most fiber-optic beam delivery systems is spherical). The change in refractive index also changes the best lens form.[13] This is illustrated by the equation for transverse spherical aberration at geometric best focus when spherical surfaces are used, which is given by

$$TSA = K(n;q;p)\left(\frac{D_L}{f}\right)^3 s_2 \tag{2}$$

where D_L is the 100%-enclosure diameter of the beam incident on the lens, f is the focal length, s_2 is the image distance, $K(n;q;p)$ is given by

$$K(n;q;p) = \pm\frac{1}{128n(n-1)}\left|\frac{n+2}{n-1}q^2 + 4(n+1)pq + (3n+2)(n-1)p^2 + \frac{n^3}{n-1}\right| \tag{3}$$

where $p=1-2f/s_2$ and $q=(r_2+r_1)/(r_2-r_1)$. The radii of the lens surfaces on the object and image surfaces are r_1 and r_2, respectively.[14] Solving $dK/dq|_{n,p}=0$ gives the best form lens shape for the conjugates of the system and the refractive index of the material used. For materials with refractive indices in the range of 1.5 to 1.8 (typical glasses), at infinite conjugates, the best lens form is very nearly plano-convex.

There are a number of materials that are candidates for use in optical systems. Since this manuscript is restricted to fiber-optic delivered systems, wavelengths above 2 μm will be ignored (work on far-IR fiber systems has not reached the point that it is a significant option). The most common materials are glasses, which are transparent in this wavelength range. The optical designer should select glasses that have good chemical and environmental resistance; this information can be obtained from the glass manufacturers. Consistent with the condition that high-index materials are generally better, glasses in the SF, LaF, and LaSF families would be good candidates. Their positions on the glass map are shown in Figure 3.

On occasion materials other than glass may be candidates for use in a system. Fused silica offers a lower expansion coefficient, a higher softening temperature and lower dispersion than glass; however, it also has a lower refractive index (~1.45). Sapphire has a comparable thermal expansion coefficient, a very high softening temperature, a high refractive index (~1.75), lower dispersion than glass or fused silica and extraordinary hardness; it is also slightly birefringent, expensive, and hard to work.[15] We could continue to work through the list of possible materials. Some of the materials that transmit in this range have higher absorption than glass, some are soluble in water, and often they are more expensive to make or finish than glass. Therefore, unless there is a compelling physical reason to pick another material (such as an unusual thermal load or caustic environment), glass remains the material of choice for use in visible and NIR beam delivery systems.

Gradient-index materials are available as a superior alternative to homogeneous glasses. The gradient-index materials will have mechanical and optical properties similar to comparable glasses, however, the refractive-index gradient, coupled with an appropriate surface curvature, allows well-corrected optics (often diffraction-limited or nearly diffraction-limited) to be produced using planar or spherical surfaces. Gradient-index materials have not been widely used because they were not reproducible and were not available in sizes over a few millimeters. An axial-gradient material, called GRADIUM™, which has the necessary reproducibility and size has only recently become commercially available. The GRADIUM manufacturing process creates refractive index profiles[16,17] like the G2SF profile shown in Figure 4. The refractive index in the GSF family of glasses varies from about 1.78 to 1.63. The GSF glasses offer the high refractive index preferred for low aberration and the axial refractive-index gradient allows superb control of spherical aberration. Our experience has shown that it is not uncommon for a GRADIUM lens to have 20-50 times less aberration than a comparable homogeneous lens. The best-form shape is not as easily predicted; for infinite conjugates it is roughly plano-convex, although depending upon the focal length and GSF glass used, biconvex and meniscus forms provide the best aberration control.

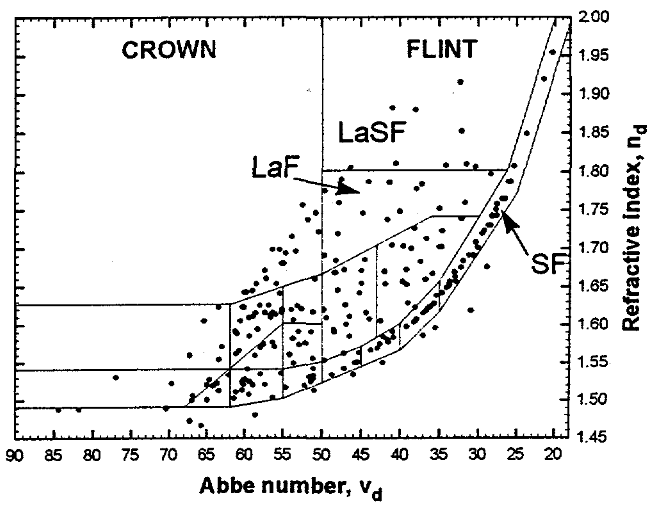


Figure 3. Glass map showing the various glass families.

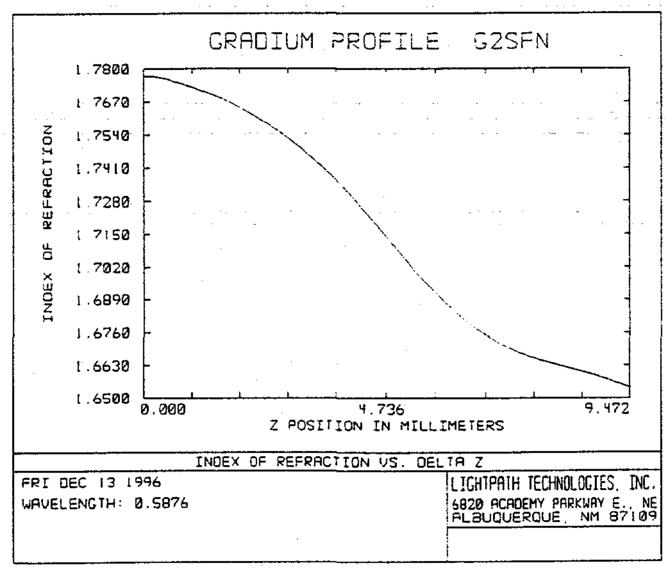


Figure 4. G2SF refractive index profile.

3.2 Thermal and Damage Properties

Two issues of particular concern for high-power laser optics are the damage mechanisms and thermal properties of the material. Damage thresholds are typically high enough that the large diameter beams typically encountered in high-power lasers pose no threat to the bulk material integrity. A much greater threat to the material is a poor surface finish, because surface imperfections can reduce the material's resistance to damage by at least an order of magnitude. One of the most highly regarded materials is fused silica, which has a damage threshold of 5×10^8 W cm^{-2} (5 J cm^{-2} for a 10 ns pulse) or 5×10^6 W cm^{-2} for a CW beam.[18] Another common material, BK7 glass, has a damage threshold of 2×10^8 W cm^{-2} (2 J cm^{-2} for a 10 ns pulse).[19] The exception to the generally good performance of optical materials is optical cement, which heats up rapidly and softens under loads of $<7.5\times10^7$ W cm^{-2} ($<$0.75 J cm^{-2} for a 10 ns pulse) or 750 W cm^{-2} CW.[20] The poor performance of cements is the reason that cemented doublets should be avoided whenever possible in high-power applications.

GRADIUM glasses exhibit damage thresholds comparable to other glasses and fused silica. Tests conducted by the University of Rochester on early GRADIUM materials indicated a damage thresholds of approximately 4×10^9 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).[21] Data reported by Newport indicated a damage threshold of 2×10^8 W cm^{-2} (2 J cm^{-2} for a 10 ns pulse at 1.06 μm).[22] 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 $\geq3.8\times10^5$ W cm^{-2}. The G3SF is capable of withstanding $\geq1.5\times10^6$ W cm^{-2} if there are no surface flaws or impurities.

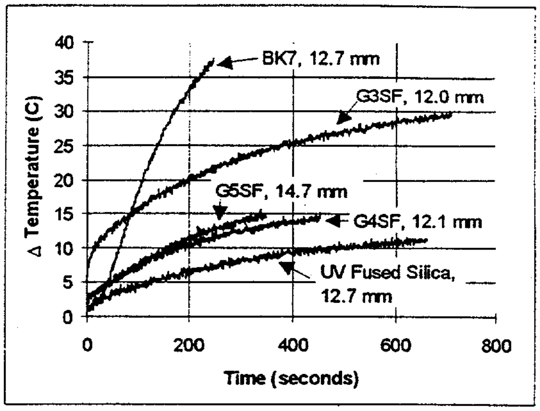


Figure 5. Temperature-time traces for 38 mm diameter AR-coated windows made from fused silica, BK7, and three GRADIUM materials. The thickness of the windows ranged from 12.0 to 14.7 mm. The incident power was 1500 W (CW, λ=1064 nm).

In high average power applications, the absorption of the optical material is critical. While a fraction of a percent is insignificant for powers on the order of tens of Watts, when several kilowatts are passing through a lens (with duty cycles in excess of 50%), differences in the absorption and thermal conductivity of the material are important. Failure to properly select the optical material results in large thermal loads on the lens. Unfortunately, useful data for evaluating different optical materials are not readily available; standard transmission curves are only useful for identifying materials that are grossly incompatible with the wavelengths of interest. As a result, poor choices are often made. This is illustrated by considering the thermal responses of different materials.

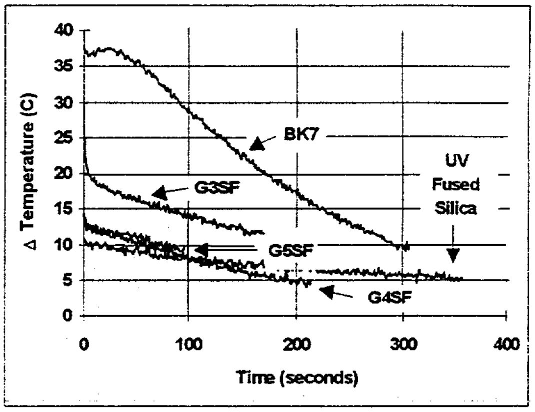


Figure 6. Temperature-time traces for the windows shown in Figure 5 after the laser shutter was closed and the windows began to cool.

AR coated windows made of G3SF, G4SF, G5SF, UV-grade fused silica and BK7 were subjected to 1.5 kW of CW Nd:YAG radiation. The temperature on the edge of the blanks was monitored with a surface-mount thermocouple. Plots of the temperature-time data are presented in Figure 5. The excellent thermal performance of fused silica is apparent from the plot. It is also clear that BK7, one of the most widely used glasses, heats up much faster than the fused silica. The GRADIUM materials exhibit thermal performance that is more like the fused silica than the BK7. The G4 and G5 materials heat up very slowly. G3 heats up more than G4 or G5 and the heating is very rapid when the laser shutter is opened.

The temperature response of the windows in the first 10-60 seconds is indicative of the thermal conductivity of the sample. Beyond that point, the data reflect the absorption of the window material (because the windows were mounted so that little conduction between the window and mount was possible). The data beyond 100 seconds is the relevant measure of the material performance; because of the low conductivity of glasses, after repeated duty cycles, the lens temperature will continue to increase as shown in Figure 5. Only when conduction to the lens mount and convection match the heating will the lens temperature stabilize.

The temperature responses of the GRADIUM, BK7, and fused silica after the shutter was closed (beam off) are shown in Figure 6. The slow initial cooling response of the BK7 (and the temperature increase) are indicative of its poor thermal conductivity. The very rapid cooling of the G3 indicates very good thermal conductivity. The G4 and G5 perform more like the fused silica, although with higher thermal conductivity (as expected). The thermal responses of the GRADIUM materials and fused silica show them to be well-suited for high power applications; BK7, however, is a poor choice (although it is often used because it is inexpensive).[23]

4. LAUNCH OPTICS

The launch optics should be of sufficient quality that the focused spot size is limited by the beam quality rather than the aberrations in the lens. A knowledge of the laser's beam quality allows the designer to determine the desired performance of the launch optic. The beam quality becomes the limiting factor when

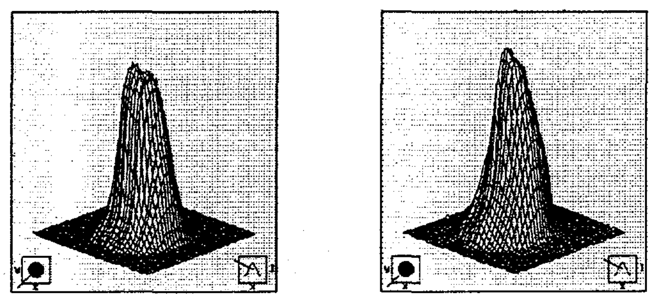
$$M^2 \geq \frac{\pi w_o}{\lambda f} \times r_{rms}, \tag{4}$$

where w_o is the r_{86} beam waist incident on the lens, f is the lens focal length and r_{rms} is the rms spot radius of the optical system. The rms spot radius can be calculated given the appropriate beam diameter and apodization. As the beam quality gets worse, the full benefit of well-corrected optics (such as GRADIUM) cannot be realized; to ensure the best performance possible from the laser, well-corrected optics should be used.

The calculation of limiting beam quality in Equation 4 is directly linked to the aberration multiplier, A, in Equation 1. If the value of M^2 from Equation 4 is called $M^2_{aberration}$ and the laser's true beam quality is M^2_{actual}, then

$$A = \max\left(\frac{M^2_{aberration}}{M^2_{actual}},\ 1\right). \tag{5}$$

For fiber launch, the most important beam parameter is the 100% enclosure radius because we want to launch all the energy into the fiber. The ability of the beam quality to limit the improvement on the focused spot to less than the improvement in the optics is illustrated by profiles of the beam from a laser at U.S. Laser Corporation (Figure 7). This laser has an M^2 value in the range of 50-100. Switching from BK7 to GRADIUM (i.e. eliminating the aberration–r_{rms} was reduced from 273 to 5 μm) reduced the r_{86} radius by 10%; the beam quality is what limited the improvement in r_{86}. The 100% enclosure was reduced by 14%, which would have allowed a 138 μm smaller fiber to be used.



GRADIUM 77 mm lens
r_{86}= 219 μm
r_{100}= 432 μm

BK7 77 mm lens
r_{86}= 244 μm
r_{100}= 501 μm

Figure 7. Profiles of focused beam from a 1.5 kW CW Nd:YAG laser using GRADIUM and BK7 77 mm efl singlets.

5. DESIGN OF THE COLLIMATING-FOCUSING OPTICS HEAD

The purpose of the optics head is to re-image the fiber face on the workpiece as perfectly as possible. In order to achieve this goal, the proper design form should be used. Since re-imaging the fiber face involves imaging finite conjugates, the most efficient layout requires two lenses, a collimating and a focusing lens. While, for fixed finite conjugates, it is unlikely that the best optical performance will be realized when each lens works at infinite conjugates, forcing each lens to work at infinite conjugates allows the focal length of the focusing optic to be changed as needed without requiring any changes to the collimating optic and it simplifies the calculation of magnification. As discussed previously, each lens should be at or near the best form shape to minimize spherical aberration.

M^2 is an unnecessary parameter for calculating the performance of the system with these large (200-1000 μm) fibers; simple geometrical optics is sufficient. The dimensions of the imaged fiber face (assuming that aberrations from imaging the fiber periphery dominate) are given by

$$r_{image} = |m| \cdot r_{source} + r_{blur} \tag{6}$$

where r_{image} is the geometrical (100% enclosure) radius of the image, m is the magnification, r_{source} is the radius of the extended source and r_{blur} is geometrical blur radius of points imaged from the edge of the extended source. The optical system will reach its practical performance limit when r_{blur} is small. For materials processing, the goal is to minimize r_{86}. The r_{86} focus is not usually a focus option in commercial ray-trace software; nominally, r_{86} is minimized about halfway between paraxial and rms foci. At this point, the amount of aberration present in the optical system can be evaluated. Based on the lens combinations tested at Argonne, a conservative, empirical rule-of-thumb to allow no significant increase in r_{86} (<5%) (i.e. keep the blur small) is that $r_{rms\ blur} \leq 0.25m \cdot r_{fiber}$.

To further reduce the size of the focused spot, either a smaller fiber or a smaller magnification must be used. Equation 1 helps the user determine the practicality of a smaller fiber. Smaller magnification requires the ratio of focusing to collimating optics focal lengths be made smaller. Because there are practical limits on the minimum working distance (in order to allow for nozzles, air-knifes, etc.), it is important to properly size the optics. A beam print should be taken of the beam exiting the fiber at a variety of power levels. From this information, the worst-case divergence angle from the fiber (this is usually less than the fiber's NA—what little energy cannot be detected by the profiler can be ignored) can be calculated. The *f/#* of the collimating optic should be chosen so that the clear aperture is about 80-90% of the optic diameter. Based on the smallest desired spot size and any working distance constraints, the minimum optic diameter can be selected. Clearly, larger standoff distances are achievable if longer focal length (and larger diameter) collimating optics are used. The most common optics diameters typically range from 25-50 mm.

Since the ultimate performance of the system is driven by the quality of the optics, well-corrected optics (at least at the level specified by the rule-of-thumb) are needed. It is difficult to meet the required optical quality with homogeneous elements using spherical surfaces. Aspheres or GRADIUM lenses are needed. Aspheres tend to be expensive and difficult to manufacture, sometimes failing to perform as expected.[24] Tests with GRADIUM lenses illustrate the level of improvement realized.

Figure 8 shows the r_{86} profile data for both step-index and gradient-index fibers from lasers at Argonne and U. S. Laser. The GRADIUM lenses produce spot sizes that are smaller than conventional homogeneous lenses for small spots. When the spot is large, so much aberration is allowable that there is not obvious benefit of good optics. The BK7 optics rapidly approach their best performance, called the BK7 limit; any smaller magnification would not result in a smaller focused spot because of the spherical aberration present. The small change in the spot sizes for the gradient-index fiber profiles is due to the fact that the gradient-index fibers tend to preserve beam quality, rather than simply scale with size. The smaller improvement realized for the GRADIUM with the step-index fiber at U.S. Laser is because the optics were underfilled and substantially less aberration resulted (*cf.* Equation 2). The data show that for a 5% improvement in 86%-energy-enclosure spot size over BK7 singlets (using the

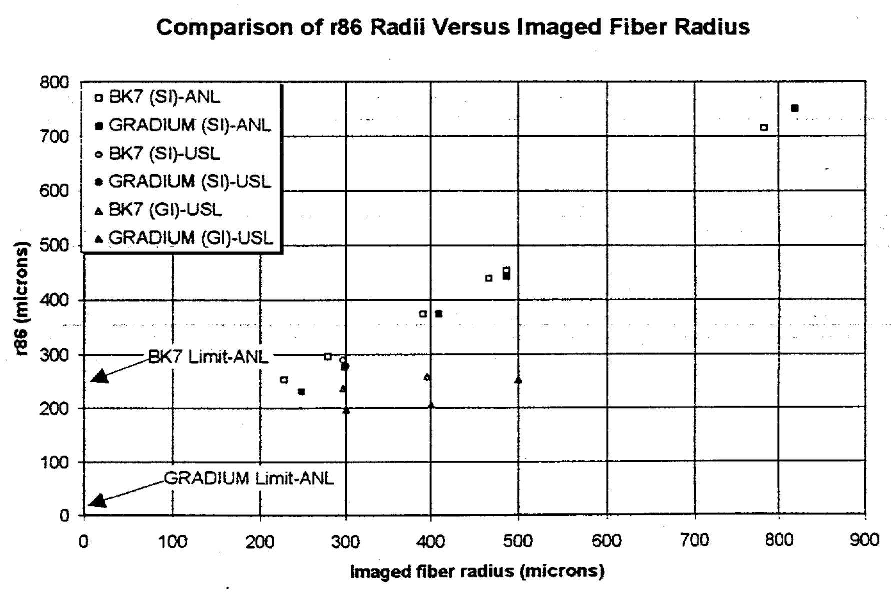


Figure 8. R_{86} radii versus imaged fiber radius for various GRADIUM and BK7 singlet focusing elements using 600-1000 μm step-index (SI) and gradient-index (GI) fibers. The performance improvements are most pronounced for smaller fiber face images.

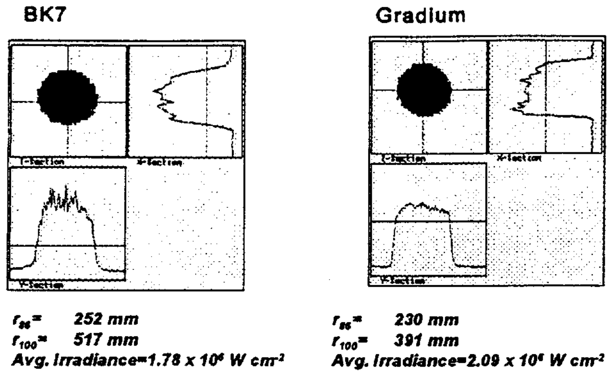


Figure 9. Cross-sectional irradiance profiles of focused spots from imaging the 1000 μm step-index fiber with pairs of BK7 and GRADIUM singlets (magnification of 0.5). The reduced aberration from the GRADIUM lenses is evident in the sharper, more "top-hat" profile.

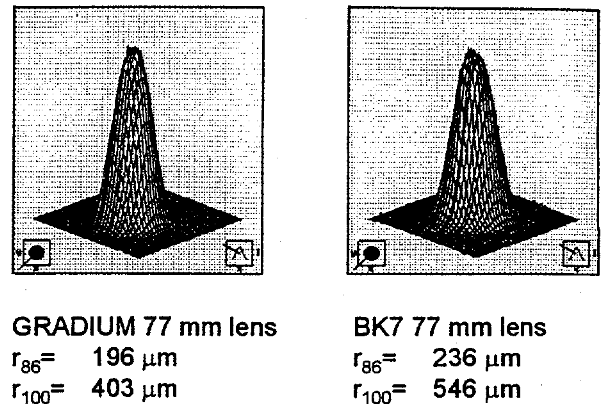


Figure 10. Focused spot profiles from a 600 μm gradient-index fiber showing the reduction in spot size realized with GRADIUM optics.

fiber and fully filled optics), $|m| \cdot r_{source}$ should be ≤300 μm.[25]

To visually demonstrate the effect of improved optics, cross-sectional intensity profiles of the focused spots from both BK7 and GRADIUM lens combinations (both have $|m|$ of 0.5) imaging a 1000 μm fiber are shown in Figure 9. The impact of the reduced aberration is clear from the GRADIUM lenses, which produced a sharper, more top-hat image of the fiber face and higher irradiance. Switching from BK7 to GRADIUM lenses reduced r_{86} of the imaged fiber face by 8.7%. The average irradiance of the imaged fiber increased by 19%. Tests at U.S. Laser with gradient-index fibers (focused spot r_{86}~200 μm) showed 15-20% reductions in r_{86} when using GRADIUM rather than BK7 singlets, as shown in Figure 10.

The importance of the improved optics is not so much the improved spot size, as the fact that improving the spot size increases the irradiance, wastes less energy, and translates into better welds. Replacing homogeneous lenses with GRADIUM lenses (maintaining the same magnification) at Unitek Miyachi resulted in a larger weld nugget and a 40% increase in penetration, as shown in Figure 11. These bead-on-plate welds were made with the head tilted at 30°.

The basic compensation mechanism for spherical aberration is defocus. The greater the spherical aberration, the more defocus required. This defocus is illustrated in Figure 12. Notice that since the GRADIUM elements have essentially no spherical aberration, no defocus is required. Thus as the laser power increases and the effective NA of the fiber changes, the total spherical aberration remains so small with GRADIUM that the position of focus remains constant. This is not the case with conventional optics. It is still possible to have spot size variability with gradient-index fibers because of the changes in the modes structure. However, the position of focus will not change.

Replace this space with high-quality scanned photograph of Unitek Miyachi results.

Figure 11. Cross-sections of welds on stainless steel coupons using a 600 μm gradient-index fiber reimaged at 1x magnification at 30° from normal incidence. The peak power was 1.5 kW. The GRADIUM lenses (left) were a pair of 80 mm focal length plano-convex lenses (GPX-30-80-2). The BK7 lenses (right) were a pair of 70 mm focal length plano-convex lenses.

Finally, there are a number of usability considerations important in the design of the optics head. First, protection for the lenses against spatter must be provided because of the close proximity of the optics to the workpiece. For this purpose an AR coated cover glass is used; it is an inexpensive consumable that protects the more expensive lenses. If for some reason an uncoated cover glass is used, care must be taken to ensure that reflections from the cover glass surfaces do not create a focused spot on or near the fiber face. Either using the ghost-image analysis feature of lens design software or manually calculating the position of the ghost image focus for all possible lenses to be used in the system will ensure that the ghost images do not damage the fiber face. One very useful accessory is an air knife; the transverse gas flow from the air knife helps reduce the spatter on the cover glass and keeps smaller aerosols, such as smoke, from damaging the cover glass. This simple accessory will further extend the life of the cover glass and reduce the consumables costs.

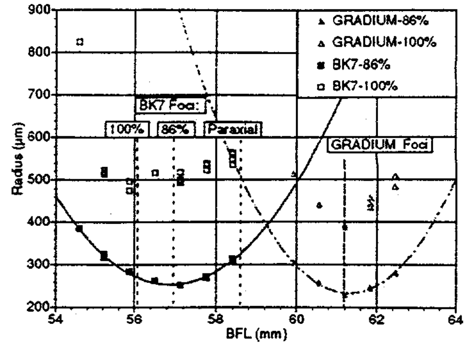


Figure 12. 86% and 100% enclosure radii for the BK7 127-BK7 65 and GRADIUM 132-65 mm lens combinations. The approximate positions of the paraxial, 86%, and 100% foci are indicated.

Cross-jets and coaxial nozzles are used to facilitate processing; they should be designed into a complete system. The cross jet, with sufficient velocity, will move the plasma plume out of the way. The cross-jet is an alternative to the air knife to protect the cover glass. However, since proper implementation of the air knife (gas pressure and orientation with respect to the weld) affects weld quality, it is not as flexible as the air knife. The coaxial nozzle makes the set-up much slower. It is generally used for assist gases when cutting. The coaxial nozzle and the air knife are not generally used together; only with special hardware designs can they be combined.

The design of the optics head mounting hardware should allow the head to be tilted. Tilting is a convenient means of further protecting the fiber from reflections, especially with highly reflective materials such as aluminum. In addition, tilting is useful for butt welds of materials with different thicknesses. The optics head should be designed so that lenses can be quickly and easily removed for inspection or change without requiring the hardware to be homed again to establish necessary reference positions. One simple feature that makes locating focus and weld inspection simple is a CCD camera which uses the same focusing lens as the laser in a through-the-lens viewing configuration. Finally, diagnostics can easily be designed into the optics head. As an example, the Nd:YAG laser at Argonne has an optics head that provides for Argonne's patent-pending weld monitor and a spectrometer to be used simultaneously. The weld monitor allows weld penetration and surface quality to be determined non-destructively. The spectrometer allows the weld plume to be monitored for certain constituents and thus ensure that, for example, the magnesium losses in aluminum welding are within some specified levels. This particular implementation does not interfere with the laser beam and, because these diagnostics are built into the head, no alignment will ever be required.

6. CONCLUSIONS

A well-designed fiber-optic beam delivery system provides the user the flexibility inherent in the use of the fiber as well as the best possible performance and convenient use. To accomplish this goal, a few basic considerations guide the user in selection and design of components. These considerations can be rephrased as simple (although generalized) imperatives:

1. Use the smallest fiber that can be used given the input beam quality of the laser.
2. Use high-quality launch optics to minimize spherical aberration so that spherical aberration does not force use of a larger fiber than necessary.
3. Use a step-index fiber if a "top-hat" profile or a constant focused spot size is important.
4. Use a gradient-index fiber if preservation of beam quality or high peak irradiance are most important.
5. Check the actual performance of the laser; since most fibers are in the "intermediate" length class, designing against the fiber's NA will result in oversized lenses.
6. Use robust connectors and the best possible fiber finish. This simple precaution will greatly extend the life of the fiber.
7. Lenses should be made of high refractive index materials, if possible. Glasses are the easiest and most economical solution, although other materials, such as fused silica or sapphire may be more appropriate in special circumstances. GRADIUM performs better than comparable homogeneous glasses because of the refractive index gradient.
8. Material selection should take damage and thermal properties into account. Many glasses (some of the SF's, BK7, etc.), although common, are actually poor choices. Low absorption, high conductivity materials are the

best choices. GRADIUM materials are excellent choices.

9. The optics head should provide ease of access to the lenses, diagnostic and monitoring capabilities when appropriate, lens protection and cross-jets/nozzles/air-knives as needed. A video camera is a nice addition.
10. Typically, a collimating-focusing lens layout is the best choice.
11. Every effort should be made to use the highest possible quality optics. The reduction in spot size and the improvement in weld quality and penetration can be dramatic.

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