Understanding High-Power Fiber-Optic Laser Beam Delivery

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March 25, 1996

Manuscript to be submitted to
Journal of Laser Applications

ABSTRACT

Fiber-optic beam delivery is commonly used on industrial laser systems. This article examines the conditions for the optimal propagation of high power beams through optical fibers. Beam quality effects by step and gradient index fibers of different lengths are considered. The differences between the diverging beam from a fiber and the beam at focus and on the fiber face are illustrated. Estimates are provided of the worst-case beam quality to be expected from fibers. Guidelines are also provided for the selection of beam delivery components based on the limitations of the optical system and the tasks to be performed.

KEY WORDS: Lasers, fiber-optics, beam delivery, beam quality, Nd:YAG, CO_2, waveguides, modes, lenses.

INTRODUCTION

The widespread availability of lasers of varying power levels and wavelengths has moved laser-based material processing from a laboratory curiosity to an economically important manufacturing technology. However, harnessing the power of a high-power laser requires knowledgeable and prudent choices be made when selecting the laser and its beam delivery system. This article focuses on issues relevant to understanding and specifying a fiber-optic beam delivery system. We will review the physics underpinning the operation of the optical fiber and provide some guidelines for specifying a system. Data obtained with high power Nd:YAG lasers will be used as illustrative examples. Because many of the considerations involved in understanding beam delivery are not dependent upon the wavelength of the laser, the discussion that follows is generally applicable, especially when restricted to wavelengths between 400 nm and 2000 nm, where the same optical materials can be used.

The beam generated by the laser is delivered to the workpiece in one of two ways: (1) free-space propagation or (2) fiber optics. Free-space propagation, *i.e.*, when the beam is relayed from source to workstation via mirrors and (often) enclosed beam tubes, has the advantage that the beam quality of the laser is not affected if high-quality optics are used. Some cooling requirements may be imposed on the optics, especially for high-power lasers. If the beam at the point of application needs to be manipulated to meet 2-D or 3-D processing requirements, then articulated joints, flying optics and other devices designed to keep the beam propagating along a predefined optical axis may be required; these devices are, however, complex, expensive, often bulky and difficult to maintain.

Fiber-optic beam delivery allows the beam to be transmitted in a small, flexible cable. Fiber-optic cables are typically available in lengths up to several hundred meters. 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. The flexibility associated with the fiber-optics eliminates the mechanical and optical complexities of components such as articulated joints and is well suited for use with robots.

Two of the most important high-power commercial laser sources are the CO_2 and the Nd:YAG. Consequently, we will discuss fiber-optic beam delivery options for these lasers. Most of the material in this paper will be targeted toward the optical fibers used in the visible and near IR because they are the most common. However, some discussion will be presented of fiber optics used for CO_2 lasers.

TYPES OF FIBERS

Gradient vs. Step

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.

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 the evanescent components, only the highest order mode ever reaches the core/cladding interface. The fiber eigenmodes are Laguerre-Gaussian, because of the spatial mode weighting induced by the refractive index profile[1].

Because of the differences in the output from these two fiber types, one fiber may be more appropriate than another for a specific task. The step-index fiber's uniform output profile has an 86% (energy enclosure) radius that is nearly the radius of the fiber. For a given fiber diameter the step-index fiber will produce a more uniform intensity profile and a wider spot.

The gradient-index fiber intensity profile, for the same fiber diameter, has a smaller 86% radius. The peak intensity is often about five times that of a comparable size step-index fiber. Thus, the gradient-index fiber may be a more appropriate choice when higher irradiance, required for deeper penetration or cutting, is required.

Hollow Waveguides

In principle, fibers can be constructed for all wavelengths of light. However, existing materials properties and refractive indices often make this very difficult for wavelengths far from the visible region. One relevant example is the wavelength of 10.6 µm (CO_2 laser) for which suitable materials are difficult to find. A common solution at this wavelength is the hollow-core waveguide. One variant is the hollow sapphire waveguide. It operates much like the conventional step-index optical fiber with a high-low-high refractive index profile. The dispersion characteristics of sapphire yield a refractive index of 0.67 at 10.6 µm and allow the fiber to operate on the principle of total internal reflection. The core is air; the lower refractive-index cladding is the sapphire. However, surface roughness of fibers produced still results in losses of 0.4 dB/m for a 1070 µm core (four times theoretical)[2].

The other hollow waveguide variants use air as the core and the cladding is a dielectric such as germanium[3] or silver halide[4] over a reflective metal (*e.g.*, silver or nickel) which also is highly conductive. Sometimes the dielectric-enhanced metal is a coating on the inside of a hollow glass tube[2]. These coated metal waveguides use the reflectivity of the metal (enhanced by the dielectric coating) to transmit the light. This approach leaves the waveguide subject to significant losses (compared to the optical fiber) and prone to significant increases in propagation losses due to bending, changes in polarization states, waveguide diameter, or mode structure. This is because "normal" reflection (as opposed to total internal reflection) at a surface is a strong function of the angle of incidence and polarization. Also, even highly reflective metals have a small, but non-zero, absorption. The absorption increases as the angle of incidence on the surface approaches normal[5]. Losses are reported to be between 0.2 and 0.8 dB/m. With cooling, however, peak transmitted powers in the 1-3 kW range have been obtained[3],[4],[2].

Beam quality may be more important than power transmission. The hollow waveguide supports a specific set of modes. Multikilowatt CO_2 lasers have $M^2<6$; Nd:YAG lasers have $M^2>50$ where M^2 is the conventional measure of beam quality. Consequently the low order CO_2 mode structure is degraded and the beam quality worsens substantially when the hollow waveguide beam delivery system is used. Consequently, waveguide or fiber-optic beam delivery for CO_2 lasers is usually not pragmatic unless flexibility overrides beam irradiance requirements.

FIBER USE CONSIDERATIONS

Fiber core size

Fiber size is an important consideration in deploying a beam delivery system. Smaller fibers produce less degradation of beam quality. Using a smaller fiber (assuming the same numerical aperture) allows the same focused spot size to be achieved with a greater stand-off distance or, alternatively, smaller spot sizes to be achieved. The smaller spot sizes result in higher irradiances; many applications require high irradiances that can only be achieved by maintaining beam quality when power is limited. The benefits expected from smaller fibers are important because multikilowatt Nd:YAG systems are currently limited to the 2 to 3 kW range.

There are important limitations to selecting the appropriate (smallest) fiber size. Clearly, the overall mechanical stability of the laser system is important. The laser beam focused spot size has to be smaller than the fiber core to avoid heat effects and allow for the mechanical tolerance of the fiber-optic connectors used for easy interchange of fibers without realignment. However, the most fundamental limitation is imposed by the combination of the laser's beam quality and the numerical aperture (NA) of the fiber. Together they prevent arbitrary usage of any focal length lenses in the launch optics. Working from the equation for the focused spot size for an M^2-times-diffraction-limited beam, only two assumptions are necessary to determine the minimum fiber size: (1) the ratio of the 86% and 100% radii is 1.5 (based on our experience) and (2) in the interest of conservative engineering, only 80% of the fiber diameter will be filled. Given these two assumptions, the minimum fiber diameter, *d*, to be selected as a function of M^2, K, λ and the NA is given by

$$d = M^2 K \frac{\lambda}{\pi} \frac{5.625}{\tan[\arcsin(NA)]} .$$

Where K is the aberration of the optics and λ is the wavelength. As an example, at a wavelength of 1.06 µm, NA=0.2 and $M^2K=70$, the minimum fiber diameter would be 650 µm; if $M^2K=100$, then the size increases to 930 µm. Consequently, most high 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. As an example, at U.S. Laser with $M^2K>80$ the laser beam is routinely launched into 560 µm fibers.

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.

Fiber Surface Finish

In conjunction with this project, we investigated the effects of fiber face 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.

We had several fiber samples 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 the capabilities of different vendors. 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 must be taken to select vendors who can meets strict specifications.

Laser polishing is a technique that uses a CO_2 laser to melt the fiber end, yielding a smooth finish after cooling and solidification. Laser polishing achieved the best overall RMS roughness (local smoothness) but yielded larger peak-to-valley values than the best mechanical polish. The laser polished ends were observed to take on a quasi-spherical curvature, protruding toward the middle of the fiber and receding near the edges. This is most likely due to surface tension effects during solidification. The fiber end curvature may be enough to cause focusing effects and degrade fiber-to-laser coupling. Overall, it was determined that laser polishing provides no particular advantages that cannot be achieved through less costly means.

Besides mechanical and laser polish, several fiber samples were cleaved and evaluated. Cleaving has traditionally been considered a superior method of end finish because the induced break generally provides a smooth, flat finish. Little work had been done, however, in cleaving large core multimode fibers for high power beam delivery. The vendor we used had recently developed a proprietary fixture and methodology for cleaving such fibers. The samples evaluated showed good local smoothness, but had large scale ripples or waves that made it impossible to get reliable interferometer readings. In addition to waviness, the cleaving process can impart a burr near the fiber edge, which could lead to disastrous consequences in extreme high power usage. We found no vendors who could provide a repeatable cleave that was as good as a mechanical polish.

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.

EQUIPMENT AND PROCEDURE

The experimental layout is shown in Fig. 1. A CW Nd:YAG laser (U.S. Laser, Wyckoff, NJ) was used in the experiments. The beam was launched into a series of fibers of different lengths, core sizes and refractive index profiles. The results from the two fibers discussed in this paper had a core diameter of 800 µm and lengths of 2-3 m. The spatial irradiance profile of the beam entering and exiting the fiber was obtained using a beam analyzer (Prometec Laserscope). This instrument samples the beam using a spinning hollow needle. A small portion of the beam energy is transmitted to a detector via a pinhole and polished metal mirrors in the needle. Two types of needles are used for near focus and collimated beams. On a diverging beam, the profiles are subject to polarization effects[6].

EFFECTS ON BEAM QUALITY

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[7],[8],[1]. 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. They are representative of an aligned beam. 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.

Fiber Length

As light of some initial distribution 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. 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 launching 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 a 2 m length of 800 µm step-index fiber. Fig. 2 shows the focused beam launched into the fiber (Fig. 2a) and the focused output from the fiber (Fig. 2b). 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. 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. This type of profile was typical of output obtained from several CW multikilowatt Nd:YAG lasers (different manufacturers) using 1000 µm fibers of 10 m length.

Fiber Type

An important difference between step-index and gradient-index fibers is their effect on the output beam quality produced. The worst case beam quality from a step-index fiber can be estimated using the conventional definition of M^2. This definition is based on a Gaussian beam and the 86% energy enclosure beam waist is used. If we substitute $0.86^{1/2} r_{fiber}$ for the beam waist and make the necessary adjustment for the angle of divergence using $0.86^{1/2}$arcsin(NA), then

$$M^2 = 0.86\,H \frac{\pi r_{\text{fiber}} \arcsin(\text{NA})}{\lambda}\ .$$

The estimate for a gradient-index fiber is considerably more difficult. However, we expect that the beam quality would be better than the step-index case.

The measured and predicted beam quality values for 800 and 1000 µm step index fibers are given in Table 2. The M^2 value for the 130 W laser beam before the fiber was 55. The profiles of the focused launch beam and the output profiles for both types of fibers are shown in Fig. 2. The measured M^2 values include the aberration effect of the focussing optic used. The maximum M^2 estimate gives a consistent upper bound to the data obtained.

Near and Far-Field Output Profiles

As discussed above, the light is transformed as it propagates through the fiber. On the output fiber face, the intensity distribution generally resembles the refractive index distribution, *e.g.* a step-index fiber has a step or top-hat distribution and a gradient-index fiber has a Laguerre-Gaussian distribution. Outside and unconstrained by the fiber, a wide variety of intensity distributions are possible because of the large number of modes present. Fig. 3 shows the evolving profiles of the diverging beam from a 800 µm step-index fiber. These diverging profiles quickly take on a quasi-Gaussian shape.

These output profiles can be used to optimize the launching of the beam. Misalignment of the fiber at the launch end preferentially induces modes with large angular momentum components that appear as rings or crescents in the output. Typically, for step-index fibers, these rings are found near the periphery of the fiber[13],[14]. The “shoulder” in the profiles in Fig. 3 is indicative of a slight misalignment of the fiber and launch optics. Collimating this output beam (Fig. 3d) makes the contributions from the higher angular momentum modes appear more distinctly as a crescent or ring. Fig. 4 shows the focused spot profiles from a 3 m length of 800 µm gradient-index fiber. The magnitude of the changes in the output profile due to preferentially exciting high angular momentum modes is dramatically illustrated. The laser beam power was reduced to 234 W to protect the connectors from the severe misalignment that resulted in substantially reduced power transmission. The ring structure is so dominant that the Gaussian shape now resembles a D-mode.

OUTPUT OPTICS

Spot Size

The laser beam delivered by the fiber needs to be transformed for a particular application. The conventional technique is to upcollimate and focus to a small spot for most applications. The collimating optic specification is dictated by the NA of the fiber. With large core fibers, short focal length optics are needed for high irradiance requirements. Cover glass protection is essential with the short standoffs and susceptibility to spatter.

One important issue in appreciating the performance of a beam delivery system is to select an appropriate metric. There are two convenient methodologies which can be used to determine the required diameters, focal lengths and positions of the output optics. The first methodology is the concept of beam quality, which is based on scaling the diffraction-limited performance of the optics. The beam quality is the ratio of the performance of the laser (*i.e.*, the beam waist and divergence) to that expected from a Gaussian beam at the same wavelength[15].The same information is also often conveyed as the product $w_o\theta$ in terms of mm-mrad. The second methodology is the geometrical magnification of the fiber face by the lenses. There is not universal agreement on the appropriate formalism to use to treat diverging, multimode laser beam from a fiber[16]. The beam quality approach is clearly the appropriate choice for the raw laser beam, particularly if it has few or low order modes present. The geometrical imaging approach is the appropriate choice for classical situations with large images and modest magnifications. These two methodologies also convey different information.

The beam quality approach allows immediate calculation of the 86% energy radius, which is generally the effective radius of the beam. The focused spot size can be determined by starting from the relationship for focusing a collimated Gaussian-beam (where θ is typically very small), $w_f = f\theta$, solving for θ in the definition of M^2, and replacing M^2 with M^2K, where K is the increase in spot size due to aberrations in the optics, yields the useful relationship

$$w_f = M^2 K \frac{\lambda f}{\pi w_o} .$$

However, calculating the 100% spot size from M^2 requires additional information or assumptions. Clearly, a single parameter is not capable of providing all of the necessary information about the laser beam[17].

The geometrical approach is the process of imaging the fiber face on to the workpiece. Diffraction and aberrations increase the actual spot size from this geometrical baseline by blurring the image of each point on the fiber face. Geometrically, the size of the image of the fiber face is given by

$$r_{spot} = \frac{d_{image}}{d_{object}} H r_{fiber} + r_{blur}.$$

If a pair of lenses (a collimating and a focusing lens) are used, the object and image distances are replaced by the collimating and focusing lens focal lengths, respectively. The geometrical approach gives the 100% radius, however additional information or assumptions are required to determine the 86% energy enclosure.

The beam quality approach facilitates easy comparisons between input to and output from the fiber; for this reason we rely on this formalism. If M^2 values are determined experimentally from the output, then any “corrections” for aberrations, etc. are implicit in the measurement. However, the geometrical optics approach gives a convenient way of estimating the focussed beam size given the physical descriptions of the fiber and optics.

Application Considerations

Conventional optics used for high power Nd:YAG laser beams are anti-reflection (AR) coated BK7 glass lenses. The cover glass also need to be AR coated to maximize transmission. Most fiber-optic beam delivery systems use AR coated optics but uncoated fiber ends. Consequently, transmission losses of 10 to 16% depending on the number of lenses used for launch and output can be expected. Minimizing the loss at the fiber ends by AR coating can improve transmission to 98%.

Most applications require a beam that exceeds a particular threshold irradiance for effective material processing. Consequently, for a given application, the laser beam power required to exceed the threshold irradiance can be computed by

$$P_t = \frac{0.86\pi I_t (w_r / F)^2}{T}$$

where I_t is the threshold irradiance, w_r is the 86% energy enclosure radius, T is the power transmission and F is a factor that depends on the characteristic of the fiber. We define F=1 for step-index fibers; F is greater than 1 for gradient-index fibers resulting in a substantial decrease in the threshold power requirement. For optimal processing in some applications the shape of the beam is important in addition to exceeding threshold irradiance. For example, a square or rectangular top-hat beam is important for effective heat treating. This beam shape is difficult to produce without resorting to faceted integrator optics that tend to be expensive. A pragmatic solution is to use cylindrical and spherical lens combinations for the focussing optic to produce an elliptical beam. This beam shape has been found to be effective for heat treating[18]. If we use values of T=0.85, F=1, an area of 4.4 mm x 3.6 mm and $I_t=10^3$ W cm^{-2}, the threshold laser beam power P_t is 503 W. The requirements for welding applications are indicated in Table 3 for steel and 5000 series aluminum alloys. The equivalent 86% spot size for the gradient-index case are used to compare the power requirements for using the 800 µm fiber. The 86% beam radii used correspond to focal lengths of 65 to 100 mm. The assumption of a constant threshold irradiance value independent of spot size may underestimate the actual values at small spot sizes. Nevertheless, the threshold laser beam power values computed indicate the advantage of using the gradient index fiber to obtain high irradiance. The computed values are consistent with findings in the field that 3 kW CW Nd:YAG lasers are often needed to weld aluminum because of the size of the focused spots. However, Table 3 also shows that reducing the size of w_r (either by using a smaller core diameter fiber or shorter focal length lenses) can significantly reduce the total laser power required.

For cutting applications, higher irradiance than those used for welding are required. When step-index fibers are used, the (near) top-hat profile and stable spot size resemble the ideal "laser knife" for cutting producing smooth kerfs[19],[20]. The gradient-index fiber producing substantially higher irradiance is suited for thicker sections or faster cutting for a given laser beam power. However, this increased irradiance is obtained at the expense of spot size stability[20]; the focused spot size from a gradient-index fiber generally varies significantly with input laser power because the launch conditions change. The relative advantages and disadvantages of the step and gradient index fibers are also relevant to drilling applications that require higher irradiance than cutting. When hole size uniformity is paramount, step-index fibers are preferred. As before, the step-index fiber will provide better uniformity and edge quality than the gradient-index fiber, although higher total power levels will be required. The gradient-index fiber will produce higher irradiance to drill deeper holes but the focused spot size variability, if not carefully controlled, can cause complications. A mode scrambler could be used with the gradient-index fiber to saturate the energy distribution and eliminate the variability in focused spot size, but the beam quality would be worsened, partially negating the irradiance advantages derived from the gradient-index fiber.

SUMMARY & CONCLUSIONS

Multimode optical fibers enable efficient flexible laser beam delivery but at a loss in the quality of the delivered beam. The fiber-optic beam delivery system effectiveness is strengthened by the optimal selection of its components not only for minimizing beam quality degradation but also for robustness. The laser beam to be delivered should be launched properly into the fiber, otherwise damage may arise. Coarse alignment of the beam launch conditions is carried out by checking transmitted power. Fine alignment can be obtained by monitoring the beam profile exiting the fiber for higher order modes. Smaller fibers tend to produce less degradation to beam quality but the spot size of the beam focused into the fiber is limited by the quality of the laser beam, focusing optic and the numerical aperture of the fiber. With the short focal lengths used, aberration-free optics can be of significance. This is also true for output optics when small spot sizes or high irradiances are desired. High power handling requires special connectors that can withstand back-reflections. These high power connectors avoid the use of components such as epoxy that are susceptible to heat. Bends in the fiber-optic cable tend to produce higher order modes that modify the beam profile. Consequently, a length of rigid sheathing for the output end of the fiber will maintain the beam quality and be resistant to handling effects.

Step-index fibers produce a top-hat profile at the output fiber face whereas the gradient-index fiber produce a Gaussian type profile. These output beam characteristics can be used advantageously for different applications. The top-hat beam produces more uniform irradiance of the workpiece and less energy, below the threshold irradiance, that results in undesirable heat effects. The Gaussian type output of the gradient-index fiber produces substantially higher irradiance at the same power level compared to the step-index case. This higher irradiance is particularly useful for processing of reflective or high thermal conductivity metals or for deeper penetration requirements. Because of the characteristic effect of the fiber, instability of the beam quality associated with the laser will be improved after fiber delivery.

A variety of optics can be utilized to deliver a beam of the required shape and irradiance to the workpiece. Recent developments in optical materials allow the manufacture of aberration-free optics that are particularly useful for short focal length lenses. Progress in the development of diffractive optics has made beam shaping easier and more affordable. Ultimately, it is the comprehension of the function and characteristics of each required component that aids in building a robust and effective system.

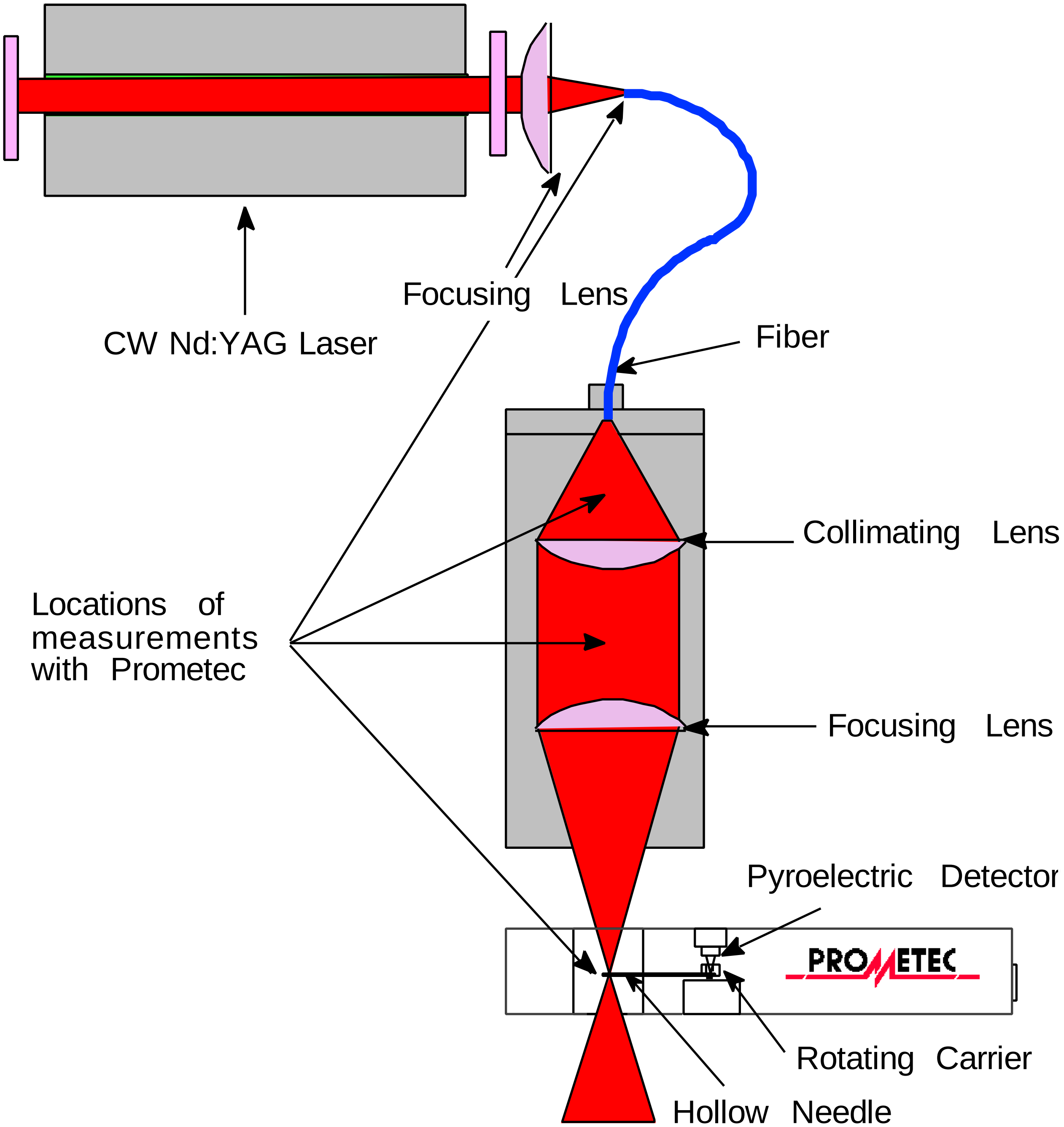
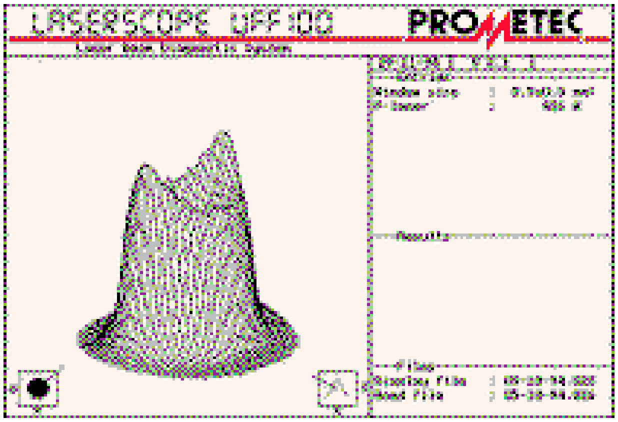
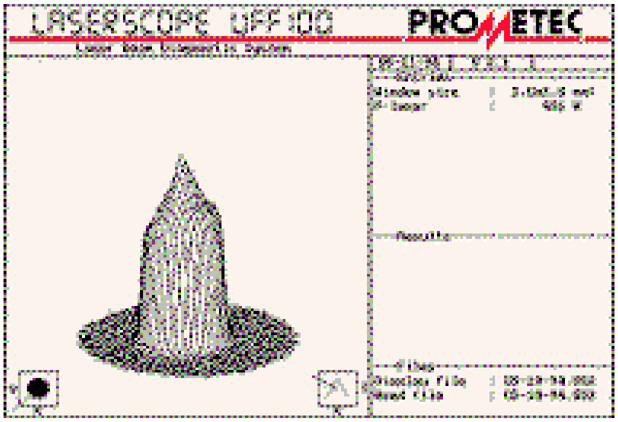


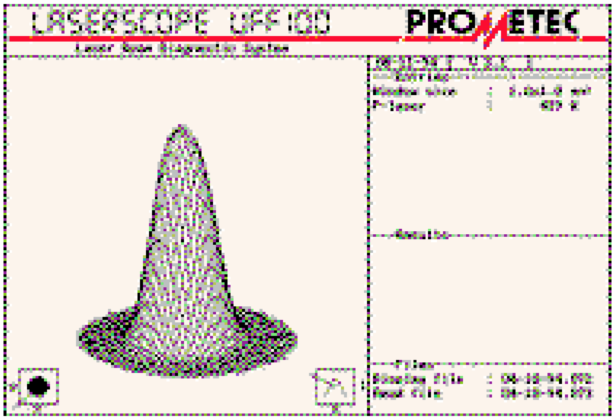
Figure 1 Experimental layout showing locations in the beam path where the Prometec was used to measure the irradiance profile.



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

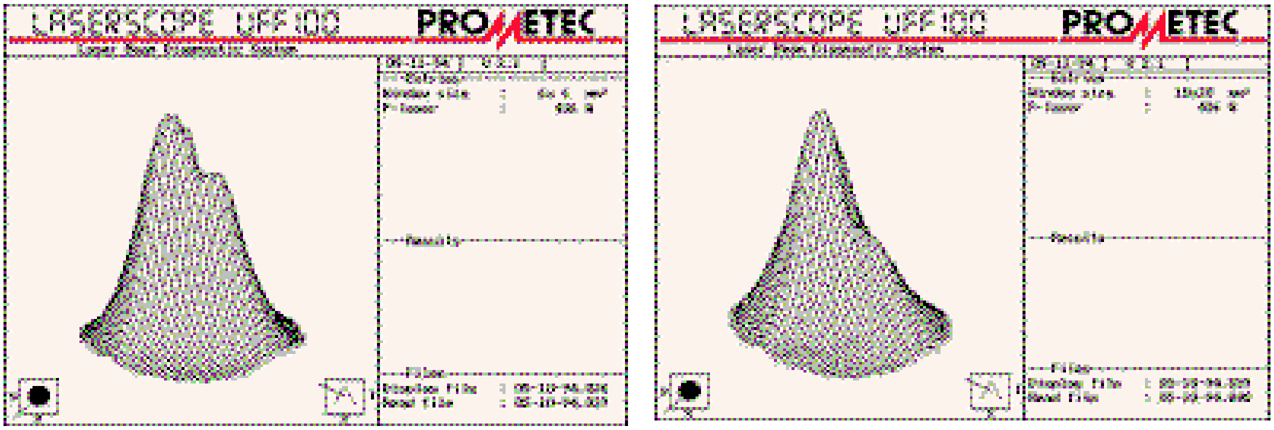


(b) Focused beam exiting a step-index fiber.



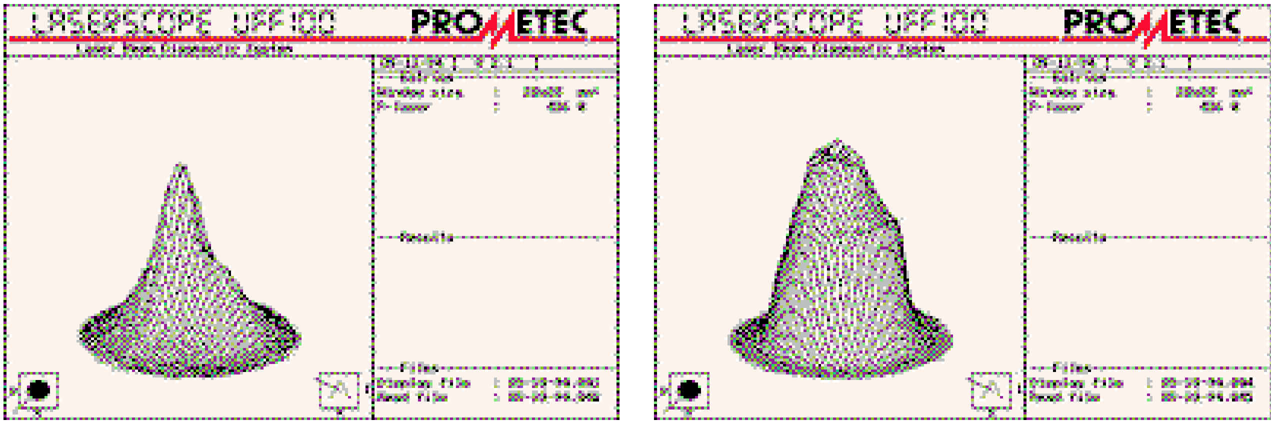
(c) Focused beam exiting a gradient-index fiber.

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.



(a) 25 mm from fiber face.

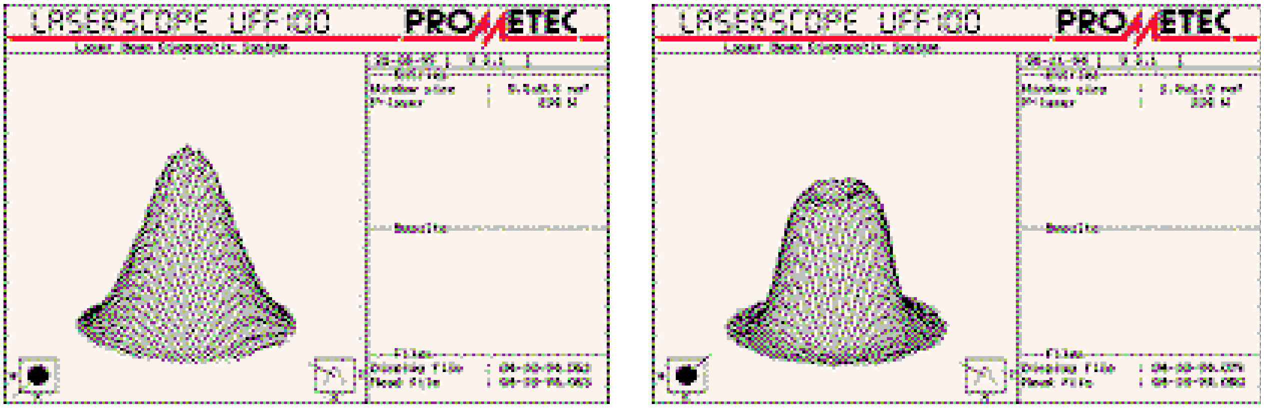
(b) 50 mm from fiber face.



(c) 75 mm from fiber face.

(d) Collimated beam from fiber.

Figure 3 Profiles of the evolving beam profile from an 800 µm step-index fiber (a) 25, (b) 50 and (c) 75 mm from the fiber face. The profile of the (d) collimated beam emphasizes the azimuthal modes by making the crescent more visible.



(a) Properly aligned beam launch.

(b) Severely misaligned beam launch.

Figure 4 Focused beam profiles from an 800 µm gradient-index fiber for (a) a properly launched beam and (b) a severely misaligned beam.

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.

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 2 Beam quality (M^2K) obtained after focussing optic using a 130 W beam (M^2=55) and different fibers with a Prometec laser beam analyzer. (SI=step index)

Fiber Size (µm)	**Lens Focal Length (mm)**	**Measured M^2K**	**Predicted Maximum M^2**
1000 SI	75	180	255
800 SI	35	132	204

Table 3 Threshold laser beam power required for welding steel and aluminum using 800 µm fibers. Threshold irradiances of $3x10^5$ and 10^6 W cm^{-2} were assumed for steel and aluminum respectively. 85% transmission was assumed.

Fiber Type	**W_r (µm)**	**Threshold Laser Beam Power (W)**	
		steel	**aluminum**
Step index	300	860	2900
	200	380	1300
Gradient index	210	440	1500
	140	190	620

REFERENCES

1. März, R. *Integrated Optics: Design and Modeling*, Boston: Artech House, pp. 69-73, 1995.

2. Nubling, R. and Harrington, J. A. Hollow waveguide delivery systems for high-power, industrial CO_2 lasers. *Applied Optics* **35**(3), pp. 372-380, 1996.

3. Hongo, A., Morosawa, K., Shiota, T., Matsuura, Y. and Miyagi, M. Transmission Characteristics of Germanium Thin Film-Coated Metallic Hollow Waveguides for High-Powered CO_2 Laser Light. *IEEE J. Quantum Elect.* **26**(9), pp. 1510-1515, 1990.

4. Gu, G. and Morrow, C. E. Concentrating CO_2 Laser Light from a Flexible Waveguide Delivery System by Using Reimaging and Nonimaging Optics. *Proc. ICALEO ‘94*, Orlando, FL: Laser Institute of America, pp. 803-809, 1994.

5. Hecht, E. *Optics*, 2nd ed., Reading, MA: Addison-Wesley, pp. 92-113, 1987.

6. Liu, Y. and Leong, K. Laser Beam Diagnostics for Kilowatt Power Pulsed YAG Laser. *Proc. ICALEO ‘92*, Orlando, FL: Laser Institute of America, pp. 77-87, 1992.

7. Jackson, J. D. Classical Electrodynamics, 2nd ed. New York: Wiley, p. 109, 1975.

8. Lee, D. L. *ElectromagneticPrinciplesofIntegratedOptics*, New York: Wiley, pp. 288-298, 1986.

9. Beck, T., Reng, N. and Richter, K. Fiber type and quality dictate beam delivery characteristics. *Laser Focus World* **29**(10), pp. 111-115, 1993.

10. Boechat, A. A. P., Su, D. and Jones, J. D. C. Dependence of output near-field beam profile on launching conditions in graded-index fibers used in delivery systems for Nd:YAG lasers. *Applied Optics* **32**(3), pp. 291-297, 1993.

11. Su, D., Boechat, A. A. P. and Jones, J. D. C. Beam delivery in large core fibers: effect of launching conditions on near-field output profile. *Applied Optics* **31**(27), pp. 5816-5821, 1992.

12. Brown, T. G. Optical Fibers and Fiber-Optic Communications. In *Handbook of Optics*, Vol. II, 2nd ed., (M. Bass, editor-in-chief) New York: McGraw-Hill, 1995.

13. Hunter, B. V. *Geometry-Induced Fluorescence Modifications: An Experimental Study of Micron-Sized Capillaries,* Ph.D. Dissertation, University of Arizona, Tucson, pp. 174-177, 1993.

14. Hunter, B. V. and Bickel, W. S. Geometry-induced fluorescence resonances in small lossy capillaries. *Applied Optics* **34**, pp. 4240-4247, 1995.

15. Jones, R. D. and Scott, T. R. Laser-beam analysis pinpoints critical parameters. *Laser Focus World* **29**(1), pp. 123-130, 1993.

16. O'Shea, D. C. personal communication, 3 May 1995.

17. Shannon, R. R. *Optics and Photonics News* **5**(11), p. 62, 1994. cf. also *Optics and Photonics News* **6**(2), pp. 5-6, 1995.

18. Hunter, B. V. and Leong, K. H. Selecting Laser Heat Treatment Optics. *Industrial Laser Review*, pp. 12-15, February 1996.

19. Hack, R., Dausinger, F. and Hügel, H. Cutting and Welding Applications of High Power Nd:YAG Lasers with High Beam Quality. *Proc. ICALEO ‘94*, Orlando, FL: Laser Institute of America, pp. 210-219, 1994.

20. Haferkamp, H., Schmidt, H., Homburg, A. and Seebaum, D. Evaluation of Innovative High Power Beam Delivery and Management Systems for Material Processing Applications. *Proc. ICALEO ‘94*, Orlando, FL: Laser Institute of America, pp. 783-792, 1994.