Chapter 8

Design Issues for High Power Fiber-optic Beam Delivery System

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8.1 Introduction

The beam delivery systems are essential for the purpose of directing the light beam from source to application location. The use of laser as a light source is quite common such as in laser material processing, medical application and scientific research. Beam delivery systems are advantageous as they allow placement of a laser in protected area suitable for its maintenance and operation. Beam delivery system is of two types:

i) Free space beam delivery system and

ii) Fiber optic beam delivery system [104–106].

The choice of particular beam delivery system depends upon the availability of space and complexity of deployment. Free space beam delivery system use mirrors and lenses for directing the beam. The transmission losses in this kind of system are mainly determined by the quality of the coated optics used and their overall number. Therefore to minimize the transmission losses it is essential to have direct line of sight which results in lower number of components used. The disadvantage of such systems is that if beam location were to be moved to other place another set of optics need to be deployed for this. The advantage of the bulk optics is that beam quality of the laser is not much affected if high quality optics is used. Fiber optics offer flexible alternative of free space beam propagation. Pure silica based large core fibers can carry high power easily due to high damage threshold of fused silica. Apart from this flexibility, fiber delivered beam are inherently enclosed and there is no need of containment to avoid accident. The breakage in the fiber can be determined by standard methods available. The quality of the delivered beam is significantly compromised in fiber-optic delivery. The fiber optics system becomes attractive when used along with suitable combination of optics to ensure the required beam quality. This article reviews the various aspects of design and development of the fiber optics beam delivery system for diode pumped solid state green lasers (DPSSGL, Nd:YAG, second harmonic, 532 nm) for pumping the dye laser (DL) oscillator and amplifiers arranged in master oscillator power amplifier (MOPA) configuration. The output DL process beam is being used for atomic vapour laser isotope separation (AVLIS) of uranium/medical isotope of interest.

8.2 Fiber-optic Beam Delivery System

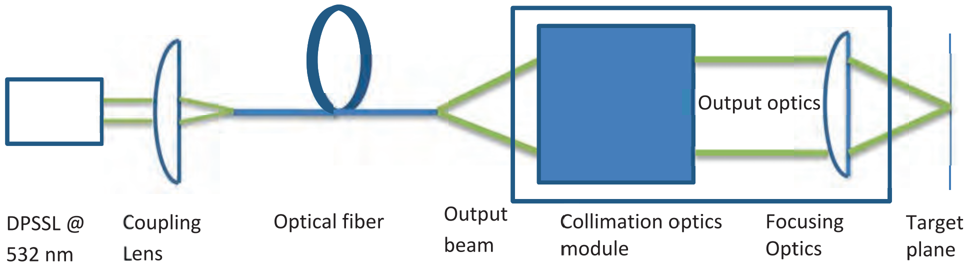

Figure 8.1: Schematic of fiber-optic beam delivery system.

The schematic of a typical fiber-optic beam delivery system components are shown in Fig. 8.1 above. The cross sectional view of fiber cable is shown in Fig. 8.2.

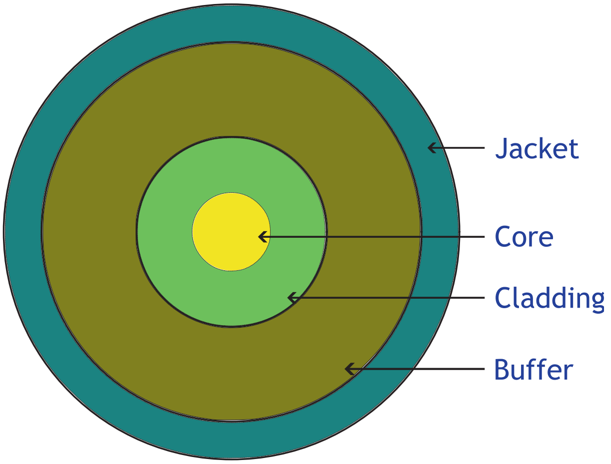

Figure 8.2: Schematic of cross sectional view of fiber-optic cable [107].

Specification of the Diode pumped solid state green lasers:

1. Average power, P_{avg}: 40-50 W
2. Wavelength, λ: 532 nm (second harmonic)
3. Mode: pulsed

4. Repetition rate, R: 6.25 kHz for each unit (these are suitably multiplexed to form 12.5 kHz pump beam for DL amplifiers/oscillators)
5. Pulse width, τ: 40 ns (FWHM)
6. Beam divergence: 10 mrad
7. Exit Beam size at laser head: 2-3 mm
8. Beam quality parameter, M^2: $\sim$35-40
9. Distance from source, i.e., lasers for beam transport: 20-25 meter (after considering the layoff geometry).

8.2.1 Fiber selection

Fiber Type

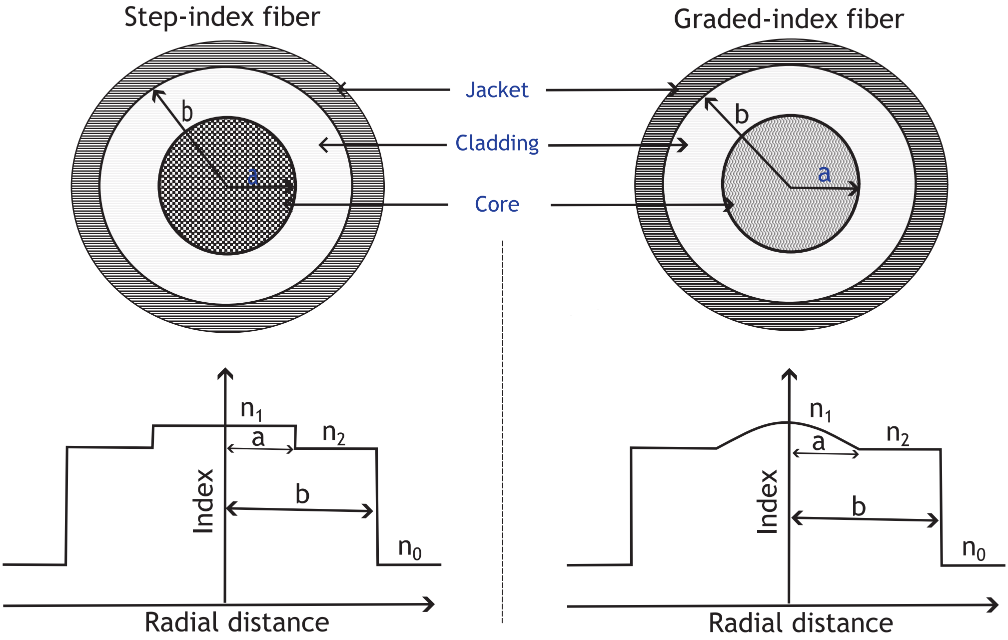

Figure 8.3: Schematic of fiber types based on refractive index profile: step-index fiber (left) and graded-index fiber (right) [108].

Large core multimode fibers can be classified into two categories depending on the refractive index profile of the fiber as shown in Fig. 8.3. The step index fiber has constant refractive index through the core and falls abruptly at the core cladding interface. The light guiding effect is achieved at core cladding interface due to refractive index difference, cladding being of the lower index of refraction. Another type of fiber has gradient index profile which has maximum index at the center of the core and falls in a parabolic fashion as it reaches the cladding. Therefore the light bending is achieved continuously as it propagates towards the interface at which beam gets total internal reflection. The difference in refractive index profile contributes to the intensity distribution at the output end of the fiber. In gradient index fiber lowest order modes don't reach the core-cladding interface and gets reflected within the core and hence each supported mode has specific mode radius and only higher order modes reach the interface. This results in an intensity distribution which is peaked towards the core. However, in step index fiber all modes gets guided at the interface and results in more uniform distribution of the intensity due to the mixing of the modes at the output end. The step index fiber is most commonly used when top hat distribution is required.

Fiber size

This is an important parameter for fiber-optic beam delivery systems. The choice of fiber size is governed by the power of the laser beam to be coupled into the fiber. Higher the size more power can be transmitted. However, smaller size fiber introduces less degradation to the beam quality defined by M^2 parameter. The focusing of the beam at the target location for high irradiance requires small size fiber. The minimum size of fiber is limited by the laser beam quality (M^2 parameter) and numerical aperture of the fiber. Together they prevent usage of arbitrary focal length of the lens used for coupling beam. First let us determine the size limited by power handling capability. The specification of DPSSL green laser is mentioned above. For pulsed laser peak intensity limits the damage threshold rather than average intensity.

Damage threshold

Damage threshold is an important parameter for selection of fiber size. Damage to the fiber can happen at both surfaces and in the bulk [108]. The damage is a phenomenon primarily a function of beam irradiance. It is important to keep the irradiance below the damage threshold also termed as laser induce damage threshold (LIDT). It is well established that damage threshold of fused silica in bulk is very high as compare to surface value. This is due to the factors like surface quality, roughness, presence of dust or another absorbing particle on the surface. The presence of these factors leads to localized heating or field enhancement which leads to the damage. The damage however could be cumulative or single shot in nature. Therefore, the preparation of good quality end face is inherent to the reliable operation of a fiber-optic beam delivery system. It must be understood that damage threshold values are quoted in terms of average irradiance over spatial cross section of the beam and for certain duration of the pulse. The peak value however can be much higher than average value over the pulse. Therefore, in case of pulsed lasers while calculating the damage threshold one needs to take into account the pulse width (FWHM) and repetition rate of the laser. Also spatial profile of the laser is important in determination of peak irradiance. The Gaussian intensity profile has twice the peak intensity as compared to the flat top intensity profile. For nonstandard beam profiles one must ensure that beam does not contain hotspots and has local intensity modulation which may exceed the damage threshold values. There are methods available to improve LIDT of the material by mechanical polishing, laser heat treatment (by CO_2 laser), cleaving the end which results in considerably flat surface. The good quality optical surface in absence of dust particle (or atmospheric turbulence) can give us reliable, safe and long term uninterrupted operation necessary for processes such as LIS. Fused silica has excellent damage threshold allowing transmission of high average power laser pulses for various applications. The fabrication technologies are mature enough to produce long lengths of continuous fiber. In telecommunication systems fused silica core of optical fiber is generally doped with fluorine/germanium, which reduces its damage threshold, to alter its index compared to the cladding. However, for application requiring delivery of high average power nanosecond pulses, it is desirable to have un-doped fused silica as core material surrounded by doped silica as a cladding material. Therefore, in general, multimode fibers consist of all silica fiber with un-doped core and fluorine doped cladding. The reported value of laser induced damage threshold (LIDT) in bulk for fused silica can range from 3-5 GW cm^{-2} [109]. The practically safe level of surface damage can be taken to be around 1 GW cm^{-2} as a rule of thumb. This value is same for CW or pulsed lasers. However, in pulsed laser, peak power density is much higher than the average power due to finite pulse size. It is therefore important to keep peak irradiance below damage threshold value. Mathematically, it can be expressed as

$$P_{peak} = K\frac{P_{avg}}{R\ \tau} \tag{8.1}$$

The values of K are 2 for Gaussian profile and 1 for flat top beam; R is repetition rate; τ is pulse width (FWHM). Now, for 1 GW cm^{-2} damage threshold, to maintain this intensity minimum focused spot size should be as per Eq. (8.2):

$$I = \frac{P_{peak}}{(\pi\ r^2)} = 1GWcm^{-2} \tag{8.2}$$

From Eq. (8.2), fiber size d_1 can be expressed as:

$$d_1 = \frac{2\ r}{c} \tag{8.3}$$

The fiber size evaluated from Eq. (8.3) is the minimum fiber size that can be used based on safe operation limits of surface damage threshold. However, one tends to choose higher value of fiber size to allow for mechanical tolerances for alignment. Another restriction on fiber size is posed by the combination of laser beam quality and NA of the fiber. This can be expressed as [104, 105]:

$$d_2 = \frac{M^2 A^2 a_1 b_1 \lambda}{c\ \pi\ tan(sin^{-1} NA)} \tag{8.4}$$

where M^2 is beam quality parameter; A = aberration multiplier (A = 1 for ideal lens); a_1 = ratio of 100% to 86% radii in exit laser beam (usually 1.5); b_1 = ratio of 100% to 86% radii in focused beam (usually 1.5); c = fiber filling factor (usually 0.8); NA = Numerical aperture of the fiber (0.22 standard NA).

From Eqs. (8.2) and (8.3) the selection of fiber size, a = max (d_1, d_2).

8.3 Effect of Fiber on Output Beam Quality

8.3.1 Fiber length

The fiber length for particular application is mostly governed by the source to target distance considering safe layoff through ducts and leaving margin for future expansion or movement. Based on the length chosen for the application it can be divided into various categories such as short, intermediate and long based on the evolution of spatial profile over propagation length. Laser beam launched into fiber has some initial distribution, but as it propagates through fiber it gets converted into modes supported in the core or gets leaked out through the cladding. The conversion into modes and their stabilization requires certain minimum length of the fiber. As discussed above there are different length scales to be considered.

Output beam profile

Short fiber introduces little or no modification to the output beam profile and is essentially transparent. On the other hand long fiber makes output beam profile independent of the input profile and closely resemble the refractive index profile of the fiber. Fiber lengths used in beam delivery application mostly falls in intermediate category. The length of fiber in this category depends on many factors like input beam profile, launching conditions, bends in the fiber and can range from 10 m to 100 m. For example highly under filled fiber will take longer lengths of the fiber to excite higher order modes than over filled fiber. The output beam quality i.e. spatial profile and divergence is strongly dependent on launching conditions [110, 111]. The beam propagates through fiber in the form of modes which can be classified in two categories meridional modes and skew modes. Merdional modes propagates through fiber by crossing through the central axis and the gets reflected at the core-cladding interface. These modes produce distribution peaked towards the axis. Skew modes propagates through fiber in annular region around the axis and results in a distribution peaked towards the edge. Meridional modes are special case of the skew when inner radius of annulus is zero. In general both modes propagate in the fiber and contribute to the output beam profile. The output beam divergence is also a function of launching condition at the input end. Off axis coupling and transverse misalignment of focused beam with respect to the longitudinal axis leads to excitation of higher angular momentum modes consequentially increasing the output beam divergence.

Polarization

The polarization of the output beam also depends upon the fiber length and degrades exponentially with fiber length [112]. The polarization scrambling happens due to presence of inherent refractive index fluctuations in the core, mode coupling, and eccentricity of core along length caused by stress, bending and twisting. In general for this application, output beam gets completely depolarized over propagation distance of 25 m to 30 m.

8.3.2 Beam propagation losses

Beam transmitted through large core multimode optical fiber suffers losses due to Fresnel reflection at interfaces like ends, Rayleigh scattering losses through the fiber length and bending losses etc. The bending loss can be minimized by always keeping bend radius above critical bending radius information of which is supplied by the manufacturer with the fiber. Fresnel losses can be minimized by depositing anti-reflection coating at both ends of fiber. Rayleigh scattering account for almost 96% of the losses in the optical fiber. Rayleigh scattering sets the lower limit of optical transmission loss in the fiber. The Fresnel reflection losses pose a greater challenge in beam delivery application where fibers are connectorized as all reflected beam gets dumped in connector and causes heating which may lead to the crack in the fiber at the point of contact with connector. Several advanced connectors are being used with water cooled arrangement to increase power handling capability of connectorized fiber. However, a fiber used in bare configuration does not have these issues apart from power getting coupling to plastic coating due to misalignment which can lead to melting of fiber due to localized heating.

8.3.3 Fiber size

The selection criteria for the fiber size is already discussed. However, fiber size plays an important role in output beam quality defined by M^2 parameter. For certain applications high irradiance at the target location is required which demands better beam quality of the exit beam and hence core size is preferred, especially when the power available is limited. The worst beam quality from a step index fiber is easy to calculate based on the definition of M^2 parameter. The definition is based on Gaussian beam where 86% energy enclosed size is used as a waist. Now if one substitutes 0.86r fiber as beam waist and divergence angle as the NA of the fiber, then [105]:

$$M^2(\text{worst}) = \frac{\left(\pi\ 0.86\ r_{fiber}\ sin^{-1}(NA)\right)}{\lambda} \tag{8.5}$$

The actual beam quality exiting from the fiber is however better than above estimate and depends upon actual divergence and waist size. The similar calculation for gradient index fiber is difficult but beam quality will be better than step index fiber of the same size under similar launch conditions.

8.4 Preparation of Fiber

The fiber preparation essentially means removal of the coating and jacket and preparing flat faces by cleaving or mechanical polishing to reduce scattering. The coating is generally polyimide and jacket for protection is of tefzel material. The coating and jacket material can be customized. The polyimide coating was chosen for its capability of handling temperature upto 250 ℃. The coating and jacket can be removed by burning them in flame and then cleaning the fiber with acetone to remove left out particles. The fiber is cleaved using a fiber cleaver. The fiber cleaving with perfectly flat ends is achieved by using scribe and cut technique where fiber is held with high tension along its length and diamond blade cutter cuts transversely by creating a crack at the cladding surface which then propagates radially due to high tensile stress with which fiber is pulled. The Fig. 8.4 above demonstrates the strategy for cleaving. The standard large core fiber cleaver is available for reliable and repeatable cleaving operation.

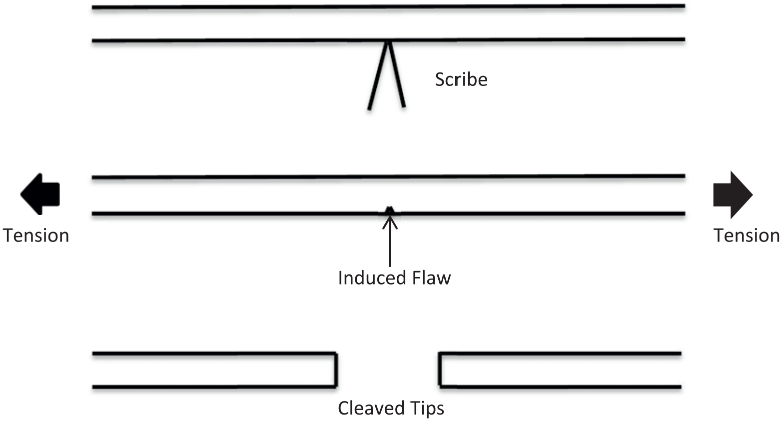

Figure 8.4: Schematic of fiber cleaving process [113].

8.5 Coupling Optics

The coupling lens is used to launch the laser beam into optical fiber as shown in Fig. 8.1. The choice of focal length of launching optics is constrained by the numerical aperture of the fiber. The quality of launching optics should be such that spot size is limited by the laser beam quality rather than aberration of the lens. Selection of focal length of coupling optics: Fiber diameter, a > focused spot size,

$$W_0 = \frac{(4\ M^2 \lambda\ f)}{\pi\ D} \tag{8.6}$$

where f = focal length of coupling lens; D = beam size at the coupling lens. Convergence angle after lens, $\theta = tan^{-1}\left(\frac{D}{2f}\right) < NA$ of the fiber (generally 0.22). Usual value of θ should be 0.8 NA for overfilled launch. For good coupling efficiency, $a = \frac{W_0}{c}$, where c is fiber filling factor usually 0.8. However, to have good tolerance on alignment and avoid heating it is common to use c < 0.8 and $\theta < 0.8$ NA, i.e. under filled launch.

$$\tan^{-1}\left(\frac{D}{2f}\right) < \sin^{-1}(NA) \tag{8.7}$$

Therefore, $\frac{D}{2f} < \tan\left(\sin^{-1}(NA)\right)$. This is the minimum focal length one can use for launching the beam. However, actual value is decided by the trade off between spot size and NA of the launched beam. Use of higher focal length creates larger spot size and low cone angle of the focused beam prompting the use of large size fiber. On the other hand short focal length lens creates smaller spot size but increase the launching cone angle. On the shorter side focal length is limited by NA of the fiber and on higher side it is limited by maximum size of the fiber that can be used (higher fiber size degrades the beam quality).

8.6 Output Optics

The laser beam delivered by optical fiber is transformed for particular application. The conventional approach is to first upcollimate the diverging beam and then focuses using appropriate lens as shown in Fig. 8.1. The collimation optics focal length and size is dictated by the NA of the fiber. Higher NA beam can only be upcollimated by short focal length lenses to collect all the light. Design of imaging system (output optics) requires only the knowledge of size and NA of the fiber. Optical fiber support large number of modes each with a specific angle of propagation. However, output divergence is a function of launch conditions and is limited by NA of the fiber. The geometric optics approach is appropriate for determination of spot size and optical system design. The optical system images the fibers face onto target planes using several lenses and spot size at target location can be expressed as [105]:

$$W_0 = Ma + w_{\text{aberration}} \tag{8.8}$$

where M = magnification of imaging system; a = fiber core size; and $w_{\text{abberation}}$ = spot size caused by aberrations in the system. The spot size achieved is limited by the diffraction and aberration in an optical system causing blur size to appear in addition to the targeted size as per the magnification. This however can be reduced by proper selection of lens curvature, material and use of aspheric optics. In most of the applications tight focusing of the fiber surface image is required which is limited by several factor. As the fiber size is large and can range from 100 μm to 1 mm and the divergence of the collimated beam is proportional to fiber size which leads to higher focusing spot size. To reduce divergence high focal length collimating lens can be used but that leads to larges beam size due to high NA of fiber and problem of spherical aberration. These are the issues that ultimately limit the performance of optical system & minimum spot size achievable from given fiber size.

8.7 Procedure for Aligning a High Power Fiber-optic Beam Delivery System

The safe and long term operation of a fiber-optic beam delivery system depends on the selection of all components and their tolerances.

i. To start with fiber must be prepared with flat ends using cleaving operation as discussed. This allows the efficient launching of the beam into fiber and avoids scattering losses and thermal damage at the interface due to poor surface finish.

ii. The mechanical mount holding the fiber must be rigid and movement of the fiber should be minimal. This is specifically applicable for bare fibers held in V groves in an optical mount. In connectorized fibers position of fiber is ensured by the threaded fitting of the chosen connector.

iii. Initially launching of the power into fiber must be done at low power to ensure fiber is kept at the best position to receive maximum power and then power should be increased gradually.

iv. It is best to align the focused spot symmetrically along the fiber axis to allow for better mechanical tolerances.

v. While selecting the fiber size, pointing stability of laser must be taken into account to avoid the fiber damage due to launching of power into cladding or buffer jacket.

8.8 Summary

Large core multimode fibers enable efficient delivery of high average power laser beam often at the expense of reduced beam quality. However, flexibility, safety and enclosure are advantages that overweigh the other limitations. The large scale use of fiber-optic delivery is supported by the optimal selection of the components and highly corrected output optics to address the issues related to degradation of beam quality.