Beam Shaping Element for Compact Fiber Injection Systems

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ABSTRACT

Injection of high power, multi-mode laser profiles into a fiber optic delivery system requires controlling a number of injection parameters to maximize throughput and minimize concerns for optical damage both at the entrance and exit faces of the fiber optic. A simple method for simultaneously achieving a compact fiber injection geometry and control of these injection parameters, independent of the input source characteristics, is provided by a refractive lenslet array and simple injection lens configuration. Design criteria together with analytical and experimental results for the refractive lenslet array and short focal length injection lens are presented. This arrangement provides a uniform spatial intensity distribution at the fiber injection plane to a large degree independent of the source mode structure, spatial profile, divergence, size, and/or alignment to the injection system. This technique has application to a number of laser systems where uniform illumination of a target or remote delivery of high peak power is desired.

Keywords: Diffracting beam integrator, lenslet array, fiber injection, beam shaping

1. INTRODUCTION

A number of medical and industrial laser applications exist in which the limiting factor for performance or the realization of additional capability resides in the transmission of the high intensity optical power (or energy) from the source to the target. Transmission systems for these applications include the use of fiber optics, hollow optical waveguides¹, or "open air" approaches using numerous optical elements to direct and reshape the laser radiation along the intended path to the target. Selection and implementation of a specific optical transmission system is highly application dependent – reflecting the optimization of mechanical constraints, operational environments, and laser source requirements. In specific applications where laser requirements are compatible and target accessibility is limited, the use of fiber optics is often the preferred transmission system. Although the use of optical fibers provides the system designer and user effective control over a number of end application parameters such as beam diameter, spatial profile and target accessibility, fiber based systems are often limited by the maximum power level that can be reliably injected into and transmitted to the target.

Maximizing power throughput and minimizing fiber damage requires a thorough understanding of fiber damage mechanisms and the control of a number of fiber injection criteria. The location and type of damage mechanism has been shown to be a strong function of the source laser, the design and alignment of the laser to the fiber injection optics², and the fiber end face preparation³⁻⁷. In addition to describing various fiber damage mechanisms and events, Setchell postulates in Reference 2 a number of other fiber injection criteria that should be considered in the design or selection of the fiber injection optics. These functional parameters include: 1) maximizing air breakdown thresholds, 2) minimizing peak fiber fluences and confining the incident laser energy to the fiber core thus maximizing the effective core area over which the energy is incident, 3) providing insensitivity to variations in input spatial profiles and laser to fiber alignment, and 4) providing a broad and predictable mode power distribution (MPD) at the fiber entrance face – minimizing the potential of internal focusing of the beam near the entry face or along the initial fiber bend.

A variety of beam shaping techniques are available that have applications in a fiber injection system to effectively minimize the peak fluence at the fiber face. Dependent on the characteristics of the source laser, the desired irradiance pattern, and the required target diameter, beam shaping methods based on field mapping or multi-faceted beam integrators may be applicable⁸. However, as discussed above a number of other parameters must also be considered before the fiber injection system can be optimized for its intended application. As an example, the simple injection lens may satisfy the required compact geometry, however, this approach for high power applications imposes a number of limitations on the power or energy that can be reliably injected and transmitted by the optical fiber. These limitations and substantial variability in performance are exhibited by relatively low air breakdown thresholds together with a strong interdependence on fiber

alignment and laser source characteristics to the peak optical intensity incident on the fiber face. (The effects of alignment and source characteristics are discussed further in Section 3). Similarly, if the incident laser mode(s) are not well defined and/or if the laser modes vary in time, beam shaping based on other field mapping techniques may not be applicable.

1.1 Application – Compact Fiber Injection System

Our interest in extending the power handling capabilities of optical fibers is currently motivated by development activities investigating the realization of laser based initiation systems⁹⁻¹². Such systems offer the potential for significant safety enhancements by replacing the “traditional” electrical detonator and associated electrical conductor with their optical equivalents – providing effective isolation of the detonation sensitive components from unintended or naturally occurring electrical sources. Critical to the realization of such a system is the miniaturization of the Q-switched laser source and the development of the fiber optic transmission system for reliable, remote delivery of the required high peak power optical stimulus. Furthermore, optimization of the system mechanical design plays a major role in determining the candidate optical architecture available for the laser resonator and the fiber injection system. Mechanical constraints drive laser designs to large mode volumes and alignment insensitive end reflectors; resulting in highly divergent and “unpredictable” multi-mode spatial outputs. Consequently, not only must the fiber injection system exhibit the desired compact geometry (typically < 25 mm) the selected architecture must also accommodate a large variation in the laser’s spatial intensity profile and ultimately provide a reproducible and acceptable intensity profile at the fiber entrance face. Given these constraints, traditional imaging approaches or other more complex beam shaping techniques^{8,13} have been abandoned in favor of those architectures employing a minimal number of optical elements in a geometry consistent with the compact nature of the intended application.

Fiber injection architectures based on various combinations of the simple lens, axicons, and diffractive mode scramblers¹⁴ together with extensive studies on fiber damage thresholds and mechanisms²⁻⁷ have been investigated at Sandia National Laboratories. Our recent investigations with a fiber injection system based on the non-imaging or diffractive beam integrator satisfies most of the functional criteria suggested above for the injection of high intensity laser pulses. The optical components and their specifications that form the basis of the compact fiber injection system evaluated and described herein are shown in Figure 1. This system is comprised of a multi-aperture, refractive, lenslet element and a primary injection lens that overlaps or integrates the beamlets from each subaperture at the lens focal plane. As will be shown, in this plane the “homogenized” intensity profile is the superposition of three effects: diffraction, interference, and spatial averaging.

Figure 1: Optical architecture and design specifications for the diffractive beam integrator and resultant fiber injection system.
(From Ref. 15)

2. THEORY – DIFFRACTIVE BEAM INTEGRATORS

The theory and design of multi-aperture beam integration systems are treated in detail in Reference 15. The basic idea of the beam integration systems is to break up the input beam into multiple beamlets and superimpose the beamlets at the target plane. The basic optical layout of a system for accomplishing this mapping using a diffracting multi-aperture beam integrator is illustrated in Fig. 1. The system consists of a lenslet array and a primary lens. The target plane is located at the focal point of the primary lens. A collimated beam of diameter D is incident on an array of lenslets, each of diameter d and focal length f , which segments the beam into multiple beamlets. The primary lens of focal length F overlaps the beamlets, bringing the chief rays of each beamlet to a common focus at the back focal point of the primary objective where

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the integrated irradiance pattern is formed. The primary lens produces a field distribution at the focal plane that is proportional to the Fourier transform of the product of the functions representing the input beam and the lenslet array.

The problem is then to map a uniform input intensity into a uniform output intensity via the Fourier transform. It can be shown that the desired lenslet phase function is

$$\Phi\left(\frac{x}{d}\right) = \beta\left(\frac{x}{d}\right)^2. \quad (1)$$

This quadratic phase factor describes a thin lens. The solution includes the parameter β that is a measure of the quality of the solution. This parameter, given by

$$\beta = \frac{\pi d S}{\lambda F}, \quad (2)$$

has the same form as the Fresnel number, differing only by a constant factor. Note that β is a dimensionless constant. The significance of β is discussed in considerable detail in Reference 8. β is related to the mathematical uncertainty principle. Increasing β decreases the effects of diffraction in the output.

Using paraxial geometrical optics it can be shown that the spot size S on the target is equal to the focal length F of the primary lens divided by the f-number of the subaperture lens,

$$S = \frac{F}{f/d}. \quad (3)$$

This result is also obtained using diffraction theory and Fourier optics. It can be shown¹⁵ that the Fresnel number for the system in Fig. 1 is given by

$$Fresnel = \frac{dS}{4\lambda F}. \quad (4)$$

In addition to the diffraction effects discussed above with respect to β , multi-aperture beam integrators generally exhibit interference effects. They are effectively multiple beam interferometers. The coherence theory of multi-aperture beam integrators is developed in Reference 15. Depending on the degree of spatial coherence of the source, the output irradiance will contain an interference or speckle component. For these conditions, the integrated irradiance of the coherent component is adequately described by

$$I(x, y) = \left| \sum_{0,0}^{M,N} A_{mn} \exp\{i[k(\alpha_m x + \beta_n y) + \theta_{mn}]\} \right|^2 |F(x, y)|^2, \quad (5)$$

where α_m and β_n are the direction cosines associated with each beamlet, θ_{mn} is the phase of the beamlet A_{mn} the amplitude of the beamlet field, and the function $F(x, y)$ is the diffraction integral of the beamlet-limiting aperture. $F(x, y)$ is the Fourier transform of the aperture function for the optical configuration in Fig. 1.

The first factor in Eq. (5) describes the averaging and interference effects of the integrator. The interference effect is a result of the sum of linear (in x and y) phase terms, which can be viewed as a Fourier series. The spatial period for the resulting interference pattern is given by

$$Period = \frac{\lambda F}{d}. \quad (6)$$

3. RESULTS AND DISCUSSIONS

Verification of the theory and subsequent design equations presented in Section 2 can be illustrated by observing the resultant intensity profiles distributed along the optical axis of the primary injection lens. Collection of these intensity images was accomplished using a COHU 4800 CCD camera configured with a suitable objective lens to achieve an approximate 10x magnification. Post processing and manipulation of the image data was accomplished using Beamcode Version 6.2 Analysis software. With this analysis package, a relative or measured estimate of the actual optical fluence

* Cell Size: 23.0 μ m (Horizontal) 27.0 μ m (Vertical)

* Beamcode is an automated optical diagnostic system providing real time analysis of the imaged intensity profiles

(J/cm²) can be determined for a particular combination of laser and injection optics. A figure of merit described by Setchell in Reference 2 and used throughout this document for quantitative comparison of the spatial intensity patterns is the ratio of the peak to average fluence (P/A),

$$\text{Peak to Average Fluence } \left(\frac{P}{A}\right) = \frac{\text{Peak Local Fluence}}{(\text{Total Energy Incident on Fiber Core})/(\text{Fiber Core Area})}. \quad (7)$$

Functionally the value of P/A is defined as the ratio of the measured peak pixel intensity to the average pixel intensity calculated and defined within an area representing the fiber core. Once this parameter is obtained, an estimate of the peak local fluence can be calculated for a measured output energy and known injection efficiency. Assuming that the peak local fluence incident on the fiber face is the limiting factor in determining the maximum output energy obtainable from such an injection system, it is obvious that minimizing the P/A value implies maximizing the fiber output energy.

3.1 Diffraction and Interference Effects

The effects of laser coherence on the performance of the evaluated diffracting beam integrator can be illustrated by observing the intensity distribution located at the focal plane of the primary injection lens when such a system is illuminated by a variety of laser sources – representing varying degrees of spatial coherence. The diffraction pattern of a single aperture of the lenslet array determines the shape of the spot on the target and the Fresnel number (or β) described in Eq. (4) yields a general measure of the diffraction structure or deviation from the geometric ideal (i.e. flat top profile). In addition, it has been shown¹⁵ that both diffraction and interference effects play an integral role in determining the ultimate intensity distribution. For example, a source that is characterized as “highly spatially coherent” produces an intensity pattern dominated by interference effects displaying large intensity fluctuations (or spikes) with a well defined periodicity at the lens focal plane. Similarly, sources having a “lesser degree” of spatial coherence exhibit a mixture of both interference and diffraction effects.

To illustrate and quantify the effects of diffraction and interference the diffracting beam integrator specified and shown in Figure 1 was illuminated using three different laser sources. Each source in turn provides a qualitative measure of the diffraction and interference effects superimposed on the resultant intensity profile. Although each laser source that we evaluated presents a different spatial intensity pattern at the input to the lenslet element, it is the spatial coherence¹ of the source that appears to dominate the resulting profiles at the injection lens focal plane.

Illuminating the diffracting beam integrator with a multimode, Q-switched, Nd:YAG laser (Laser Phonics Model YQL-102) diffraction effects are distinguishable in the intensity profiles shown in Figure 2a. Clearly visible in the intensity profiles are the shape of the lenslet elements (hexagonal) and the expected diffraction pattern. With this laser source lenslet diffraction dominates the intensity structure and the effects of the Fresnel number can be experimentally observed and analytically verified. Overlaying the calculated diffraction profile with the experimental results as displayed in Figure 2b, reveals excellent agreement with the measured data – suggesting that the structure observed does indeed result from lenslet diffraction.

Figure 2: a) Measured intensity profile at the focal plane of the diffracting beam integrator illustrating diffraction effects ($P/A = 2.50$) and b) Calculated 1-dimensional diffraction pattern. (From Ref. 15)

The effects of a high spatially coherent source are illustrated using a CW Cr:Nd:GSGG, TEM₀₀ laser (AMOCO Model 1061-40P). As expected, the intensity profile shown in Figure 3a displays both diffraction and interference effects. The hexagonal shape of the lenslet elements and a slowly varying intensity modulation earlier attributed to diffraction effects are apparent, however, the intensity profile is clearly dominated by narrow spikes – indicative of interference effects.

Confirmation that these spikes do represent the interference effects that result from the “coherent” superposition of the beamlet fields can be made by comparing the calculated and measured periodicity of this structure. From Eq. (6) the spatial periodicity for the interference structure is calculated to be $14.3\mu\text{m}$ while the measured value shown in Figure 3a is $16.3\mu\text{m}$. It should be noted that Eq. (6) derived for the periodicity of the interference pattern are based on paraxial approximations and assume a one dimensional lenslet pattern. The calculated intensity profile and its periodicity can be further refined to include the effects of both the hexagonal lenslet array structure and system aberrations using optical modeling software. Analytical results obtained using the optical modeling package ASAP* summarized in Figure 3b reveals the effects of the lenslet geometry and those aberrations on the intensity profile at the focal plane. Assuming a perfectly coherent source, the model suggest the dominance of the interference structure as well as the expected 2-dimensional dependency for the periodicity.

Figure 3: a) Measured intensity profile at the focal plane of the diffracting beam integrator illustrating interference effects ($P/A = 8.08$ and Period = $16.3\mu\text{m}$) and b) Calculated interference pattern (ASAP Model, Period = $13.8\mu\text{m}$). (From Ref. 15)

Effects of partial spatial coherence have been illustrated using a third laser source. In this case the laser source reflects the resonator and the lasing material properties currently baselined for the optical initiation system described in Section 1. Illumination of the diffracting beam integrator with this multimode, Q-switched, Cr:Nd:GSGG illustrates the superposition of both diffraction and interference. As shown in Figure 4, the diffraction structure illustrated in Figure 2a is visible (i.e. spot geometry and Fresnel number), however, interference features characterized by narrow, periodic “spikes” are also observable. As may be anticipated, it is the interference structure that will ultimately determine the peak local fluence at the fiber entrance face and hence will play a major role in establishing the maximum energy that can be reliably injected and transmitted by the optical fibers. The effect of this interference structure is further reflected in an increase in the P/A figure of merit when compared to the example shown in Figure 2.

Figure 4: Measured intensity profile at the focal plane of the diffracting beam integrator illustrating effects of a partially coherent source ($P/A = 3.19$). (From Ref. 15)

* Advanced System Analysis Program – optical software program for geometrical and physical modeling. ASAP is a trademark of Breault Research Organization.

3.2 Spot Diameter, Beam Averaging, and Alignment Sensitivity

Characterization of the intensity profiles collected along the optical axis of the diffracting beam integrator yields an estimate and location for the minimum beam diameter and further describes how the profile behaves past the lens focal plane. Using a purely functional description for the measured beam diameter defined as the physical diameter in which 98% of the energy is contained, the spot size along the optical axis is plotted in Figure 5 for both the diffracting beam integrator and the injection lens alone. As expected the minimum spot size is achieved at the focal plane of the injection lens and that the growth in the beam diameter behind this plane is described by the paraxial approximation given by the input beam diameter and the primary lens focal length (i.e. $NA = D/(2F)$) for both injection configurations. Comparing the beam diameter calculated using Eq. (3) (310 μm) to the measured minimum value shown in Figure 5 (353 μm) suggests

Figure 5: Measured beam diameter with and without the lenslet array. (Laser source: Q-switched, Cr:Nd:GSGG). (From Ref. 15)

reasonable agreement between the intended design and actual performance. Differences between the calculated and measured results are easily accounted for in those assumptions inherent in Eq. (3) for the calculated beam diameter (i.e. aberration free optical system and an ideal source with essential zero beam divergence) and the functional definition for beam diameter presented earlier. Another potentially important feature displayed in Figure 5 is the greater effective "depth of focus" around the focal plane or target location for the integrator when compared to the simple lens configuration. This characteristic is significant when the diffracting beam integrator is incorporated into an assembly where alignment or position insensitivity are highly desirable.

The averaging aspect of the diffracting beam integrators and the subsequent insensitivity of the intensity distribution at the target plane to spatial perturbations of the input source is a critical injection criteria given the nature of the intended laser source for this application. Applying various apertures to the input source

and hence effectively exposing different near-field features to the lenslet array can yield some insight into the sensitivity of the diffracting beam integrator to these changes. The results of such an experimental characterization for the pulsed, Cr:Nd:GSGG are shown in Figure 6. The contour sequence and P/A values displayed in Figure 6 shows little change in the output intensity profile at the lens focal plane until the input beam diameter is comparable in size to the diameter of a single lenslet element on the array (1.25 mm). When this occurs, the primary injection lens no longer "overlaps" or integrates inputs from multiple lenslet elements and the corresponding Fresnel number dominates diffraction effects. In the limit of illuminating a single lenslet, this effectively yields the spatial profile that would result using just the primary injection lens slightly defocused from its focal plane. (This slight "defocus" is a result of the non-zero optical power provided by the lenslet element).

Input Beam

Figure 6: Measured intensity profiles at the focal plane of the diffracting beam integrator illuminated under various source apertures. (Laser source: Q-switched, Cr:Nd:GSGG). (From Ref. 15)

Another often troublesome design issue with fiber injection systems and a parameter substantially relaxed by the use of the diffracting beam integrator is the alignment or centration of the input beam on the primary injection lens. As shown in Figure 7 when the input beam is displaced across the injection lens without the lenslet array the spatial intensity profile incident at the fiber face is strongly effected – resulting in higher peak fluences physically decentered from the fiber core. In contrast, with the lenslet array the spatial profile and P/A figure of merit remains unchanged over a wide range of lateral misalignment. Once again it is expected that insensitivity to alignment will significantly relax the mechanical requirements for orienting the laser source to the fiber injection system.

Figure 7: Measured intensity profiles at the fiber face location with and without the lenslet with linear displacement of the source. (Laser source: Q-switched, Cr:Nd:GSGG) (From Ref. 15)

3.3 Compact Fiber Injection System – Design and Performance

The combination of the refractive lenslet array and primary injection lens provide the optical designer the potential for a compact mechanical geometry and an effective approach at addressing a number of the fiber injection criteria presented earlier in Section 1. As illustrated in earlier sections, the effects of diffraction, interference, and spatial averaging all contribute to the spatial intensity profile incident at the fiber injection face. It can be argued that minimizing the peak to average fluence incident on the fiber entrance face implies: 1) minimizing interference effects, 2) obtaining a high Fresnel number, and 3) sizing the lenslet apertures for effective spatial averaging of the input source. Ideally, the resultant spatial profile should completely fill the fiber core and exhibit no intensity fluctuation – achieving a value of unity for the peak to average (P/A) figure of merit. Realistically, the system designer is faced with a number of optical and mechanical constraints that will ultimately increase the P/A value at the fiber injection plane. First and foremost, selection of a laser source with “poor” spatial coherence is essential to minimize interference effects that could dominate the peak intensity value (Ref. Figures 2, 3, and 4). Secondly, obtaining a high Fresnel number (Eq. (4)) requires the optimization of a number of functional parameters that could ultimately effect spatial averaging and the initial power mode distribution at the fiber face.

Contrasting the performance of the simple lens with the diffracting beam integrator provides further insight into those optimization criteria and the ultimate applicability of the diffracting beam integrator for a specific fiber injection system. Given the simple lens injection architecture, the desired fiber location is located behind the focal plane of the injection lens. This location inhibits internal focusing of the incident energy within the optical fiber and provides a diverging power mode distribution dictated by the injection lens f-number. Maximizing the throughput for this approach implies maximizing the air breakdown threshold. This is accomplished by controlling the minimum spot size and subsequently the lens focal length. However, as the lens focal length is increased to accommodate a higher threshold breakdown, the injected N.A. or entrance angle to the fiber is correspondingly decreased and subsequently the mode power distribution is reduced. In contrast, the diffracting integrator distributes the input laser energy over a larger cross sectional area and into multiple foci representing the number of active lenslet elements. Consequently, eliminating air breakdown allows the designer the “freedom” to select the primary lens focal length to better match the acceptance angle of the optical fiber. However, as the focal length of the primary lens is varied the f-number of the lenslets must be correspondingly adjusted to maintain the desired spot size per Eq. (3). Maintaining the desired spot size can be achieved, however, the impact on the Fresnel number

and the integrators spatial averaging behavior must also be evaluated. It is this interdependence that must be optimized given the specifics of the desired injection geometry.

Characterization of a compact fiber injection system based on the diffracting beam integrator is currently under investigation at Sandia National Laboratories. Although the initial number of fiber assemblies subjected to damage testing (3ea.) does not constitute a statistically significant test set, the measured thresholds for front face damage appears to be consistent with that reported by Setchell for well prepared end faces² (200J/cm²). Preliminary results on the three fiber assemblies are characterized by high injection efficiency ($\approx 88\%$), a low peak to average intensity distributions at both the entrance face (3.36) and exit face (2.24), and a correspondingly high level of energy transmission prior to a breakdown event. (A breakdown event is indicated by physical observation and/or by measuring a significant change in the fiber transmission). In the case of the front or entry face damage shown in Figure 8, an estimate of the peak local fluence prior to fiber damage can be determined using Eq. (7) and the following measured test parameters: 1) P/A figure of merit (3.36), 2) output energy (87.3 mJ), 3) injection efficiency (86%), and 4) fiber core diameter (365 μ m). The calculated peak fluence in this test case exceeded 320J/cm².

Another instructive feature further characterizing the performance of the diffracting beam integrator for fiber injection applications can be revealed in where and how the optical fiber is damaged. Again, the preliminary data suggests that front or entry face damage is the predominate mechanism for the evaluated fiber injection system. Physical inspection of those damaged front face surfaces (Figure 8) reveals the same structure and approximate periodicity as those features characterized earlier as interference effects (Figures 3 and 4).

Figure 8: a) Photograph of fiber entry face damage and b) Magnified section of fiber displaying periodicity of the damage structure (Period = 13.8 μ m)

In summary, we have built and characterized a diffracting beam integrator for applications requiring uniform illumination – to a large extent insensitive to the source characteristics. We have applied the pertinent design equations and illustrated the effects of diffraction, interference, and spatial averaging on the integrator's performance. Preliminary characterization and applicability of this approach for the injection of high intensity pulses into optical fibers has been demonstrated. Finally, additional statistical testing and further development of "next" generation diffracting beam integrators are current activities at Sandia National Laboratories. With continued testing and characterization of the refractive lenslet array against other lasers sources and injection lenses we hope to develop better analytical tools and offer an improved lenslet design that could mitigate interference effects at the fiber entrance face or target location.

4. ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Lockheed Martin for the United States Department of Energy under Contract DE-AC04-94AL85000. The authors would like to acknowledge Daniel and David Brown at MEMS Optical, Inc. for fabrication of the evaluated lenslet array element. We would also like to thank those talented contributions of Paul Klinsborn of Allied Signal Inc, Kansas City Division for fiber preparation along with Bob Setchell and Dante Berry of Sandia National Laboratories for their assistance in providing further component evaluations. Lastly, we would like to acknowledge Stephen Yao for his assistance in preparing this document for publication.

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