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# Laser Beam Shaping Techniques

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## ABSTRACT

Industrial, military, medical, and research and development applications of lasers frequently require a beam with a specified irradiance distribution in some plane. A common requirement is a laser profile that is uniform over some cross-section. Such applications include laser/material processing, laser material interaction studies, fiber injection systems, optical data/image processing, lithography, medical applications, and military applications. Laser beam shaping techniques can be divided in to three areas: apertured beams, field mappers, and multi-aperture beam integrators. An uncertainty relation exists for laser beam shaping that puts constraints on system design. In this paper we review the basics of laser beam shaping and present applications and limitations of various techniques.

**Keywords:** Laser beam shaping, beam profiles, field mapping, beam integrators

## 1. INTRODUCTION

Beam shaping is the process of redistributing the irradiance and phase of a beam of optical radiation. The beam shape is defined by the irradiance distribution and the phase of the shaped beam is a major factor in determining the propagation properties of the beam profile. Applications of beam shaping include laser/material processing, laser/material interaction studies, laser weapons, optical data/image processing, lithography, printing, and laser art patterns. In this paper we provide an overview of the techniques for producing shaped beams that are uniform over a specified cross-section. The shaped beam cross section may be arbitrary, including rectangular, circular, triangular, hexagonal, and ring shaped. In-depth infromation is provided by the references. The theory and techniques of laser beam shaping are addressed in the book edited by Dickey and Holswade.[1]

Laser beam shaping techniques can be divided into three broad classes. The first is the trivial, but useful, aperturing of the beam illustrated in Fig. 1. In this case the beam is expanded and an aperture is used to select a suitably flat portion of the beam. The resulting irradiance can be imaged with magnification to control the size of the output beam. The major

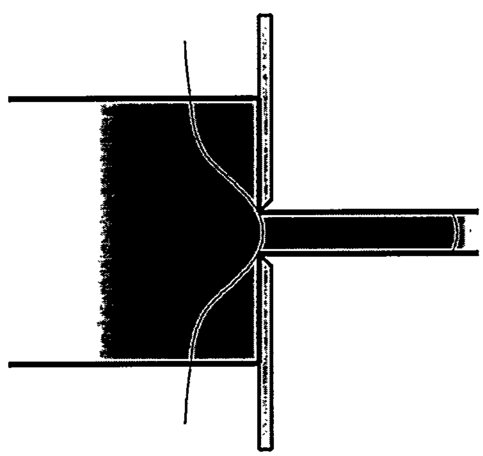

Fig. 1 Uniform irradiance obtained by aperturing input beam.

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disadvantage of this technique is that it is not lossless. In most cases it is desirable, for obvious reasons, that the beam shaping operation conserve energy. Further, if the input beam irradiance is not suitably smooth, it might not be possible to find an aperture size and position that gives the desired result. In that case, some form of input beam homogenization might be required. This type of beam shaping will not be treated further.

The second major technique for beam shaping is what might be called field mapping. Field mappers transform the input field into the desired field in a controlled manner. The basic field mapper concept is illustrated in Fig. 2 for the case of mapping a single mode Gaussian beam into a beam with a uniform irradiance. In the figure, Gaussian distributed rays are bent in a plane so

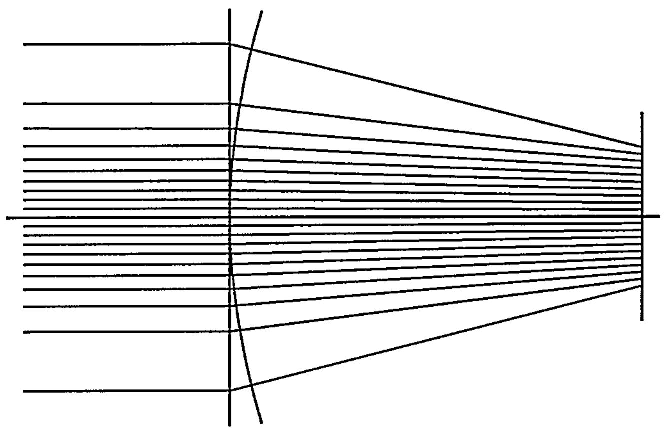


Fig. 2 Schematic of the field mapping concept (From Ref. 1).

so that they are uniformly distributed in the output plane. The ray bending described in the figure defines a wavefront that can be associated with an optical phase element. Field mappers can be made effectively lossless. The field mapping approach to beam shaping is applicable to well defined single mode laser beams.

The remaining class of beam shapers is beam integrators, also known as beam homogenizers. A representative example of a beam integrator is shown in Fig.3. In this configuration, the input beam is broken up into beamlets by a lenslet array and

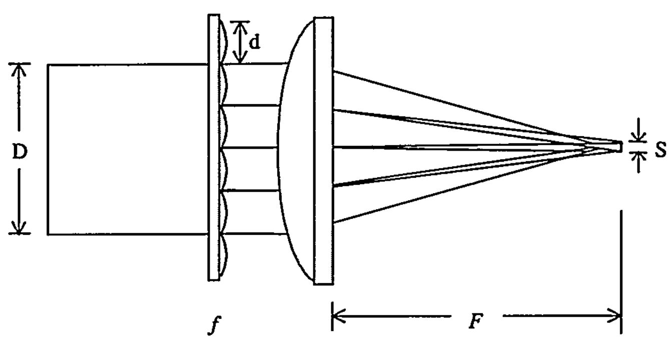



Fig. 3 A multi-aperture beam integrator (From Ref. 1).

superimposed in the output plane by the primary lens. The term integrator comes from the fact that the output pattern is a sum of diffraction patterns determined by the lenslet apertures. Beam integrators are especially suited to multimode lasers with a relatively low degree of spatial coherence. They can also be designed to be effectively lossless.

In Section 2 we discuss a constraint on beam shaping that results from the application of diffraction theory to the beam shaping problem. The result is an uncertainty principle type relation that involves the input and output beam sizes. The theory and design of field mappers is discussed in Section 3. Beam integrators are treated in Section 4. In Section 5 we briefly discuss beam shaping using diffractive diffusers, which are technically field mappers but exhibit speckle properties associated with beam integrators. Finally, in Section 6 we discuss the importance of validating and refining the beam shaping system design using sophisticated optical software.

## 2. THE UNCERTAINTY PRINCIPLE AND $\beta$

The concept of field mapping is applicable to beam integrators as well as field mappers. The basic field mapping problem can be expressed in terms of the Fresnel integral as,

$$U(x_0, y_0) = \frac{\exp(ikz)}{i\lambda z} \iint U(x_1, y_1) \exp \psi(x_1, y_1) \exp\left\{\frac{ik}{2z}\left[(x_0 - x_1)^2 - (y_0 - y_1)^2\right]\right\} dx_1 dy_1, \quad (1)$$

where $k = 2\pi/\lambda$,

$U(x_1, y_1)$ is the complex representation of the input beam,

$\psi(x_{1,} y_1)$ is the phase function representing the lossless beam shaping element,

$U(x_0, y_0)$ is the shaped complex field in the output plane at distance z.

By expanding the last exponential in the integrand and including the remaining quadratic phase function in the beam shaping element, $\psi$, one can express the beam shaping problem as a Fourier transform (Fraunhofer integral),

$$U(x_0, y_0) = \frac{\exp(ikz)}{i\lambda z} \exp\left[x_0^{\,2} + y_0^{\,2}\right] \iint U(x_1, y_1) \exp \psi(x_1, y_1) \exp\left[-i\frac{2\pi}{\lambda z}(x_0 x_1 + y_0 y_1)\right] dx_1 dy_1, \quad (2)$$

where $\psi$ in this equation differs from that of Eq. (1) by a quadratic phase factor. In terms of either of these two equations, the beam shaping problem is to determine the phase function, $\psi$, when $U(x_1 . y_1)$ and the magnitude of $U(x_0 . y_0)$ are specified. This is equivalent to simultaneously specifying the magnitude of a function and the magnitude of its Fourier transform.

The uncertainty principle of quantum mechanics, or equivalently the time-bandwith produce inequality associated with signal processing can be applied to the beam shaping problem. The uncertainty principle is a constraint on the lower limit of the product of the root-mean-square width of a function and its root-mean-square bandwith,[2,3]

$$\Delta_x \Delta_\upsilon \geq \frac{1}{4\pi}. \quad (3)$$

Applying the uncertainty principle to the beam shaping problem of Eq. (1) or Eq. (2) one obtains a parameter $\beta$ of the form,[1]

$$\beta = C\frac{r_0 y_0}{zf}, \quad (4)$$

where $r_0$ is the input beam half-width, $y_0$ is the output beam half-width, and $C$ is a constant that depends on the exact definition of beam widths. As will be discussed in the following sections, a good field mapping solution to Eq. (1) or Eq. (2) is obtainable if $\beta$ is suitably large. Also, and not unrelated, $\beta$ is the parameter involved in the stationary phase method of solution of Eq. (1) or Eq. (2).[1]

## 3. FIELD MAPPERS

The beam shaping problem described by Eq. (2) can be directly implemented by the system shown in Fig. 4.[1,4,5,6] In the figure, the last two elements comprise the beam shaping system; the first two elements are a beam expanding telescope. The beam shaping system consists of a shaping element (phase function $\psi$) and a Fourier transform (focusing) lens. The beam expanding telescope, which may or may not be necessary, provides a mean of increasing $\beta$ by increasing the input beam diameter. Using the method of stationary phase, Romero and Dickey[6] have obtained solutions for converting

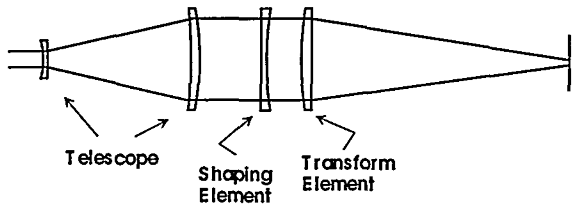



Fig. 4 Beam shaping system implementing Eq.2 (From Ref. 5).

Gaussian beams into uniform profiles with both rectangular and circular cross sections. In these solutions, the phase $\psi$ in Eq. (1) and Eq. (2) is given by $\psi = \beta\phi$. For a circular Gaussian beam input, the problem of turning a Gaussian beam into a flat-top beam with rectangular cross section is separable. That is, the solution is the product of two one-dimensional solutions. $\beta$ and $\phi(\xi)$ are thus calculated for each dimension. The phase element will then produce the sum of these phases $(\beta_x\phi_x(x)+\beta_y\phi_y(y))$. The corresponding one dimensional solution for $\phi$ is

$$\phi(\xi) = \frac{\sqrt{\pi}}{2} \cdot \xi \cdot erf(\xi) + \frac{1}{2} \cdot \exp(-\xi^2) - \frac{1}{2}, \tag{5}$$

where

$$\xi = \frac{\sqrt{2} \cdot x}{r_0} \text{ or } \xi = \frac{\sqrt{2} \cdot y}{r_0},$$

and $r_0 = 1/e^2$ radius of the incoming Gaussian beam.

The solution for the problem of turning a circular Gaussian beam into a flat-top beam with circular cross section is

$$\phi(\xi) = \frac{\sqrt{\pi}}{2} \cdot \int_0^{\xi} \sqrt{1-\exp(-\rho^2)}\, d\rho, \tag{6}$$

where

$$\xi = \frac{\sqrt{2} \cdot r}{r_0},$$

and $r$ = radial distance from the optical axis.

As previously mentioned, the quality of these solutions depend strongly on the parameter $\beta$. For the two solutions given in Eq. (3) and Eq. (4), $\beta$ is given by

$$\beta = \frac{2\sqrt{2\pi}\, r_0\, y_0}{f\lambda}, \tag{7}$$

where:

$r_0 =$ $1/e^2$ radius of incoming Gaussian beam,
$y_0 =$ half-width of desired spot size (the radius for a circular spot, or half the width of a square or rectangular spot).

The effects of $\beta$ on the quality of the solution for the problem of mapping a Gaussian beam into a flat-top beam with a rectangular cross section is illustrated in Fig. 5. In the figure we give simulation results for a shaped beam profile with a rectangular cross section with $\beta$ values of 4, 8, and 16.

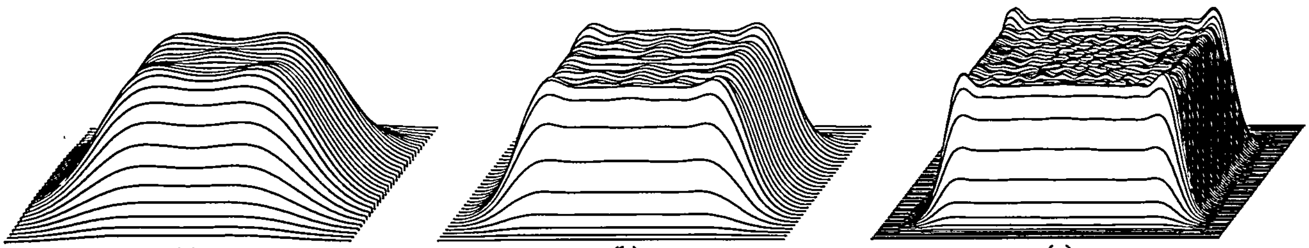



Fig. 5 Simulated shaped beam with square cross section. (a) $\beta = 4$. (b) $\beta = 8$. (c) $\beta = 16$.

The beam shaping configuration just discussed is very general. Solutions for different profiles and cross sections can be obtained using the method of stationary phase. Also, the phase element can be designed using genetic algorithms[1,7] and the Gerchberg-Saxton algorithm.[8] There are several properties associated with the lossless beam shaping configuration shown in Fig. 5 that are important to system design considerations. We will list them here, noting that the details are provided in the references.

- Element Spacing: Assuming the validity of the Fresnel integral, the spacing between the phase element and the Fourier transform lens is not critical.
- Single Element Design: The phase element and the Fourier transform lens can be combined as one element.
- Scaling: The Fourier transform lens focal length may be changed to scale the output spot size without changing $\beta$.
- Positive/Negative Phase: The sign of the beam shaping element phase, $\psi$, can be changed without changing the output beam profile (irradiance). It does, however, change properties of the beam before and after the output plane. In one case the beam goes through a focus before the output (focal) plane; in the other case the beam goes through a focus after the output plane.
- Quadratic Phase Correction: The solutions given in Eq. (5) and Eq. (6) were derived assuming a plane wave (uniform phase) input beam. Small quadratic phase deviations associated with a diverging input correspond to a small shift in the output plane with a proportional scaling of the shaped beam size.
- Collimation: The output beam can be collimated using a conjugate phase plate in the output plane that cancels any non-uniform phase component.

Another interesting field mapping configuration has been suggested by Rhodes and Shealy[9] that is especially applicable to the production of relatively large collimated beams with a uniform irradiance profile. The basic concept is illustrated in Fig. 6. In the figure, the second surface of the first lens directs the incident rays so that they are uniformly distributed at the

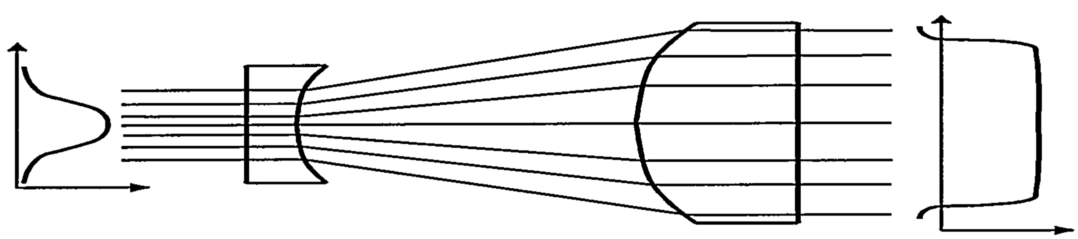


Fig. 6 Two lens system for large collimated beams.

first surface of the second lens. That surface then redirects the rays so that they are collimated. A general theory of this two lens beam shaping system is detailed by Shealy (Chapter 4) and, Evans and Shealy (Chapter 5) in Reference 1. Their approach is geometrical optics, which assumes a large $\beta$. The design approach starts with the eikonal and invokes conservation of energy along a ray bundle between the two surfaces. Special attention is given to constant optical path length designs that give a collimated (minimum divergence) output. The result is a differential equation for the lens surface. They also develop parallel methods for two lens systems using gradient-index (GRIN) glasses.

It is interesting to note that the first lens in Fig. 6 effectively accomplishes the same function as the combination of the shaping element and transform lens in Fig. 4. The main difference is that the output surface for the system in Fig. 4 is assumed planar, while the output surface of the first lens in Fig. 6 is the first surface of the second lens.

## 4. BEAM INTEGRATORS

A multi-aperture integrator system basically consist of two components; 1) a subaperture array consisting of one or more lenslet arrays which segments the entrance pupil or cross section of the beam into an array of beamlets and applies a phase aberration to each beamlet, and 2) a beam integrator or focusing element which overlaps the beamlets from each subaperture at the target plane. The target is located at the focal point of the primary focusing element, where the chief rays of each subaperture intersect. Brown et al.[1] provide a detailed treatment of beam integrators.

Beam integrators can be loosely divided into two categories; diffracting and imaging. A simple diffracting beam integrator (also called a non-imaging integrator) is illustrated in Fig. 3, consisting of a single lenslet array and a positive primary lens. The target irradiance is the sum of defocused diffraction spots (point spread functions) of an on-axis object point at infinity (assuming a collimated input wavefront). The diffracting beam integrator is based on the assumption that the output is the superposition of the diffraction fields of the beamlet apertures. The diffraction field is obtained using the Fresnel integral. If the beam is not spatially coherent over each beamlet aperture a more complicated integral is required and, generally, one would not be able to obtain a reasonable replica of the lenslet aperture. For example, a spatially incoherent field is approximated by a Lambertian source that radiates over a large angle and would not produce a localized irradiance distribution at the output plane.

Figure 7 illustrates an imaging multi-aperture beam integrator. This type of integrator is especially appropriate for spatially incoherent sources. From a ray optics perspective, these sources produce a wavefront incident over a range of field angles on the lenslet apertures. The first lenslet array segments the beam as before and focuses the beamlets onto a second lenslet array. That is, each lenslet in the first array is designed to confine the incident optical radiation within the corresponding aperture in the second array. A second lenslet array, separated from the first by a distance equal to the focal length of the secondary lenslets, together with the primary focusing lens forms a real image of the subapertures of the first lenslet array on the target plane. The primary lens overlaps these subaperture images at the target to form one integrated image of the subapertures of the first array element. Re-imaging the lenslet apertures mitigates the diffraction effects of the integrator in Fig. 3. Imaging integrators are more complicated than diffracting integrators in that they require a second lenslet array and an associated alignment sensitivity. Diffracting integrators are more frequently the integrators of choice.

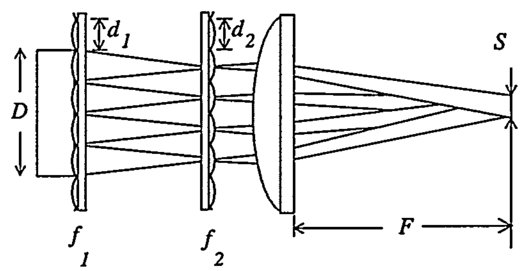



Fig. 7 Basic configuration for the imaging integrator.

There are four major assumptions in the development of diffracting beam integrators. They are as follows:

1) The input beam amplitude (or equivalently irradiance) is approximately uniform over each subaperture. This allows for the output to be the superposition of the diffraction patterns of the beamlet defining apertures. It is expected that small deviations will average out in the output plane. That is, the errors associated with a particular aperture will not dominate.
2) The phase across each subaperture is uniform. The discussion in 1) applies in this case also. In addition, a linear phase across a subaperture results in a redirection of the beamlets, causing a misalignment in the output.
3) The input beam divergence does not vary significantly with time. Generally, an input beam divergence will result in a non-overlapping of the beamlets in the target plane. This can be corrected in many cases with correction optics in the input beam. However, a time varying divergence would negate the possibility of correction.

4) The input beam field should be spatially coherent over each subaperture. This is inherent in assumption 1) since the diffraction patterns are assumed to be described by a Fresnel integral.

The imaging integrator does not require assumption 4) since it does not necessarily require that the output pattern be described by a diffraction integral.

The basic problem for the diffracting integrator is that each lenslet then maps a uniform input intensity into a uniform output intensity via the Fourier transform. It can be shown that the desired lenslet phase function is

$$\Phi\left(\frac{x}{d}\right)=\beta\left(\frac{x}{d}\right)^2. \tag{8}$$

This quadratic phase factor describes a thin lens. Again the solution includes the parameter $\beta$ that is a measure of the quality of the solution. This parameter, for this case, is given by

$$\beta=\frac{\pi dS}{\lambda F}, \tag{9}$$

where $d$, $S$, and $F$ are defined in Fig. 3.
Note that $\beta$ is a dimensionless constant and, as previously discussed, is related to the mathematical uncertainty principle. Increasing $\beta$ 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,

$$S=\frac{F}{f/d}. \tag{10}$$

This result is also obtained using diffraction theory and Fourier optics.

In addition to the diffraction effects discussed above with respect to $\beta$, 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 1. 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

$$I(x,y)=\left|\sum_{0,0}^{M,N}A_{mn}\exp\{i[k(\alpha_m x+\beta_n y)+\theta_{mn}]\}\right|^2 |F(x,y)|^2, \tag{11}$$

where $\alpha_m$ and $\beta_n$ are the direction cosines associated with each beamlet, $\theta_{mn}$ 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. 3.

The first factor in Eq. (11) 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

$$Period=\frac{\lambda F}{d}. \tag{12}$$

It should be noted that when the coherence between the beamlets is negligible Eq. 11 reduces to

$$I(x,y) = \sum_{0,0}^{M,N} |A_{mn}|^2 |F(x,y)|^2, \tag{13}$$

which is just the diffraction pattern of a single lenslet aperture. Simulations of beam integrator outputs are presented in Section 6.

## 5. DIFFRACTIVE DIFFUSERS

The characteristics of diffractive diffusers, also called diffuser beam shapers, are discussed by Brown (Chapter 6) in Reference 1. Diffuser beam shapers are essentially field mappers. They are designed to diffract the incident beam into the desired irradiance distribution with a built in speckle (or random) pattern. The basic design procedure is;[1] 1) multiply the desired irradiance pattern (magnitude) by a random function (speckle pattern), 2) inverse Fourier transform this result to get the input field, 3) binarize the phase of inverse transform function to define the beam shaping diffuser. The technique is illustrated in the following figure.

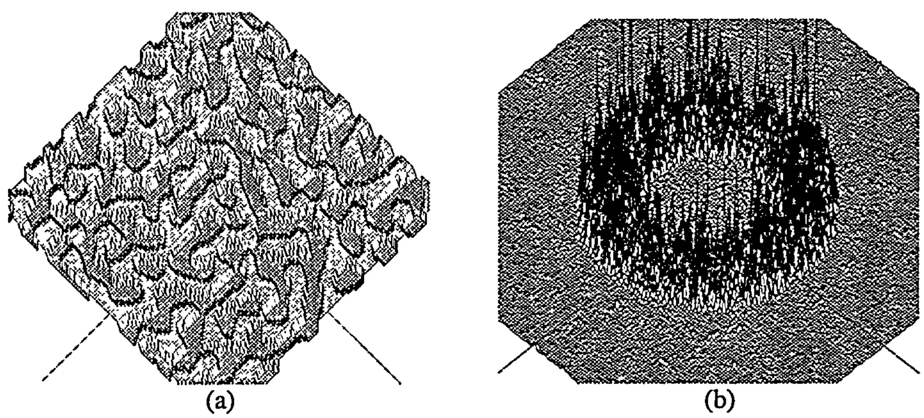


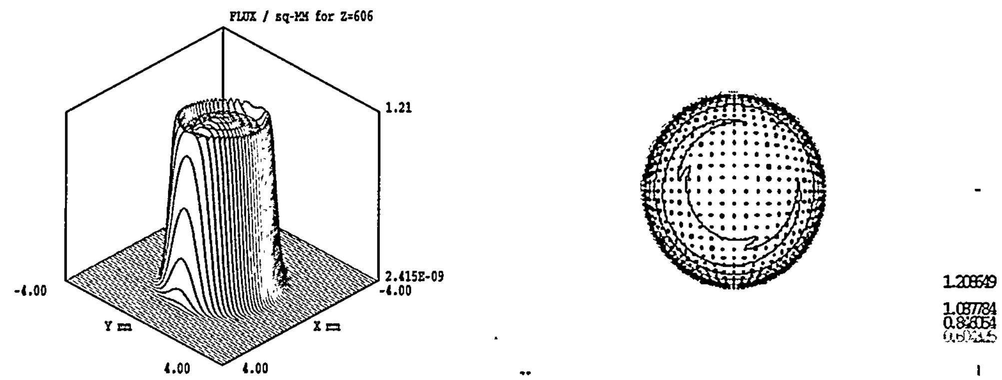
Fig. 8 Simulated diffuser beam shaping. (a) A portion of the binary (2 levels) phase structure for the ring diffuser. (b) Simulated intensity plot of the ring diffuser. This simulation used a Gaussian input beam of diameter 0.5 mm. A spherical phase curvature was then applied to simulate a lens with a focal length of 10.0 mm. Using scalar wave theory the field was propagated 10.0 mm to the focal plane of the lens.

Diffuser beam shapers generally offer the advantage of being much more tolerant to alignment errors than conventional field mappers. Although we class them as field mappers, their speckle and alignment tolerance properties are more like beam integrators. Perhaps they can be viewed as beam integrators with lenslet aperture size approaching zero with the phase varying from lenslet to lenslet.

## 6. DESIGN AND ANALYSIS CONSIDERATIONS

An important and necessary step in the application of a laser beam shaping technique is the modeling and simulation of the beam shaper element using a computer-based high fidelity optical design and analysis program. Two types of analysis programs are available. General geometric optical design programs like ZEMAX™ and OSLO™[10] establish and verify the basic geometrical properties of an optical system using beam shaping technology. They also usually have some capability for the calculation of beam propagation and diffraction properties with some fidelity. These programs can, of course, be used to perform optimization of specific geometrical and system parameters. In contrast, more detailed, realistic wavefront analysis can be performed with optical propagation codes like GLAD™ and ASAP™.[11] These programs also incorporate effects like high order or multimode laser inputs and can account for other factors, including beam polarization and spatial coherence effects. Additionally, ASAP, being a raytrace-based propagation code, can permit the simultaneous visualization of both geometric and diffraction performance of an optical system.

As brief examples, we illustrate how one propagation analysis code, ASAP, can be used to visualize and fine tune the performance of both a field mapping-based and a lenslet-based beam integrator system. For the field mapper example, we use the system illustrated in Fig. 4, and choose a laser beam radius, $r_0 = 6.75$ mm (after afocal magnification), and a desired spot half-width, $y_0 = 2$ mm. The transform lens f = 400 mm, and the laser operates at $\lambda = 10.6$ µm. The coefficients describing the aspheric profile of the beam shaper are extracted from Ref. 4. The value of $\beta$ for this system is 16.
Figure 9 (a) is an isometric view of the intensity distribution, and Fig. 9 (b) superimposes the intensity contours over the spot diagram at the irradiance plane. In this view we may visualize the spherical aberration responsible for the beam shaping effect.

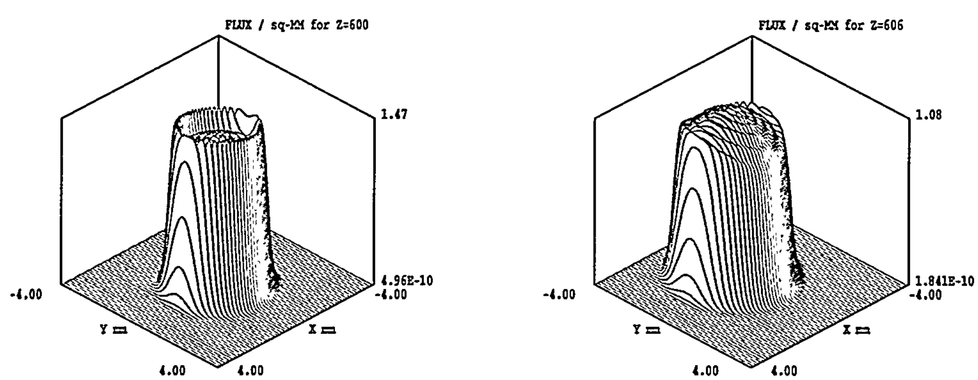



(a) (b)

Fig. 9 Beam irradiance performance for a field mapper system with $\beta = 16$. a) Isometric view. b) Geometric spot diagram superimposed over irradiance contours.

The ASAP-based irradiance calculation shows that the 98 percent radius is 2.10 mm, a 5 percent error. Axial adjustment of the spot focal plane by 6 mm yields the nearly desired spot, although the beam profile has been altered a small amount. (Fig. 10 (a)).

If the mode structure, including the amplitude and phase distribution of a specific laser are known then the effect on performance can also be calculated. The program permits inclusion of known phase and amplitude distributions. The sensitivity to manufacturing tolerance and misalignment on the design can also be studied. As an example, Fig. 10 (b) illustrates the effect on the beam after a 10 degree tilt in the transform lens.




(a) (b)

Fig. 10 Effect of geometric modifications to field mapper beam shaper system
(a) A 6 mm axial focal plane shift changes beam scale by 5 percent.
(b) Effect of 10 degree rotation in transform lens.

In the second example, a beam integrator system using a multiple lenslet array, as illustrated in Figure 3, would be difficult to design and analyze purely analytically. However, three-dimensional propagation codes like ASAP have been used to simulate and verify the design fairly readily. The example system uses an array of hexagonally packed lenslets, each with a

1.5 mm aperture, to reduce a collimated $\lambda = 1.06$ μm, 5 mm diameter beam to a 220 μm diameter for injection into an optical fiber. Fiber injection systems are treated in detail by Weichman et al[12]. ASAP was used to analyze and optimize performance as a function of axial focus spot position. Figure 11 shows the geometric spot diagram and through-focus diffraction effect on spot size.

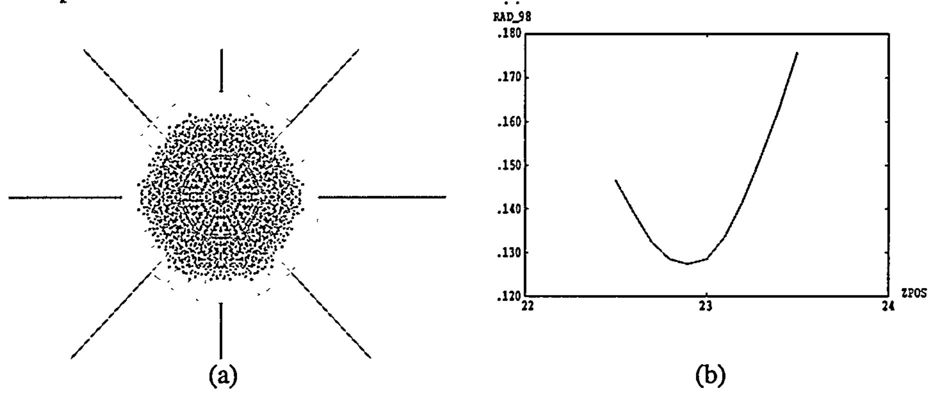



Fig. 11 (a) Focal plane geometric spot diagram.
(b) Diffraction spot size vs focal plane position for central 98 percent of beam energy.

Figure 12 shows the irradiance distribution at the minimum spot position for a uniform illumination, perfectly coherent laser beam. Note how the irradiance pattern is dominated by interference between the lenslet beams, demonstrating that for the given parameters, the resultant spot is not uniform.

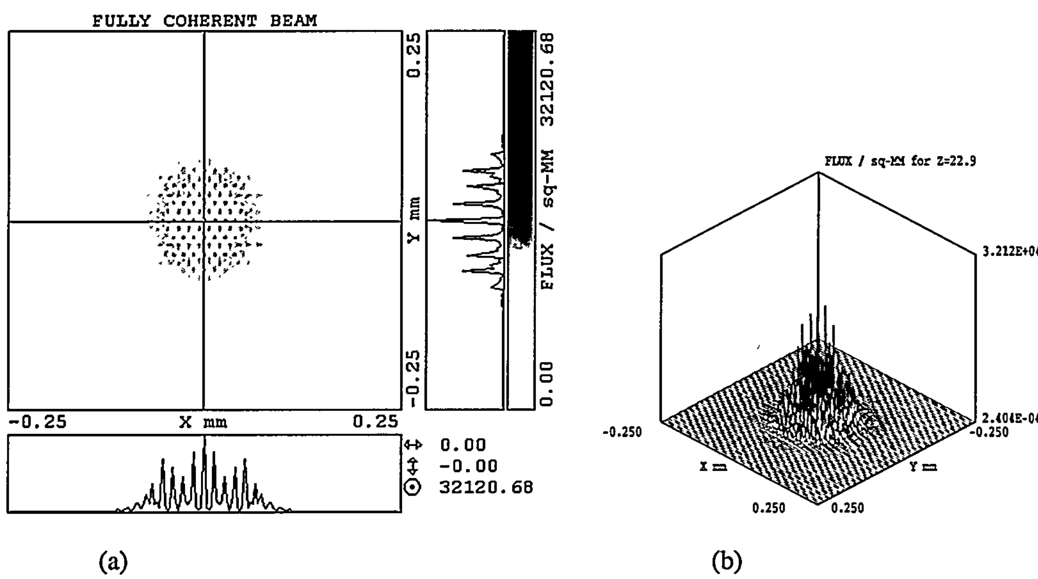



Fig. 12 Lenslet array beam integrator analysis—fully coherent laser beam input
(a) Image simulation and (x,y) profiles. (b) Isometric view. (at fiber injection plane)

If we use a source laser with limited spatial coherence, we can reduce the interference effects on the spot irradiance distribution. Figure 13 shows the calculation of a spatial coherence width small compared to each lenslet aperture. Note how the contrast of the interference fringes is reduced significantly.

## 7. SUMMARY

In this paper we have discussed what we believe to be the three major approaches to laser beam shaping, outlined the basic characteristics of each, and suggested the importance of the use of high fidelity optical software to the design problem.

Although we have included basic design equations, space limits require that the interested reader consult the literature for a more detailed treatment.

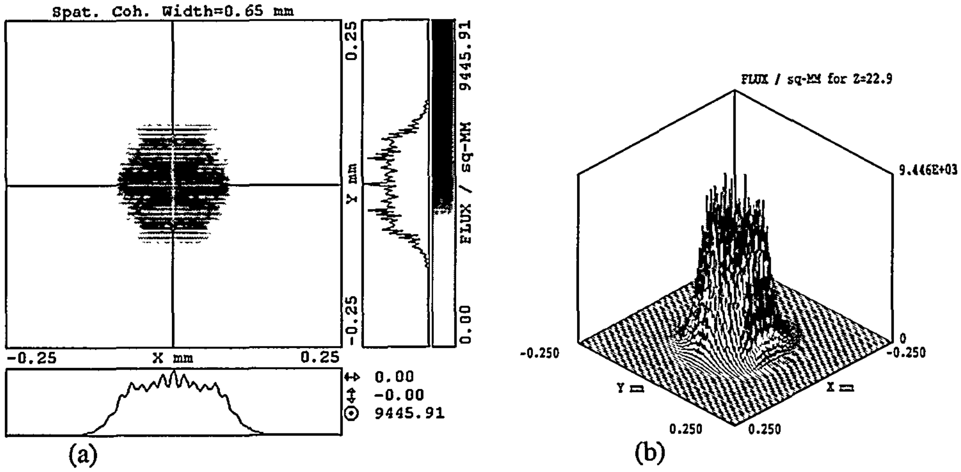



Fig. 13 Lenslet array beam integrator analysis—input laser beam with coherence width of 0.65 mm. (a) Image simulation and (x,y) profiles. (b) Isometric view. (at fiber injection plane).

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[10] ZEMAX is a product of Focus Software, Inc. Tucson, AZ. OSLO is a product of Sinclair Optics, Inc. Fairport, NY.

[11] GLAD is a product of Applied Optics Research. ASAP is a product of Breault Research Organization.

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