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Gaussian laser beam shaping: test and evaluation

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ABSTRACT

A method for converting single mode Gaussian beams into beams with uniform irradiance profiles is described. This technique has application to laser cutting and welding, laser ablation, semiconductor mask fabrication, and other tasks. Currently, designs for rectangular and circular flat top profiles have been investigated. Experimental results are presented for an element that converts a single mode Gaussian beam into a square, flat top spot. The design is based on a Fourier transform relation between the input and output beam functions and can be implemented as a diffractive or refractive element. The form of the element reduces to a common equation that is scaled for the particular geometry involved. This scale factor contains the product of the widths of the input and output beams, the focal length of the system, and the wavelength. It is a dimensionless quantity that uniquely determines the quality of the target spot, regardless of wavelength or system geometry. A designer can thus start from a desired target quality and lay out the required optical system to achieve that quality, in contrast to an iterative approach.

Key words: beam shaping, Fourier optics

1. INTRODUCTION

Many experiments and industrial applications require a laser beam irradiance that is nominally constant over a specified area. Such applications include laser/material processing, laser/material interaction studies and lithography. In many cases it is desirable, for obvious reasons, that the beam shaping operation conserves energy.

The multifaceted integrator approach to laser beam shaping is especially suitable to laser beams with highly irregular (multimode) irradiance distributions.^{1,2} The number and size of the facets is selected to accomplish the required integration or, equivalently, averaging. Doherty³ has treated the problem of irradiance mapping for laser beams with radial symmetry and regular irradiance distributions. Dickey and O'Neil⁴ give a general formulation of multifaceted beam integrator problem and introduce a configuration that minimizes deleterious diffraction effects.

For single mode beams with a Gaussian profile it is possible to map the beam into a uniform intensity profile with steep skirts. This mapping can be accomplished with simpler optics that is more flexible with respect to scaling and does not have the interference patterns inherent in multifaceted beam integration. Several authors address the problem of mapping a Gaussian beam into one with a uniform irradiance distribution. Lee⁵ employs an iterative technique to design a phase filter to convert a Gaussian beam into a more uniform irradiance distribution. Veldkamp^{6,7} uses an iterative technique to design binary gratings to accomplish the profile shaping. Aleksoff et al.⁸ uses the geometrical optics approximation to develop a holographic system that maps a Gaussian beam into a rectangularly shaped beam with uniform amplitude and phase. Eismann et al.⁹ applies the Gershberg-Saxton algorithm, or equivalently, phase retrieval to synthesize a two element design that produces a beam with uniform amplitude and phase. In a recent paper, Golub et al.¹⁰ present numerical and experimental results for a diffractive beam shaper based on a geometrically-derived phase function.

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2. THE ANALYTICAL SOLUTION

Our approach to lossless beam shaping consists of a phase element in conjunction with a Fourier transform lens. The optical field at the focal plane of the transform lens is proportional to the Fourier transform of the product of the input optical field and phase of the phase element.¹¹ The approach involves solving for the phase function that minimizes the mean square difference between the desired irradiance and the irradiance produced by the phase element. That is, we want to find ϕ that minimizes an integral of the form

$$R = \int \left| \mathfrak{F} \left[\left(2/\sqrt{\pi} \right)^{1/2} e^{-x^2} e^{i\phi} \right] - (1/\alpha)^{1/2} \text{rect}(f/\alpha) \right|^2 df, \quad (1)$$

where $\mathfrak{F}$ denotes a Fourier transform operation, f denotes the corresponding frequency domain variable, α defines the size of the output, and the problem is scaled to a unit width $(1/e^2)$ Gaussian beam function. Here, the problem is formulated in one dimension, which is also appropriate to the separable problem of converting a circular Gaussian beam into a uniform beam with a square cross section. Unfortunately, we were not able to obtain a global solution to Eq. (1). We were able to obtain solutions to the problem using the method of stationary phase.¹² In two dimensions, the general form of the equation to be solved is

$$F(\omega_x, \omega_y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\xi, \eta) \exp(i(\beta\phi(\xi, \eta) - \xi\omega_x - \eta\omega_y)) d\xi d\eta, \quad (2)$$

where $\xi = x/r_i$ and $\eta = y/r_i$ are normalized input variables with r_i defining the length scale, and $\omega_x = x_f/r_o$ and $\omega_y = y_f/r_o$ are normalized output variables at the focal plane of the Fourier transform with r_o defining the length scale. The stationary phase solution improves asymptotically with increasing dimensionless parameter $\beta = 2\pi r_i R_o / f\lambda$ where R_o is the size of the output beam, λ is the optical wavelength and f is the focal length of the transform lens.

The stationary phase evaluation of integrals of the type given by Eq. (2), generally, leads to second order partial differential equation for the phase function ϕ . The resulting partial differential equation can then be solved for ϕ , subject to an energy boundary condition determined by Parseval's theorem. The partial differential equation reduces to a second order ordinary differential equation for both the separable and circularly symmetric problems. The optical element is then designed to realize $\beta\phi$.

Romero and Dickey¹³ have obtained solutions for converting Gaussian beams to uniform profiles with both rectangular and circular cross-sections. 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. β 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 ϕ is¹³

$$\phi(\xi) = \frac{\sqrt{\pi}}{2} \cdot \xi \cdot \text{erf}(\xi) + \frac{1}{2} \cdot \exp(-\xi^2) - \frac{1}{2}, \quad (3)$$

where

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

and $r_o = 1/e^2$ 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

$$\phi(\xi) = \frac{\sqrt{\pi}}{2} \cdot \int_0^{\xi} \sqrt{1 - \exp(-\rho^2)} d\rho, \quad (4)$$

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 β . For the two solutions given in Eq. (3) and Eq. (4), β is given by

$$\beta = \frac{2\sqrt{2\pi} r_0 y_0}{f\lambda}, \quad (5)$$

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 solutions described in this section assume that the input Gaussian beam has a uniform (constant) phase at the beam shaping element. For a Gaussian beam this condition is obtained at the beam waist, but it is not always convenient to locate the beam waist at the shaping element. One practicable solution lies in the fact that the Gaussian beam's phase causes a shift in the location of the output plane.¹⁴ That is, the desired profile is located a distance from the focal plane of the transform lens. There is also a slight magnification associated with the shift of the output plane. Thus, the profile will still be uniform, although at a slightly different location and magnification. Another solution involves adjusting the telescope to place a beam waist on the phase element.

3. DESIGN CONSIDERATIONS

A primary design advantage of this lossless beam shaping technique is that the designer can start with a desired target spot quality and determine the optical system required, rather than designing multiple optical systems in the hope of producing an acceptable output.^{14,15} This is because the dimensionless quantity β of Eq. (5) completely determines the quality of the spot at the target plane. In other words, different optical configurations and wavelengths will produce the same target spot quality if they share the same value of β . Low values of β produce target spots with more rounded sides and wider skirt regions, while higher values of β more closely approach the geometric ideal of a uniform intensity profile with infinitely steep sides.

Fig. 1 Standard layout for beam shaping systems.

Fig. 1 shows a standard layout for a beam shaping optical system. For most design situations, the size of the target spot and the wavelength will be determined by the application. The focal length of the transform lens may also be determined by standoff or other considerations, although a minimum focal length will maximize β . The final variable is the Gaussian beam radius at the shaping element. To achieve the desired β , the beam size should be expanded by an afocal telescope, as shown in the figure. The required phase profile imparted on the beam by the phase element is then found by multiplying the phase

function of Eqs. (3) or (4) by β . This multiplication scales the phase function to the particular geometry of the application.

3.1. Target spot quality

Since β determines target spot quality independent of the circumstances of the design, graphs of the beam shape versus particular values of β are useful. Aperture radii were truncated at $2r_0$ in these simulations, where r_0 was the $1/e^2$ radius of the beam. Fig. 2(a) shows a square target spot with $\beta = 4$. The profile is fairly rounded. Fig. 2(b) shows the square target spot with $\beta = 8$. The skirts of this spot have narrowed considerably. Fig. 2(c) shows the square target spot with $\beta = 16$. The skirts of this spot have narrowed further. This system design is beginning to approach the geometric ideal of a uniform profile with infinitely steep sides. For the case of a circular, uniform target spot, Fig. 2(d) illustrates the profile for $\beta = 8$ and $3r_0$ truncation. This spot behaves similarly to the square case as β changes. Unlike the square case, however, the circular case exhibits noticeable ripple on the profile as the beam is truncated to $2r_0$.

Fig. 2 Profiles of square and circular spot geometries. (a) Square profile, $\beta = 4$. (b) Square profile, $\beta = 8$. (c) Square profile, $\beta = 16$. (d) Round profile, $\beta = 8$.

3.2. Positive and negative phase functions

The phase function has two solutions, positive and negative, for a given configuration. With reference to Eq. (1), ϕ is the phase delay suffered by a wave in passing through the phase element. This situation is analogous to the phase delays introduced by thin lenses.¹¹ For a positive phase function ϕ , Eq. (3) and Eq. (4) show that the phase delay will vary from zero at the optical axis to increasingly positive values as we move away from the axis. This situation is the same as that for a negative thin lens, and additional insight into the beam shaping system can be gained by viewing the shaping element geometrically, as is illustrated in Fig. 3. The target plane is the focal plane of the transform, or focusing, element and this is where the desired target spot appears. For an element with a positive phase function (a), the beam continues to decrease in size after the target plane. For an element with a negative phase function (b), the beam passes through a minimum diameter before reaching the target plane.

Fig. 3 Positive (a) and negative (b) phase functions.

3.3. Alignment and scaling errors

Unlike methods based on multifaceted integrators, this lossless beam shaping method is sensitive to alignment errors and variations in the input beam size. Fig. 4 shows the effect of decentering the Gaussian beam on the phase element by $0.1r_0$, along one of the element axes. Since the shaping element is designed for a particular input beam size, which in part determines the scaling factor β , it stands to reason that deviations from the design input beam size will affect the target spot. The following cases show the degradation in the square target spot for the $\beta = 8$ design of Fig. 2(b), with a positive phase function. In Fig. 5(a), the input Gaussian beam size is 10% larger than the size used in the design. The target spot shows significantly raised edges. Fig. 5(b) shows the target spot for an input beam size that is 10% smaller than that used in the design.

Fig. 4. Input beam decentered along element axis by $0.1r_0$, $\beta = 8$ case.

Fig. 5 Effects of deviations in input beam size from design values: (a) Input beam 10% larger than design size. (b) Input beam 10% smaller than design size.

Target plane defocus also affects the quality of the target spot for the following reasons. In the derivation of the phase element, the problem was to minimize the difference between the desired irradiance at the target plane and that produced by the system. There were no constraints on the phase of the beam at the target or on the beam irradiance outside the transform plane. Since the phase is generally not uniform at the target plane, the shaped beam will not display the symmetry about the target plane characteristic of Gaussian beams at their waist. The irradiance of the beam will thus deviate from the desired shape when the target plane is moved away from the focal point of the transform lens. The following cases apply to the $\beta = 8$ design of Fig. 2(b), with a positive phase function. Fig. 6(a) shows the effect of moving the target

plane away from the transform lens by $f/50$, where f is the focal length of the lens. Fig. 6(b) shows the effect of moving the target plane toward the transform lens by $f/50$.

Fig. 6 Defocus effects: (a) Target plane defocused by $+f/50$. (b) Target plane defocused by $-f/50$.

4. EXPERIMENTAL EVALUATION

A beam shaping system was developed for an application that required a long working distance, limited beam sizes, and operation at $10.6\ \mu\text{m}$. This resulted in a maximum target spot quality given by $\beta = 4.8$. The phase element was fabricated in ZnSe as a 16-level diffractive optic. Fig. 7 shows the element profile along the x axis as measured by a stylus profilometer. The desired profile in terms of element thickness is shown by the smooth curve overlaid on the measured profile. In order to match the 2π phase shifts of the diffractive optic, 2π phase shifts (or thickness shifts of $\lambda/(n-1)$) were applied to the graph of desired profile as well. Overall, the measured element profile was in reasonable agreement with the desired profile, except for a displacement near the center of the element.

Fig. 7 Measured profile of shaping element along x axis. It is a 16-level diffractive approximation to the desired profile shown by the smooth curve.

The phase element was tested on a different laser than that for which it was designed, although the measured beam dimensions were within the design goals. The laser beam passed through the beam shaping optical system and on to a target plane. A lens beyond the target plane relayed and magnified the target spot onto a pyroelectric array camera. The focus and magnification of the relay system were set by placing a calibrated pinhole at the target plane and adjusting the lens for a sharp image on the camera. The laser beam dimensions at the input of the optical system were determined with orthogonal scanning knife-edges in conjunction with an automated focusing system. This device computed the internal beam waist size and location as well as the beam divergence. It then computed the same parameters for the external laser beam. These quantities then determined the initial beam size at the telescope system.

Before presenting the experimental results, it is instructive to see the predicted spot geometry for the actual beam input parameters. The system was modeled using the computed beam radii for the x and y axes at the first telescope lens. There was a difference of roughly 5% in the computed radius of curvature for the x and y axes, but this was ignored in the modeling. In Fig. 8, predicted target spot profiles for the x

and y axes are shown, scaled to normalized position units. The optical system was initially aligned using a visible reference beam. Final alignment of the beam shaping element was accomplished by viewing the target image with the pyroelectric array camera. Fig. 9 shows a contour plot of the target spot when the system was aligned. The square appearance is evident. Profiles of this image were extracted and are plotted in Fig. 10. These profiles use the same normalized position units as the predicted profiles of Fig. 8. The measured profiles are smaller than predicted, and they deviate somewhat from the desired uniform irradiance. Nevertheless, they show a general agreement with the predicted uniform profiles.

Fig. 8 Predicted target spot profiles. Normalized units.

Fig. 9 Contour plot of the target spot for a $b = 4.8$ system. Contours have equal intervals of 3.2% of the maximum value.

Fig. 10 Measured profiles of the target spot, normalized to the same units as the predicted spot. (a) X axis. (b) Y axis.

The size difference is partly a function of difficulties in establishing the best target plane. Distance measurements from the transform lens were somewhat inexact, and compensation was necessary for the curvature of the input beam. Also, the relay lens and the camera were mounted independently, so that it was difficult to move the target plane once the relay focus was set. Most likely, the relay magnification and focus varied during the alignment process. These uncertainties, coupled with alignment issues for the shaping element, made for difficulties with several independent adjustments during system alignment. It would have been best to be able to mount the camera, re-imaging lens, and pinhole together on a common structure, with the pinhole mounted kinematically. When the camera system was used to find the best target plane, the pinhole could be replaced to mark it exactly. Also, a good approximation to the target plane position could be found by removing the shaping element from the system. The focused beam waist would occur very close to the system focal point, and would account for curvature in the input beam. Telescope separation could be adjusted to put the target plane at the desired location, with fewer subsequent adjustments to make during alignment.

Differences in the measured profile uniformity are at least partly the result of two factors. First, the test laser displayed near-field deviations from a Gaussian shape due to its unstable resonator configuration. These near-field deviations tend to be masked in far-field beam measurements due to diffraction effects from the focusing lens. Second, the measured element profile shown in Fig. 7 differed somewhat from the desired profile, leading to a difference in the phase delay applied to the beam.

5. FURTHER APPLICATIONS

A drawback of existing beam shaping systems is the limited depth of field. The uniform profile appears only at the target plane, and the profile quickly degrades beyond it. A desirable extension would be to create a uniform beam that could propagate for considerable distances. In other words, besides a uniform profile at the target plane, what is desired is a uniform phase front. The uniform profile would then continue to propagate subject only to diffraction effects from its finite dimensions. Fig. 11 shows an illustration of such a scheme. The phase of the shaped beam is calculated at the target plane. A corrector plate is then designed so that the beam exiting the plate has a uniform phase front. Fig. 12 illustrates a system that increases the depth of field of the uniform beam by using a relay lens. The relayed beam is symmetric about the relayed target plane, so there is a longer distance where the beam maintains the desired tangential dimensions.

Fig. 11 Optical system for creating a uniform beam.

Fig. 12 Relay system for extending the uniform beam's depth of field.

6. ACKNOWLEDGEMENTS

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