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Estimation of the laser beam enabling rectangular processing by the inverse diffraction theory

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ABSTRACT

A small rectangular laser spot has been widely studied for laser processing and laser repair technology. It is usually made by converging the input beam with the lens. Faithful reproduction of the laser spot is dependent on NA of the imaging lens. The small rectangular spot can be obtained by high NA lens, which is limited by many factors, such as high energy loss due to the reflection on the surface, large mass and volume, and strong sensitivity to aberrations and misalignment. On the other hand, the beam cannot be faithfully reproduced because of the diffraction with the low NA lens which has no such the limitations. One of the alternative ways to produce small rectangular profiles by using the low NA lens system is to estimate the input beam profile leading to the output profile of the sharp rectangular shape.

Before estimation, we first defined spatially broad functions that did not contain high spatial frequencies and have sharp rectangular cross-sectional profile. Then, we calculated the input beam profiles leading to these functions by the inverse diffraction theory. We also confirmed that the quantization for realizable input beam profile could not much affect rectilinearity of the output beam.

1. Introduction

The majority of applications of focused laser beams require incoming beam shaping in order to enhance their performance. The beam shaping has been accomplished by using the lens array [1], the Levenson's mask [2] and the DOE [3]. The careful control of the focal spot is required in optical lithography, laser repair, and laser-based material processing [4]. The laser repair technique recovers defective products, and brings the cost reduction. Rectilinear processing is in great demand for laser repair devices. We present a method for obtaining a small rectangular spot in the imaging system.

Imaging properties are determined by numerical aperture (NA) of the imaging lens. Though high NA lens system can reproduce sharp rectangular profile with micron order, it narrows the depth of focus. A shallow depth of focus makes the alignment of processing more difficult. In addition, the high NA lens system increases surface reflection, the system complexity and processing cost. On the other hand, low NA lens system has long depth of focus and large working distance. However, it is impossible to produce sharp rectangular profile below micrometer-orders due to diffraction. The low NA lens system has an optical transfer function with low cut-off frequency, so that rejects the fine structure of the object.

Therefore, as long as using the low NA lens system, a rectangular aperture has become a reduced round rectangular intensity profile in the image plane. One of the alternative ways to produce small rectangular profiles by using the low NA lens system is to estimate the input beam profile leading to the output profile with sharp rectangular shape. In usually, the flat top beam has been extensively studied as a rectangular cross-section beam [3,5]. However, the flat-top beam contains high spatial frequencies with which beam spot tends to diverge by diffraction. Therefore, we defined functions with narrow bandwidths and horizontally rectangular cross-sections. Then, we calculated the input beam profiles leading to these functions by the inverse diffraction theory.

In this paper, we used the Rayleigh–Sommerfeld–Debye diffraction theory for calculation. We introduce the band-limited angular spectrum that decreases the error due to aliasing of the spectrum. The inverse diffraction theory and the band-limited angular spectrum method were shown in Section 2. Section 3 explained some definitions of the beam profile functions having narrow bandwidths and rectangular cross-sections. Results in Section 4 shows the beam profile that was calculated by our method is superior to that of the simple rectangle profile as an input.

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2. Theory

2.1. The Rayleigh–Sommerfeld–Debye formula of the inverse diffraction

We represent the input field as u_{-1} and the output field as u_{+1}, which satisfy the Helmholtz equation,

$$(\nabla^2 + k^2)u_s = 0, \quad (s = -1, +1). \tag{1}$$

It is known that there is a relation of the following equation between the input field and the output field,

$$u_s(x_s, y_s, z_s) = \int\int_{-\infty}^{\infty}\int\int_{-\infty}^{\infty} u_{-s}(x_{-s}, y_{-s}, z_{-s}) \times \exp\left\{si\left[k_s(x_s - x_{-s}) + k_y(y_s - y_{-s}) + k_z(z_s - z_{-s})\right]\right\} dk_x dk_y dx_{-s} dy_{-s} \quad (s = +1), \tag{2}$$

where $k_z = \sqrt{k^2 - (k_x^2 + k_y^2)}$, $k = 2\pi/\lambda$. The symbols k_x and k_y are wave numbers in the x and y directions, respectively. It is called as a homogeneous wave at $k^2 \geq k_x^2 + k_y^2$, and is called as an inhomogeneous wave (evanescent wave) at $k^2 < k_x^2 + k_y^2$, in the input field. If it is $z_{+1} > z_{-1}$, the inhomogeneous component attenuates with $\exp[-|k_z|(z_{+1} - z_{-1})]$. Therefore, the inhomogeneous wave can be neglected if the distance of the input field and the output field is away to some degree. As far as the inhomogeneous wave can be disregarded, the input and the output are reversible relation. We used the Rayleigh–Sommerfeld–Debye formula of a diffraction integral [6] as the inverse diffraction without the inhomogeneous components, setting $s = -1$ in Eq. (2). Setting the sampling window to S_x and S_y, and the sampling interval to Δx and Δy, we discretize the Eq. (2) as follows.

$$u_s(x_s, y_s, z_s) = \frac{\Delta x \Delta y}{S_x S_y} \sum_{k_x=1}^{1/\Delta x} \sum_{k_y=1}^{1/\Delta y} \sum_{x_{-s}=1}^{S_x} \sum_{y_{-s}=1}^{S_y} u_{-s}(x_{-s}, y_{-s}, z_{-s}) \times \exp\left\{is\left[k_x(x_s - x_{-s}) + k_y(y_s - y_{-s}) + k_z(z_s - z_{-s})\right]\right\}, \tag{3}$$

$s = +1$ and -1 represent the forward and the backward diffraction, respectively.

2.2. The band-limited angular spectrum method

Eq. (2) can be decomposed into three equations by using the angular spectrum. The angular spectrum of the field u_{-s} at $z = z_{-s}$ is given as:

$$U_{-s}\left(k_x, k_y\right) = \Delta x \Delta y \sum_{x_{-s}=1}^{S_x} \sum_{y_{-s}=1}^{S_y} u_{-s}(x_{-s}, y_{-s}, z_{-s}) \times \exp\{-si(k_x x_{-s} + k_y y_{-s})\}. \tag{4}$$

Because this equation represents the discrete Fourier transform of u_{-s}, the fast Fourier transform can be applied. Next, the angular spectrum U_{-s} at $z = z_s$ is given by the following equation.

$$U_s(k_x, k_y) = U_{-s}(k_x, k_y)P(k_x, k_y) \tag{5}$$

where $P(k_x, k_y) = \exp[sik_z(k_x, k_y)(z_s - z_{-s})]$ is called as the propagator. Finally, the field u_s at $z = z_s$ is given by the following equation.

$$u_s(x_s, y_s, z_s) = \frac{1}{S_x S_y} \sum_{k_x=1}^{1/\Delta x} \sum_{k_y=1}^{1/\Delta y} U_s(k_x, k_y) \exp\{si(k_x x_s + k_y y_s)\}. \tag{6}$$

The fast Fourier transform can be also applied, since this equation represents the inverse discrete Fourier transform of u_s.

When the fast Fourier transform is used by the angular spectrum method, the areas of the sampling window in the input field should be doubled in consideration of the periodism of data along both x and y axes [7]. Though the angular spectrum method gives an excellent result in the near-field region, its accuracy falls when the distance exceeds about $10S_x$ or $10S_y$. This error of the angular spectrum method cannot be avoided only by expanding the sampling

window. Because the propagator $P(k_x, k_y)$ vibrates very frequently in significant value of k_x and k_y when $|z_s - z_{-s}|$ grows, the aliasing error is caused when discretizing it. Therefore, the propa-

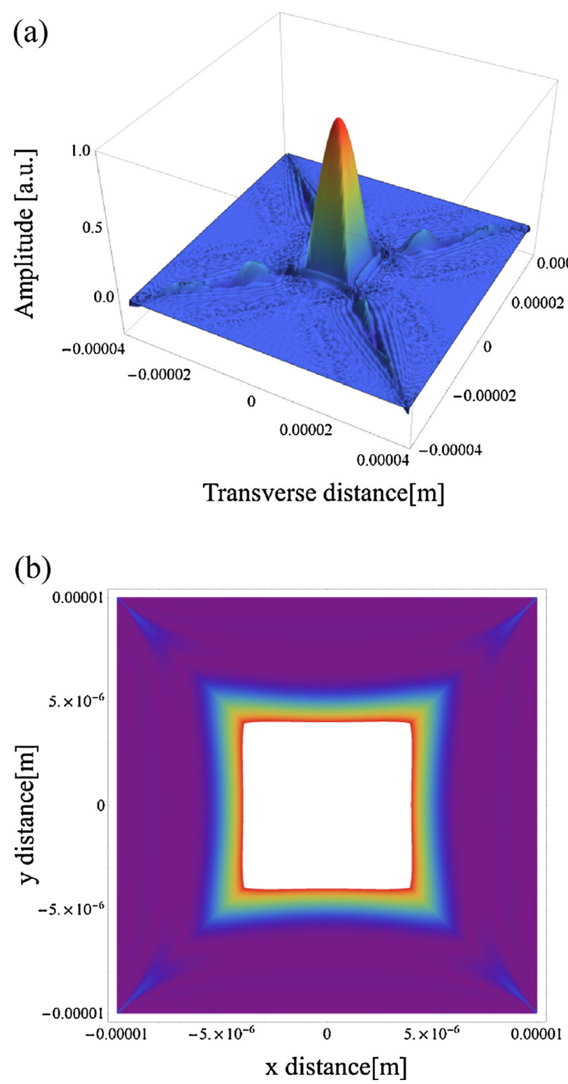

Fig. 1. Example of the modified-sinc function. (a) Three dimensional intensity distribution. (b) Horizontally cross-sectional profile clipped at 30% below to the intensity top.