Optics & Laser Technology 47 (2013) 183–188

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

A novel laser intensity function and its fitting method

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ARTICLE INFO

Article history:
Received 17 April 2012
Received in revised form
5 September 2012
Accepted 7 September 2012
Available online 12 October 2012

Keywords:
Intensity distribution
Transcendental function
Multivariate optimization

ABSTRACT

A novel transcendental function is presented to describe laser intensity distribution instead of Gaussian functions, and its fitting method is given in this paper. The transcendental function based on the Gaussian functions is fitted with multivariate optimization method, which is carried out with direction search method and least square method in practice. Four kinds of distribution laser intensity are fitted with the transcendental function in this article, validity and effectiveness of the fitting method are verified by these numerical simulations.

1. Introduction

Thermal lensing effects often occur in modern lasers such as high-power lasers, lithography objectives and so on, lenses in these apparatus will have deformations, stress and strain due to laser heating [1,2], the refractive indices of optical materials will change [3,4], stress birefringence [5,6] and self-focusing [7] also occur. Since optical performance of these apparatus is seriously affected due to thermal lensing effects, the effects should be considered at early time of optical design. And in thermal analysis of thermal lensing effects, the raw discrete data of laser intensity distribution on surfaces of lenses should be analyzed by optical software at first. Then, the raw discrete data will be fitted as laser intensity functions. Finally, the functions will be multiplied with material absorption factor, and applied on surfaces of lenses as thermal load. Usually, laser intensity functions were supposed to be Gaussian forms which include Gaussian form [8–11], sub-Gaussian form [12], super-Gaussian form [13–15] and elliptical-Gaussian form [16,17] in the past research. But laser intensity distribution on surfaces of lenses does not often obey Gaussian forms due to refraction of aspheric or thick lens [18–20], so it seems unsuitable to fit the raw discrete data of laser intensity distributed on surfaces of lenses with Gaussian functions. The other ways to describe laser intensity in nonlinear optics are Gaussian decomposition method (GD) [21–23] and Fresnel–Kirchhoff method (FK) [24–26], but their mathematical forms are complicated for thermal analysis.

In this article, a novel transcendental function is proposed to describe distribution of laser intensity on lenses, and its form includes Gaussian forms. Since the function is unable to be fitted directly, we solve parameters of the function with multivariate optimization method, and get the laser intensity function finally.

2. Raising of a transcendental laser intensity function

In the research related with laser beams, laser intensity distribution on surfaces of optical components was usually described as Gaussian form [9–11], which is shown as follows:

$$I(x,y) = I_0\,e^{-2((x^2+y^2)/w^2)}, \tag{1}$$

where I_0 denotes energy density of the laser beam at the center (W/m^2), and w is the radius of laser beam. The geometric interpretation is depicted in Fig. 1.

While, several other researchers thought that if add a factor 'l' to Gaussian function, the new function can be described laser intensity distribution better [12–15]. And its form is described as follows:

$$I(x,y) = I_0\,e^{-2((x^2+y^2)/w^2)^l}, \tag{2}$$

where l is a positive real factor. And when $l<1$, it is called sub-Gaussian distribution; when $l=1$, it is called Gaussian distribution, which has the same form as Eq. (1); when $l>1$, it is called super-Gaussian distribution, and when $l\to\infty$, Eq. (3) describes uniform distribution.

In addition, laser intensity distribution described by Eq. (1) is circular, an elliptical-Gaussian function was raised to describe laser distribution in some articles [16,17], and its form is described as follows:

$$I(x,y) = I_0\,e^{-2((x^2/u^2)+(y^2/v^2))}, \tag{3}$$

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0030-3992/$ - see front matter
http://dx.doi.org/10.1016/j.optlastec.2012.09.009

where u and v are waist radius of laser beam. When $u=v$, it has the same form as Eq. (1).

Obviously Eq. (1) is a special kind of Eqs. (2) or (3), therefore Eqs. (2) and (3) can be more suitable for describing laser intensity distribution. And it also can be seen from structure of above equations that the indices which is in bracket of exponent are all quadratic, here we use two positive real factors instead of them, and construct a transcendental function as Eq. (4) to describe distribution of laser intensity:

$$I(x,y)=I_0\,e^{-2((|x|^j/u^j)+(|y|^k/v^k))^l}, \quad (4)$$

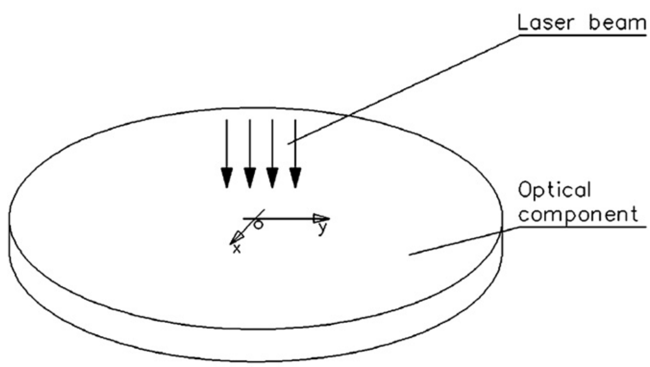

Fig. 1. Schematic diagram of laser intensity distribution on optical component.

where j, k and l are all positive real factors. When $j=k=2$ and $l=1$, Eqs. (4) and (3) have the same form; when $j=k=2$ and $u=v=w$, Eqs. (4) and (2) have the same form. In other words, function described by Eq. (4) includes Eqs. (1)–(3), therefore it is more applicable.

3. Solving of parameters in the transcendental function

3.1. Transformation of the transcendental function

The nonlinear function should be transformed to a linear one before its fitting with least square method. Since Eq. (4) is nonlinear, we transform it to a new form as follows:

$$\left|-\frac{1}{2}\ln\left[\frac{I(x,y)}{I_0}\right]\right|^{1/l}=\frac{|x|^j}{u^j}+\frac{|y|^k}{v^k}, \quad (5)$$

As can be seen from Eq. (5), it is unable to fit the equation with least square method directly for unknown terms on each side of it.

3.2. Solving method of the parameters

The standard deviation between the raw discrete data of laser intensity and its fitting function $I(x,y)$ described by Eq. (4) can be

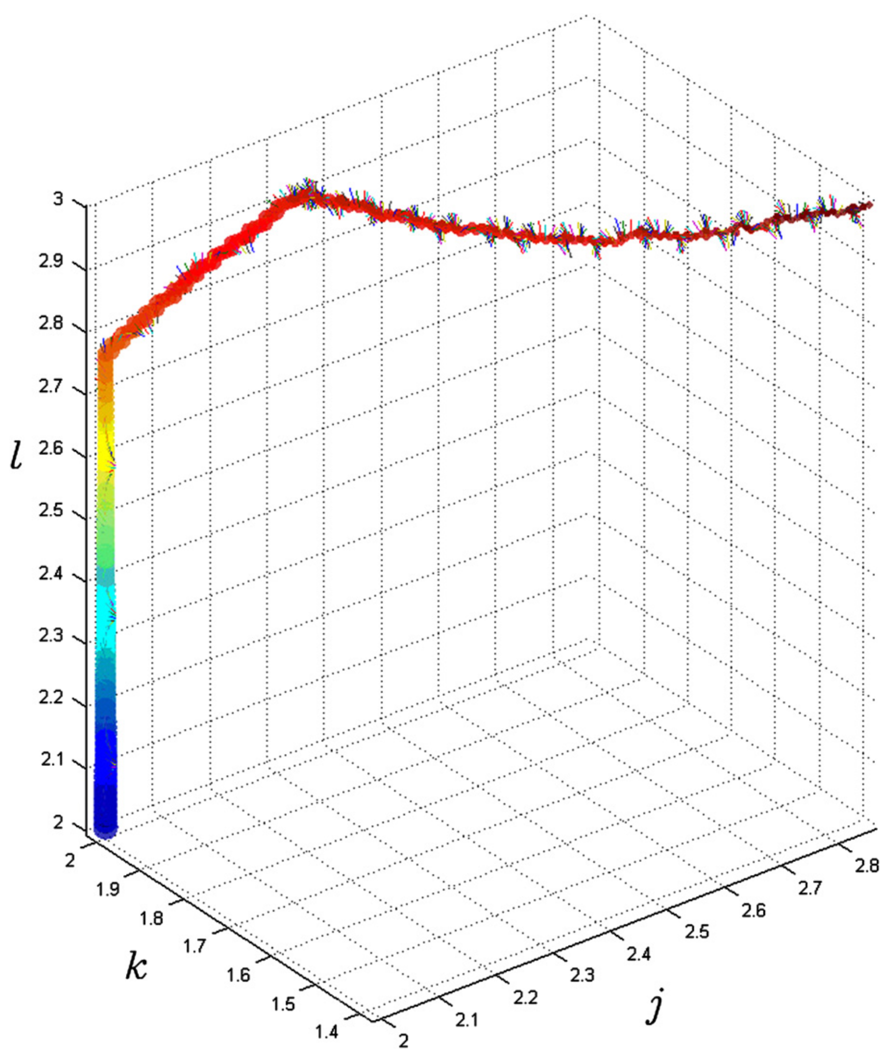

Fig. 2. Schematic diagram of computing process in Example 3.