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Automatic optimization design of Gaussian beam shaping system by using ZEMAX software

Yuhan Gao [a,*], Zhiyong An [a], Jinsong Wang [a], Weixing Zhao [b], Fang Song [a]

[a] School of Optics and Electronics Engineering, Changchun University of Science and Technology, Changchun, Jilin 130022, China
[b] Nanjing Optotek Corporation, Nanjing, Jiangsu 210001, China

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ABSTRACT

This paper studies the method of automatic optimization design of Gaussian beam shaping. Firstly, the principle of Gaussian beam shaping was studied theoretically and the flattened Lorentzian function (FL) is chosen as the distribution of flattened beam. The mapping function of arbitrary ray in incident plane and image plane was deduced based on the law of conservation of energy. And then, according to the characteristics of this system, Zemax programming language (ZPL) was used to compile ZPL macro orders to optimize the Gaussian beam shaping automatically. Finally, optical analyzing software was used to test the aspheric lens system. The method is not only simple but also practical with high efficient energy conversion and significant engineering application value.

1. Introduction

Laser beam shaping is a process of redistributing the irradiance and phase of an optical radiation beam from an input plane to an output plane [1–3]. As the laser beam has the characteristic of Gaussian energy distribution, in the field such as laser processing, laser welding and laser medicine, the non-uniform distribution of energy will induce high local temperature. This will destroy the properties of materials and influence the effect between the laser and materials. Therefore, in order to eliminate the negative effects of non-uniform temperature, Gaussian beam has to be converted to the flattened beam with uniformly distributed energy [1–8]. Beam shaping techniques include aperture shaping, diffractive optical elements shaping, aspheric lenses shaping and so on. Comparing with other techniques, aspheric lens shaping is an effective method with the advantages of high energy utilization and high temperature resistant. So it is more suitable for high-power laser beam shaping. Although the principle of beam shaping is almost perfect, but the traditional method is still a complicated work which needs a lot of calculation. This paper studies the design of Gaussian beam shaping by using optical software Zemax. And Zemax programming language (ZPL) was used to compile macro orders to accomplish the optimization automatically.

* Corresponding author. Tel.: +86 43185583328; fax: +86 43185380236.
E-mail address: gaoyuhan@126.com (Y. Gao).

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2. The principle of beam shaping

Frieden firstly proposed the method of converting the Gaussian beam to the flattened beam by using aspheric lens in the 1960s [1]. Fig. 1 shows the schematic diagram of a Keplerian beam shaping [4,6]. The first and last surfaces are shown as plane. As Fig. 1 shows, r_1 is any ring of radii on incident plane, r_2 is the corresponding radii on exit plane, ω is the waist of Gaussian beam, R is the radius of the flattened beam, the aspheric surface parameters are described by $z(r_1)$ and $z(r_2)$. According to the law of conservation of energy, it can get Eq. (1).

$$2\pi \int_0^{\infty} I_{\text{in}}\left(\frac{r_1}{\omega_0}\right) r_1 \mathrm{d}r_1 = 2\pi \int_0^{\infty} I_{\text{out}}\left(\frac{r_2}{R_0}\right) r_2 \mathrm{d}r_2 \qquad (1)$$

2.1. The intensity distribution

Suppose that the input beam is single-mode Gaussian beam (TEM_00), so the distribution of the input beam can be described as follows:

$$I_{\text{in}}\left(\frac{r_1}{\omega_0}\right) = \frac{2}{\pi\omega_0^2} \exp\left[-2\left(\frac{r_1}{\omega_0}\right)^2\right] \qquad (2)$$

The choice of the distribution of the flattened beam is crucial. Several analytic functions with a uniform central region have been studied [9–14]. Usually, the flattened beam can choose the function such as: super-Gaussian function (SG), flattened Gaussian function (FG), Fermi-Dirac function (FD), super Lorentzian function (SL) and flattened Lorentzian function (FL). The expression of SG, FG, FD, SL and FL distribution are listed in Table 1.

Table 1
The distribution of SG, FG, FD, SL and FL.

Function	Distributions
SG	$\frac{4^{1/p}p}{2\pi R_{SG}^2 \Gamma(2/p)} \exp\left[-2\left(\frac{R}{R_{SG}}\right)^p\right]$
FG	$\frac{2(N+1)}{\pi R_{FG}^2} \sum_{m,n=0}^{N} \left[\frac{m!n!2^{(m+n)}}{(m+n)!}\right] \exp\left[-2(N+1)\left(\frac{R}{R_{FG}}\right)^2\right] \sum_{m,n=0}^{1} \frac{1}{n!m!} \left[(N+1)\left(\frac{R}{R_{FG}}\right)^2\right]^{m+n}$
FD	$\frac{3\beta^2}{\pi R_{FD}^2} \left\{3\beta^2 + 6\mathrm{di}\log\left[1+\exp(-\beta)\right] + \pi^2\right\}^{-1} \left\{1+\exp\left[\beta\left(\frac{R}{R_{FD}}-1\right)\right]\right\}^{-1}$
SL	$\frac{q\sin(2\pi/q)}{(2\pi^2 R_{SL}^2)} \frac{1}{1+(R/R_{SL})^q}$
FL	$\frac{1}{\pi R_{FL}^2} \frac{1}{[1+(R/R_{FL})^q]^{1+(2/q)}}$

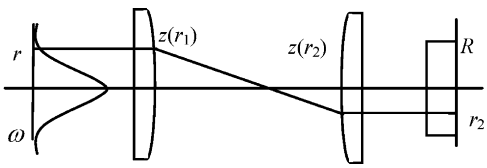

Fig. 1. Schematic diagram of beam shaping.

2.2. The mapping function

The mapping function, which means the relationship between r_1 and r_2, should be deduced firstly. So the choice of the distribution of the flattened beam is of significant. Put the distribution of the output beam into Eq. (1), the flattened Lorentzian function (FL) can solve the analytic functions. So we can use the FL as the output beam distribution. The expression of FL is as follows:

$$\frac{1}{\pi R_{FL}^2} \frac{1}{[1+(r_2/R_{FL})^q]^{1+2/q}} \tag{3}$$

where q is the shape parameter and R_{FL} is the width parameters of the flattened Lorentzian profile. The profile is determined by q. Fig. 2 shows the profiles of FL function according to different q. Fig. 2 indicates that when q becomes larger, the profile of the FL function is more tend to the flattened beam.

Then put the FL function into Eq. (1), it can get:

$$\int_0^{r_2} 2\pi \frac{1}{\pi R_{FL}^2} \frac{1}{[1+(r_2'/R_{FL})^q]^{1+2/q}} r_2' \mathrm{d}r_2'$$
$$= 2\int_0^{r_2} \frac{1}{[1+(r_2'/R_{FL})^q]^{1+2/q}} \frac{r_2'}{R_{FL}} \mathrm{d}\frac{r_2'}{R_{FL}} \tag{4}$$

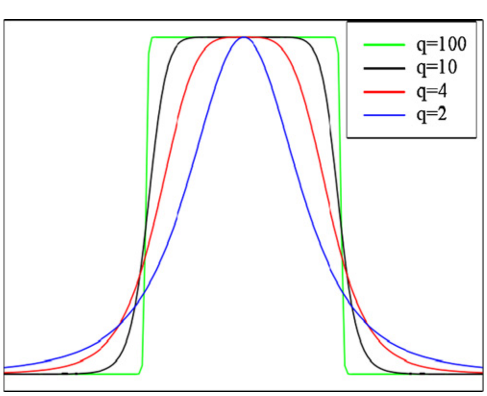

Fig. 2. The profiles of FL function with different q.

If $(r_2'/R_{FL})^q = t$, the function (4) can be expressed as

$$2\lim_{t_0\to 0}\int_{t_0}^{(r_2/R_{FL})^q} \frac{t^{1/q}\cdot 1/qt^{1/q-1}}{(1+t)^{(1+2/q)}}\mathrm{d}t$$

$$= 2\lim_{t_0\to 0}\int_{t_0}^{(r_2/R_{FL})^q} \frac{t^{2/q+1}}{t^2 q(1+t)^{1+2/q}}\mathrm{d}t$$

$$= -\frac{2}{q}\lim_{t_0\to 0}\int_{t_0}^{(r_2/R_{FL})^q} \left(\frac{1}{1+1/t}\right)^{1+2/q} \mathrm{d}\left(1+\frac{1}{t}\right)$$

$$= -\frac{2}{q}\lim_{t_0\to 0}\int_{t_0}^{(r_2/R_{FL})^q} \left(\frac{1}{1+1/t}\right)^{1+2/q} d\left(1+\frac{1}{t}\right)$$

$$= \lim_{t_0\to 0}\left(-\frac{2}{q}\right)\cdot\left(-\frac{q}{2}\right)\left(1+\frac{1}{t}\right)^{-2/q}\Bigg|_{t_0}^{(r_2/R_{FL})^q}$$

$$= \left[1+\left(\frac{R_{FL}}{r_2}\right)^q\right]^{-2/q}$$

Put the distribution of the input beam into Eq. (1), it can get:

$$\int_0^{r_2} 2\pi\frac{2}{\pi\omega_0^2}\exp\left[-2\left(\frac{r_1'}{\omega_0}\right)\right]^2 r_1'\mathrm{d}r_1'$$

$$= -\int_0^{r_1}\exp\left[-2\left(\frac{r_1'}{\omega_0^2}\right)\right]^2 \mathrm{d}\left[-2\left(\frac{r_1'}{\omega_0^2}\right)\right]^2$$

$$= 1-\exp\left[-2\left(\frac{r_1^2}{\omega_0^2}\right)\right]$$

So the mapping function is

$$1-\exp\left[-2\left(\frac{r_1^2}{\omega_0^2}\right)\right] = \left[1+\left(\frac{R_{FL}}{r_2}\right)^q\right]^{-2/q}$$

$$r_2 = \frac{R_{FL}\sqrt{1-\exp[-2(r_1/\omega_0)^2]}}{q\sqrt{1-\{1-\exp[-2(r_1/\omega_0)^2]^{q/2}}} \tag{5}$$

3. The optical design

3.1. The traditional design

Kreuzer proposed a current method in 1969 [15]. The schematic of calculating the aspherical surface parameters is shown in Fig. 3.