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Design and Optimization of a Linear Laser Beam

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In order to improve the uniformity of linear laser distribution and the sharpness of laser beam line width, a laser beam shaping system is designed and optimization. This system contains two kinds of optical element. One is a laser beam expander, which can reduce the divergence of laser beam and adjust the width of laser line. The other is an aspheric column lens, which can change the Gaussian beam distribution into the straight line distribution. The beam expander adopts 2× beam expander with the form of Galilean telescope and the expression of aspheric column lens is solved by the law of energy conservation and refraction rule. The ray tracing and the optimization of the whole system will be performed by the optical design software. The experimental results show that the laser beam shaping system has obtained a 0.32 mm line width spot in 1 m working distance, which increases by three-times the uniformity than the traditional method.

Keywords: Linear laser, beam shaping system, intensity distribution, optical design, optimization

1 INTRODUCTION

The linear laser has widely applications in recent years, such as cutting wood and textiles, line generator in building and diameter measurement of axes etc [1-4]. This kind of laser is usually made up by the semiconductor laser as light source and a cylindrical lens as optical expander to generator a linear

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light spot in certain field of view [5]. However, since the laser beam has a Gaussian like intensity distribution, the linear spot often has the higher brightness in central part and lower brightness in two end parts and the width of line is also asymmetry [6, 7]. In fact, ideal linear laser should be a well-defined line with uniform in both width and intensity in certain distance.

Such line shape laser beam can be obtained by using a beam shaping system with a zoom optical element, but it often adopts a complicated diffractive optical system [8]. Another method is through Powell prism, but the surface of prism is designed only by the tests, there no common theory can guard the design [9]. In this article, we present a simple theoretical method for design and optimization such laser shaping system and perform a comparable experiment to illustrate the effectiveness of this method.

2 SYSTEM DESIGN

Based on the conversation of energy, the common shaping methods to average the laser beam intensity distribution are adopted the diffraction optical elements, binary optical elements, complicated prism or lens system etc, but the design is either difficult or need more optical elements. In the laser shaping system, the parameter β ($\beta = 2\sqrt{2}\pi r_0 y_0 / f\lambda$) determines the shaping methods and the shaping results, where r_0 is input beam waist radius, y_0 is the radius of the desired output dimension, and f is the focal length of the optical system and λ is the wavelength of laser. When $\beta < 4$, it cannot obtain the ideal shaping results. When $4 < \beta < 32$, the diffraction effect need to be considered. When $\beta > 32$, the diffraction effect can be neglected and calculated by the geometric optics [10]. In this article the laser needs to be applied in the measurement of structural light like shafting measuring which requires the laser beam has a very uniform intensity distribution and narrow line width to improve the measurement precision. For simplicity, the design of linear laser is only used the geometric optics; that is, $\beta > 32$.

In most laser application, it is necessary to focus, modify, or shape the laser beam by using lenses and other optical elements. In general, laser beam propagation can be approximated by assuming that the laser beam has an ideal Gaussian intensity distribution, as shown in Figure 1. The laser beam diameter is defined that its intensity maximum value drops off to $1/e^2$ (13.5%). The system design of linear laser is as Figure 2. The focusing system directly places in front of our semiconductor laser and then the certain diameter laser beam will transmit into a cylinder lens to enlarge in only one direction. And then in some distance forms a straight line spot. Since the intensity distribution of TEM_{00} mode is like the Gaussian distribution, which makes the centre of line shape spot bright and the two ends dark. This phenomenon will influence the laser spot quality and linearity, which will limit the application of this kind of laser.

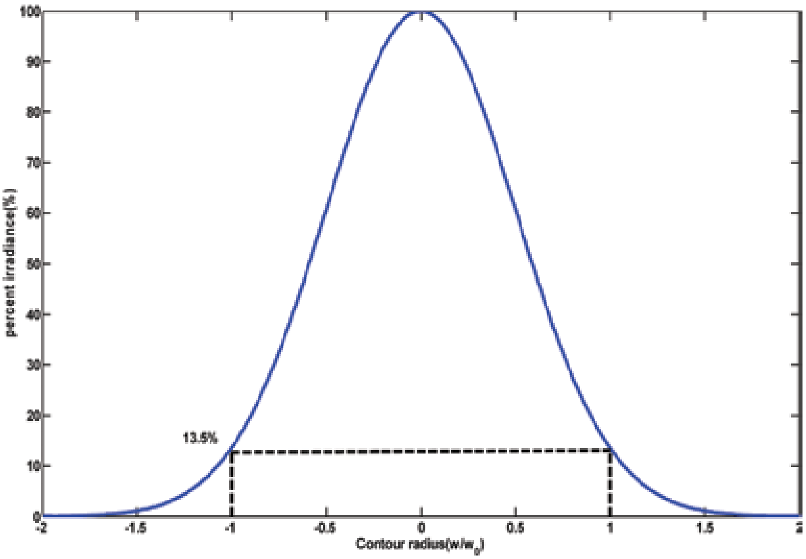

FIGURE 1
Graph of the intensity distribution of a Gaussian TEM_{00} mode.

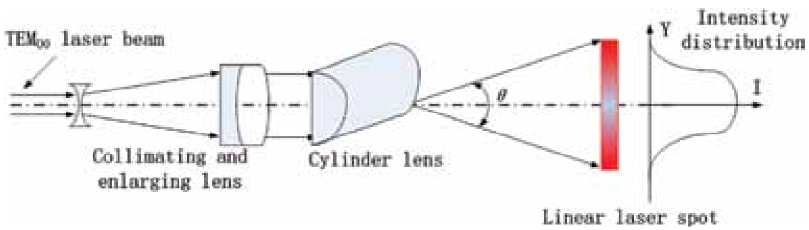

FIGURE 2
Schematic diagram of the system design of linear laser system.

In order to improve the uniformity of linear spot, Powell [9] designs the optical element which bears some resemblance to a prism with a small radius at its apex expands the laser beam in one direction only. The basic line expander of Powell's prism is shown as Figure 3. From the ray tracing software of Zemax, the Powell line expander will make the two ends of line bright and the centre dark. In this article the method based on the aspheric column lens is presented to replace the cylinder lens in the Figure 2. The basic parameters for the system design are listed as Table 1.

The initial incidence of laser beam is expressed as a Gaussian beam in only the y-direction, y, [10]:

$$I_y = \exp(-2y^2 / \omega_0) \tag{1}$$

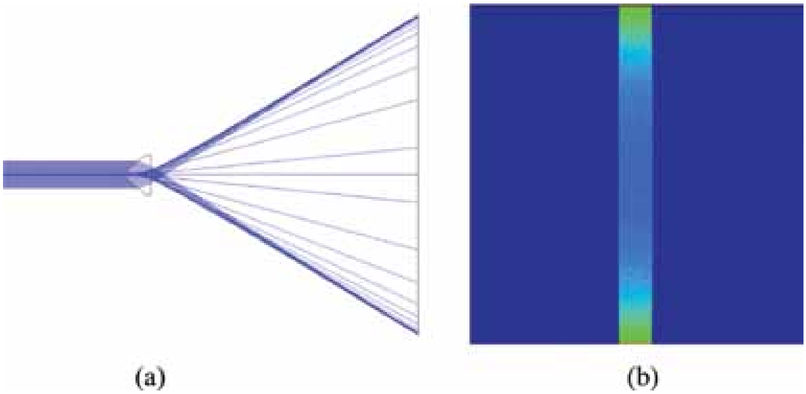

FIGURE 3
The Powell line expander: (a) layout of optical design and (b) line intensity distribution.

TABLE 1
Parameters for the design

No.	Parameter	Unit	Value
1	λ: Wavelength	nm	532
2	n: Refractive index		1.5
3	ω_0: Radius of beam waist	mm	4
4	y_{max}: Radius of column lens	mm	5
5	d: Working distance	mm	1000
6	θ: divergence angle	degree	60
7	I_y: Intensity distribution of line spot	W/cm^2	constant

where I_y is the normalized Gaussian optical intensity distribution (and it will not influence the design of aspheric column lens as shown in Figure 4) and ω_0 is the radius of beam waist. According to the rule of energy conservation, the energy of incident plane y below the y_a is equal to the energy of output plane Y upon the Y_a in the unit width. So now Equation (1) can be written as

$$1\times\int_0^y \exp(-2y^2/\omega_0^2)dy = I_y Y\times 1 \tag{2}$$

and from Equation (2) we have

$$I_y = \int_0^{y_{\max}} \exp(-2y^2/\omega_0^2)dy / Y_{\max} \tag{3}$$

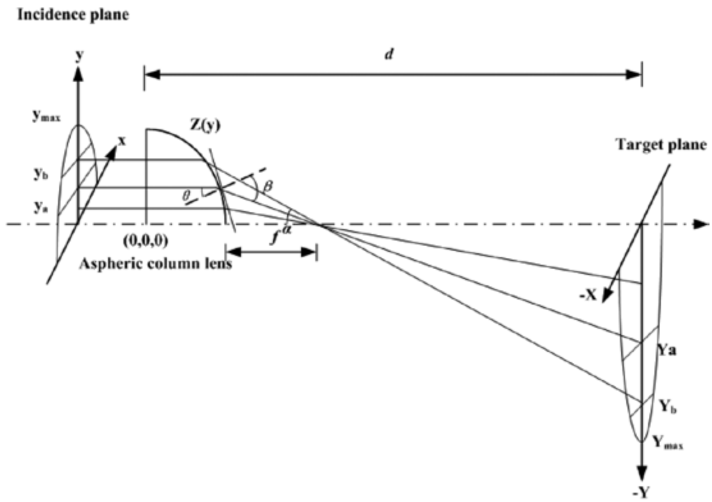

FIGURE 4
The intensity distribution after the aspheric column lens.

where y_{max} is the maximum aperture of column lens with the incident Gaussian laser beam, $Y_{max} = d \times \theta/2$ is the half length of line spot formed by our design system. Because the Gaussian function in Equation (3) cannot be integrated, we choose the Taylor series expansion for this function firstly, and then to integrate it to give

$$\exp(-2y^2/\omega_0) \approx 1 + (-2y^2/2\omega_0) + \frac{(-2y^2/2\omega_0)^2}{2!} + \frac{(-2y^2/2\omega_0)^3}{3!} + \frac{(-2y^2/2\omega_0)^4}{4!} \quad (4)$$

Substituting Equation (4) and the parameters listed in Table 1 into Equation (3), and then using Equation (2), we can obtain the relation of energy partition as

$$Y = 25.5754y - 2.1312\, y^3 + 0.1601y^5 - 0.0095y^7 + 0.00046252y^9 \quad (5)$$

where Z is defined as the vector height of aspheric column lens and θ_0 is the incident angle. The relationship of these two parameters is written as

$$\frac{dZ}{dy} = -\tan\theta_0 \quad (6)$$

The geometric relation between each parameter can be shown as Figure 4, which the collimated incidence Gaussian beam transmits into the aspheric column lens. From the refractive rule we have

$$n \sin \theta_0 = \sin \beta \tag{7}$$

where n is the refractive index and β is the refraction angle. The triangle relation shown in Figure 4 can be written as

$$\tan \alpha = \frac{Y + y}{d - Z} \tag{8}$$

where α = β − θ. From Equations (6) to (8) Z can be written as

$$\frac{dZ}{dy} = -\frac{\sin\left[\arctan\left(\frac{Y+y}{d-Z}\right)\right]}{n - \cos\left[\arctan\left(\frac{Y+y}{d-z}\right)\right]} \tag{9}$$

According to the differential equation given as Equation (9), Z of the aspheric column lens can be derived as (the analytical solution is unavailable)

$$\begin{aligned} Z =& 6.01882 - 1.04718\, y - 0.0255754 y^2 + 0.0010656 y^4 \\ & -0.0000533673\, y^6 + 2.37486 \times 10^{-6}\, y^8 - 9.25032 \times 10^{-8}\, y^{10} \end{aligned} \tag{10}$$

3 EXPERIMENTAL APPARATUS AND PROCEDURES

According Equation (10) the aspheric column lens can be fabricated through the diamond lathe and the experimental configuration is like that shown in Figure 2. A photograph of the experimental arrangement is shown in Figure 5. By using the laser beam analyser (SP503U; Spiricon, Inc.) to measure the intensity distribution of the line laser designed by above theory. The laser beam analyser has been placed on the working distance of 1, 2 and 4 m. For the limitation of its aperture, this device only place in the centre of laser line and the wavelength range covered by this device is between 400 to 1100 nm.

In our experiment the laser source with the battery and the 2× beam expander have been assembled into one adapter sleeve. The beam expander makes the waist of laser source be 4.00 mm and more uniformity. The fabri-

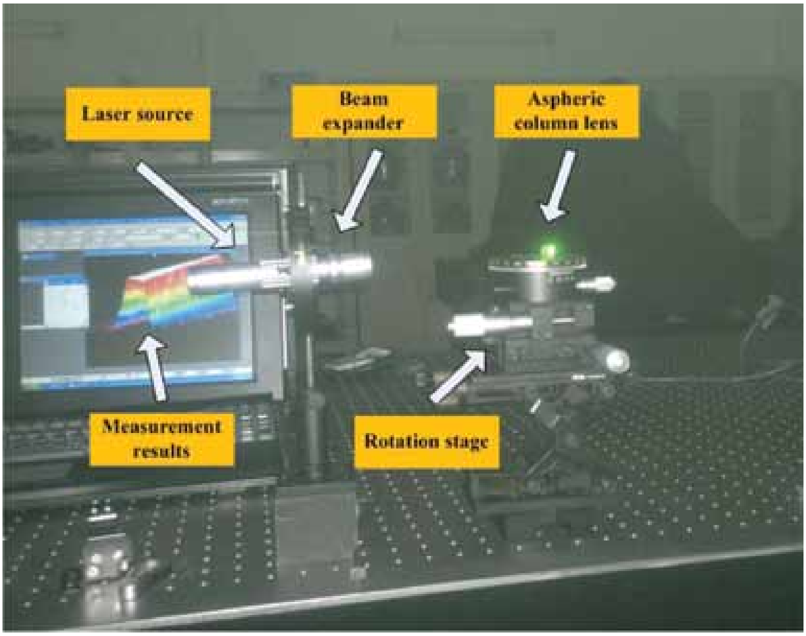

FIGURE 5
Photograph of the experimental set-up.

cated aspheric column lens is placed on the four-axis rotation stage which can be convenient to adjust the position and angle of the lens.

4 RESULTS AND DISCUSSION

The three-dimensional (3-D) optical intensity distribution of line-shape laser is measured by the device in the working distance 1 m. The measurement result is shown as Figure 6(a). The width of laser line is about 0.32 mm, and has a very smooth flat-top optical intensity distribution, which agrees well with the theoretical analysis. Comparing with the traditional linear laser, which often use the cylindrical lens, the intensity distribution of this designed laser is more uniformity almost three-times, as shown in Figure 6(b) in the same experimental setup. The uniformity is defined as the I_{max}-I_{min}/I_{max}. The intensity of line shape spot is almost a constant, which shows that the introducing the appropriate aspheric column lens can make the intensity uniform. In the working distance 1, 2 and 4 m, the measurement optical intensity distributions of line laser are all like those shown in Figure 6, this means the aspheric column lens is a good choice for the laser beam line generator.

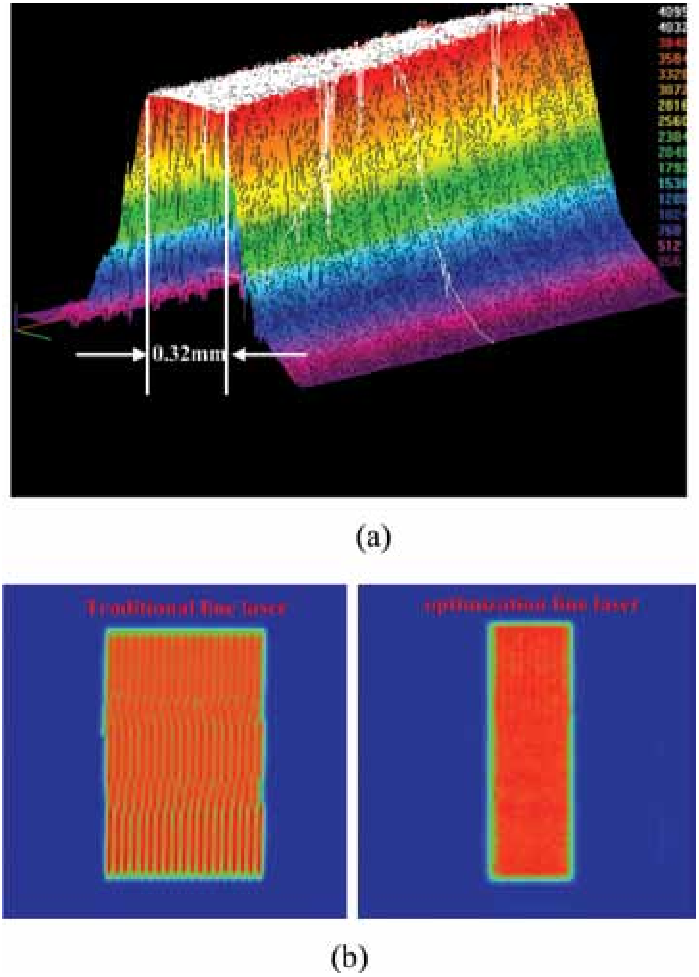

FIGURE 6
Measurement results by the laser beam analyser: (a) 3-D optical intensity distribution of line-shape laser and (b) comparison with a traditional line-shape laser.

5 CONCLUSIONS

In this paper a more uniformity intensity distribution line laser is design and optimized. This shaping optical system is designed by the law of conservation of energy and the refractive law. The theoretical and experimental results agree well and the optical intensity distribution is more uniformity than traditional line laser. The range of working distance is wider and can be used in the collimated and converged incident Gaussian beam. This kind of line laser can be more suitably applied in the fields which need more uniformity and sharpness line laser.

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