

Generation of concentric multi-ring laser beam pattern with different intensity distribution

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A method to shape the incident laser beam into a concentric multi-ring pattern with different intensity distribution is presented based on geometrical transform method and energy conservation. The output two and three rings are designed as examples to verify the validity of the method. The real shaped rings are produced by the spatial light modulation (SLM) and the experimental results show that the shaped laser beam can satisfy the design requirements.

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High-power laser beams have been applied widely in manufacturing, such as laser welding, laser cladding, and material surface processing. However, the original laser beam is meeting challenges in some applications^[1]. In laser heat treatment of aircraft components like gyroscopes, the components need to be strengthened in a ring region and some others require to be welded in a ring pattern. Also in laser thermal simulation such as engine parts, the multi-ring pattern laser beam is demanded. The original laser beam is limited by its physical feature, so the laser beam shaping^[2] must to be considered to get the corresponding rings pattern with different intensity distribution to meet the requirements in such applications.

Many methods to shape laser beam into single- and multi-ring patterns have been sufficiently studied^[3–6], but the multi-ring patterns generally have small size, equal distances, and uniform intensity. Besides, the beam pattern with proportional intensity distribution has also been obtained^[7], but the beam pattern is spots array and not suitable for rings pattern. In this letter, we present a method to realize concentric multi-ring beam patterns of different intensity distribution based on geometrical transform method and energy conservation, and the shaped two and three rings are designed as examples to verify the validity of the method.

Given that the number, location and intensity distributions of the required output rings and the radius of the input plane, the phase of the element can be calculated according to the four parameters. The output single ring, double rings, three rings, etc., can be realized by the phase modulation of the element, as shown in Fig. 1. The phase of the element is designed by the geometrical transform method^[8]. High power laser beams generally have high order transverse modes and can be approximately expressed as flattop beams. It is assumed

that the distribution in each ring at the output plane is uniform, and the intensity ratio of multi rings at the output plane are also given, so according to the conservation of energy, we have

$$\int_0^{r_{in}} I_0 \cdot 2\pi r dr = \sum_{i=1}^M \left(\int_{R_{i0}}^{R_i} I_i \cdot 2\pi \rho d\rho \right), \quad (1)$$

where R_{i0} and R_i are the inner radius and outer radius of the i th ring at the output plane, respectively; I_i is the intensity of the i th ring at the output plane and M is the number of the output rings; r_{in} is the radius of the input plane and I_0 is the intensity of the input plane.

As shown in Fig. 2, the input plane can also be divided into M rings and each ring corresponds to one ring at the output plane. For sake of simplicity, the beam in the i th ring at the input plane will be shaped to the i th ring at the output plane according to the same sequence from the center to the outside.

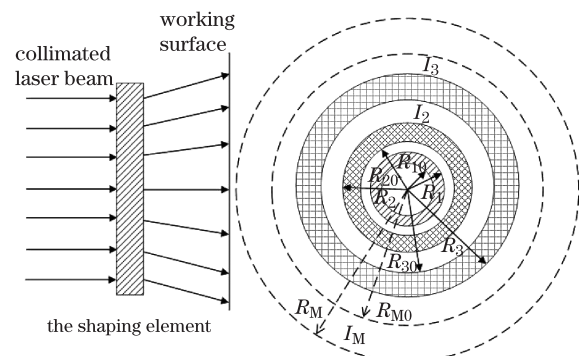


Fig. 1. Schematic diagram of the beam shaping.

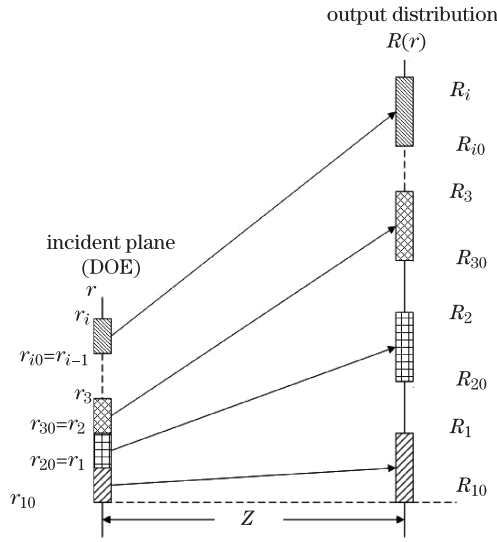


Fig. 2. Relationship of the input and output planes. DOE: diffractive optics element.

Based on the principle of conservation of energy, we have

$$\int_{r_{i0}}^{r_i} I_0 \cdot 2\pi r dr = \int_{R_{i0}}^{R_i} I_i \cdot 2\pi \rho d\rho, \quad (2)$$

where r_i and r_{i0} are the outer and inner radii of the i th region at the input plane, respectively. The spatial relationships $\rho = R(r)$ between the incident beam of each ring at the input plane and the output beam of each ring at the output plane can be solved by

$$\int_{r_{i0}}^r I_0 \cdot 2\pi r dr = \int_{R_{i0}}^{R(r)} I_i \cdot 2\pi \rho d\rho, \quad (3)$$

Thus the phase profile at the input plane can be achieved by

$$\frac{d\phi(r)}{dr} = \frac{2\pi R(r) - r}{\lambda z}, \quad (4)$$

where λ is the wavelength of the laser beam and z is the distance between the input plane and the output plane. $\phi(r)$ is the phase profile at the diffractive optics element (DOE). Substituting $R(r)$ into Eq. (4), and we have

$$\frac{d\phi(r)}{dr} = \frac{2\pi}{\lambda} \sqrt{\frac{r^2 - r_{i0}^2}{r_i^2 - r_{i0}^2} (R_i^2 - R_{i0}^2) + R_{i0}^2 - r}. \quad (5)$$

Therefore the phase profile at the input plane can be obtained by solving Eq. (5). The intensity distribution at the output plane can be available based on scalar diffraction theory,

$$E(\rho) = ikz^{-1} \exp(ikz) \int_0^{\infty} g(r) \exp\left[\frac{ik}{2z}(r^2 + \rho^2)\right] J_0\left(\frac{kr\rho}{z}\right) r dr, \quad (6)$$

where $g(r) = \sum_{m=1}^N \exp(i\phi_m) \text{rect}[(r - (m - 1/2)\Delta r) / \Delta r]$, $k = 2\pi/\lambda$, ρ is the distance from a given spot to the origin at the output plane, and ϕ_m is the phase of the m th ring at the input plane.

Based on the above method, various kinds of multi-ring beam patterns can be available. The output two and three rings will be designed as the illumination. The relative intensity ratio of the output two rings is known quantity of 1:1 and $R_{10}=0.00$ mm, $R_1=5.00$ mm, $R_{20}=9.00$ mm, $R_2=11.00$ mm. The power ratio of each ring at the output plane can be calculated as 0.38:0.62. For an ideal plane wave with 8-mm diameter, the locations of each ring at the input plane can be acquired according to Eq. (2), and $r_{10}=0.00$ mm, $r_1=2.48$ mm, $r_{20}=2.48$ mm, $r_2=4.00$ mm. According to Eq. (5), the phase of the DOE can be obtained. The output intensity distribution calculated by using Eq. (6) is shown in Fig. 3(a).

The relative intensity ratio of the output three rings is known quantity of 2:3:5 and $R_{10}=0.00$ mm, $R_1=3.00$ mm, $R_{20}=6.00$ mm, $R_2=8.00$ mm, $R_{30}=10.0$ mm, $R_3=14.00$ mm. The power ratio of each ring at the output plane can be calculated as 0.03:0.14:0.83. For an ideal plane wave with 8-mm diameter, the locations of each ring at the input plane can be acquired according to Eq. (2), and $r_{10}=0.00$ mm, $r_1=0.70$ mm, $r_{20}=0.70$ mm, $r_2=1.67$ mm, $r_{30}=1.67$ mm, $r_3=4.00$ mm. The output intensity distribution calculated by using Eq. (6) is shown in Fig. 3(b).

The result shows that the location, width, and intensity distribution of the rings can meet the requirements. The total diffraction efficiency which means the amount of light power in the three rings divided by the total light power is more than 90%, and the average intensity error is less than 5%.

The calculated phase data can be taken into the spatial light modulation (SLM) to produce the shaped laser

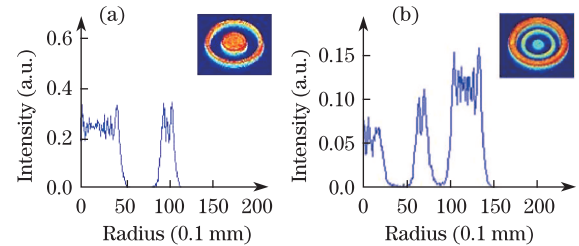


Fig. 3. Output rings. (a) Two rings; (b) three rings.

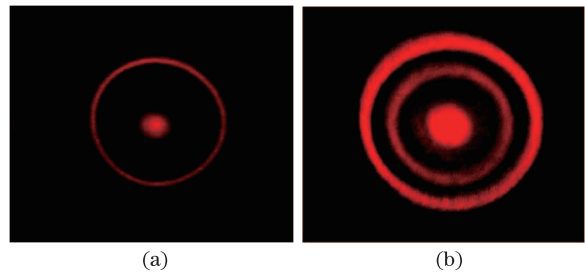


Fig. 4. (Color online) Multi-rings shaping beam distribution. (a) Two rings; (b) three rings.

beam. In the experiment system, a collimated He-Ne laser with a wavelength of 6328 nm is used as the light source. The shaped laser beam with two and three rings pattern can be received on the screen which is shown in Fig. 4. The experimental results have verified the validity of the design method.

In conclusion, Many kinds of multi-ring beam patterns with the known parameters of rings number, location, and intensity distributions can be obtained by means of this method. We present the design methods of two and three rings beam pattern with different intensity distribution. The result shows that the average intensity distribution error is less than 5% and the total diffraction efficiency is more than 90%. This kind of laser beam shaping method provides an effective way to get the rings pattern and should have many potential laser applications.

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