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Complex Structured Light Field Generation Based on the Diffraction Principle of Microporous Arrays

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Abstract: Diffraction of light waves is a phenomenon often seen in daily life and scientific experiments. The diffraction phenomenon is often complex and regular when light waves encounter periodic structures. In this paper, a detailed theoretical and experimental study is carried out on the diffraction and spatial modulation of light waves by microporous arrays. The physical principle of microporous diffraction is analysed mathematically, the diffraction effect of microporous arrays on light wave diffraction is numerically simulated, and the light intensity distribution of far-field structures in the light field under the conditions of different microporous arrays arrangement is obtained through simulation. And the experiments are conducted to verify the numerical simulation, and the experimental results are in good agreement with the simulation results. Finally, the significance and value of the study of microporous array diffraction are summarized and prospected.

1. Introduction

In people's daily life, water waves, sound waves, electromagnetic waves and light waves are easy to notice the diffraction phenomenon. For the diffraction of light waves, there are many examples in life, put your hand in front of a light source, and then slowly close two fingers, while observing the light transmitted from the gap between the fingers. When the fingers are close to each other and almost completely together, you begin to see dark lines parallel to the fingers. These parallel lines are diffraction patterns. This phenomenon also occurs when light "bends" around particles of the same order of magnitude as the wavelength of the light. A good example of this is the diffraction of sunlight by clouds, which we commonly refer to as silver-rimmed clouds. A good example of this is the diffraction of sunlight by clouds, which is often referred to as "silver lines". Alternatively, it is common to see clouds appearing as faint blues, pinks, purples, and greens, which occur when light is diffracted from water droplets in the clouds. Diffraction can even be found on the surface of a CD or DVD disk, which has a series of light tracks evenly and closely spaced on the surface, which act as diffraction gratings. In fact, diffraction of light is the phenomenon whereby light passing through a small hole or obstacle will deviate from its straight path of propagation and travel around and behind the obstacle [1].

In the laboratory, the phenomenon of diffraction is usually studied using a laser as a light source. Geometrical optics shows that light propagates in a homogeneous medium according to the law of straight lines, and light propagates at the interface between two media according to the laws of emission and refraction. However, light is a kind of electromagnetic wave, when a beam of light through the barrier with microporous, according to the principle of physical optics, its intensity can wave to the law of linear propagation is not delineated by the geometric shaded area, but also make the geometric illumination of the area of the emergence of some of the dark spots or dark lines. In short, the diffraction effect makes the distribution of light intensity in the space behind the obstacle is different from the distribution of light intensity given by geometrical optics, but also different from the distribution of light intensity when the light wave propagates freely, and the diffracted light intensity has a kind of redistribution. Diffraction causes all geometric shadow boundaries to lose their sharp edges. The Italian physicist and astronomer F.M. Grimaldi first precisely described the phenomenon of light diffraction in the 17th century, and 150 years later, the French physicist A.-J. Fresnel first elucidated the phenomenon in the 19th century [6]. In experiments, a diffraction system is usually composed of a light source, a diffraction screen, and a receiving screen to better observe the light source. We will carry out experiments to observe the periodic pattern of light intensity after diffraction by micropores, and the diffraction experiments using arrays of micropores will make the arrangement of the structure flexible and adjustable and will be distributed in a two-dimensional way.

2. Theoretical analysis

In life diffraction and interference often appear at the same time, their two in the physical theory of no special, important difference, interference is only a few light waves when the phenomenon, known as interference. Interference also refers to the physical phenomenon of superposition of two or more columns of waves overlapping in space, resulting in the formation of new waveforms, and the interference of light brings the theory of fluctuations of light to a new level. In history, the interference phenomenon and its related experiments are an important basis for proving the volatility of light, but this interference property of light was not gradually discovered until the early nineteenth century, mainly because of the difficulty of obtaining a coherent light source. British physicist Thomas Young in 1801 to do experiments to demonstrate the interference of light demonstration, known as Young's double slit experiment. This experiment gave strong support to the light fluctuation theory because the experiment observed interference fringes is Isaac Newton represented by light particles cannot explain the phenomenon, the Young's double slit experiment led most of the physicists from then on gradually accepted the light fluctuation theory. In fact, Young's double slit interference experiment is from a point light source outgoing wave propagation to a side of the baffle with two slits, the two slits to the point light source at an equal distance, and the distance between the two slits is very small. Because the two beams of light source is the same frequency, the same vibration direction of light, so you can get interference fringes on the observation screen [2].

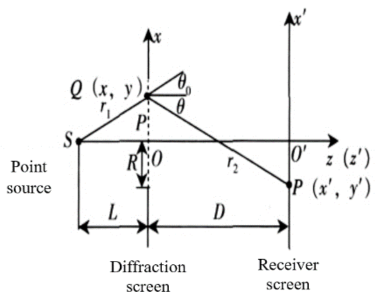

Figure 1: Diffraction schematic

(1) Interference formula:

$$E = E_1 + E_2 + E_3 \dots + E_n \tag{1}$$

In the experiment, the observation screen shows a line of interference fringes, which are composed of bright and dark stripes.

The formula for the light intensity at the centre of one of the bright fringes is:

$$x \pm k = Ik\,\frac{D}{d}x, k = 0,1,2,3 \dots \tag{2}$$

The equation for the light intensity at the centre of the dark pattern is:

$$x \pm k = \pm(2k-1)\frac{D}{2d}\lambda, k = 1,2,3 \dots \tag{3}$$

(2) Fresnel diffraction as well as Fraunhofer diffraction:

Diffraction phenomena are divided into two categories, one is Fresnel diffraction, and the other is Fraunhofer (J. Fraunhofer, 1787- 1826) diffraction (as shown in Fig. 1). The Fresnel diffraction condition is that the distance from the light source to the diffraction screen or the distance from the receiving screen to the diffraction screen is finite, or both are finite. The incident light or the diffracted light is non-parallel light, or neither of them is parallel light in Fresnel diffraction. The so-called Fraunhofer diffraction condition is that the distance said above are both infinite. And to know the light intensity distribution at any point on the viewing screen, use the Fresnel-Kirchhoff formula. From the above figure Q (x, y) is seen to be an arbitrary point on the circular aperture [3]. According to the Fresnel-Kirchhoff formula, the complex amplitude of the light wave vibration at a point P (x′, y′) on the diffraction screen. Kirchhoff diffraction formula:

$$\overline{U}(P) = \frac{-i}{2\lambda}\iint_{\Sigma_0}(cos\theta_0 + cos\theta)\overline{U_0}(Q)\frac{e^{i\frac{2\Pi}{\lambda}r_2}}{r_2}d\Sigma; \tag{4}$$

When parallel light is incident, it still belongs to near-field diffraction, i.e., Fresnel diffraction, considering the distribution of light intensity on the finite-range diffraction screen, when:

$$\cos\theta_0 = 1, L = \sqrt{A} = \infty, \frac{ae^{i\frac{2\pi}{\lambda}\sqrt{A}}}{\sqrt{A}} \rightarrow \overline{U}(x,y) \tag{5}$$

For positive parallel light incidence, the $\overline{U}_1$(x, y)could be written as the form of $\overline{U}_1$(x, y)=$\overline{U}_0$(x, y) t(x, y), $\overline{U}_0$(x, y)is the complex amplitude of the incident wave, which can be regarded as a constant A, t(x, y)is the complex transmittance number, which can be written for circular Confronts and Fay diffractions:

$$\overline{U}\ (x'\,.\ y') = \frac{-iA}{\lambda D}\iint_{\Sigma 0} t(x,y)e^{i\frac{2\Pi}{\lambda}r_2}d\sum = \mathrm{C}\iint_{\Sigma 0}\mathrm{t(x,y)}\,e^{i\frac{2\Pi}{\lambda}r_2}d\sum. \tag{6}$$

Among them,

$$t(x,y) = \{\begin{matrix} 1, & \sqrt{x^2+y^2} \leqslant R \\ 0, & \sqrt{x^2+y^2} > R \end{matrix}, \quad C = \frac{-iA}{\lambda D}. \tag{7}$$

Diffraction angle of two-dimensional fronts and fees θ_1, θ_2 Corresponding far−field r_2 can be written as: $r_2 = r_0 - x\sin\theta_1 - y\sin\theta_2$, then the angle of diffraction (math.) θ_1, θ_2 is corresponding complex amplitude is:

$$U(\theta_1,\theta_2) = Ce^{i\frac{2\pi - n_n}{\lambda}}\int_{\Sigma} t(x,y)\mathrm{ex\,p}[-i\frac{2\pi}{\lambda}(x\sin\theta_1 - y\sin\theta_2)]dxdy, \tag{8}$$

or

$$U(f_x, f_y) = Ge^{i\frac{2\pi}{A}t_0} \int_{\sum_e} \int t(x, y) exp[-i2\pi(f_x x - f_y y)]dxdy \quad (9)$$

Among them, $f_x = x'/\lambda z = \sin\theta_1/\lambda, f_y = {}_y'/\lambda z = \sin\theta_2/\lambda$. The above two formulas are the standard forms of Fraunhofer and Fee diffraction, which can be written as the Fourier transform of the complex transmittance *t(x, y)*, with the spectral space corresponding to the focal plane of the receiving screen or lens at infinity. The above two correspondences closely integrate mathematical theory with physics, thus creating modern information optics [3].

3. Simulation analysis

The experiment of microporous diffraction was achieved by setting the parameters and thus the MATLAB program, importing the above equations into MATLAB for calculation and visualizing the results. The wavelength is set to 1.064e-6 and the wave number is 2π/λ, the d_1 is the distance from the lens to the viewing screen, while d_2 is the propagation distance after focusing. Subsequently, two right-angle coordinate systems are generated as the dimensions of the diffraction and observation screens, respectively. Simulated substitution calculations are performed for different numbers of holes to obtain a partial diffraction theory pattern. The number of the micropore on the diffraction screen can be changed by changing the Edge, which is the number of sides of the polygon. First, by observing the light intensity distribution of single and double holes in Fig. 2, it can be useful to verify the experimental data and formulas to see if there are any wrong steps. The first figure is the light intensity diffracted by a single micro-hole, you can see that there is only one beam of light and the light intensity is very strong; the second figure is a double-hole diagram, also known as the double-slit diagram, from which you can see that the diffracted light intensity on the observing screen presents a bright and dark vertical stripe distribution, which is the classical double-slit interference phenomenon of the distribution of light intensity, bright and dark stripes are also referred to as interference fringes.

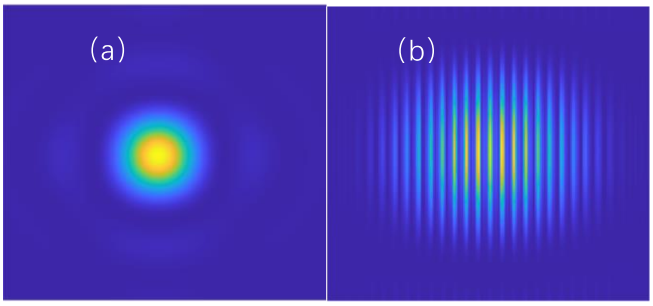

Figure 2: (a) Light intensity distribution of the viewing screen after focusing on the case of a single aperture. (b) Distribution of light intensity on the viewing screen after focusing on the case of two holes.

Next, we can derive the polygonal porous diffraction structure by modifying the data. For example, Fig. 3 shows 3, 5 and 7 holes in order from left to right. After careful observation, it is concluded that the distribution of light points in the 7-hole plot of Fig. 3 (c) shows a heptagonal pattern, while Fig. 3 (b) has a pentagonal shape, and so on, which proves that the light intensity distribution of microporous diffraction is regular. In addition, after observing the 2 holes in (b) of the above figure and comparing it with the 3 holes in this figure, it is found that there is no obvious circular symmetry in their light intensity distributions, whereas when the number of micro holes is increased to 5, the light intensity distributions appear obviously circular and symmetrically, and the same point can be observed in the 7-hole figure in (c) as well. In addition, from (b), it can be clearly observed that the centremost point is surrounded by 10 light dots, which grows exponentially compared to 5 micro holes, and the number of peripheral circular patterns is also 10, and it is not difficult to see that the number of peripheral very small light dots is 14, which is also a multiple of the number of micro holes, when viewed closely in the (c) 7-hole plot.

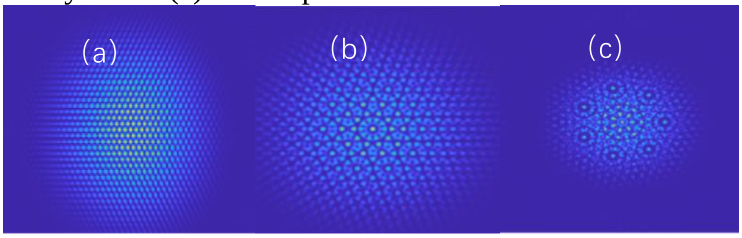

Figure 3: (a) Far-field optical field distribution after 3-hole diffraction array. (b), Far-field optical field distribution after 5-hole diffraction array. (c) Distribution of far-field light field after 7-hole diffraction array.

By modifying the Edge will be adjusted to the number of holes tends to be infinite, will form a single ring, for example, Figure 4, from the figure can be seen in a single ring of light intensity is from strong to weak, the inner ring of the light intensity of the strongest, and there are dark and light streaks interspersed with the characteristics of the phenomenon we usually call Bessel Beam, the specific performance is the centre of a point of light intensity is very strong, around the intensity of the light into the water wave-like. This kind of beam has strong relay value and can keep the light intensity basically unchanged in the process of propagation.

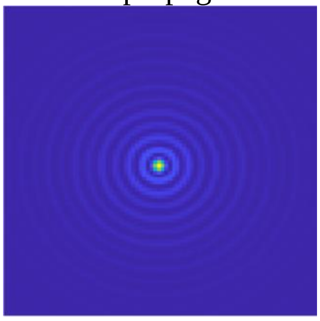

Figure 4: Distribution of far-field light field after diffraction of a light wave by a single circle

Figure 5 shows a two-loop diagram that set r_2 as $10e-4$, At the same time, change Edge2 to 100 to get a double-ring diagram with two rings inside and outside. The light intensity distribution of the double-ring diagram is slightly different from that of the single-ring, the single-ring diagram is the diffraction phenomenon of light, while the double-ring diagram is the interference phenomenon. And the double-ring diagram has an obvious intensity change, which can be seen in Fig. The light intensity of the outer ring has an obvious intensity change. Fig. 5 (b) Diagram of $d_2 = 0.53$, the propagation distance of a point light source after focusing it by a lens —— d_2 modification from 0.33 to 0.53 results in Fig. 5 (b), where it can be found that the obtained pattern is basically the same as the previous single-ring light intensity distribution, and there is no excessive difference. Therefore, it can be obtained that the Bessel beam obtained by forming a ring with a larger number of micro holes has a structure with strong transmission properties, which can keep the intensity of light basically unchanged during the transmission process [4]

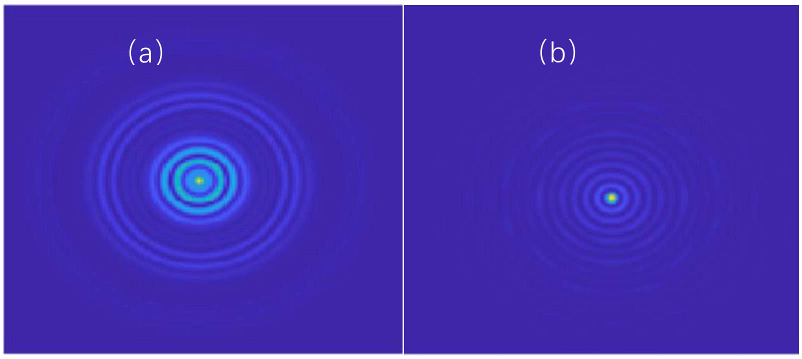

Figure 5: (a) Far-field distribution of the optical wave through double-ring diffraction array. (b) Far-field distribution of the optical wave through double-ring diffraction array at d2=0.53

The light intensity distribution of points diffracted by varying numbers of micropores exhibits a more distinctive shape. By modifying the r_2 (inner ring radius value) parameter, these points can be arranged around another circle composed of multiple micro-apertures. For example, as shown in Figure 6, within the six micro-apertures on the inner side of the circle, the light intensity diffuses gradually from the inside to the outside of the circle, decreasing from strong to weak. Compared to the ordinary single-ring distribution, an additional pattern of bright dots is observed. These dots correlate with the multiplicative relationship between the number of apertures.

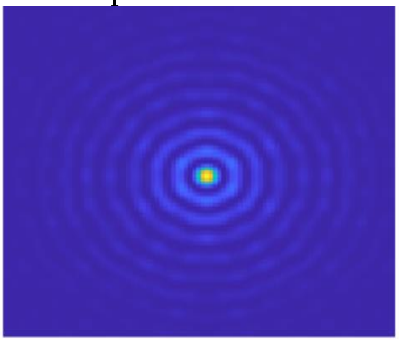

Figure 6: Far-field optical field distribution of light waves after passing through the inner ring 6-hole diffraction array.

The figure below shows the 7-hole diffractograms with the radii of the micropores reduced from $14.14e-5$ to $100e-5$,This figure shows that compared to other normal images, the holes become larger, more light is transmitted, and the diffraction effect changes from a regular multi-point structure to six major points of light, accompanied by a regular dark pattern and a hexagonal pattern. After experiments and summarization, it is concluded that: if the radius of the small hole increases, the small hole diffraction effect will be weakened. When the size of the hole is much larger than the wavelength, the effect of the diffraction will be almost unobservable. When the radius of the aperture increases, the light will undergo less bending and diffusion after passing through the aperture. The extent of the diffraction phenomenon depends on the limitation of the light wave as it passes through the aperture. If the aperture is large enough, the light wave can be seen to travel almost in a straight line without any noticeable diffusion effect.[5]

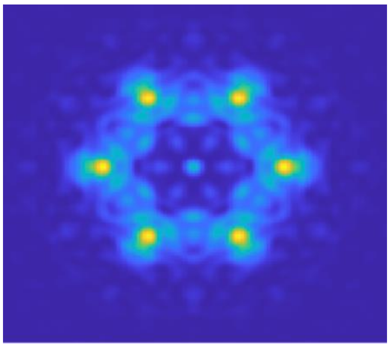

Figure 7: Distribution of far-field light field after light wave passing through a 6-hole diffraction array of radius 100e-5

After observing these symmetrical and regular diffractograms, an asymmetrical 3-hole diffractogram was made on reflection, as shown in Fig. 7. The diffracted points of light are tilted, and after comparing with the original standard symmetrical 3-hole diagram, it is found that the diffractogram of the asymmetrical structure is not well diffracted in part of the area, and there are many more or fewer dark lines. Theoretically, an asymmetric aperture array implies that the positions between the apertures are offset or misaligned. An asymmetric aperture array results in additional interference effects in the diffraction pattern and deviation from the expected diffraction pattern. The actual test results differ from the theory due to the fact that the theoretical data is more accurate, and the shape of the asymmetric structure is more reasonable.

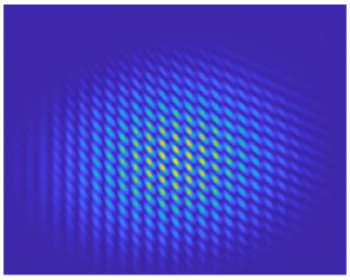

Figure 8: Far-field distribution of the optical wave after passing through 3-hole asymmetric diffraction array.

4. Experimental analysis

In the laboratory, we use a HeNe laser as a point light source, as in Figure 9, the laser is shot from the laser, through the beam expander mirror, to obtain an approximate plane wave, through the two mirrors, the light will be reflected to the intended light path, and then through the thin steel plate, through the laser processing to obtain the micro-aperture, A4 paper, as a temporary diffraction screen, you can clearly see the distribution of the micro-aperture, and then withdrawn. The laser will hit the focusing lens to obtain the far field distribution near the focal plane, and finally the CCD will be placed on the focal plane and used to record the light intensity distribution. In Fig. 9, 3 micro holes of the same size and equal spacing are poked on the diffraction screen, and then the paper sheet is fixed by the experimental equipment to obtain the porous diffraction screen required in the experiment. After performing 3 sets of experiments, Fig. 6, Fig. 8, and Fig. 9 were obtained, showing the results of double and 3 holes for experiment and simulation, and 6 holes for experiment, respectively. From Fig. 6, the experimental and simulated results are very similar in that both are characterized by double-slit interference fringes, light and dark. The experimental results in Fig. 7 account for dust, but through the help of auxiliary lines, it is not difficult to see the general outline of a triangle, which is also basically the same as the 3-hole diagram in the simulation part.8 is the experimental 6-hole diagram, and it can be seen that the number of light spots within the auxiliary lines is 12, which is twice as many as 6, and forms a hexagon, which is in line with the law summarized in the simulation experiment. After the experiment, it is concluded that the simulation and theory are valid and have physical significance, and the results are valid and reliable [7].

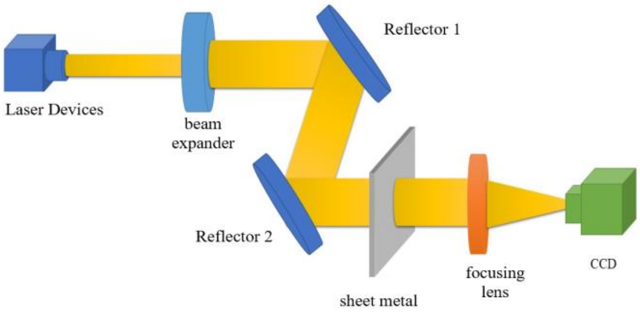

Figure 9: Schematic diagram of diffraction experiment

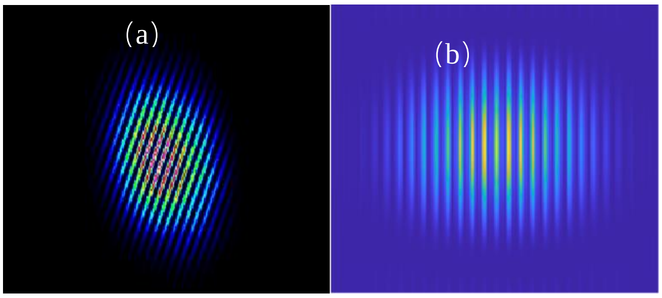

Figure 10: (a) Experimental plot of the optical wave passing through 2-hole diffraction array. (b) Simulation of the optical wave passing through 2-hole diffraction array

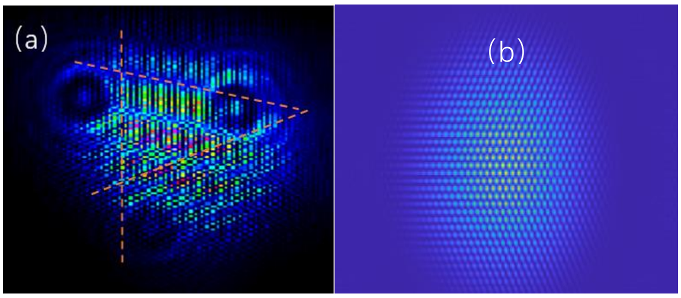

Figure 11: (a) Experimental plot of the optical wave passing through 3-hole diffraction array. (b) Simulation of the optical wave passing through 3-hole diffraction array

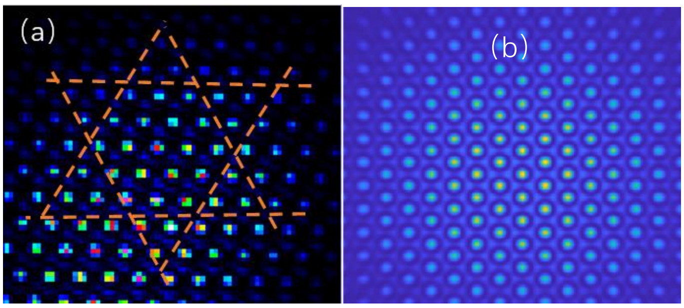

Figure 12: (a) Experimental plot of the optical wave passing through 6-hole diffraction array. (b) Simulation of the optical wave passing through 6-hole diffraction array

5. Conclusion

In this paper, the periodicity of diffraction from microvia is confirmed by the theory of light diffraction and interference, and the equations of Fresnel diffraction and Fraunhofer diffraction of light waves passing through the small vias are analysed, and the simulation program is used to carry out the simulation calculations, and the diffraction intensity distributions of the 3-vias, 7-vias, 6-vias of the inner ring and the double ring are obtained in the simulation. At the same time, experimental studies were carried out to realize the diffraction experimental studies of the HeNe laser source for the diffraction screen with 2 holes, 3 holes and 6 holes (as shown in Fig.10, Fig. 11 and Fig. 12). The experimental results are contrast to the corresponding simulation results with good agreement, which illustrates the validity of the experiments and arguments and the effectiveness of the numerical algorithm. This experiment demonstrates the characteristics of the double ring, future experiments can be increased to 3-ring, 4-ring and so on, through the experiments carried out in this speculation, 3-ring, and more diffracted light field patterns specifically with the double ring is not much different. Microporous diffraction, as demonstrated in the literature, has a periodic nature, which is useful in many fields of science, such as particle manipulation, which requires a very complex light field with a periodic structure, so that the atoms can be arranged through a specific light field; if there is a means of arranging the light field in a special way, the atoms can be brought to the desired position through reasonable means and laws, so that the purpose of control can be achieved.

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