Analysis of Cr atom focusing deposition properties in the double half Gaussian standing wave field*

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The use of the dipole force on atoms is a new technology that is used to build nanostructures. In this way, a high quality standard nano-grating can be obtained. Based on the semi-classical model, the motion equation is investigated and the trajectories of atoms in double half Gaussian standing wave field are simulated. Compared with the Gaussian standing wave field, the double half Gaussian standing wave can well focus the Cr atoms. In order to obtain this kind of beam, a prism is designed and the experimental result shows that the beam is well generated.

Keywords: double half Gaussian beam, atom lithography, motion trajectory

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1. Introduction

In the modern electronics industry, nano-fabrication has become a key technology. The focusing of neutral atoms by use of laser fields is a new way to obtain the nanostructures.[1,2] The dipole force of neutral atoms in the optical fields can be used to control the movement of atoms. When the atoms pass through the laser standing wave, the density distribution of the atom molasses will be changed because of the effects of dipole force. The atoms will be focused onto the node or the antinode of the standing-wave. Standing-wave light field repeats with a period of order $\lambda/2$, where λ is the wavelength. And, finally, the atoms will be deposited onto the substrate, forming a periodic nano grating. Because of the formation of the grating period can be directly traced back to laser wavelength, the nano grating can be used as a nano length standard.[3] In 1992, Timp *et al.*[4] first used a laser to focus Na atoms, and obtained a nano structure with a period of 294.5 nm. In 1993, McClelland *et al.*[5] used chromium to fabricate a nano structure (212 nm). Nano structures with aluminum and ytterbium have also be reported.[6,7] Our group has also fabricated a standard nano structure by use of the atom lithography.[8,9]

Recently, the atom focusing characteristics of the non-traditional Gaussian optical fields also have been analyzed.[10] In former research, Arun *et al.*[11] have investigated the atom-lithography with multi-layer light masks. They used multi-layer light mask to focus the atoms. When the laser beams are used to focus atoms, they must have the same phase. However, in fact, several laser beams with the same phase are impossible to achieve in experiment. In this paper, the focusing properties of chromium atoms in the double half Gaussian beam (DHGB) standing wave field is studied based on the semi-classical model. DHGB is a new kind of laser beam that has a special shape, such as the separating of the traditional Gaussian beam into two parts so that the two parts of DHGB have the same phase. Meanwhile, with different parameters of DHGB, we discuss the different focus properties in different cases. We also discuss the effects on the deposition result of atoms by the atomic beam divergence angle.

2. DHGB

The light intensity of DHGB can be expressed by

$$I_0(z) = \begin{cases} I_1 \exp\left[-\dfrac{z^2}{\omega_0^2}\right], & (z < z_0), \\ 0, & (z_0 < z < z_0 + d), \\ I_2 \exp\left[-\dfrac{(z-d)^2}{\omega_0^2}\right], & (z > z_0), \end{cases} \quad (1)$$

where I_1 and I_2 are the maximal light intensities of the double light, ω_0 is the beam waist, and d is the width of the part where the light intensity is equal to zero.

Figure 1 shows the intensity distribution of DHGB needed. This kind of beam can be easily obtained by geometrical optics. So, a prism is designed to separate the Gaussian beam into two parts to realize the DHGB. We can let the prism have a higher percentage of transmittance by coating on the front and back surfaces.

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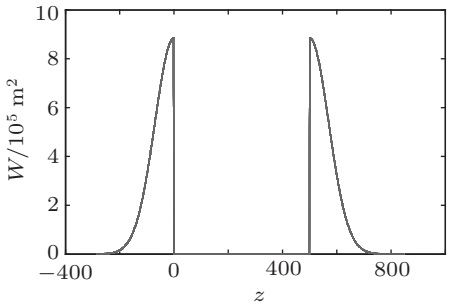


Fig. 1. Intensity distribution of the DHGB.

Figure 2 shows the simulated optic path and output of the prism by use of ZEMAX. From Fig. 2, it is clearly seen that when the traditional Gaussian beam passes through the prism, DHGB can be easily generated. We use CCD to obtain the shape of the output beam.

Figure 3 shows the obtained beam. The CCD image indicates that from the designed optical system, an ideal DHGB can be received. From Fig. 3 the effect of Fresnel diffraction at a straight edge can be clearly seen. In order to reduce the effect of diffraction, a lens is used.

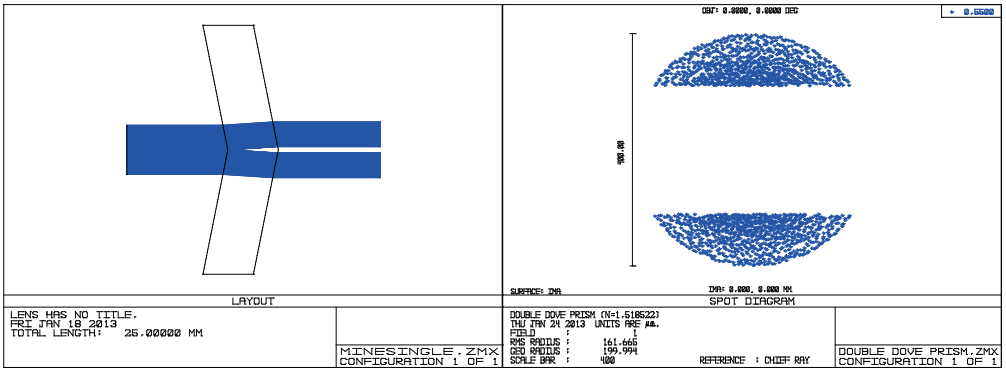


Fig. 2. (color online) Results of simulation with ZEMAX, showing the beam path (left) and output beam (right).

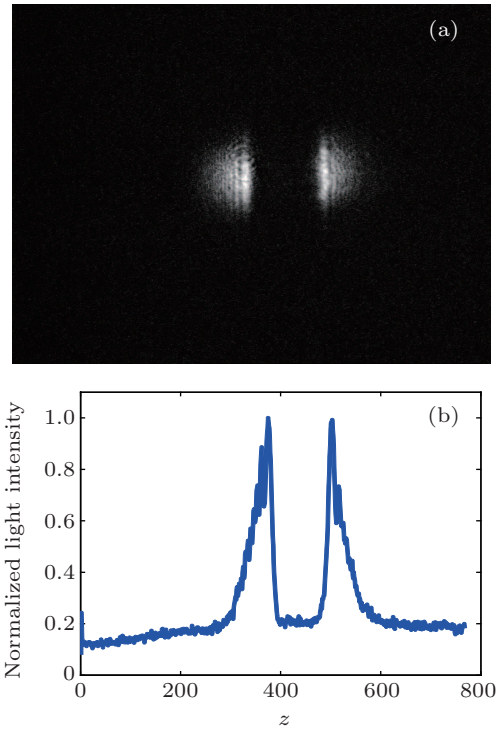


Fig. 3. (color online) DHGB obtained. Panel (a) shows the origin CCD picture and panel (b) displays the intensity distribution along the z axis.

Figure 4 is captured near the focal plane (1 cm after the focal plane) when a double half Gaussian beam passes through a lens. In the picture, the effect of diffraction almost disappears. Before we use a standing wave field to focus the atoms, a lens can be used to eliminate the diffraction. So, the DHGB generated can be used in the subsequent experiment.

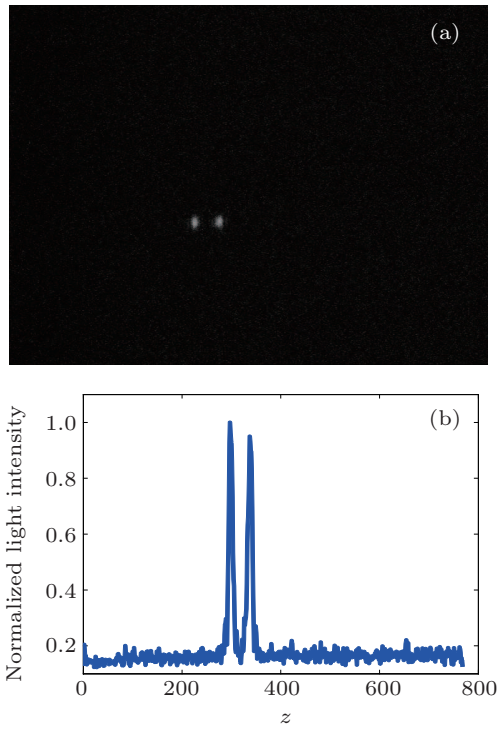


Fig. 4. (color online) DHGB passing through a lens. Panel (a) shows the origin CCD image, and panel (b) displays the intensity distribution along the axis.

3. Theory model

The standing wave field of DHGB can be written as

$$I(x,z) = I_0(z)\sin^2(kx), \tag{2}$$

where k is the wave number.

In semi-classical theory, when the atoms pass through the standing wave field, the effect of spontaneous radiation can normally be neglected and the system reaches a relatively stable state. While the dipole force of atoms is related to the potential of the optical field, in this field the potential can be written as[12]

$$U(x,z) = \frac{\hbar\Delta}{2}\ln\left[1+\frac{I(x,z)/I_s}{1+(2\Delta/\Gamma)^2}\right], \tag{3}$$

where Γ is the natural line width, I_s the saturation light intensity associated with the atom transition, Δ the detuning of the laser frequency from the atomic resonance, and $I(x,z)$ the laser intensity. In the standing wave field, we only consider the effects of the dipole force. So, in the whole process, the total energy of the atoms are conserved. The kinetic energy can be expressed as the total energy minus the potential energy. So, by the Lagrange function in the conservative system, the final movement equations can be easily achieved as

$$\frac{\mathrm{d}^2x}{\mathrm{d}z^2} = \frac{1+(\mathrm{d}x/\mathrm{d}z)^2}{2(E_0-U)}\left(\frac{\mathrm{d}x}{\mathrm{d}z}\frac{\partial U}{\partial z}-\frac{\partial U}{\partial x}\right). \tag{4}$$

In the end, we solve Eq. (4) by Rung–Kutta method, then the trajectory of atoms in the optical field can be obtained. The effects of density modulation of atoms can also be obtained by laser standing wave field.

4. Simulation results

4.1. Without divergence angle

In this paper, chromium atoms are taken as working particles. The corresponding energy level $^7S_3 \rightarrow {}^7P_4^0$, $\lambda = 425.55$ nm, $\Gamma = 2\pi\times 5$ MHz, $I_s = 85$ W/m^2, $\Delta = 2\pi\times 250$ MHz, $\omega_0 = 60$ μm, $P = 2.9$ mW. With the above parameters, the trajectory of atoms in the optical field can be calculated. Firstly, we assume that all atoms are incident in the direction parallel to the z axis; that is, the atoms have only longitudinal velocity and no other transverse components (i.e., $v_z = 957$ m/s). Figures 5(a) and 5(b) show the trajectories of atoms in Gaussian beam standing wave and DHGB standing wave respectively. Now, the parameters of the DHGB are taken to be $d = 600\lambda$ and $I_2 = 8I_1$. The reason why we make $I_2 = 8I_1$ will be explained later.

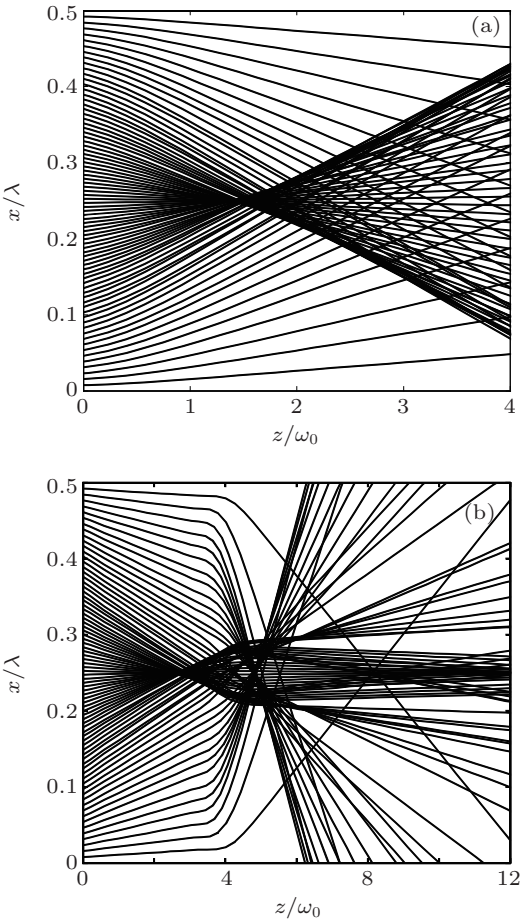


Fig. 5. Trajectories of atoms without divergence angle. Panel (a) shows the trajectory passing through Gaussian beam standing wave, and panel (b) exhibits the trajectory passing through DHGB standing wave.

Figure 5 shows the trajectories of atoms in the standing wave fields. It is clear that, when DHGB is used to focus the atoms, movement loci of atoms change greatly. In order to study the effect of DHGB, the atom density distribution is used.

From Figs. 6 and 7, it is clear that when the atoms pass through the Gaussian beam standing wave field, the good result of the density modulation of atoms by laser is only near the focal plane. At the position $z = 0$, a good deposition result can be obtained, but at $z = 2.136\omega_0$, the effect of density modulation is almost equal to zero. When the atoms pass through the DHGB standing wave, good effect of density modulation can be obtained not only at $z = 0$ but also at a long distance near the focal plane. When $-5.34\omega_0 < z < -2.848\omega_0$, although the effect weakens with the increase of distance, the effect begins to turn better again. When $z > 1.78\omega_0$ the result of atom flux becomes excellent and its full width at half maximum (FWHM) can be kept within about 0.9 nm.

By contrast, it is clearly seen that when the atomic beam is focused by DHGB, the clear nano grating can be deposited in a long range. This DHGB can be used to raise the depth of field.

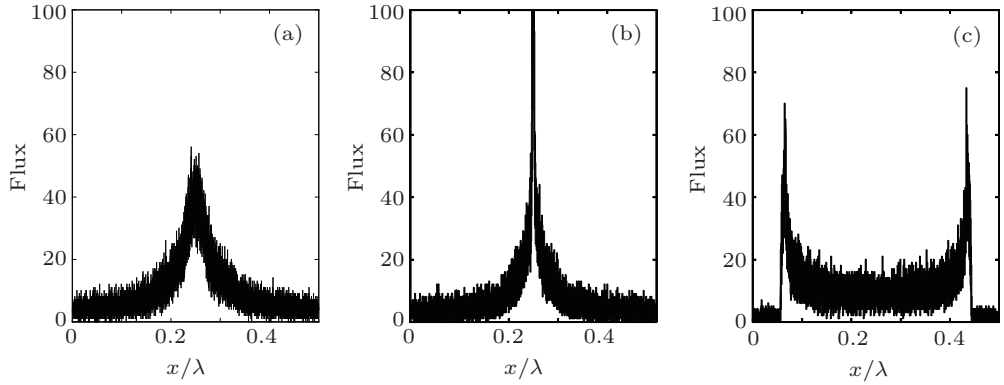


Fig. 6. Fluxes of atomic beam without divergence, passing through Gaussian beam standing wave at different positions (along the atomic motion direction, $z = 0$ is the position where the standing wave ends up): (a) $z = -0.72\omega_0$, (b) $z = -0.356\omega_0$, and (c) $z = 2.136\omega_0$.

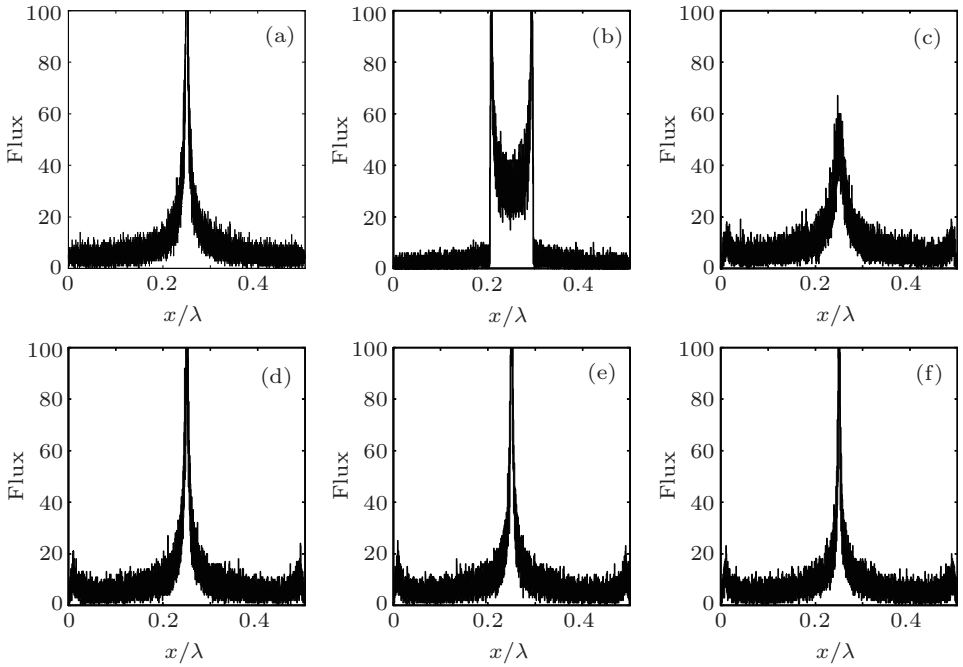


Fig. 7. Fluxes of atomic beam without divergence, passing through DHGB standing wave at different positions (along the atomic motion direction, and $z = 0$ is the position where the standing wave ends up): (a) $z = -5.34\omega_0$, (b) $z = -2.848\omega_0$, (c) $z = 1.78\omega_0$, (d) $z = 3.2\omega_0$, (e) $z = 4.272\omega_0$, and (f) $z = 6.052\omega_0$.

4.2. With divergence angle

In the paraxial approximation, all the atoms can be assumed to be incident in the direction parallel to the z axis, but this assumption cannot hold true in experiment. After the atoms are cooled by laser, a small divergence angle must exist finally. Because of the existence of this angle, the result of the deposition will be changed greatly. So, in order to obtain the exact solution, the divergence angle must be taken into consideration.[13]

Frist, the longitudinal velocity of atoms obeys the Maxwell–Boltzmann statistics,

$$\rho_0(v_z) = \frac{1}{2}\left(\frac{M_\mathrm{a}}{2\pi k_\mathrm{B} T_0}\right)^2 v^3 \exp\left(-v^2/2v_0^2\right),$$

where $v_x = \alpha v$, M_a is the atom mass, k_B the Boltzmann constant, T_0 the oven temperature, the transverse velocity obeys the Gaussian spread function

$$\rho_\mathrm{c}(v_x) = \sqrt{\frac{M_\mathrm{a}}{2\pi k_\mathrm{B} T_\mathrm{c}}} \exp\left(-\frac{M_\mathrm{a} v_x^2}{2k_\mathrm{B} T_\mathrm{c}}\right),$$

where T_c is the transverse temperature. To measure the relation between the divergence angle and the velocity, the following probability density distribution can be used:

$$P(v,\alpha) \propto v^4 \exp\left[-\frac{v^2}{2v_0^2}\left(1+\frac{\alpha^2}{\alpha_0^2}\right)\right], \tag{5}$$

where α_0 is the FWHM of the divergence angle, and $\alpha_0 = 0.16$ mrad; v_0 is the most probable speed when the oven temperature $T_0 = 1923$ K, $v_0 \approx 957$ m/s, which is measured; the size of the divergence angle is 2 mrad, the parameters of

DHGB are $d = 600\lambda$ and $I_2 = I_1$. It is found that the maximum of the density distribution at the focal plane decreases with the rise of the atomic beam's divergence angle. In order to describe the deposition results, the FWHMs are analyzed at various positions of atoms along the z direction.

Figure 8 shows the FWHMs with Gaussian beam and DHGB along the z axis. When the atomic beam with divergence angle passes through the Gaussian beam standing wave, the FWHM will increase at the location that is far from $z = 0$. Meanwhile, when the atomic beam passes through the DHGB standing wave, the FWHM will also increase. In contrast, its increasing speed is greatly slower than that in the case of the Gaussian beam standing wave. For example, at $z = 16$ (340.8 μm away from $z = 0$) the FWHM is about 85 nm with the Gaussian beam standing wave, but with the DHGB standing wave, the FWHM is only 50 nm. This means that, when the DHGB standing wave that is used to focus the atoms can reach a long distance, the obtained FWHM is small. This can improve both the depth of field of the atom lens and the contrast of the nano-grating deposited. This method makes the deposition result less sensitive to the location of the substrate, and can also greatly improve the success rate of experiments.

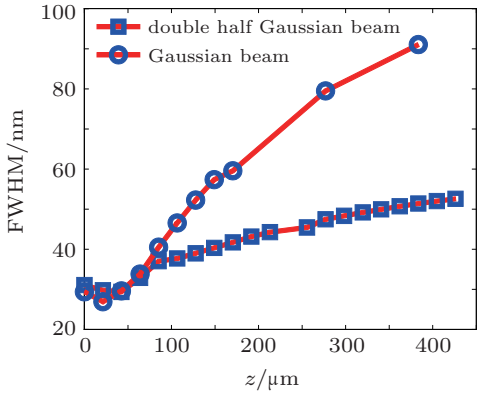


Fig. 8. (color online) The FWHMs versus position in z axis, along the atomic motion direction, $z = 0$ is the position where the standing wave ends up, the open circle represents the result with Gaussian beam standing wave and the open square denotes the result with DHGB standing wave.

4.3. Improvement of the height at focal plane

When the DHGB standing wave is used to focus the atoms, the atom height at the focal plane can be improved by adjusting the parameters; for example, the value of n of the DHGB. Figure 9 shows the simulation result of the maximum of atom height at focal plane versus the value of n in a range from 1 to 8.

It follows from the simulation result that the value of n plays a very important role in the experiment. A better deposition result is received by use of a larger value of n because it is just like using a composite lens to eliminate aberration. Here, we let $n = 8$ and $d = 600\lambda$.

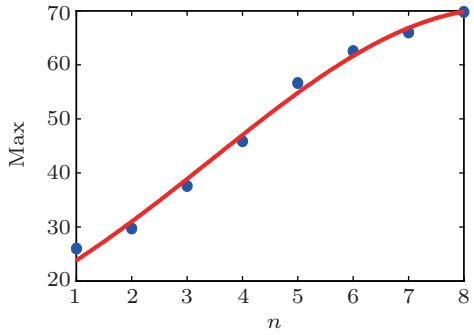


Fig. 9. (color online) Atom flux maximum versus n.

Figure 10 shows that, when $n = 8$, more atoms will focus at the focal plane. The FWHM is used to make a detailed description.

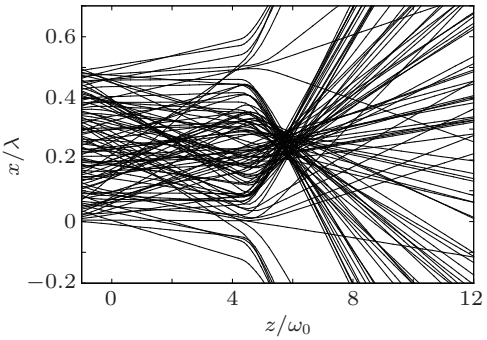


Fig. 10. Trajectories of atoms with divergence angle ($n = 8$ and $d = 600\lambda$.)

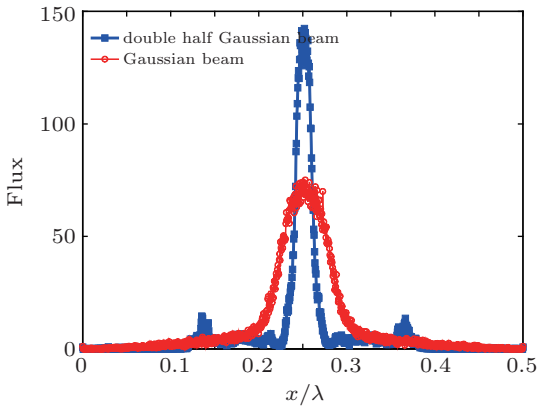


Fig. 11. (color online) Maximum contrast when the atomic beam has a divergence angle. The solid circle indicates the result from the Gaussian beam standing wave, the solid square denotes the result from DHGB with $n = 8$, and $d = 600\lambda$.

Figure 11 shows the simulation results of using the above parameters. From Fig. 11, it follows that a better deposition result can be obtained by adjusting the light intensity. In Fig. 11, by comparison with the result from Gaussian beam standing wave, the maximum of the atom height is nearly doubled and the FWHM decreases from 23.82 nm to 7.57 nm. The quality of the deposition result and the resolution of the nano grating are greatly enhanced. At the same time, the system depth

of field decreases, which means that a good result is acquired only at the focal plane. So, different values of n can be chosen to enhance either the resolution or the depth of field.

5. Conclusions

In this paper, we make a detailed analysis of the atom focus properties in the double half Gaussian beam standing wave field. A new way to improve the focusing quality of atom lithography is found. The numerical solutions show that when the atoms pass through the DHGB standing wave field, a better focus result can be obtained. By adjusting the value of n for the double half Gaussian beam, either the depth of field or the FWHM at the focal plane can be improved. The DHGB can also be generated using a prism that we have designed. This kind of beam can be used in subsequent experiments.

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