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Optimization of laser focused atomic deposition by channeling*

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Laser focused atomic deposition is a unique and effective way to fabricate highly accurate pitch standards in nanometrology. However, the stability and repeatability of the atom lithography fabrication process remains a challenging problem for massive production. Based on the atom–light interaction theory, channeling is utilized to improve the stability and repeatability. From the comparison of three kinds of atom–light interaction models, the optimal parameters for channeling are obtained based on simulation. According to the experimental observations, the peak to valley height of Cr nano-gratings keeps stable when the cutting proportion changes from 15% to 50%, which means that the channeling shows up under this condition. The channeling proves to be an effective method to optimize the stability and repeatability of laser focused Cr atomic deposition.

Keywords: laser focused atomic deposition, nano-grating, length transition standards, channeling

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1. Introduction

Laser focused atomic deposition[1] (LFAD), or the so-called atom lithography, is a unique fabrication technology for the pitch standard fabrication at nanoscale. The most obvious advantage of LFAD is the self-traceability of nano-grating pitch to a natural constant, which produces a series of characteristics, such as uniformity, homogeneity, and consistency.[2] Since the invention of Cr atom lithography in 1992,[3,4] a series of different working elements have been demonstrated successfully, such as Cr,[5,6] Al,[7] Yb,[8] and Fe.[9] Nowadays, the LFAD technology has even shown the ability of inventing natural square rulers at nanoscale,[10] which opens a new way for fabricating angle standards precisely.

However, the stability and repeatability of the atom lithography fabrication process remains a challenging problem for massive production. As a result of atom–light interaction, the structure of nano-gratings depends on the laser intensity, standing wave cutting proportion, working distance, and so on. Previous study has pointed out that there are three basic models[11] for the atom–light interaction, which are the thin lens model, thick lens model, and channeling model. In the former two, the atoms are focused outside and inside the standing wave, respectively. And the channeling condition means that the atoms are focused multiple times during the deposition process. Generally, the multiple focusing process offers a much longer stable working distance for the sample location in the direction of the atom beam, which helps to improve the stability and repeatability of atom lithography gratings. Up to now, most discussion of atom–light interaction is about the thick lens model, the effect of channeling has not been elucidated well, both experimentally and theoretically.

Motivated by these aspects above, in this paper, we aim to figure out the optimal theoretical parameters for channeling and therefore utilize these parameters to improve the stability and repeatability of the nano-gratings experimentally. In detail, we have simulated the key process of atom focusing to decide the optimal condition for channeling. Then the corresponding experiments are conducted to examine the theoretical prediction. Finally, channeling is proved to be an effective way to increase the stability and repeatability of Cr atom lithography.

2. Theoretic analysis

The schematic of laser focused Cr atom deposition is illustrated in Fig. 1.[12] When the collimated Cr atoms pass through the standing wave, a dipole force is imposed on the atoms to focus them to the nodes or antinodes of the standing wave based on a near resonant detuning. Then the one-dimensional nano-gratings form with a period of half of the laser wavelength.

As mentioned before, the interaction between the laser standing wave and Cr atoms can be explained as the relationship between a lens and light, where the standing wave acts as an atom lens. The thin lens model, thick lens model, and

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channeling are illustrated in Fig. 2. Compared with thin lens and thick lens, it is obvious that the atoms are focused multiple times in a relatively longer region, which offers a longer working distance for the deposition. Because of the channeling, we should obtain similar grating structures (same peak to valley height or full width at half-maximum). In this way, the channeling helps to promote the stability and repeatability of the fabricating process.

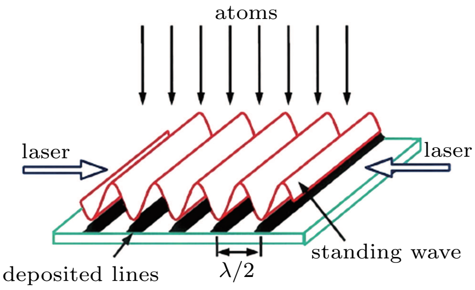

Fig. 1. The schematic of laser focused atomic deposition.[12]

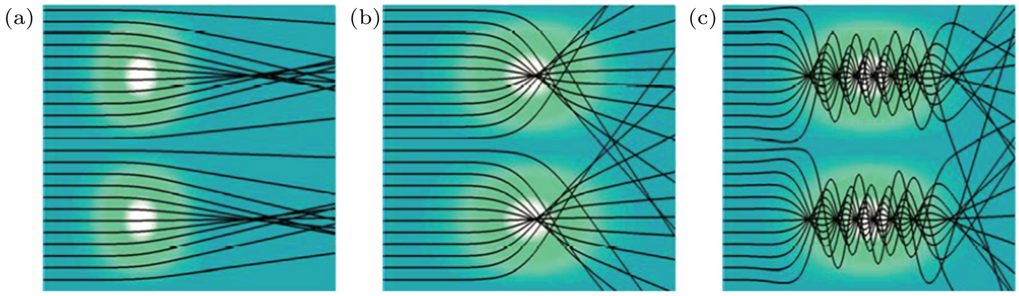

Fig. 2. Types of atom lenses: (a) thin lens, (b) thick lens, and (c) channeling.[13]

The optical potential well in the laser standing wave can be expressed as[14]

$$U = \frac{\hbar\Delta}{2}\ln\left[1+\frac{I(x,y,z)}{I_s}\frac{\Gamma^2}{\Gamma^2+4\Delta^2}\right], \tag{1}$$

where $\hbar = h/2\pi$, h is the Planck constant, Δ is the laser detuning, Γ is the resonance line-width, $I(x,y,z)$ is the laser E-field intensity, and I_s is the atomic saturation intensity.

The intensity distribution of the laser standing wave when we only care about laser the incidence direction (x-direction) can be expressed as[15]

$$I(x) = I_{\max}\sin^2(kx), \tag{2}$$

where $I_{\max}$ is the maximum of the laser intensity, and $k = 2\pi/\lambda$ is the laser wave vector.

From formulas (1) and (2), we can see that two factors, the laser intensity and laser detuning, influence the optical potential well.

3. Theoretical simulation

In order to figure out the optimal experimental parameters for different models, we first simulate the process of laser focusing atoms using Matlab in the classical model of LFAD. We choose $I_{\max} = 100$ kW/m^2 and $\Delta = 50\Gamma$ ($\Gamma = 5\times 2\pi$ MHz), which are the general experiment condition in LFAD. The distribution of atoms in the standing wave is shown in Fig. 3, where 0–100 in x-axis and y-axis means a standing wave. From the picture, we can see that there is one focus of atom beam in the standing wave, which means that the model of laser standing wave in this condition is the thick lens model.

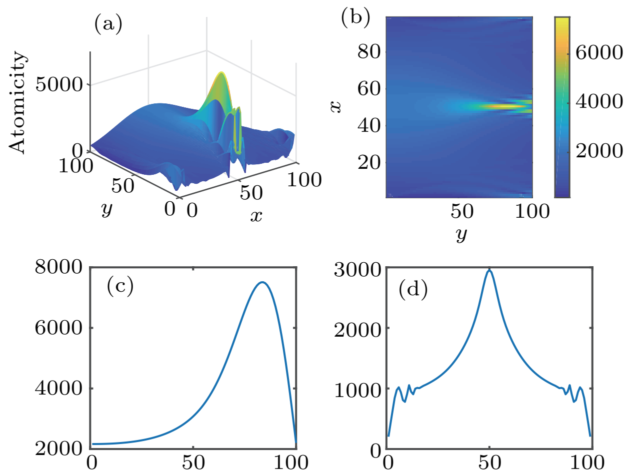

Fig. 3. Distribution of atoms in the standing wave: (a) 3D picture, (b) 2D picture, (c) section of $x = 50$, (d) section of $y = 50$ (x-axis represents the laser beam direction and y-axis represents the atom beam direction).

When $I_{\max} = 100$ kW/m^2 is kept unchanged, detuning decreases from 150Γ to 10Γ, the simulated results are shown in Fig. 4. We can tell that when $\Delta > 80\Gamma$, there is no focus in the laser standing wave, which means that the lens model is thin lens, when $80\Gamma > \Delta > 30\Gamma$, there is one focus in the lase standing wave, which means that the lens model is thick lens, and when $\Delta < 30\Gamma$, there are more than one focus in the laser standing wave, which means that the lens model is channeling.

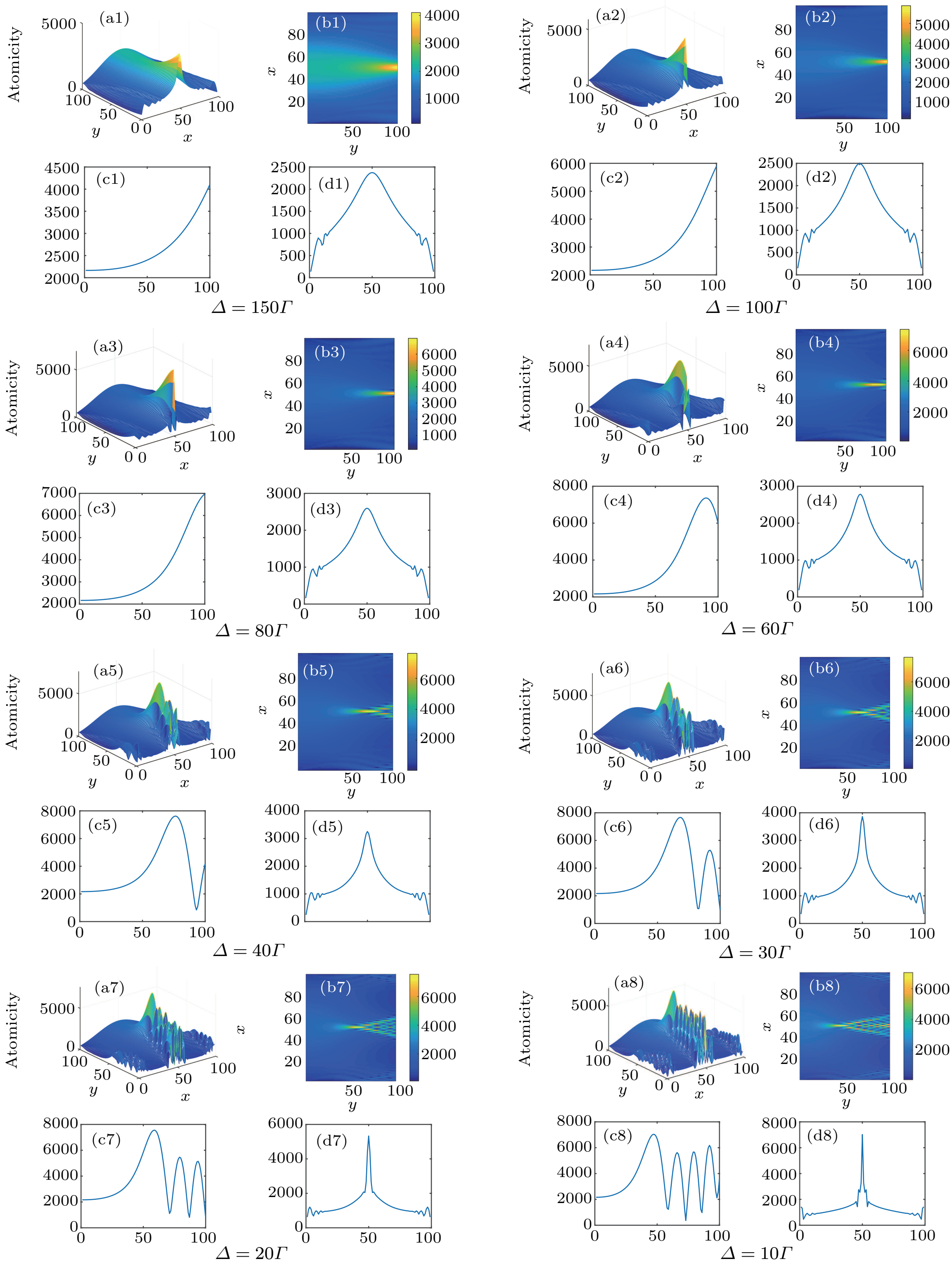

Fig. 4. Simulated diagram of LFAD ($I_{max} = 100$ kW/m^2).

When $\Delta = 50\Gamma$ is kept unchanged, the laser intensity increases from 40 kW/m^2 to 2000 kW/m^2, the simulated results are shown in Fig. 5. We can tell that when $I_{max} < 60$ kW/m^2, there is no focus in the laser standing wave, which means that the lens model is thin lens, when 130 kW/m$^2 > I_{max} > 60$ kW/m^2, there is one focus in the lase standing wave, which means that the lens model is thick lens, and when $I_{max} > 130$ kW/m^2, there are more than one focus in the laser standing wave, which means that the lens model is channeling. From the picture, we also can tell that when $I_{max} = 500$ kW/m^2 the channeling is ideal for experiment.

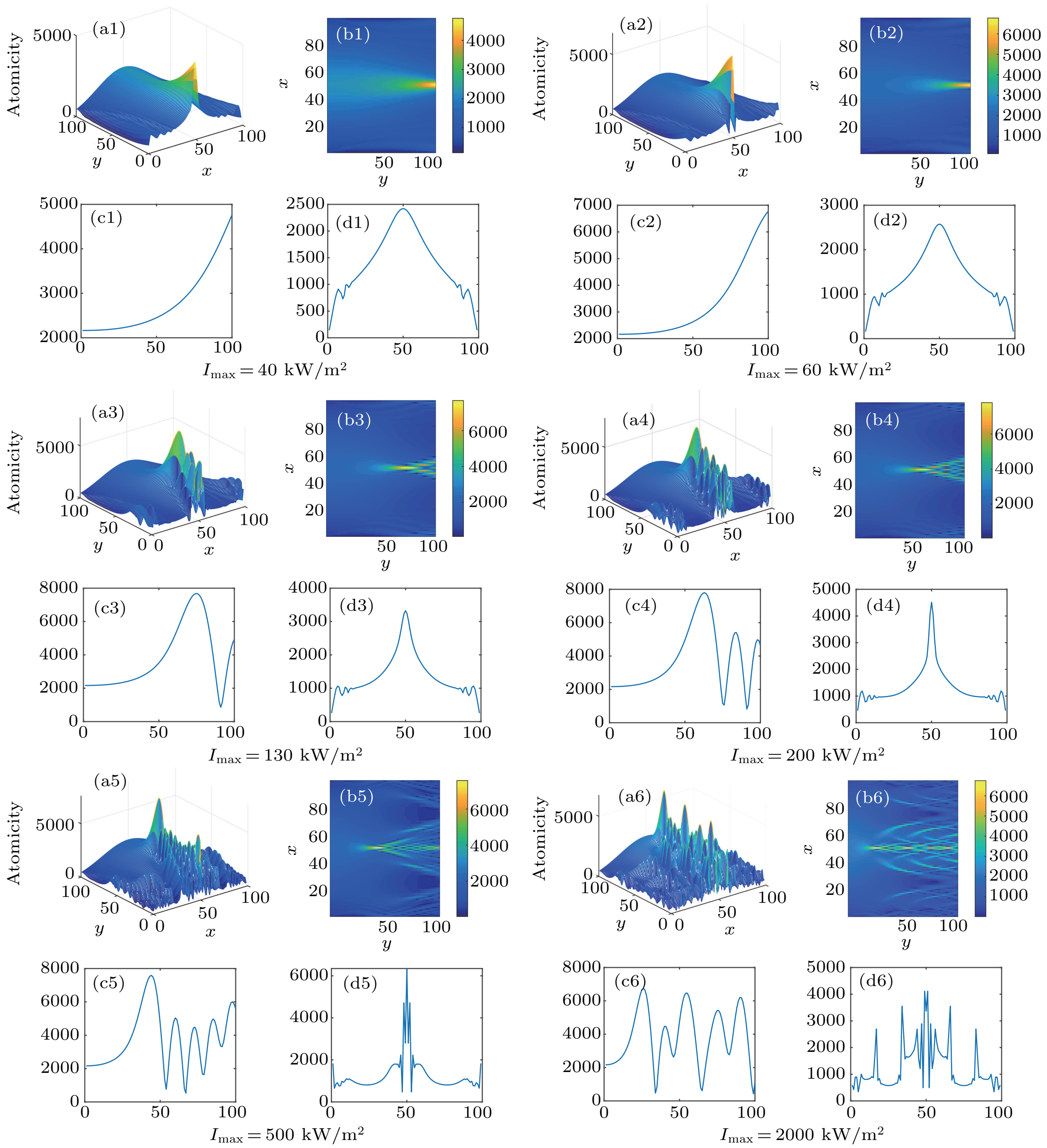

Fig. 5. Simulated diagram of LFAD ($\varDelta = 50\varGamma$).

4. Experiment optimization

The experimental facility and schematic diagram of LFAD are shown in Fig. 6. Briefly, a 1550 ℃ high-temperature oven produces a Cr atom beam with the most-probable mean longitudinal (z direction) velocity of 960 m/s. With the help of Doppler cooling, a well collimated atomic beam with a divergence angle of less than 1 mrad is obtained. The laser is divided into four beams used as laser frequency stabilization, laser cooling, laser focusing, and fluorescence detection, respectively.

In our experiment, the detuning $\varDelta = 50\varGamma$ is unchanged because of the acoustic optical modulator (AOM). The only way to change the potential well is changing the laser intensity. There are two ways to change the laser intensity including the laser power and laser waist radius. In a general experiment, the laser power is 16 mW and the waist radius is 0.2 mm, which means the intensity $I_{max} = 127$ kW/m^2. Under this experiment condition, the lens model is thick lens. In order to get the condition of channeling, we have to increase the laser power and decrease the waist radius.

After clearing all optical lenses and improving the output power of the laser, the laser power of the standing wave is enhanced to 32 mW. In order to decrease the waist radius, a group of lenses are added in the light path of the standing wave between M3 and M9. The focal lengths of the two convex lenses are respectively 150 mm and 75 mm, shrinking the waist radius to 0.1 mm. Then the laser intensity is up to 1019 kW/m^2. Under this condition, the simulated result is shown in Fig. 7. There are several focuses in the standing wave, which means that it is an ideal channeling.

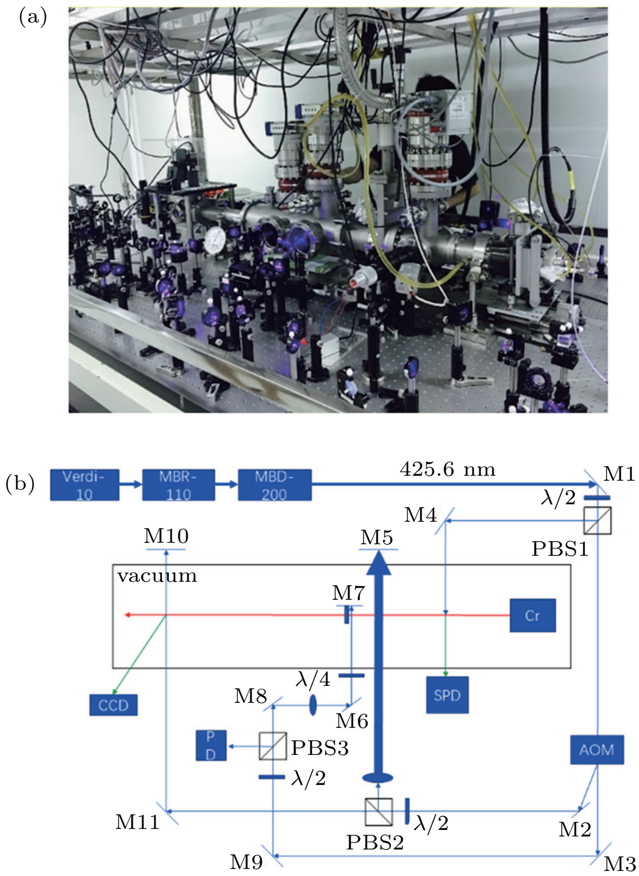

Fig. 6. Experimental facility schematic diagram of LFAD: (a) Cr atom lithography system, (b) schematic diagram.

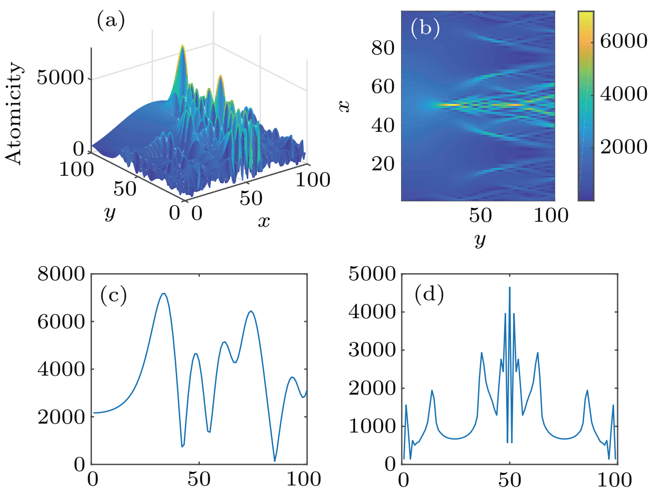

Fig. 7. Simulated diagram of LFAD ($\Delta = 50\Gamma$, $I_{\max} = 1019$ kW/m^2).

5. Experimental verification

We conducted an experiment to examine our predictions of channeling. In the experiment, the laser power of the standing wave was 32 mW, the waist radius was 0.1 mm, and the deposited time was 1 hour. The cutting proportion of the standing wave was changed from 15% to 50% without changing any other factor. The experiment results are shown in Table 1 and Fig. 8. We did the experiment three times in every cutting proportion, the peak-to-valley height of nano-grating fabricated by LFAD fluctuated in a reasonable range. The experiment results proved that the lens model is channeling. The stability and repeatability of the experiment results in channeling are better than those in thick lens and thin lens, which means that the optimized result is satisfactory.

Table 1. Peak-to-valley height of nano-gratings in different cutting proportion.

Cutting proportion/%	15	25	35	45	50
Height/nm	29	25	28	24	28
	26	28	26	22	30
	25	27	26	28	27

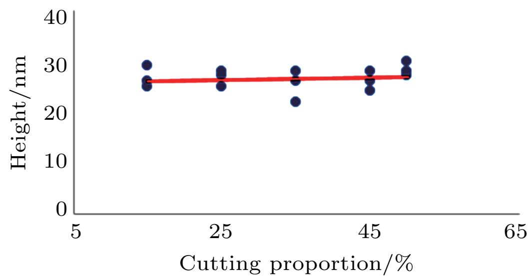

Fig. 8. Peak-to-valley height of nano-gratings in different cutting proportion.

6. Conclusion

In order to improve the stability and repeatability of the laser focused Cr atom deposition process, we adopt the channeling to figure out the optimal parameters for nano-gratings fabrication. Based on the three kinds of atom–light interaction models, the key parameters, such as the laser intensity, are optimized to conduct the corresponding experiments. According to the experimental observations, the peak to valley height of Cr nano-gratings keeps stable when the cutting proportion changes from 15% to 50%, which means that the channeling shows up under this condition. By using the channeling properly, it is possible to improve the stability and repeatability of the laser focused Cr atomic deposition to a higher level, which makes contributions to the massive fabrication of self-traceable pitch standards.

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