Structured mirror array for two-dimensional collimation of a chromium beam in atom lithography*

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Direct-write atom lithography, one of the potential nanofabrication techniques, is restricted by some difficulties in producing optical masks for the deposition of complex structures. In order to make further progress, a structured mirror array is developed to transversely collimate the chromium atomic beam in two dimensions. The best collimation is obtained when the laser red detunes by natural line-width of transition $^7S_3 \rightarrow {}^7P_4^0$ of the chromium atom. The collimation ratio is 0.45 vertically (in x axis), and it is 0.55 horizontally (in y axis). The theoretical model is also simulated, and success of our structured mirror array is achieved.

Keywords: atom lithography, structured mirror array, laser Doppler cooling, two-dimensional collimation

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1. Introduction

Since its development in the 1990s, atom lithography has the potential to contribute significantly to the advancement of new nanotechnologies.[1] However it is not used as widely as promised, due to the difficulties in producing the optical mask for the deposition of complex structures. Several studies have been carried out in order to achieve the expansion of atom lithography, including two-dimensional (2D) atomic crystal,[2] cubic atomic crystal,[3] nanofabrication of a 2D array,[4] polarization gradient light mask,[5] and holographic light mask.[6]

In our group, a pitch standard of 213-nm spatial period has been fabricated using the atom lithography.[7] The broadening of Cr nanostructures has been studied.[8] Other relevant work covers the influence of the divergence angle on deposition of neutral atoms[9] and one-dimensional (1D) collimation of the chromium beam.[10,11] In order to realize the 2D nanolattice, the atomic beam must be transversely collimated in two dimensions. Laser Doppler cooling is an excellent method for collimation without significant loss of flux.[12] The relevant investigations include 2D collimation using a reflecting axicon,[13] three-dimensional (3D) cooling of neutral atoms via radiation pressure of counter-propagating laser beams,[14] and laser cooling of Rb to 1.5 μK in a fountain clock.[15]

In this work, a structured mirror array is developed to collimate the chromium beam in two dimensions. Orthogonal counter-propagating laser beams or 2D optical molasses are produced inside the array. The size and accuracy of this component are very promising. The obvious reduction of the divergence angle of chromium atomic beam in two dimensions is observed.

2. Theories

The interactions of laser light with atoms and the optical field in mirror array are two vital points to be discussed in advance. The collimation ratio ρ is used to evaluate the collimation

$$\rho = \alpha_1/\alpha_0, \tag{1}$$

where α_1 is the angle divergence of the collimated atomic beam and α_0 is the angle divergence without collimation. They are defined by

$$\alpha = \Delta x/L. \tag{2}$$

During the propagation of atoms, the transverse width of the Cr beam is broadened and Δx is the broadening width while L is the propagating distance.

2.1. Laser Doppler cooling

The force exerted on atoms with a speed of v by counter-propagating near-resonant light is[16]

$$F(v) = (-\hbar k\gamma_- + \hbar k\gamma_+)\boldsymbol{e_x} + (-\hbar k\gamma_- + \hbar k\gamma_+)\boldsymbol{e_y}, \tag{3}$$

where $\boldsymbol{e}_x$ and $\boldsymbol{e}_y$ are the direction vectors in x and y axes, respectively, k is the modulus of laser wave vector, and

$$\gamma_\pm = \frac{1}{2}s_0\Gamma\left[1 + s_0 + 4(\delta \mp \omega_D)^2\Gamma^{-2}\right]^{-1}, \tag{4}$$

where $s_0 = I/I_s$ being the saturation coefficient, $\Gamma = 5$ MHz the natural line-width of transition $^7S_3 \rightarrow {}^7P_4^0$ of chromium

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atom, and $\omega_D = -kv$ the Doppler shift. The first term on the right-hand side of the above formula is the force of laser along the x direction, while the second is along the y direction.

On the assumption that the transverse velocity distribution and density distribution of the atomic beam are both Gaussian in the initial state, the trajectories of 10^5 Cr atoms are calculated. The counts of atoms in each area element in a cross section of the atomic beam satisfy the distributions as shown in Fig. 1.

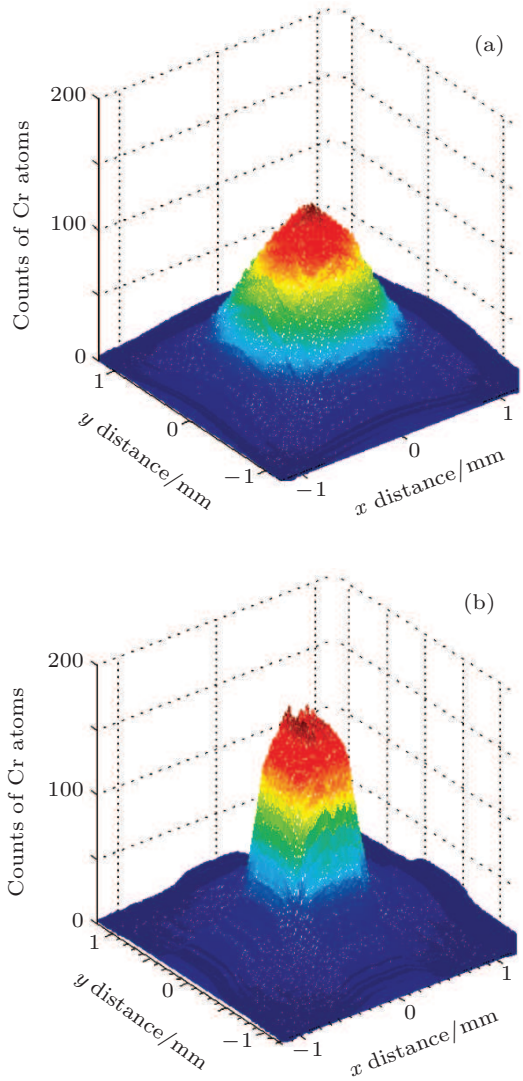


Fig. 1. (color online) Theoretical simulation obtained by tracing the trajectory of 10^5 Cr atoms and statistically counting the atom numbers in each area element: (a) without collimation and (b) with collimation.

2.2. Optical field in structured mirror array

The 2D collimation has been achieved by some approaches, such as a reflecting axicon[13] and two orthogonal beams.[14] In our work, two requirements must be considered, i.e., the compatibility for our experimental arrangement and the expandability for the 2D atom lithography.

A pentaprism is mostly used in a camera to deviate a beam of light by 90°. It is an ideal structure for our mirror array. As shown in Fig. 2, three sufficiently large mirrors are UV glued onto the facets of a pentaprism which is excavated in its center for the atomic beam to pass through. The mirrors are coated with multilayer dielectric films to ensure that the reflectivity exceeds 95%. According to the Doppler cooling theory, the angle tolerance between two counter-propagating beams must be restricted within 1 mrad. The light beams reflect from 3 surfaces 5 times in total. Thus the angle tolerance of each surface is calculated to be within 10″.

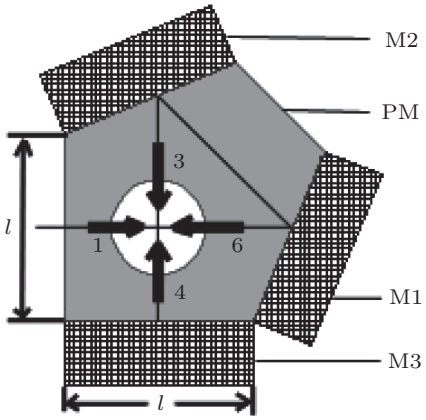


Fig. 2. Structured mirror array, where M1, M2, and M3 denote mirrors, and PM refers to pentaprism.

Assuming that the orthogonal beams are linearly polarized, the optical path of incident light starting from the crossing point O and reflecting from M1, M2, and M3 back to O is given by

$$\Delta = 2l\left(1+\sqrt{2}\right)+l. \tag{5}$$

The phase difference is

$$\delta = \Delta \cdot \frac{2\pi}{\lambda} + \pi. \tag{6}$$

Orthogonal standing waves are shown in Fig. 3. It is possible to use it as a two-dimensional optical lattice[17] in atom lithography. However, due to the unstable phase difference of each light field inside the mirror array, the standing waves will be influenced to become 1D as shown in Fig. 4 or even deconstructed. By strictly controlling the mechanical vibration and the angle tolerance of the structured mirror array, the phase difference can be locked and the 2D atom lithography can be realized.

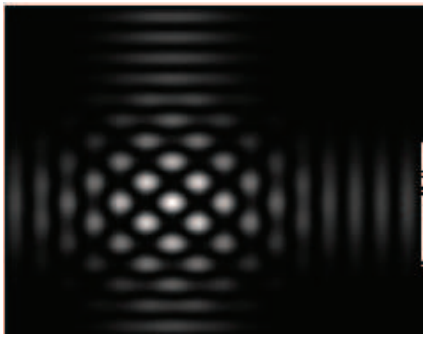


Fig. 3. Light field in the mirror array.

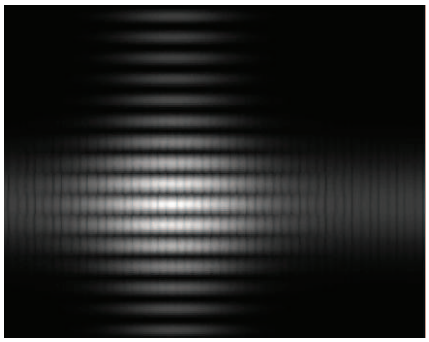


Fig. 4. Light field when phase difference is unstable.

3. Experiment

3.1. Arrangement

The arrangement with coordination is shown in Fig. 5. The experimental steps are similar to those in our previous work of 1D collimation of a chromium atomic beam.[10] Instead of the 3 slits, a 2 mm×2 mm aperture is used as the pre-collimator, placed about 550 mm from the oven. The mirror array, fixed on a level adjustment set, is placed about 30 mm from the pre-collimator according to the following steps. First, 1D collimation is carried out to make sure that the atomic beam is perpendicular to the laser beam. Then the mirror array is adjusted so that the light reflects back along the same path. Meanwhile, the atomic beam will pass through the centre of the hole in prism as shown in Fig. 2.

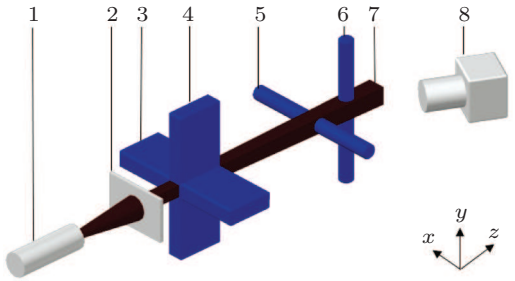


Fig. 5. (color online) Schematic plot of 2D collimation. 1: Cr oven, 2: pre-collimator, 3: horizontal cooling light, 4: vertical cooling light, 5: horizontal detecting light, 6: vertical cooling light, 7: Cr atomic beam, 8: CCD camera.

Another change from 1D collimation is the fluorescence detecting system. At a distance $L = 1000$ mm from the pre-collimator, two perpendicular laser beams are used to induce the fluorescence. These two beams of light are locked at the transition frequency of chromium $^7S_3 \rightarrow {}^7P_4^0$ by fluorescence differential signaling method.[10] The laser induced fluorescences (LIFs) in the two dimensions are detected to determine the angle divergence and calculate the collimation ratio, using formulas (1) and (2). In this case, L is the distance between pre-collimator and the detecting light, and the broadening of the Cr beam is given by

$$\Delta x = x_2 - x_1, \tag{7}$$

where x_1 is the width of the Cr beam in the place of the pre-collimator, which is equivalent to the slit width of the pre-collimator, and x_2 is the width of the Cr beam in the place of the detecting light, which approximately equals the width of the LIF. The width of the LIF is determined by the following procedures. The fluorescence profiles in x axis and y axis are obtained by polynomial fitting of the grayscale profiles of the LIF image as shown in Fig. 7 and Fig. 8, respectively. The full width at half maximum (FWHM) of the fluorescence profile is the width of the LIF. According to the Gaussian lens formula, given the focal length of the lens f, the distance from the fluorescence to lens d, the size of CCD pixel Δ, and the number of pixels in image N, the width of the fluorescence W can be calculated by

$$W = N \cdot \Delta \cdot \frac{d}{f}. \tag{8}$$

3.2. Collimation results

A CCD camera is used to photograph the fluorescence images. As shown in Fig. 6, the left parts of the images in Figs. 6(a) and 6(b) are the horizontal section of fluorescence induced by horizontal light, while the right parts are the vertical sections of fluorescence induced by vertical light. The profiles of the fluorescence intensity in x and y axes are analyzed, respectively, and the results are shown in Figs. 7 and 8. The dot profiles are obtained by measuring the grayscale profiles of the fluorescent image along the x and y axes. Solid curves denote the 9-order polynomial fitting of dot profiles.

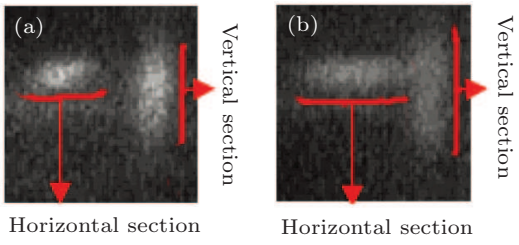


Fig. 6. (color online) Fluorescent images captured by CCD camera. The left parts of images (a) and (b) are the horizontal sections of the fluorescence induced by horizontal light, and the right parts are the vertical sections of the fluorescence induced by vertical light. (a) Cr atomic beam is collimated by Doppler laser cooling, (b) it is without collimation.

After collimation, the intensities are higher and the angle divergences are narrower. The initial angle divergences in vertical and horizontal directions are calculated to be 5.86 mrad and 5.76 mrad, respectively. After Doppler cooling, it narrows to 2.61 mrad in vertical direction and to 3.17 mrad in horizontal direction. According to Eq. (1), the collimation ratios are calculated to be 0.45 and 0.55 respectively.

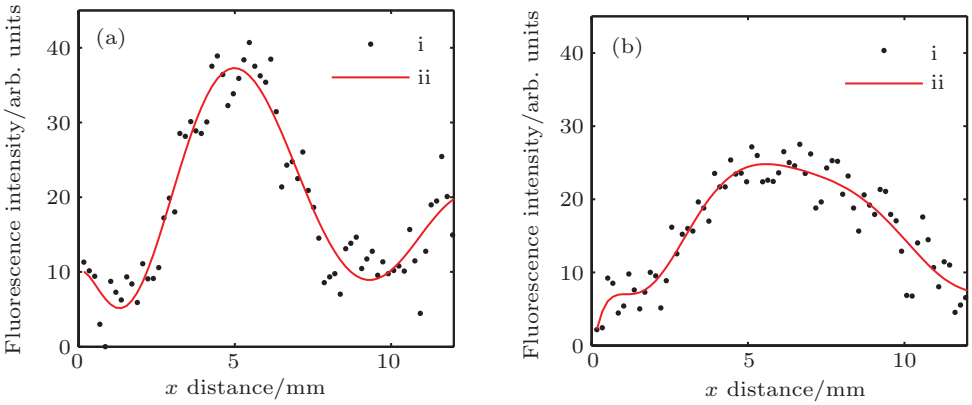


Fig. 7. (color online) Fluorescent profiles in horizontal direction. Solid line denotes the 9-order polynomial fitting of dot profile. Panel (a) shows the case with collimation, and panel (b) exhibits the case without collimation.

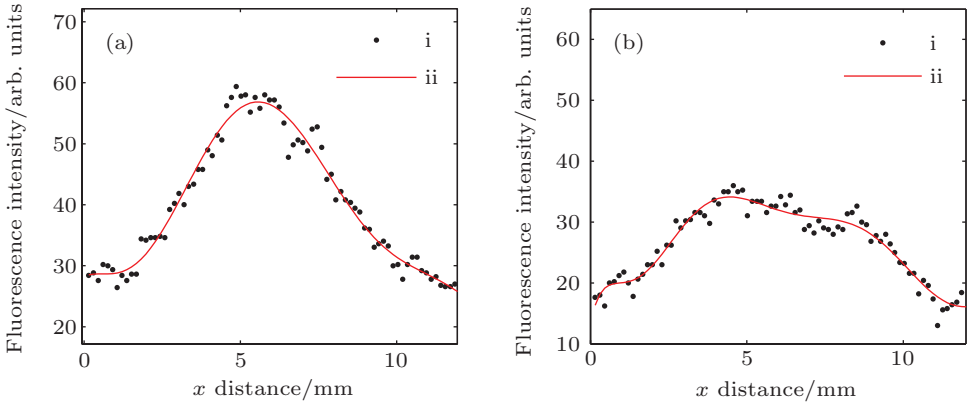


Fig. 8. (color online) Fluorescent profiles in vertical direction. Solid line denotes the 9-order polynomial fitting of dot profile. Panel (a) shows the case with collimation, and panel (b) displays the case without collimation.

4. Conclusions

By using the novel structured mirror array, the atomic beam is successfully collimated in two dimensions. The collimation ratio, defined by formula (1), is 0.45 in the horizontal direction (x axis) and it is 0.55 in the vertical direction (y axis). The initial angle divergences are 5.86 mrad in the horizontal direction and 5.76 mrad in the vertical direction, and they narrow to 2.61 mrad and 3.17 mrad after Doppler cooling, respectively. This progress enables us to move forward to the 2D deposition of a nano-lattice.

References

[1] McClelland J J, Scholten R E, Palm E C and Celotta R J 1993 *Science* **262** 877
[2] Hemmerich A and Hänsch T W 1993 *Phys. Rev. Lett.* **70** 410
[3] Hemmerich A, Zimmermann C and Hansch T W 1993 *Europhys. Lett.* **22** 89
[4] Gupta R, McClelland J J, Jabbour Z J and Celotta R J 1995 *Appl. Phys. Lett.* **67** 1378
[5] Brezger B, Schulze T, Schmidt P O, Mertens R, Pfau T and Mlynek J 1999 *Europhys. Lett.* **46** 148
[6] Mützel M, Tandler S, Haubrich D, and Meschede D 2002 *Phys. Rev. Lett.* **88** 083601
[7] Ma Y, Li T B, Wu W, Xiao Y L, Zhang P P and Gong W G 2011 *Chin. Phys. Lett.* **28** 073202
[8] Lu X D, Li T B and Ma Y 2010 *Chin. Phys.* B **19** 123201
[9] Zhang W T, Zhu B H, Huang J, Xiong X M and Jiang Q B 2012 *Chin. Phys.* B **21** 033301
[10] Ma Y, Zhang B W, Zheng C L, Ma S S, Li F S, Wang Z S and Li T B 2006 *Acta Phys. Sin.* **55** 4086 (in Chinese)
[11] Zhang B W, Zhang W T, Ma Y and Li T B 2008 *Acta Phys. Sin.* **57** 5486 (in Chinese)
[12] Scholten R E, Gupta R, McClelland J J and Celotta R J 1997 *Phys. Rev.* A **55** 1331
[13] Balykin V I, Letokhov V S, Minogin V G, Rozhdestvensky Y V and Sidorov A I 1985 *J. Opt. Soc. Am.* B **2** 11
[14] Steven Chu, Hollberg L, Bjorkholm J E, Alex Cable and Ashkin A 1985 *Phys. Rev. Lett.* **55** 48
[15] Wang B, Lü D S, Qu Q Z, Zhao J B, Li T, Liu L and Wang Y Z 2011 *Chin. Phys. Lett.* **28** 063701
[16] Smeets B, Herfst R W, Maguire L P, Sligte E, van der Straten P, Beijerinck H C W and van Leeuwen K A H 2005 *Appl. Phys.* B **80** 833
[17] Blakie P B and Clark C W 2004 *J. Phys.* B: *At. Mol. Opt. Phys.* **37** 1391