Collimation of atomic beam for the fabrication of nano-scale length standards

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Abstract: To meet the requirement of Nano-scale dimensional metrology, length standards with features below 100 nanometers were indispensible instruments. The length standards with periodic length of 213±0.1 nm were successfully fabricated through atom lithography, which was connected to atomic transition frequency and thus retraceable to a constant measured with highly accuracy. For further improvement of the quality of these standards, the evaluation and optimization of collimating the atomic beam were described in this article. A knife-edge was settled to cut the atomic beam collimated by the laser Doppler cooling. The fluorescence of the beam was collected to calculate its angular distribution and equilibrium transverse temperature. The stimulated absorption rate was considered and discussed. Full angular width at half maximum as small as 0.544 mrad was observed, corresponding to temperature of 343.8 μK. Several angular distributions were measured by changing the laser characteristics to optimize the collimation.

Key words: atom lithography; Doppler cooling; transverse temperature; knife-edge; angular distribution

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用于研制纳米长度标准的激光准直原子技术研究

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摘 要: 亚百纳米长度计量标准是实现在纳米尺度精确计量的关键器件。我们课题组已利用原子光刻技术研制出了周期为 213±0.1nm 的光栅，该光栅的周期对应于原子的跃迁频率，具有直接溯源性和高的精确度。理论与实验数据表明原子的横向准直效果是影响光栅对比度的主要因素。因此,文中将介绍几种原子准直技术的优化与估算方法。利用刀口技术分析了激光多普勒准直原子技术的效果。利用 CCD 收集的荧光分析原子的发散角与横向温度,并考虑与分析了吸收率对测量结果的影响。原子的发散角为 0.544 mrad,对应的横向温度为 343.8 μK。文中还分析了各种实验参数对准直效果的影响。

关键词: 原子光刻； 多普勒冷却； 横向温度； 刀口； 角分布

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0 Introduction

Collimated atomic beam plays an important role in direct-write atom lithography[1] and many other applications. Since the deflection of atomic beam by resonance radiation pressure[2] was realized, much work has been done in the related field. Detailed measurement of the angular distribution of atoms has been presented with some approximations[3]. However, the stimulated absorption rate[4], which varies at different angles due to the Doppler effect, must be brought into consideration.

Our group has fabricated a pitch standard of 213 nm spatial period by atom lithography[5]. In the experiments, we apply laser Doppler cooling to collimate the chromium beam[6]. Compared with nozzles or apertures, Doppler cooling has the merits of high degree of collimation without significant loss of flux[1]. To better evaluate the result of collimation, the stimulated absorption rate is added in this article to give out more precisely the angular distribution of atoms.

In this article, the effect of some parameters on the angular distribution are analyzed including the frequency detune between laser and atoms, the laser power, the laser beam width and the oven temperature.

1 Theories

1.1 Knife-edge method

The knife-edge method is a conventional way to measure the transverse temperature and angular distribution of an atomic beam. It is described in the work by R. E. Scholten et al[3]. The angular distribution is obtained by symmetrizing the derivative fluorescence spatial intensity profile $F(x)$,

$$f(\alpha)=-L\frac{\mathrm{d}F(x)}{\mathrm{d}x} \tag{1}$$

And the transverse temperature[1,3] is given by

$$T_x=T_0\cdot\alpha_{\mathrm{FWHM}}^2/4(\sqrt{2}-1) \tag{2}$$

Where α_{FWHM} is the full angular width at half maximum of the symmetrized curve.

However, $f(\alpha)$ is the angular distribution of fluorescence, which is assumed to be proportional to the angular distribution of atoms $P(\alpha)$. We introduce a coefficient κ as the fluorescent yield, and

$$f(\alpha)=\kappa P(\alpha) \tag{3}$$

But the coefficient κ is a function of angle because the fluorescent yield is frequency dependent. Here we use the stimulated absorption rate to figure it out.

When excited by a resonant light, the atoms absorb photons and emit fluorescence. The absorption rate w is given by[4],

$$w=\frac{\Gamma}{2}\frac{\Omega^2/2}{\delta^2+\Omega^2/2+\Gamma^2/4} \tag{4}$$

Where Γ is the natural linewidth, Ω is the Rabi frequency, δ is the laser detune from the atomic transition frequency. Bringing in the saturation factor $s=\frac{2\Omega^2}{\Gamma^2}=\frac{I}{I_s}$, the Doppler shift $\omega_D=kv_x\cdot\omega_\gamma v_0\alpha/c$ and the $^7S_3\rightarrow{}^7P_4^0$ transition of chromium atoms, the stimulated absorption rate is given by

$$w=\frac{\Gamma}{2}\frac{s\Gamma^2/4}{(\alpha v_z\omega_\gamma/c)^2+(1+s)\Gamma^2/4} \tag{5}$$

In longitudinal direction, the atoms experience a thermal distribution.

$$f(v_z)\mathrm{d}v_z=v_z^2\exp(-M_a v_z^2/2k_BT_0)\mathrm{d}v_z \tag{6}$$

We have

$$\kappa(\alpha)\propto\int_0^\infty wf(v_z)\mathrm{d}v_z=\frac{s\Gamma^3}{8N}\int_0^\infty\frac{v_z^2\exp(-Mv_z^2/2k_BT_0)}{(\alpha v_z\omega_\gamma/c)^2+(1+s)\Gamma^2/4}\mathrm{d}v_z \tag{7}$$

Where

$$N=\int_0^\infty v_z^2\exp(-Mv_z^2/2k_BT_0)\mathrm{d}v_z \tag{8}$$

The fluorescent yield κ is numerically solved as shown in Fig.1. From Fig.1, we can see $\kappa(\alpha)\sim1$. So we can get that the distribution is broadened, compared to the conventional method but at a very little amount, and finally we obtain the optimized angular distribution of atoms.

$$f'(\alpha)=\frac{f(\alpha)}{\kappa(\alpha)}\sim f(\alpha) \tag{9}$$

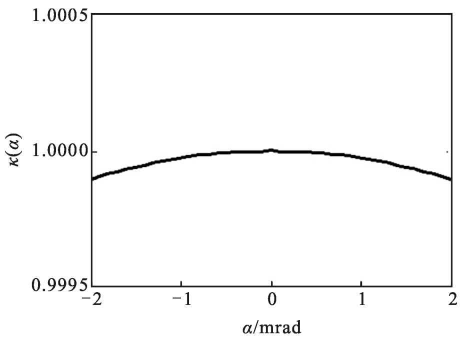


Fig.1 Fluorescence yield $\kappa(\alpha)$

1.2 Laser Doppler cooling

We set two counter-propagating laser beams which is red detuned passing perpendicularly across the atomic beam. According to the theory, the force exert on the atoms with speed of v by the light field is

$$F(v)=-\hbar k\gamma_p^{-}+\hbar k\gamma_p^{+} \tag{10}$$

Where k is the wave vector of laser, and[7]

$$\gamma_p^{\pm}=\frac{s_0\Gamma/2}{1+s_0+4[(\delta\pm\omega_D)/\Gamma]^2} \tag{11}$$

Where $s_0=I/I_s$ is the saturation coefficient, Γ=5 MHz is the natural line-width of $^7S_3\rightarrow{}^7P_4^0$ transition of chromium atom, $\omega_D=-k\cdot v$ is the Doppler shift. The first term of the formula is the force of laser along the x direction, while the second term is on the contrary.

2 Measuring the angular distribution and transverse temperature

2.1 Arrangement

The arrangement of the experiment is shown in Fig.2. All depositions are carried out in a turbo-molecular pumped vacuum system with typical pressure 10^{-5} Pa. ^{52}Cr is a particularly good atom for the study of atom lithography. In Fig.2 the frame represents the vacuum chamber. The Cr beam is produced using a radiatively heated tantalum crucible with a 1 mm circular aperture. Typically operating temperature is 1 650 ℃. The 425 nm laser experiment-wanted is provided by a laser system such as: A frequency-doubled CW single-mode Ti:Sapphire laser system, pumped by a 532 nm LD−pumped solid-state laser, produced blue light at 425.55 nm. In the experiment, the atom beam is mechanically precollimated in the transverse direction to a divergence of about 4.5 mrad with a three-slit precollimated aperture with the size of each slit of 0.6×1 mm, which is settled 769 mm from the Cr oven[8].

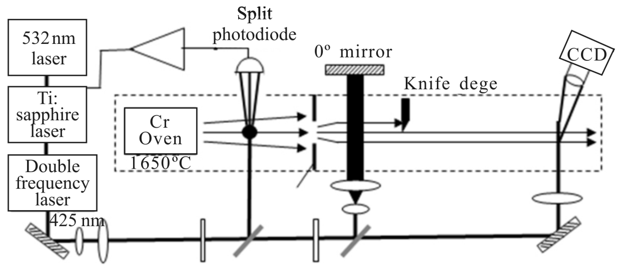
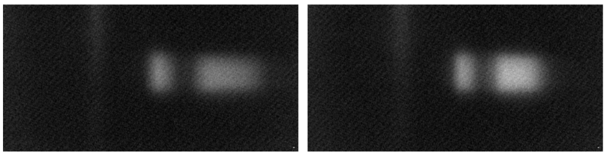


Fig.2 Arrangement of the experiment

The 425 nm laser beam is split 3 parts. The fist part is used to stabilize the frequency of laser by the laser-induced fluorescence technique[9]. The second part of laser beam is used to collimate Cr beam transversely. Before it enters into the vacuum chamber, we place two cylinder lenses to expand the laser beam to 20 mm×3 mm. The collimation beam is retroreflected by a 0° mirror (reflection>95%) on the other side of the vacuum chamber and aligned parallel to itself to better than 1 mrad. The second part of laser beam is used to intersect with the Cr atoms and generating fluorescence, 660 mm away from the second part laser. The CCD camera is used to capture the image of fluorescence here and monitor the effect of laser collimation. The more detailed information about this experiment can be found in ref[8].

We determine the angular distribution in the atom beam after interaction with the laser collimating using the knife edge technique. The atomic beam was partially blocked by a knife edge, located a distance l=120 mm beyond the cooling region, as shown in Fig.2.

Figure3 is experimental result of laser collimation of Cr atoms taken by CCD camera. In Fig.3(a), the collimating laser beam is blocked, and we show the Cr beam fluorescence images before laser collimation. In Fig.3(b), the collimating laser beam is intersect with the Cr atoms, and we show the Cr beam fluorescence images after laser collimation. We can see from the picture, the image with laser collimating clearly shows a narrower, brighter distribution of atoms.



(a) Before collimation (b) After collimaton

Fig.3 Fluorescence image taken by CCD camera

In this part, we will use the knife edge technique to determine the angular distribution of the atom beam. The measuring process is summarized as shown in Fig.4. In Fig.4, a is the intensity curve of Fig.3 (a)–before collimation, b is its derivative. Firstly, the fluorescence image is denoised with the mean filtering approach and transformed to the fluorescence density curve, which is shown in curve a in Fig.4. Then the curve is differentiated, which is shown in curve b in Fig.4. At last, we can get the angular distribution of the atoms from the Fig.5. According to the relation $\alpha=x/L$, where α is the angle of the atom′s velocity, L is the position of the fluorescence, x is the distance between the knife-edge and the fluorescence.

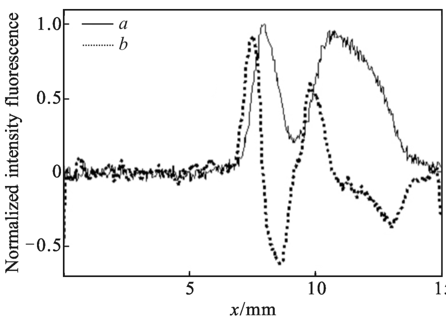


Fig.4 Processing the measurement

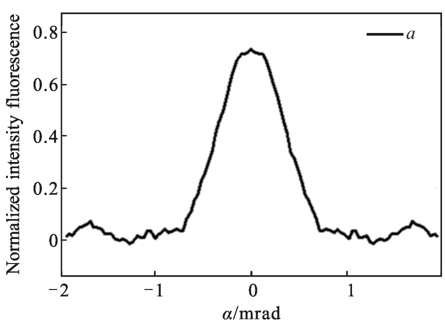


Fig.5 Angular distribution before laser collimation

The Angular distribution of the atoms after laser collimation can be got using the same way. Fluorescence image after laser collimation taken by CCD camera is shown in Fig.6. And the angular distribution of the atoms after laser collimation is shown in Fig.7. We can get from this curve that the full angular width at half maximum as small as 0.544 mrad is observed, corresponding to temperature of 343.8 μK.

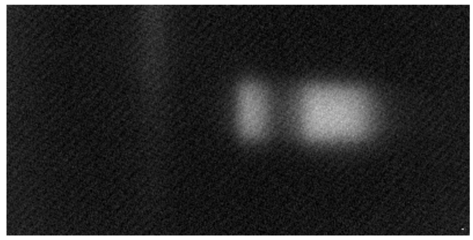


Fig.6 Fluorescence image after laser collimation taken by CCD camera

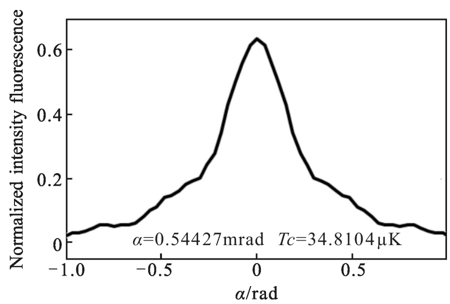


Fig.7 Angular distribution after laser collimation

2.2 Laser Doppler cooling with different influence factors

2.2.1 Laser detunes

We use a direct digital synthesizer to generate a series of RF signals to drive the acousto-optical modulator. Adjust the AOM so that the laser beam is diffracted and red detuned. We derived the full angular width at half maximum, as well as the 50% and 90% quantiles to evaluate the degree of collimation as shown in Tab.1 and Fig.8.

Tab.1 Collimating angle of different detunes

Detunes	$-1/4\Gamma$	$-1/2\Gamma$	$-\Gamma$	-2Γ	-4Γ
α_{FWHM}/mrad	1.289 4	0.945 6	0.848 9	0.859 6	1.031 5
50%/mrad	0.774 8	0.620 7	0.547 8	0.578 0	0.628 1
90%/mrad	1.996 7	1.899 6	1.943 8	2.329 0	1.755 3

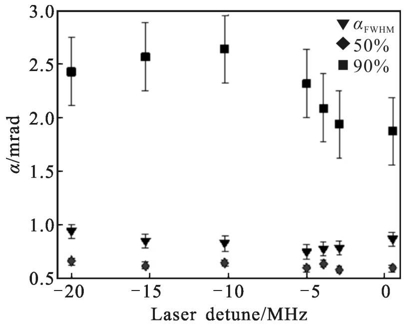


Fig.8 Collimation angle at different detunes

2.2.2 Laser intensity

By regulating the amplitude of the RF signal applied to the AOM, we change the diffraction coefficient to obtain several cooling light of different powers for a series of angular distributions. The calculation and experimental results are shown in Tab.2 and Fig.9. The collimation angle reaches the best when the laser power is 15 mW. Exceeding that amount will extend no improvement to the collimation angle.

Tab.2 Different angular distributions over different laser powers

Powers/mW	5	9	15	30	60
α_{FWHM}/mrad	0.752	0.741	0.763	0.720	0.709
50%/mrad	0.555	0.588	0.628	1.108	0.516
90%/mrad	2.388	2.068	2.088	2.668	2.065

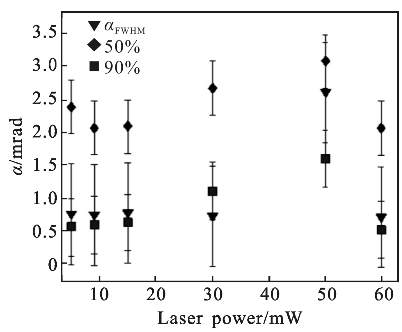


Fig.9 Collimation angle verses laser power

2.2.3 Laser beam width and oven temperature

According to the absorption and transition theory and on account of the Doppler cooling limit, we obtain the appropriate laser beam width of 13.7 mm[6]. Increasing the laser width would be no significant impact on the collimation of the chromium beam. We also change the oven temperature to measure the angular distribution of atomic beam. The results differ with the increasing of the temperature, as shown in Tab.3.

Tab.3 Different angular distributions over different oven temperatures

Temperature/℃	1 600	1 610	1 620	1 630	1 640	1 650
Angle/mrad	1.053	0.999	0.827	0.806	0.806	0.763
50%/mrad	0.787	0.844	0.806	0.785	0.793	0.628
90%/mrad	2.360	2.364	2.390	2.431	2.477	2.088

3 Discussions & conclusions

We have evaluated the collimation of atomic beam with knife-edge and fluorescence analyses. By bringing in the stimulated absorption rate, we optimize the measurement of angular distribution. We study the connections between angular distribution of the chromium beam and the factors including the performance of laser and oven temperature.

The collimation of the atomic beam reaches a highest degree, with the laser detune of and power of 50 mW and beam width of 13 mm. Increasing the power or beam width would be no significant impact on the collimation of the chromium beam. It coincides with the theory of interaction between photons and flying atoms.

We significantly narrow the divergence angle of atomic beam compared to those without knife-edge and real-time fluorescent imaging analysis. It can help us improve the features of nanofabricated standard pitch.

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