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Studies on the Effect of Laser Cooling in Atom Lithography for Nanometrology

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Abstract: To meet the requirement of nanoscale dimensional metrology, lengthy standards with features below 100 nanometers are indispensable instruments. Our group has successfully fabricated length standards through atom lithography. For further improvement of the quality of these standards, laser cooling of Chromium atom beam was studied through a transverse Doppler cooling scheme. Moreover, utilizing the SDK of CCD camera, we developed an image collecting software, which had functions of real-time display for gray-scale image and image measure. In our experimental setup, with the software, we could detect LIF spots from marginal beams to monitor and analyze the effect of laser cooling.

Keywords: Laser cooling; Atom lithography; Nanometer scale length standards; Doppler cooling; SDK; Image collecting software

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Introduction

With the drive toward miniaturization of a wide range of technologies, such as electronics, magnetics, and biotechnology, dimensional metrology on the nanometer scale has become an increasingly important area for research. One of the key elements of dimensional measurement on any scale is the development of length standards. However, it is difficult to transfer a well-defined macroscopic length standard to the nanometer scale because uncertainties that may be insignificant on the larger scale can become dominant in the transfer process, not to mention other effects such as thermal expansion, material graininess and so on [1,2].

In recent years, a new approach to establish length standards in nanometer scale is the technique of atom lithography [3,4]. This technique typically uses a series of cylindrical atomic lenses formed by an optical standing wave field to focus or manipulate neutral atoms and further deposit these atoms onto a substrate [5], forming a highly regular array of lines whose average pitch can be traced directly to an atomic transition frequency. Atomic frequencies can be used as absolute standards and so we can fabricate the length standards in nanometer scale through this method. An important precondition of this technique, however, is the collimation of the atom beam before it enters the interaction region [6]. The purpose of atom beam collimation is to minimize the divergence angle of atoms reaching the substrate without significant loss of atom flux. The effect of collimation has great influence on the fabrication of the structure of length standards. In our experiment, this is done by one-dimensional transverse Doppler cooling of the chromium (Cr) atom beam (we use chromium in the whole experiment).

In this paper, we introduce the transverse Doppler cooling of Cr atom beam in our experiment. In addition, making use of the software developing kit (SDK) of the CCD camera which is used to detect the laser induced fluorescence (LIF) spots from marginal beams,

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we developed an image collecting software, which had basic functions of real time display for gray-scale image and image information measure such as the FWHM. In our current experimental setup, with the software, we could monitor and further analyze the effect of the laser cooling.

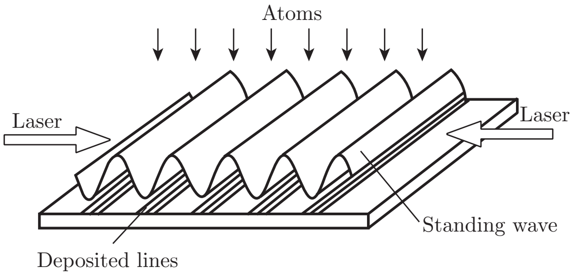


Fig. 1 Schematic of atom lithography.

Experiment

As shown in Fig. 2, the interior of the dashed boundary represents vacuum chamber. MBR110, a Ti: Sapphire laser, which is pumped by a solid laser (Verdi10) typically, produces a laser beam tuned at 851nm. Then the frequency of this laser beam is doubled by MBD200, a frequency doubler which outputs blue light at 425.55nm. A1 means 1/2 wave plate; PBS1 means polarizing beam splitter prism; M1, M2, M3, M4, M5, M6 means high reflection mirror; L1 means lens; AOM1, AOM2 means acousto-optic modulator; SPD means split-photodiode; DFA means differential amplifier; PC means pre-collimation aperture whose structure is shown in Fig. 3; ZL1, ZL2 means cylindrical lens, CCD means CCD camera.

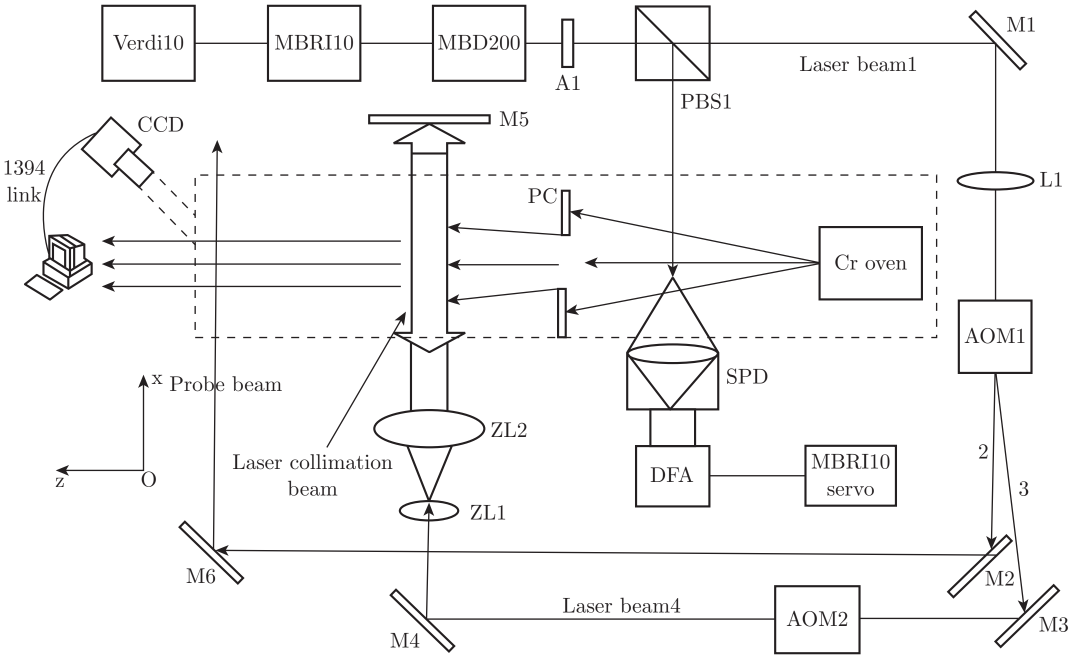


Fig. 2 Schematic of laser cooling of Cr atom beam.

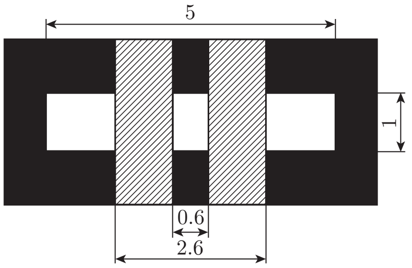


Fig. 3 The pre-collimation aperture.

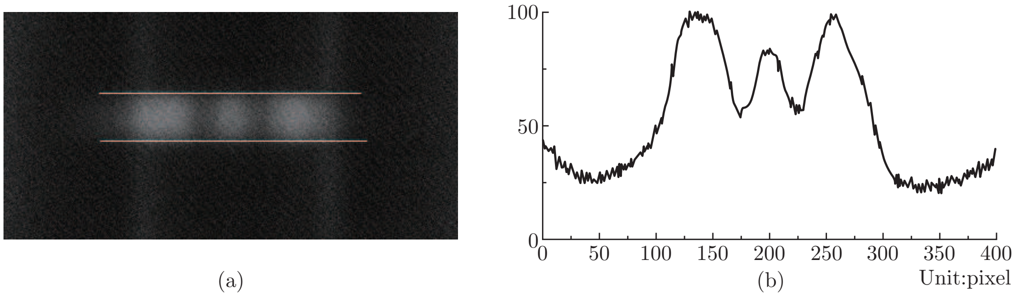
^{52}Cr is a particularly good atom for the study of atom lithography. Firstly, ^{52}Cr has the largest abundance (84%) in these isotopes and has no hyperfine states and no nucleon spin; Secondly, ^{52}Cr has an optical transition from the ground state to an excited state $^7S_3 \rightarrow {}^7S_4^0$, with the wavelength λ=425.55 nm in vacuum. In the vacuum chamber, the Cr beam is produced using a radiatively heated tantalum crucible with a 1 mm circular aperture. Typically operating temperature of 1650℃ produces a most probable longitudinal velocity of 960 m/s. Then in the whole process, the Cr beam passes through frequency stabilization section, laser collimation section and fluorescence probe section in turn, propagating along the direction of Oz. In the figure, SPD and DFA make up the differential feedback circuit. And making use of this unit the frequency of the main laser beam (laser beam1) is stabilized at Cr atom resonance frequency with wavelength λ=425.55 nm based on the detection of a laser induced fluorescence (LIF) signal from the Cr beam [7]. This atom beam is pre-collimated with the pre-collimation aperture PC which is 450 mm away from the Cr oven. The structure of PC is showed as Fig. 3; the aperture is divided into three smaller apertures, producing a central beam of atoms that will be used in laser-focused atomic deposition, and two marginal beams that will be used in fluorescence probe later monitoring the effect of laser cooling. When the laser beam1 passes through AOM1, two laser beams are produced, laser beam2 (0th order laser) and laser beam3 (+1st order laser whose frequency detunes +250MHz). Then laser beam4 (-1st order laser whose frequency is red-detuned and adjustable) is produced when laser beam3 passes through AOM2. So the frequency of laser beam4 is controlled by AOM1 and AOM2 in common. Because only the red-detuned laser can cool atoms according to the principle of Doppler cooling, we should ensure the frequency of laser beam4 below laser beam1 (main laser beam)'s appropriately. Typically in our experiment the magnitude of this frequency is -5 ± 0.26 MHz away from the Cr atom resonance frequency. Before laser beam4 enters laser collimation section of the vacuum chamber, it is expanded to a $1/e^2$ width of 24 mm along the atom beam, and a $1/e^2$ width of 3 mm transverse to the atom beam with two cylindrical lens ZL1 (f=12.7 mm) and ZL2 (f=150 mm). After that, laser beam4 (as laser collimation beam) enters laser collimation cavity and we must align it perpendicular to the atomic beam better than 1mrad. The collimation beam is reflected by a 0° high reflection mirror on the other side of the vacuum chamber and meanwhile we must align the reflected beam with the incidence beam better than 1mrad. This makes up our so-called Doppler cooling mechanism which provides us excellent collimation effect. When the atom beams pass through this laser collimation section, the transverse kinetic energy along Oz direction of Cr atoms is reduced dramatically. The distance between the collimation section and Cr oven is 600 mm [8].

After the laser collimation section, the Cr beam goes through the fluorescence probe section which is used to detect the effect of laser cooling. Laser beam2 is used as the fluorescence probe beam, whose frequency is equal to the Cr resonance frequency as the 0th order laser of AOM1. 1470 mm away from the Cr oven, laser beam2 is sent into the fluorescence probe section where it intersects with three atom beams. And we must ensure fluorescence probe beam is aligned with laser collimation beam better than 1mrad because the alignment is extremely crucial. In the intersection position, three LIF spots are produced because the interaction between the probe beam and atom beams. Then we use a CCD camera to detect the three fluorescence spots and through a 1394 firewire the image collected by the CCD camera is transmitted to a computer. Further with the developed image collecting software which has basic functions of real time display for gray-scale image and image measure, we can monitor and analyze the effect of laser cooling.

Development of image collecting software

The CCD we use in the experiment is the marlin 146b CCD of AVT company. Although the CCD has image collecting and displaying software by itself, the software only can display the original collected fluorescence image as showed in Fig. 4(a). In order to intuitively observe and qualitatively analyze the effect of laser cooling, we need to process the original image data and get the gray-scale curve chart of the corresponding image as showed in Fig. 4(b). The gray-scale curve chart could be the gray-scale value of some single row or the average gray-scale value of several adjacent rows, which could be chosen. In Fig. 4(b), the average gray-scale value of the rows between two white lines as showed in Fig. 4(a) constitutes the corresponding curve chart. Making use of the SDK, with Visual C++, we develop our image collecting and processing software which includes the before-mentioned basic function and other functions.

The flow of developing our image collecting and displaying software with Visual C++ is as follows. First, we should load the dll (dynamic link library) document in the SDK into our MFC project in VC++ by means of implicit linking. Then by invoking the functions in the dll document we can drive the CCD camera to carry out corresponding operations, such as initializing the



(a) (b)

Fig. 4 (a) Original collected fluorescence image. (b) Corresponding gray-scale curve chart.

camera, configuring the running parameters of the camera and collecting the original image. After the collecting of each image frame, by programming we can process the original image data and achieve the needed functions, including converting to gray-scale curve chart and its display and so on.

As showed in Fig. 5, the main functions of our developed software include: the display of the original image, the display of the gray-scale curve chart corresponding to the gray-scale value of some single row or the average gray-scale value of several adjacent rows, the online measure of Full Width Half Maximum (FWHM) of the gray-scale curve chart, the removal of background image noise and the real-time parameter adjusting of shutter time, gain and brightness, and some other functions.

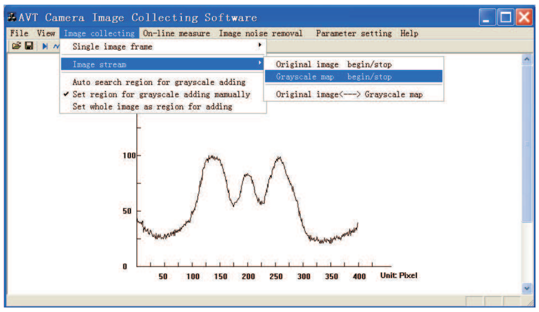


Fig. 5 Developed image collecting and processing software.

Studies on the effect of laser cooling

In the experiment, through our developed image collecting and processing software, we can intuitively observe the effect of laser cooling. As showed in follows, Fig. 6(a) and Fig. 6(b) are the original collected fluorescence image before and after laser cooling respectively. Figure 7 (a) and Figure 7 (b) are corresponding gray-scale curve charts respectively, whose gray-scale value is the average of the various rows of the fluorescence spot regions.

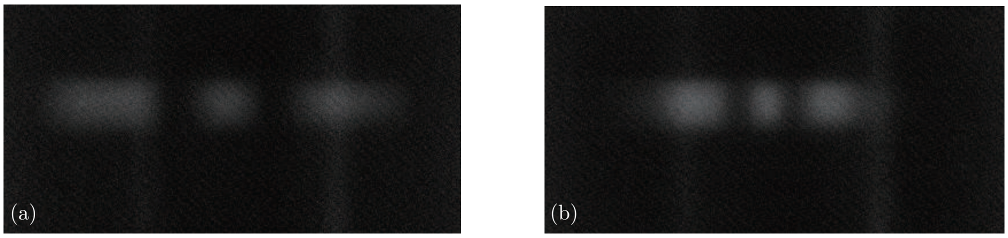


Fig. 6 (a) LIF spots before laser cooling. (b) LIF spots after laser cooling.

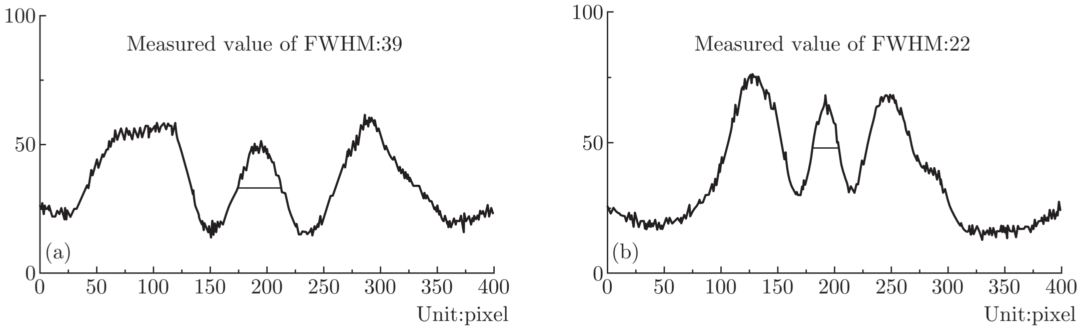


Fig. 7 (a) Corresponding gray-scale curve chart before laser cooling. (b) Corresponding gray-scale curve chart after laser cooling.

Observing the gray-scale curve charts, we can find the dramatic effect of laser cooling in our atom lithography experiment. The FWHM of the curve chart is reduced nearly half and the peak value is increased remarkably. Through measuring the before-mentioned parameters in our developed software, we can further analyze the effect of laser cooling. As showed in Fig. 7(a) and Fig. 7(b), the FWHM of the central curve before and after laser cooling is 39 and 22 respectively, and the peak value is increased from 50 to 68. Table 1 lists the

Table 1 The ratio of FWHM and peak value after laser cooling against before laser cooling.

	Left marginal spot	Central spot	Right marginal spot
FWHM ratio	0.54	0.56	0.57
Peak value ratio	1.33	1.36	1.20

ratio of FWHM and peak value after laser cooling against before laser cooling. Through the value of ratio, we can analyze the effect of laser cooling concretely. And these data have showed our good laser collimation of Doppler cooling in atom lithography.

Conclusions

In this paper, laser cooling of Chromium atom beam was studied through a transverse Doppler cooling scheme. We developed a proper image collecting and processing software to monitor the effect of laser cooling. Through the gray-scale curve chart we observed the good collimation effect of laser cooling. But we didn't mention how low temperature the Cr atom could be cooled to concretely. In our subsequent experiment, using Knife-edge technique we could measure the temperature of the atom beam after laser cooling.

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