Directly Trapping Atoms in a U-Shaped Magneto-Optical Trap Using a Mini Atom Chip *

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(Received 26 May 2008)

We experimentally demonstrate the trapping of ^{85}Rb atoms directly on a chip-size U-shaped magneto-optical trap (U-MOT). The trap includes a U-shaped wire on the chip, two bias magnetic field coils and laser beams. The capture volume of the U-MOT is theoretically calculated, and the trap is experimentally realized. With 2 A current applied to the U-shaped wire and 2-Gauss horizontal bias field, more than 2×10^6 atoms are trapped. In contrast with an ordinary mirror-MOT, this U-MOT captures atoms directly from the background, thus the trap size is greatly reduced. Based on this mini trap scheme, it is possible to realize a chip-size atom trap array for quantum information processing.

PACS: 32. 80. Pj, 39. 90. +d, 03. 75. −b

The atom chip is one of the best candidates for integration and miniaturization of the devices for the matter wave optics, such as the magneto-optical trap (MOT) etc.[1] Based on the technological progresses of the semiconductor processing, gold wires can be deposited on a chip in a scale of micrometres, and hence one can design the magnetic field for a miniature atom trap in the scale of micrometres. In a typical atom chip, atoms can be cooled and trapped within a small volume above chip surface, and almost all the complex laser cooling apparatus can thus be realized in portable atom chips, such as Bose–Einstein condensation (BEC) machines,[2] atom interferometers,[3,4] or atomic clocks.[5] Besides single or double traps, even multi-micro-traps or magnetic trap arrays can be realized on the atom chip.[6,7] The so-called atomic lattice is one of the most powerful platforms for quantum information processing, where each micro-trap can correspond to one qubit. However, for most atom-chip experiments, a macro mirror-MOT is also necessary. Atoms must be cooled and trapped in the mirror-MOT before loaded onto the chip surface,[8,9] and the mirror-MOT has a pair of anti-Helmholtz coils which produce the quadrupole magnetic fields required for the mirror-MOT. These two coils occupy sizeable space and consume much power in the whole atom chip system. They represent the bottleneck for the further integration and miniaturization of the atom chip system. In order to eliminate the cumbrous coils and thus shrink the experimental apparatus, it is important to develop a new technique to trap atoms without the large anti-Helmholtz coils.

In this Letter, we report the experimental result of trapping ^{85}Rb atoms directly on a well-designed chip-size U-shaped MOT. We firstly analysed the capture volume of the U-MOT to demonstrate whether it is possible to trap enough atoms. Then we carry out experiment and trap as many as 2×10^6 cold ^{85}Rb atoms directly from background atomic vapour. Furthermore, based on our experimental results, we propose a new method to realize an atomic lattice on an atom chip without any transfer between traps.

The capture volume of the U-MOT, which is defined as the effective trapping region, is very small.[10] It also depends on the dimensions of the U-shaped wire and the bias magnetic field. Different from a normal MOT, whose capture volume depends on the overlapping region of the laser beams, the capture volume of the U-MOT depend on the quadrupole magnetic field. The effective trapping region of the quadrupole magnetic field is more larger than that of the laser beams because its linear increasing region is smaller than the overlapping region of the laser beams. Assume that the wire has no thickness,[8] and then the quadrupole magnetic field B can be estimated by

$$B = \mu_0 I/2\pi r + \boldsymbol{B}_{\text{bias}}, \tag{1}$$

where μ_0 is the susceptibility of vacuum, I is the operating current, r is the radial distance from the wire, and $\boldsymbol{B}_{\text{bias}}$ is the horizontal bias field. From Eq. (1), we can calculate the distribution of the magnetic field of the U-MOT, as well as its capture volume. As shown in Fig. 1(a), the capture length of the z (or y) direction

*Supported by the National Basic Research Programme of China under Grant Nos 2005CB724505/1 and 2006CB921203, the National Natural Science Foundation of China under Grant No 10774160, and the Chinese Academy of Sciences.

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is about 2 mm if the current is 2 A and the bias field is 4 Gauss. The capture length in the x direction is 2 mm. The whole capture volume is then about 8 mm^3, as shown by triangles in Fig. 1(c). If the current value is constant, then the larger the bias field is, the smaller the capture volume is. However, the capture ability of the U-MOT represents the most number of cold atoms that can be trapped, it depends not only on the capture volume, but also on the quadrupole field gradient. The quadrupole field gradient is determined by the value of $(\mu_o I/2\pi r_0^2)$, where $r_0 = \mu_o I/2\pi B_{\rm bias}$ is the centre position of the quadrupole field. As shown by the circles in Fig. 1(c), a larger bias field provides a larger field gradient. With a 2 A current and a 1Gauss bias field, the capture volume can be larger than 100 mm^3. It seems that the number of trapped atoms may be close to that of a normal MOT under such condition. The field gradient is 2.5 Gauss/cm, however for an efficient MOT it is slightly smaller; thus if the bias field is suitably adjusted, a considerable number of atoms could be directly trapped by a U-MOT.

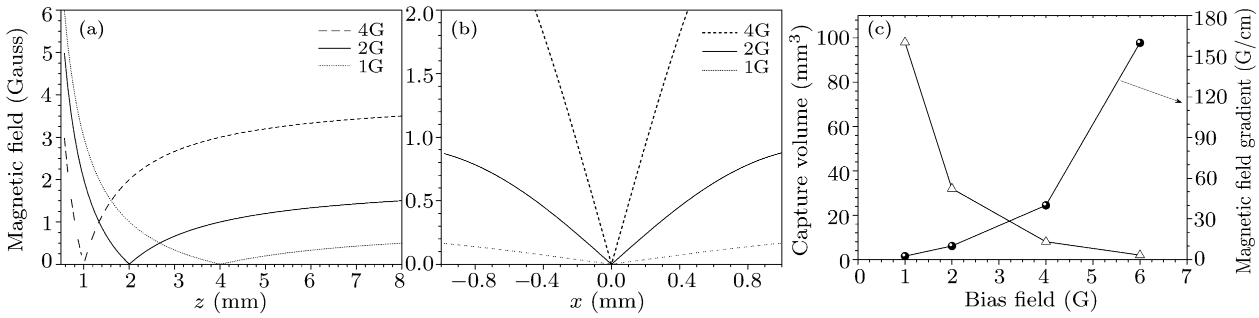

Fig. 1. Magnetic field and capture volume of U-MOT. (a) z-direction magnetic field, $I = 2$ A, $B_{\rm bias} = 1, 2, 4$ G. (b) x-direction magnetic field. (c) Capture volumes of for different bias fields (triangles); field gradient for different bias field (circles).

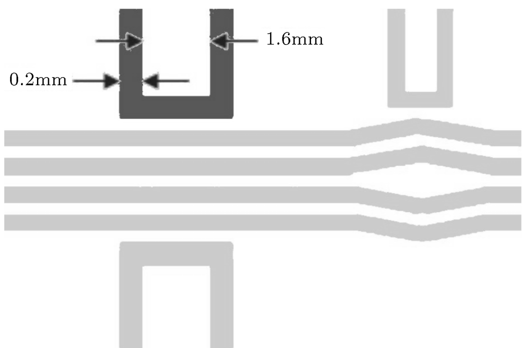

Fig. 2. Wire structures of the atom chips, including U-shaped traps, guiding wires, double Y-shaped splitting and recombining wires. Only the marked U-shaped wire is used in the present experiment.

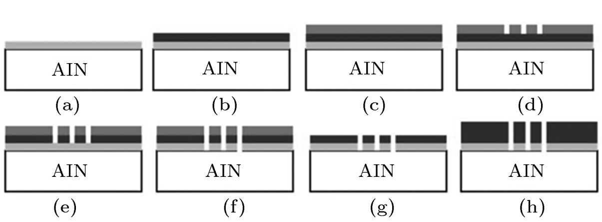

Fig. 3. Fabrication process of the atom chips with the substrate of AlN ceramic. (a) Evaporating Pt, (b) evaporating Au, (c) attaching photoresist, (d) photolithography, (e) etching Au, (f) etching Pt, (g) cleaning the photoresist, (h) electroplating Au.

The detailed structure of the gold wires on the atom chip is shown in Fig. 2, they include U-shaped traps, four wires for atom guiding, double Y wires for an atom beam splitter and recombiner.[11,12] The width of the U wires is 200 μm, and the width of the other wires is 45 μm. However, only the marked U-shaped wire (Fig. 2) is used in the present experiment.

This atom chip is fabricated by the wet etching method with an electroplating technique.[13] Figure 3 shows the fabrication process. The substrate is 1-mm-thick nitride aluminium (AlN) ceramic, which has relatively good thermal conductivity. It helps to sink the heat of the wires quickly. In order to increase the adherence strength between the substrate and the gold layer, a thin layer of platinum (Pt) is coated on the substrate before depositing the gold (Au). After depositing the gold film, standard photolithography and wet etching techniques are used to obtain the patterned wires on the chip. In fact, the main parts of the gold film are preserved on the substrate, except some 10 μm gaps that are used to isolate all of the patterned wires electrically. It is helpful to maintain the surface as a mirror.[14] The original thickness of the wires is several tens of nanometres. In order to increase the thickness of the wires, the electroplating process is applied many times, and the plating speed is well controlled to form a perfect mirror surface. The thickness of 3 μm is optimal for mirror reflection, and the best reflection index is more than 90% for 780 nm laser radiation. The fabrication process is used to overcome the inconsistency between the width of the gaps and the thickness of the gold wires. The wet etching could not only have vertical etching, but also has transverse etching. If the vertical etching is too deep, the transverse width will increase accordingly. The dimension of the finished chip is 1.5 cm×1.5 cm.

We installed the chip onto an oxygen-free copper block using a high vacuum thermal conductive epoxy (EPO-920). There is a ceramic block around the copper to hold the poles for electric connections. One side of the poles is connected to a twenty-pin feedthrough via high vacuum insulated wires. The other side of the poles is connected to gold wires on the chip through 25 μm gold threads. The whole chip setup is installed in a glass vacuum cell, and the inner pressure is pumped down to 10^{-7} Pa, a 20l ion pump is used to maintain the ultra high vacuum. A rubidium (Rb) dispenser is used to produce the atomic vapour. We firstly applied an intense current (5 A) on the dispenser to emit enough rubidium vapour, and lower the vacuum to 8×10^{-6} Pa, then we hold this vacuum during the experiment by reducing the current down to 4 A. An ordinary CCD camera is used to monitor atomic fluorescence of the trap area, and a calibrated photodiode and image lenses are used to measure the intensity of fluorescence and hence the number of trapped atoms.[15]

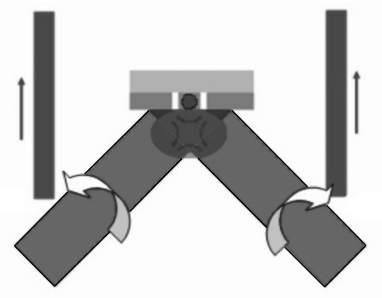

Fig. 4. Configuration of the U-MOT. Two pairs of laser beams are used. One pair is propagated just above the plane of the atom chip, the other pair is reflected by the chip at an angle of 45°. The micro quadrupole magnetic field results from the U-shaped wire on the chip and an extra bias magnetic field is provided by a pair of Helmholtz coils.

The configuration of the U-MOT is shown in Fig. 4. Two pairs of laser beams are used to cool and trap atoms. One pair of laser beams is propagated just above the plane of the chip, and the other pair is reflected by the chip surface at an angle of 45°. The micro quadrupole magnetic field is provided by the U-shape wire on the chip, the axis of the micro quadrupole magnetic field also tilted by 45° with respect to the mirror surface. An extra bias magnetic field is provided by a pair of Helmholtz coils. The diameter of the laser beams is 1 cm and the intensity is 9 mW/cm^2. The detuning of the cooling laser frequency is set to match the 13 MHz red shift to the atomic resonance of ^{85}Rb: $5S_{1/2}$, $F = 3 \rightarrow 5P_{3/2}$, $F = 4$. The power of the repumping laser is 6 mW, and its frequency is tuned into resonance with ^{85}Rb: $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$, $F = 3$.

In order to trap more atoms, the centre of the laser beams is carefully adjusted to overlap with the centre of the micro quadrupole field. Fortunately, the centre of the micro quadrupole field can be calculated from $\mu_o I/2\pi B_{\rm bias}$. When the current of the U wire is set to 2 A and the bias field is set to 2 Gauss, the centre of the micro quadrupole field is 2 mm below the surface of the chip. Therefore, we need to adjust the position of the laser beams to match the centre of the micro quadrupole. After carefully adjustment, we obtained a fluorescence signal of trapped atoms in the U-MOT as shown Fig. 5(a) and the spatial distribution of cold atoms shown in Fig. 5(b). The number of atoms is 2×10^6. This capture efficiency is almost the same as in the traditional technique, namely loading from a mirror-MOT.

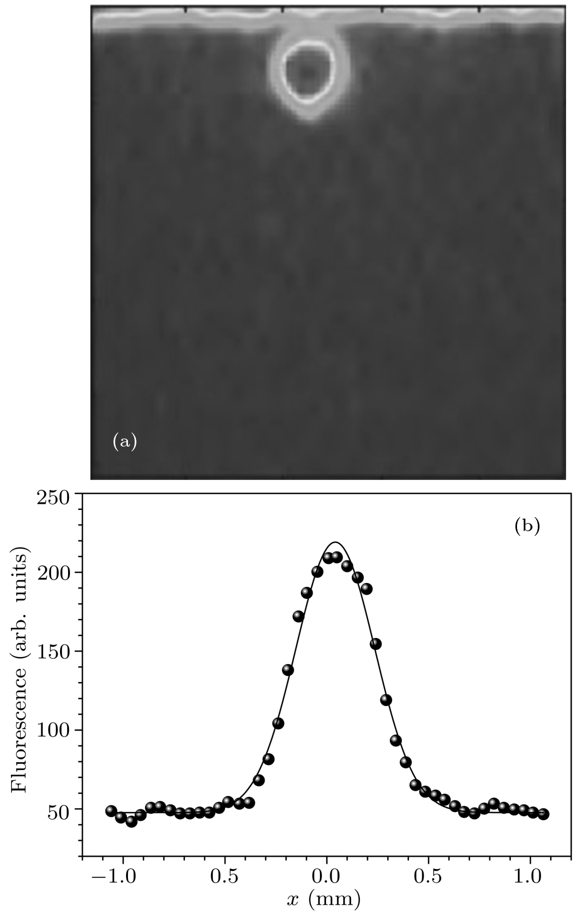

Fig. 5. Experimental demonstration of the U-MOT: (a) the fluorescence signal of trapped atoms in the U-MOT, (b) the density distribution of cold atom in the U-MOT.

Besides this centre-to-centre adjustment, the choice of the centre position of the trap is also very important. As shown in Fig. 1(c), the capture volume is proportional to the current and inversely proportional to the bias field. Therefore, an intense current in the U-shaped wire and a small bias field will form a larger capture volume. However, the field gradient also depends on the bias field and the relation is one of proportionality. This means that a smaller bias field will decrease the field gradient and hence decrease the capture ability of the U-MOT. The best ratio between the current and bias field, which also determines the centre of the quadrupole field, is hard to calculate theoretically, but it is easier to determine experimentally. The experimental result of dependence of capture ability on parameters is shown in Fig. 6. When keeping the current fixed and decreasing the value of the bias field, the capture ability increases at first, and then it decreases. The optimum position occurs at point A (Fig. 6), for which the bias field is 2 Gauss when the current is 2 A, the corresponding trap volume is 40 mm^3 and the field gradient is 10 Gauss/cm. Increasing the current, which is limited by the conductivity of the U wire, would further increase the capture ability of the U-MOT.

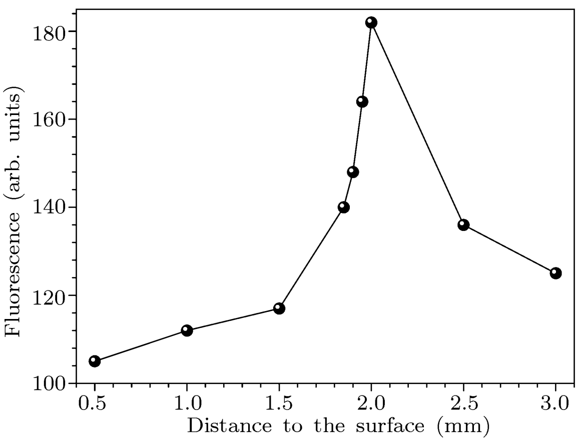

Fig. 6. Dependence of capture ability on the position of the micro quadrupole magnetic centre.

As shown in Fig. 7, if an array of U-shaped wires are fabricated on a chip instead of a single U-shaped wire, then with exactly the same configuration of laser beams, an array of U-MOTs can be realized simultaneously. When altering the optical beams from Gaussian beam to plane beam, all the U-MOTs will have the same capture efficiency. In other words, all the traps have the same amount of atoms, which is useful for future experiments, on quantum information processing, etc. With the corresponding Z-shaped wires on the chip, magnetic atomic lattice can readily be created by adiabatic transferring them from the corresponding U-MOTs.

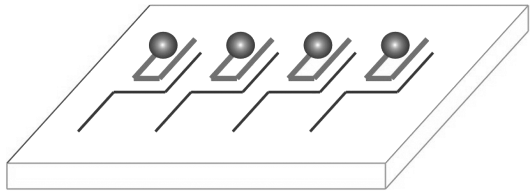

Fig. 7. Structure of an array of U-MOTs for atom lattice.

In conclusion, we have designed and realized a chip-size U-MOT. With 2 A current applied to U-shape wire and 2-Gauss horizontal bias field, as many as 2×10^6 cold ^{85}Rb atoms are directly trapped in this U-MOT. The number of cold atoms is enough for further experiments, such as quantum computer and cold atom interferometer. In contrast with an ordinary mirror-MOT, the size of this U-MOT is greatly reduced due to the omission of the larger anti-Helmholtz coils. This new miniature scheme is useful for further experiment, such as static magnetic traps for atoms. It is also possible to create an atom lattice on a single atomic chip, which may find application for quantum information processing in the future.

We would like to thank Chen Bingruo and Liu Zhiping for their help in atom chip fabrication.

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