Chin. Phys. B Vol. 19, No. 2 (2010) 023204

Production and guidance of pulsed atomic beams on chip*

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(Received 19 December 2008; revised manuscript received 7 July 2009)

We demonstrated two experimental methods of producing and guiding pulsed atomic beams on chip. One is to trap atoms first in a U-type magneto-optical trap on the chip, then transfer them to the magnetic guide field and push them simultaneously by a continuous force from the power imbalance of the magneto-optical trap laser beams hence the pulsed cold atom beams are produced and move along the magnetic guide to the destination. The other is to trap atoms directly by a H-type magneto-optical trap, then push them to make them move along the magnetic guide field, thus high rate cold atom beams can be produced and guided on the chip.

Keywords: atom guide, atom chip, pulsed atomic beam

PACC: 3280P, 4250

1. Introduction

The atom chip has attracted more and more attention recently due to its inherent application in the integration and miniaturization of atom optical devices.[1,2] For example, the chip-based atom interferometer will be more applicable;[3−8] chip-based Bose–Einstein condensate (BEC) is a robust way to achieve the compact atom laser.[9−15] The most important problem for atom chip experiments is how to produce and guide atoms near the surface of a chip. Several groups have presented results about chip-based atom guiding.[16−23] However, studies of producing atomic beams on the atom chip are scarce. Of course, freely expanded cold atoms can be used for the atom guiding,[19,21,23] but due to the freely expanding character, the wave packets of the guided atoms are spreading longitudinally, and the atom flux cannot be high. In order to solve this problem, static magnetic traps were used to accelerate and transfer atoms, but there need be extra controlling devices, such as macro magnetic coils, transport wires or extra laser beams.[20,22]

In the present paper, we demonstrate the methods of producing and guiding pulsed atomic beams on a chip. What is different from the previous work is that here there is no need for macro coils, transport wires or extra laser beams and the cold atoms are directly trapped and guided on the atom chip. The wave packets of the pulsed atoms are tight in the longitudinal direction. Atoms are first trapped from the vacuum background by a U-type magneto-optical trap (U-MOT), then pushed by one pair of the magneto-optical trap (MOT) beams and guided away from the trapping area. In order to simplify the process and increase the atom flux, we also directly trap atoms by a H-type magneto-optical trap (H-MOT) and thus the cold atoms could be guided without transferring. In this case, in the guiding process there is no need to stop while the next H-MOT is loaded, and the high rate cold atomic beams, even quasi-continuous, can be produced. The guided atomic beams can be used for atom interferometer,[3−5] atom laser,[24−26] atomic clock[27] and even neutral atom quantum computer.[28−30]

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*Project supported by the National Basic Research Program of China (Grant Nos. 2005CB724505/1 and 2006CB921203), and the National Natural Science Foundation of China (Grant No. 10774160), and the Science Foundation of Wuhan National Laboratory for Optoelectronics (Grant No. P080001).

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2. Experimental setup

Our atom chip was fabricated by combining wet etching method with the electroplating techniques.[31] After fabrication, the atom chip was mounted inside an ultra high vacuum glass cell. The dimension of the atom chip was 15 mm × 15 mm, and the wire structure on the atom chip is shown in Fig. 1. Only the dark wires were used for trapping and guiding experiments. The width of U-shape wire was 0.2 mm, the width of each straight wire was 45 μm and the space between two straight wires was 10 μm.

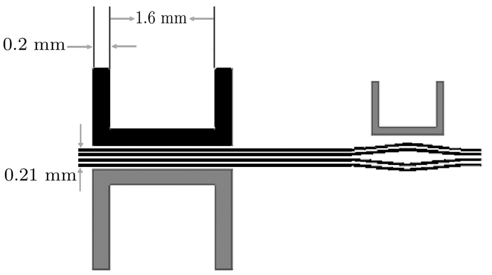


Fig. 1. Wire structure of the atom chip.

The guiding potential is created by the four straight parallel wires with an external horizontal bias magnetic field; this is the standard guiding configuration.[16,32] The four wires carrying parallel currents can be considered as a single wire with higher current carry ability. The magnetic field distribution can be described as

$$B = \sum_{i=1}^{4} \mu_0 I_i / 2\pi r_i + B_{\text{bias}} \ , \tag{1}$$

where μ_0 is the susceptibility of vacuum, I_i is the operated current, r_i is the radial distance from the i-th wire, and B_{bias} is the horizontal bias field. As shown in Fig. 2, the direction along the guiding is indicated by y direction and the other two directions are x and z directions. There is a minimum field point above the current-carrying wires in the x–z plane, which forms the guiding potential for weak-field seeking atoms. The position of the zero field point, which is determined by $z = 4\mu_{\text{o}} I_{\text{i}} / 2\pi B_{\text{bias}}$, depends on the bias magnetic field when the operation current is fixed. The magnetic potential above the double Y-shape part of the four wires is almost the same as that of the straight wires because of the same currents and small separation between centres (200 μm).

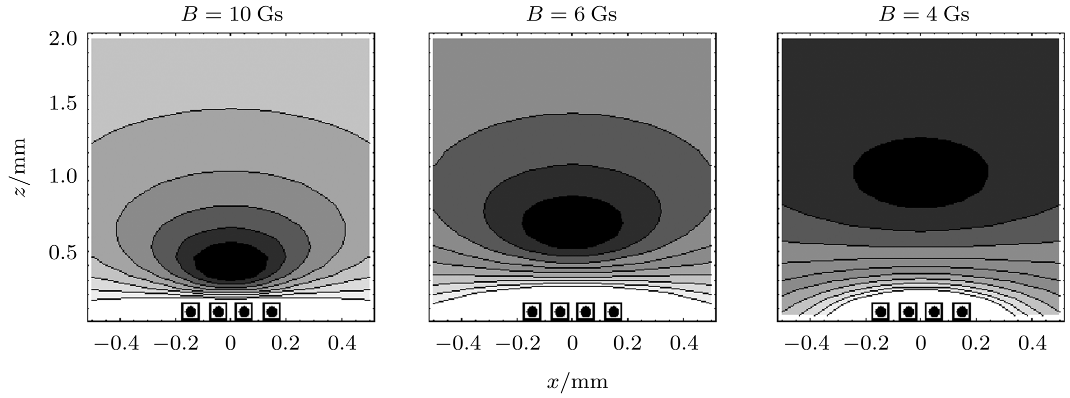


Fig. 2. Magnetic field distribution of four current-carrying wires, showing that the positions of guiding potential minimum are different at the bias magnetic field values of 10 Gauss, 6 Gauss and 4 Gauss (1 Gs = 10^{-4} T).

The experimental setup is shown in Fig. 3. First of all, a U-MOT was used to trap the atoms.[31,33] Two pairs of laser beams were used in the experiment. One pair of laser beams was arranged near the surface of the chip and propagated in the direction parallel to the guiding wires, the other pair was reflected by the chip surface with an angle of 45°, which is shown in Fig. 3. The diameter of the laser beams was 10 mm and the power intensity was 9 mW/cm^2. The detuning of the cooling laser frequency was set to be 13 MHz red shift to atomic resonance of ^{85}Rb: 5S$_{1/2}$, F = 3 $\rightarrow$ 5P$_{3/2}$, F = 4. The power of the repumping laser was 6 mW, and its frequency was tuned to resonance of ^{85}Rb: 5S$_{1/2}$, F = 2 $\rightarrow$ 5P$_{3/2}$, F = 3. The atomic vapour was provided by an Rb dispenser. An ordinary CCD camera was used to monitor atomic fluorescence of the trap area, and a digital CCD camera and image lenses were used to record fluorescence signals and to measure the number of trapped atoms.

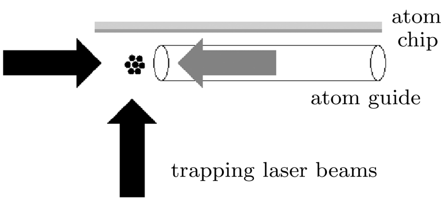


Fig. 3. Experimental setup, where cold atoms are trapped by a U-MOT first, and then launched to the guiding area by the unbalanced trapping laser beams.

3. Pulsed atom guide

With a 2-A current in the U-shape wire and a 2-Gs bias magnetic field, about 2×10^6 atoms were trapped directly from background.[31,34] The U-MOT magnetic field was shut off after 200 ms trapping process and the guiding potential was applied simultaneously ($I_i = 0.5$ A, $B_{\rm bias} = 2$ Gs). The potentials of the guide and the U-MOT overlap with each other under these parameters. Then cold atoms were launched by unbalancing intensities of the laser beams, and they flowed along the guiding wires. Due to the guiding potential, cold atoms were confined in the x–z plane, but they were free in the y direction. The imbalance force of two MOT beams in the y direction effectively pushed atoms along the guiding direction.[35] This is similar to the one-dimensional moving molasses, where the force came from the unbalanced frequency detuning.[36] The forces due to gravity and the power imbalance of the other beams should also be considered, but they were counteracted by the guiding force. At low temperature (Doppler cooling limit, $kV \ll \varDelta$), the force formed by the unbalanced laser beams can be simply described as[35,36]

$$F \approx \hbar k \frac{\varGamma}{2} \frac{I_{\rm L}/I_{\rm s}}{1 + I_{\rm L}/I_{\rm s} + (2\Delta/2\varGamma)^2} - \hbar k \frac{\varGamma}{2} \frac{I_{\rm R}/I_{\rm s}}{1 + I_{\rm R}/I_{\rm s} + (2\Delta/2\varGamma)^2}, \qquad (2)$$

where $\hbar k$ is the photon momentum, $\varGamma$ is the line width of the excited state, $I_{\rm s}$ is the saturated intensity, $\varDelta$ is the detuning of the laser, V is the average velocity of the atoms, $I_{\rm L}$ and $I_{\rm R}$ are the intensities of the left and the right laser beams, respectively. Thus the atoms feels a constant force $F \propto I_{\rm L} - I_{\rm R}$ for $kV \ll \varDelta$; then the atoms is uniformly accelerated in the unbalanced laser field ($a \propto (I_{\rm L} - I_{\rm R})/m$). It is worth while mentioning that the atom beams are accelerated only until the Doppler frequency shift is big enough to balance the force of the two laser beams. However, this does not happen in the short accelerating time for our experiment.

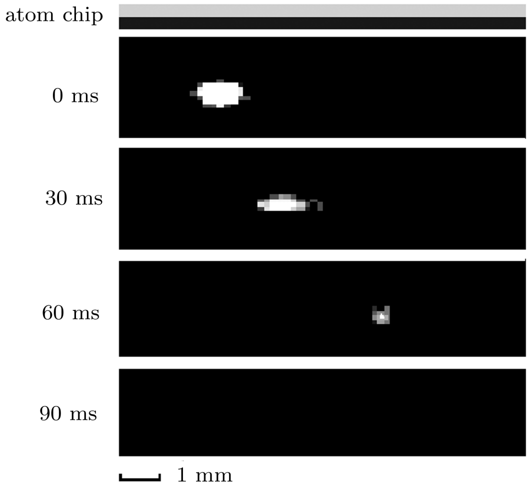


Fig. 4. TOF fluorescence signals of the guided atoms on the atom chip. Guiding position is 2 mm beneath the chip surface, and the atoms move 3.7 mm in 60 ms.

The time of flight (TOF) fluorescence signal is shown in Fig. 4. The guiding distance is about 0.9 mm in the first 30 ms and 3.7 mm in a whole guiding time of 60 ms; the average velocity is 0.06 m/s. The unbalanced power of two parallel laser beams is about 2% of the whole power (9 mW), which has no distinctive effect on the U-MOT. The unbalanced laser beams supply a continuous constant push force, which accelerates the atoms uniformly. The effective acceleration is 2 m/s^2, which is coincident with the theoretical analysis as shown in Fig. 5. Increasing the unbalanced laser intensity, the corresponding acceleration is also increased, which is also shown in Fig. 5. When the unbalanced laser intensity is bigger than 2 mW/cm^2,

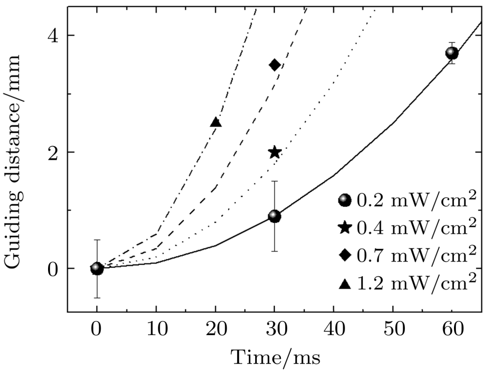


Fig. 5. Curves for guiding distance versus guiding time, where symbols are for the experimental data and lines are for theoretical results at different imbalanced laser intensities.

the U-MOT is no longer stable and the atom number is decreased rapidly.

To estimate the guide efficiency, we now shut down the quadrupole magnetic field of the U-MOT and let the cold atoms expand freely. The TOF fluorescence signals are shown in Fig. 6. In the expanding process, atoms are confined by the force of the MOT laser beams combined with the gravity. The atoms trend to the atom chip surface for the slightly higher intensity in the upward-direction laser beams caused by the nonideal reflection of the atom chip. The atom loss caused by the free expanding and the collision with the background vapour is shown in Fig. 7 as black spheres.

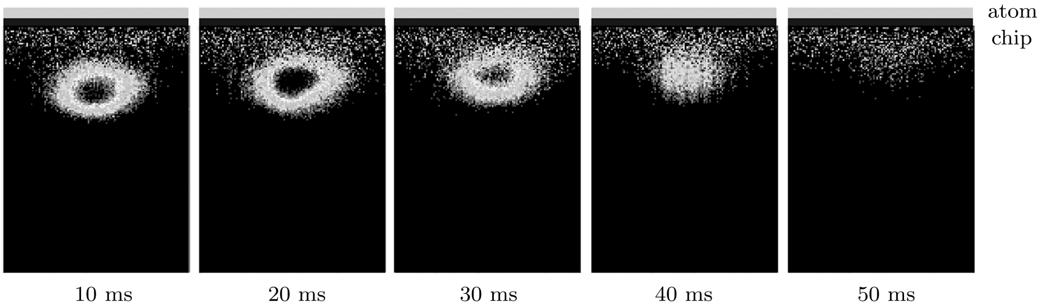


Fig. 6. Evolution of TOF fluorescence signals of cold atoms in the molasses on a chip.

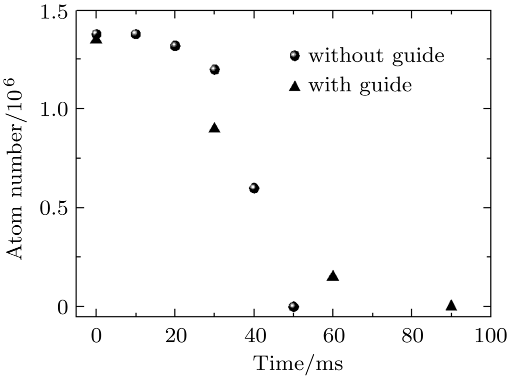


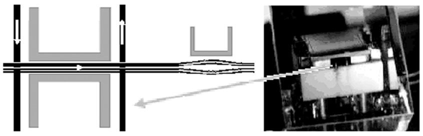
Fig. 7. Atom numbers versus TOF time, black spheres are for free expanding case and the triangles are for the case with guiding potential.

As shown in Fig. 7, guiding potential does make half of the atoms spread along the guide, meanwhile the loss rate of atoms decreases a little. The guiding distance is about 4 mm, which is limited by both the length of the atom guide and the loss rate. In order to avoid the Majorana transitions at the zero field point, a constant bias magnetic field is added along the guiding direction. However, two other main loss mechanisms still exist. One is the loss of strong-field seeking atoms. This is the reason why the atoms lost in the guiding stage are even more than in the free expanding in the first 30 ms. The other and also the main loss mechanism is the continuous interaction between the atoms and the MOT beams. The latter can be avoided by shutting down the MOT beams after the atoms have been launched. Increasing the total number of trapped atoms and using a non-state-selected atom guiding on the atom chip (such as evanescence wave guiding)[37,38] are the effective ways to increase the number of guided atoms and the guiding distance.

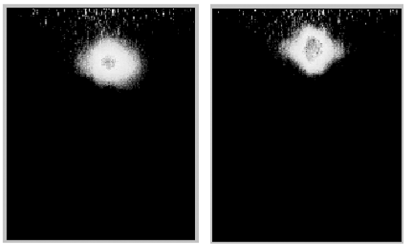
4. High rate atom guide

Up to now, we could produce pulsed atomic beams on the atom chip. However, the guide must be shut down when we load the next MOT on this kind of beam machine. Thus we could not expect to achieve a large rate flux if we want to keep the guide life longer. In order to solve this problem, we demonstrate trapping atoms directly in the guide with an H-MOT. As shown in Fig. 8(a), an extra pair of parallel wires that are perpendicular to the guiding wires is applied. This wire pair combining with the guide lines can also produce a quadrupole magnetic field for an MOT. With a 2-A current in the H-type wires, the atoms can be trapped directly in the H-MOT. As shown in Fig. 8(b), the H-MOT has the same efficiency as the U-MOT.

Then if we shut down the current of the extra pair of parallel wires, the potential for the cold atoms changes from a quadrupole magnetic field to a magnetic guide. And hence, the atoms will be pushed and move along the guide by the force from the power imbalance of the MOT laser beams as what we declared above. In this case, the guiding potential works all the time even when we load the MOT. Thus the atomic beams will not be lost in the absence of the guiding potential during the load of the next MOT. Without transferring and shutting down the guiding potential, five atomic beams were produced and guided per second in the experiment. The TOF fluorescence signal is the same as that shown in Fig. 4.



(a)



UMOT HMOT

(b)

Fig. 8. (a) Configuration of the H-MOT (left) and position of the extra wires (right); (b) comparison between fluorescence signals of a U-MOT and an H-MOT with the same current (2 A) and bias magnetic field (2 Gs).

What is more, with this kind of beam machine, quasi-continuous atomic beam can be produced when the flux is big enough for the atoms to spread out to the point of overlapping. Due to the long loading time (200 ms) of the MOT and the short guiding time (60 ms), we have not realized the quasi-continuous atomic beams in the guide. However, we consider it is a potential manner to generalize quasi-continuous atomic beam on a chip if we have a curving guide which could guide the atoms out of the laser area to increase the guiding life.

5. Conclusion

We demonstrated two simple schemes to produce and guide a pulsed atom cloud on a chip. One starts with the U-type magneto-optical trap, and the other starts with the H-type magneto-optical trap. Cold atoms can be guided about 4 mm away from the trapping area. It is far enough to carry out further experiment, such as the guided atom-wave interferometer. The guiding length can be increased by shutting down the MOT laser beams after acceleration or using a curving guide to guide the atoms out of the laser field. What is more, the moving speed of the guided atom beam can be adjusted by controlling the amount of trapping laser unbalance and pushing time.

Acknowledgment

We would like to thank Chen Bing-Ruo and Liu Zhi-Ping for their help in atom chip fabrication.

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