Demonstration of a cold atom beam splitter on atom chip*

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We report an experimental demonstration of a new scheme to split cold atoms on an atom chip. The atom chip consists of a U-wire and a Z-wire. The cold atom cloud is initially loaded and prepared in the Z-trap, which is split into two separate parts by switching on the current of the U-wire. The two separate atom clouds have a distance more than one millimeter apart from each other and show almost symmetrical profiles, corresponding to about a 50/50 splitting ratio.

Keywords: beam splitter, cold atoms, atom chip

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1. Introduction

Development of atom beam splitters for cold atoms is an important topic of theoretical and experimental study, which is an essential component in quantum optics and atomic physics. The atom beam splitters have the applications to the observation of fundamental physics phenomena, such as measurement of number-squeezed states and Poisson states of cold atoms in optical lattices,[1] fundamental interference studies with heavy molecules,[2] matter-wave interferometry,[3] and so on. There are two primary types of beam splitters for cold atoms. One is employing periodic optical potential acting like physical diffraction gratings[4–6] or pulsed magnetic field gradient using Stern–Gerlach effect[7] to split cold atoms in momentum space and then generating a spatial separation. The atoms splitting in momentum space has been demonstrated in developing various atom or molecule interferometers[8–12] with high precision measurements of rotation,[13,14] acceleration,[15] and gravity.[16–18] The other is dynamically splitting a single trap into a double well potential to split a wave packet into two spatially separated wave packets, which can be realized by optical dipole traps,[19–22] magnetic traps[23,24] or time-averaged adiabatic potentials.[25,26] Dynamical splitting in the spatial domain can keep the atoms confined, which is useful for the versatility of interferometers.[27]

An atom chip using micro-fabricated wires and electrodes to generate magnetic and electric fields in the vicinity surface of a planar substrate is an extremely versatile tool for robust trapping and manipulating ensembles of cold atoms.[28] The ability of the atom chip to generate various magnetic potentials and integrate other atom-optical elements has made it an ideal tool for the splitting of cold atoms in the spatial domain. Since the first beam splitter was demonstrated in an atom chip with Y-shaped wires by Schmiedmayer *et al.*,[23] much progress has been made in creating a beam splitter by various wire configurations.[29–31] In this paper, we report an experimental investigation of a new beam splitter on an atom chip. The wire layout of the atom chip consists of a U-wire and a Z-wire, which can transfer and trap cold atoms. The cold atoms are initially loaded and prepared in the Z-trap. After we switch on the current of the U-wire, the atom cloud can be split into two separate parts.

The rest of the paper is organized as follows. In Section 2, we briefly show the theoretical calculation and analysis. In Section 3, our experimental setup and procedure are described. The experimental results are presented and discussed in Section 4.

2. Theoretical calculation and analysis

The wire layout of the atom chip used in our experiment is shown in Fig. 1(a), which consists of a U-wire and a Z-wire that have a height of 5 μm. The width of the U-wire is 200 μm and 100 μm for the Z-wire, while the length of the central bar of the U-wire and Z-wire are 600 μm and 1900 μm, respectively. The distance between the two central bars of the U-wire and Z-wire is 10 μm (160 μm center-to-center). The arms of the U-wire and Z-wire can be treated as semi-infinite long wires. Combined with an external bias field B_y, the magnetic trap generated by the U-wire is a three dimensional quadrupole trap and the Z-wire creates an Ioffe–Pritchard-type (IP) trap.

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With appropriate laser light, the U-trap is well-suited to create a magneto-optical trap. The Z-trap has a nonzero field in the minimum which could avoid Majorana spin-flip losses and can be used for evaporative cooling to realize Bose–Einstein condensation (BEC). If the currents of the U-wire and Z-wire are coexistent and the directions of the currents are shown in Fig. 1, there is a new trap created that can be used to split cold atoms. In order to understand the mechanism of the new trap splitting cold atoms, we should calculate the magnetic field generated by the wire layout.

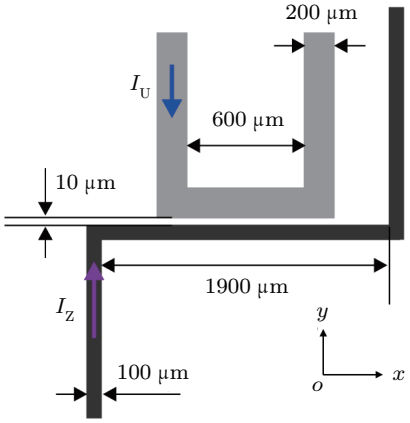


Fig. 1. (color online) Wire layout of the atom chip used in our experiment. (a) The atom chip consists of a U-wire (I_U, 200-μm wide) and a Z-wire (I_Z, 100-μm wide). The length of the central bar of the U-wire and Z-wire are 600 μm and 1900 μm, respectively. The distance between the two central bars is 10 μm.

If we treat the wires as infinitely thin and ignore the width of the wire, the magnetic field of an observation point P generated by a DC current I with an element of length $\mathrm{d}\boldsymbol{l}$ is[33]

$$\mathrm{d}\boldsymbol{B} = \frac{\mu_0 I}{4\pi}\frac{\mathrm{d}\boldsymbol{l}\times P\boldsymbol{R}}{\boldsymbol{R}^3}, \tag{1}$$

where R is the coordinate vector from the element of length to the observation point P, μ_0 is the permeability constant of free space. The direction of the magnetic field can be defined by the right-hand rule. However, a real micro-fabricated wire has a rectangular cross section and the width (w) is greater than the height (h). When the width of the wire becomes comparable to the distance between the trap minimum and the chip surface, the width should be considered. The whole magnetic field of the observation point P is the integral of all the wires,

$$\boldsymbol{B} = \frac{\mu_0 I}{4\pi w}\int_w\int_l \frac{\mathrm{d}\boldsymbol{l}\times\boldsymbol{R}}{\boldsymbol{R}^3}\mathrm{d}w. \tag{2}$$

The consequent potential experienced by the atoms is

$$V = g_F\mu_B m_F B, \tag{3}$$

where μ_B is the Bohr magneton, g_F is the Lande factor, and m_F is the magnetic quantum number.

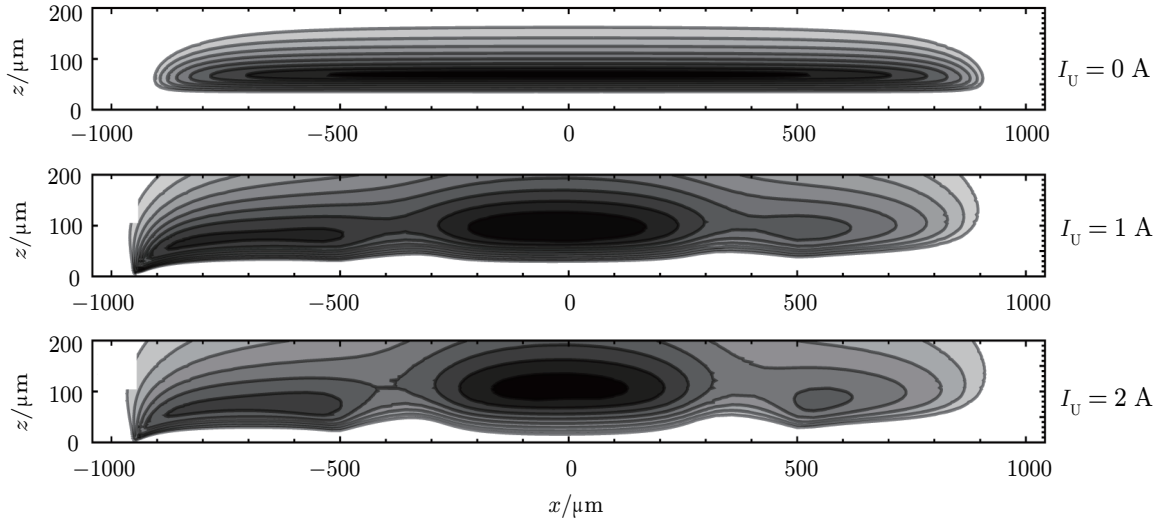


Fig. 2. Contour plots of the magnetic field in the xz plane for different currents of the U-wire, where the external bias field B_y is 50 Gs (1 Gs = 10^{-4} T) and the current of the Z-wire I_Z is 2 A. The Z-trap (a) can deform into three traps after switching on the current of the U-wire. Panels (b) and (c) are corresponding to $I_U = 1$ A and $I_U = 2$ A.

We calculate the magnetic field generated by the wire layout in Fig. 1, and the results are shown in Fig. 2, in which we assume the external bias field B_y is 50 Gs and the current of the Z-wire I_Z is 2 A. Figure 2 shows the contour plots of the magnetic field in the xz plane for different currents of the U-wire. When we switch off the current of the U-wire ($I_U = 0$), it can be seen that the trap is a Z-trap which is a very elongated trap (see Fig. 2(a)). When we switch on the current of the U-wire ($I_U = 1$ A and $I_U = 2$ A), the elongated trap transforms from a single trap to three traps and hence splitting cold atom is possible (see Figs. 2(b) and 2(c)). The distances between the center of the two side traps of Figs. 2(b) and 2(c) are 1264 μm and 1359 μm, respectively, corresponding to $I_U = 1$ A and $I_U = 2$ A. Figure 3 shows the magnetic field in the x direction

for different I_U. The Z-trap (blue line) has a very flat bottom. After switching on the current I_U, the center of the bottom has a zero field minimum which may result in cold atoms being lost from the trap due to Majorana spin-flip.

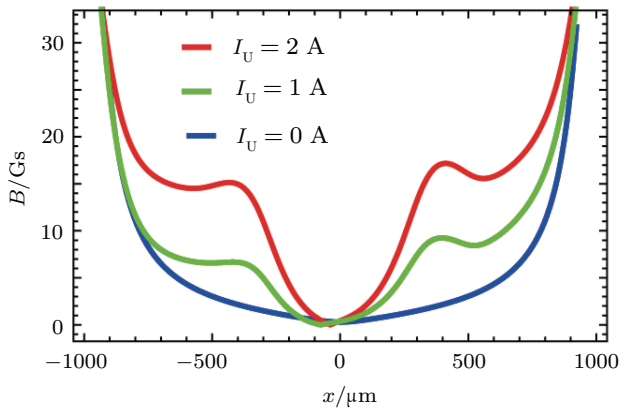


Fig. 3. (color online) The magnetic field in the x direction for different I_U. The bottom of the Z-trap (blue line) is very flat and has a non-zero field minimum. The center of the bottom has a zero field minimum (green and red lines) after switching on I_U.

3. Experiment procedure

The general setup of our experiment is detailed in Ref. [32]. In the first step, we use a mirror-MOT[34] for previous cooling and collecting of ^{87}Rb atoms from the background vapor cell. The background pressure of the vapor cell is about $1\times\ 10^{-8}$ Pa. Within 8 s we accumulate about $(3\sim5)\times10^6$ ^{87}Rb atoms with a temperature of about 200 μK at a distance of about 6 mm from the chip surface. Then we compress the mirror-MOT by increasing the current of the anti-Helmholtz coils for a time of 10 ms. Meanwhile, we switch on the current of the U-wire ($I_U = 3.6$ A) and the external bias field along y axis ($B_y = 1.5$ Gs) to create a quadrupole trap and the atoms are transferred from mirror-MOT to U-MOT without substantial loss. Subsequently, we switch off the current of the anti-Helmholtz coils and ramp down I_U from 3.6 A to 1.2 A in 8 ms to move the atoms closer to the chip surface. The cold atoms have a distance of 900 μm from the chip surface. After holding the atoms in the U-MOT for 8 ms, all magnetic fields are switched off and the cold atoms are further cooled through polarization gradient cooling by linearly increasing the cooling laser detuning from 20 MHz to 50 MHz for a time of 4 ms. The atoms are cooled down to 20 μK and have a Gaussian diameter of about 1100 μm.

After cooling and trapping, a bias field of 10.5 Gs along x axis is applied for 1 ms to define a quantization axis. Meanwhile, with a pulse of 500 μs and 0.8 mW of σ^+ light on the $|F=2\rangle \rightarrow |F'=2\rangle$ transition, the atoms are optically pumped into the low-field-seeking $|F=2, m_F=2\rangle$ spin state in preparation for loading into the Z trap. About $(1\sim1.5)\times10^6$ ^{87}Rb atoms with a temperature of about 100 μK are loaded into the Z trap by switching on $I_Z = 2$ A and $B_y = 11$ Gs within 1 ms. To this end we linearly ramp up the bias field B_y to 50 Gs for a time of 115 ms to adiabatically compress the atoms while the current I_Z is kept constant. After holding the atoms in the Z-trap for 10 ms, we rapidly switch on the current of the U-wire to split the atoms.

4. Results and discussion

The experimental results are shown in Fig. 4. About 1×10^6 ^{87}Rb atoms are initially loaded and prepared in the Z-trap as shown in Fig. 4(a).

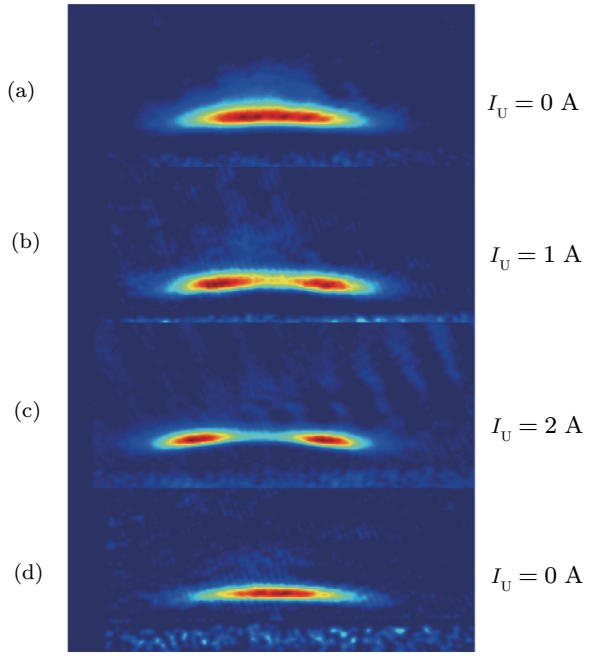


Fig. 4. (color online) Absorption images of the cold atoms in the xz plane under different I_U. (a) Cold atoms are initially loaded and prepared in the Z-trap ($I_U = 0$ A). (b)–(c) The atom cloud is split into two parts with almost symmetrical profiles ($I_U = 2$ A and $I_U = 4$ A), corresponding to a 50/50 splitting ratio. (d) After switching off the current of the U-wire , the two separate atom clouds are recombining to a single atom cloud again.

We can see that the atom cloud is a long strip shape with a Gaussian diameter of 1732 μm in x direction and 278 μm in z direction. After we switch on the current of the U-wire, the atom cloud is split into two parts as shown in Figs. 4(b) and 4(c). The distances between the two atom clouds in Figs. 4(b) and 4(c) are 1092 μm and 1293 μm, respectively, corresponding to $I_U = 1$ A and $I_U = 2$ A. The number of the atoms in each of the clouds in Fig. 4(c) are 2.9×10^5 (left) and 2.5×10^5 (right), respectively, and almost half of the atoms have been lost in the splitting process. The two atom clouds show almost symmetrical profiles, corresponding to about a 50/50 splitting ratio. According to the theoretical calculation, the Z-trap is deforming into three traps when the currents of the Z-wire and U-wire are coexistent. However, the experimental results show that the atom cloud is only splitting into two parts. We can understand this result from Fig. 3, which shows the bottom of

the Z-trap is very flat and has a non-zero field minimum. After switching on the current of the U-wire, the magnetic field at the center of the bottom of the trap is reduced to zero while the magnetic field gradient around the center is increased, which makes the trap look like a funnel. The center part of the long strip-shaped cloud is lost due to Majorana spin-flip. In the mean time, the two side parts of the long strip-shaped cloud are loaded separately into the two side traps. After we switch off the current of the U-wire, the two separate atom clouds are recombining to a single atom cloud again as shown in Fig. 4(d), which has about 1.6×10^5 atoms.

5. Conclusion

In conclusion, we have experimentally demonstrated a simple scheme of splitting cold atoms on an atom chip. The wire layout of the atom chip consists of a U-wire and a Z-wire. The cold atoms are collected by a mirror-MOT and initially loaded and prepared in a Z-trap. By switching on the current of the U-wire, the atom cloud in the Z-trap has been split into two separate parts, which show almost symmetrical profiles, corresponding to about a 50/50 splitting ratio. The two atom clouds are a distance of more than one millimeter apart from each other.

References

[1] Bloch I, Dalibard J and Zwerger W 2008 *Rev. Mod. Phys.* **80** 885
[2] Juffmann T, Milic A, Müllneritsch M, Asenbaum P, Tsukernik A, Tüxen J, Mayor M, Cheshnovsky O and Arndt M 2012 *Nat. Nanotechnol.* **7** 297
[3] Cronin A, Schmiedmayer J and Pritchard D E 2009 *Rev. Mod. Phys.* **81** 1051
[4] Martin P J, Oldaker B G, Miklich A H and Pritchard D E 1988 *Phys. Rev. Lett.* **60** 515B
[5] Kasevich, M and Chu S 1991 *Phys. Rev. Lett.* **67** 181
[6] Wu S, Wang Y J, Diot Q and Prentiss M 2005 *Phys. Rev. A* **71** 043602
[7] Machluf S, Japha Y and Folman R 2013 *Nat. Commun.* **4** 2424
[8] Rasel E M, Oberthaler M K, Batelaan H, Schmiedmayer J and Zeilinger A 1995 *Phys. Rev. Lett.* **75** 2633
[9] Brezger, B, Hackermuller L, Uttenthaler S, Petschinka J, Arndt M and Zeilinger A 2002 *Phys. Rev. Lett.* **88** 100404
[10] Wang Y J, Anderson D Z, Bright V M, Cornell E A, Diot Q, Kishimoto T, Prentiss M, Saravanan R A, Segal S R and Wu S 2005 *Phys. Rev. Lett.* **94** 090405
[11] Pezze L and Smerzi A 2006 *Phys. Rev. A* **73** 011801
[12] Li W, He T and Smerzi A 2014 *Phys. Rev. Lett.* **113** 023003
[13] Lenef A, Hammond T, Smith E, Chapman M, Rubenstein R and Pritchard D 1997 *Phys. Rev. Lett.* **78** 760
[14] Gustavson T L, Landragin A and Kasevich M A 2000 *Class. Quantum Gravity* **17** 2385
[15] Peters A, Chung K Y and Chu S 1999 *Nature* **400** 849
[16] Peters A, Chung K Y and Chu S 2001 *Metrologia* **38** 25
[17] Fixler J B, Foster G T, McGuirk J M and Kasevich M A 2007 *Science* **315** 74
[18] Dubetsky B and Kasevich M A 2006 *Phys. Rev. A* **74** 023615
[19] Houde O, Kadio D and Pruvost L 2000 *Phys. Rev. Lett.* **85** 5543
[20] Shin Y, Saba M, Pasquini T A, Ketterle W, Pritchard D E and Leanhardt A E 2004 *Phys. Rev. Lett.* **92** 050405
[21] Mu R W, Wang Z L, Li Y L, Mu X M Ji R W, Wang Z L, Li Y L, Ji X M and Yin J P 2010 *Eur. Phys. J. D* **59** 291
[22] McDonald G D, Keal H, Altin P A, Debs J E, Bennetts S, Kuhn C C N, Hardman K S, Johnsson M T, Close J D and Robins N P 2013 *Phys. Rev. A* **87** 013632
[23] Cassettari D, Hessmo B, Folman R, Maier T and Schmiedmayer J 2000 *Phys. Rev. Lett.* **85** 5483
[24] Müller D, Cornell E A, Prevedelli M, Schwindt P D D, Zozulya A and Anderson D Z 2000 *Opt. Lett.* **25** 1382
[25] Schumm T, Hofferberth S, Andersson L M, Wildermuth S, Groth S, Bar-Joseph I, Schmiedmayer J and Kruger P 2005 *Nat. Phys.* **1** 57
[26] Lesanovsky I and von Klitzing W 2007 *Phys. Rev. Lett.* **99** 083001
[27] Shin Y, Sanner C, Jo G B, Pasquini T A, Saba M, Ketterle W, Pritchard D E, Vengalattore M and Prentiss M 2005 *Phys. Rev. A* **72** 021604
[28] Fortágh J and Zimmermann C 2007 *Rev. Mod. Phys.* **79** 235
[29] Hinds E A, Vale C J and Boshier M G 2001 *Phys. Rev. Lett.* **86** 1462
[30] Hommelhoff P, Hänsel W, Steinmetz T, Hänsch T W and Reichel J 2005 *New J. Phys.* **7** 3
[31] Ke M, Yan B, Cheng F and Wang Y Z 2009 *Chin. Phys. B* **18** 4823
[32] Yan B, Cheng F, Ke M, Li X L, Tang J Y and Wang Y Z 2009 *Chin. Phys. B* **18** 4259
[33] Jackson J D 1999 *Classical Electrodynamics*, 3nd edn. (New York: Wiley)
[34] Reichel J, Hänsel W and Hänsch T W 1999 *Phys. Rev. Lett.* **83** 3398