Eur. Phys. J. D **35**, 69–73 (2005)
DOI: 10.1140/epjd/e2005-00171-0

The European Physical Journal D

A reciprocal magnetic trap for neutral atoms

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Received 16 March 2005
Published online 21 June 2005 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 2005

Abstract. A novel magnetic trap for confining ultracold neutral atoms in a ring is proposed. The magnetic trap is generated by a microfabricated ferromagnetic structure integrated on an "atom chip". The structure is based on previously demonstrated fabrication techniques and is capable of creating tightly confining reciprocal traps with trap frequencies as large as 50 kHz. Also, the trap exhibits significantly smaller magnetic field inhomogeneities compared to other proposals for current-based reciprocal traps. The suitability of this trap for atom interferometry and the study of low dimensional ultracold systems is outlined.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 03.75.Dg Atom and neutron interferometry – 03.75.Be Atom and neutron optics

The ability to confine and manipulate ultracold atoms in tunable magnetic traps has given rise to an emerging field of integrated atom optics. This field finds wide applicability in atom interferometry, quantum information processing, physics of low dimensional systems and atom-light interactions in novel trap geometries. Microfabricated atom traps are well suited to these applications due to the combination of tight confinement, precise control of magnetic fields and robustness [1].

One particular field that has received widespread attention is the possibility of integrated atom interferometers to serve as highly accurate gradiometers and rotation sensors. For instance, free space interferometers sensitive to the Sagnac phase shift have been demonstrated with a short term sensitivity of 2×10^{-8} rad/s/$\sqrt{\text{Hz}}$ [2]. Since the Sagnac phase shift is proportional to the area enclosed by the interfering paths, the sensitivity could be increased by guiding ultracold atoms around large area reciprocal traps.

The basic requirements for guided atom interferometry are a coherent beamsplitter and an ability to guide the atoms without a loss of coherence. Coherent splitting and merging of ultracold atoms with optical beamsplitters has been demonstrated [3]. The loss of coherence during propagation along the waveguide can be due to many factors. The atom guide does not have to be single mode, and theoretical studies have shown that multimode guided atom interferometers can exhibit good fringe contrast [4]. However, this contrast is not immune to intermode scattering. The contrast is preserved only if the atomic motion along the guide is adiabatic. This means that the magnetic field and trap parameters need to be sufficiently homogeneous along the guide. Also, for atoms propagating along curved paths, the radial trap frequency needs to be sufficiently large to compensate for centrifugal forces. Another source of concern is the presence of the room temperature substrate close to the ultracold atoms. For a guided atom interferometer in which the atoms are confined close to the surface of an atom chip, thermal fluctuations in the metallic wires on the chip can act as a source of decoherence and loss [5]. A third source of inhomogeneity and decoherence peculiar to microfabricated atom chips is the fragmentation of atom clouds [6]. This effect is due to small imperfections on the surface and edges of the wires resulting in small modulations of the magnetic field. For atoms trapped less than around 150 μm from the surface of the chip, these modulations can break up the atom cloud. Thus, any integrated atom interferometer has to circumvent these limitations. In our proposed scheme, this is achieved by realizing tightly confining, symmetric traps located far (>100 μm) from the atom chip substrate.

Symmetric, reciprocal traps are an attractive proposition for rotation sensors since they exhibit a large common mode rejection of stray fields and time independent field variations along the propagation paths and can potentially enclose large areas. While reciprocal traps based on permanent magnets are easy to implement, they sacrifice dynamic tunability of the trap parameters and the ability to rapidly switch off the trap for time of flight diagnostics. Reciprocal traps based on current carrying wires are hard to design due to the constraint of coupling the current into and out of the ring. Large area ring traps have been demonstrated [7]. In these traps, the atoms observe significant magnetic field inhomogeneities along the propagation path. Also, the trap frequencies are on the order

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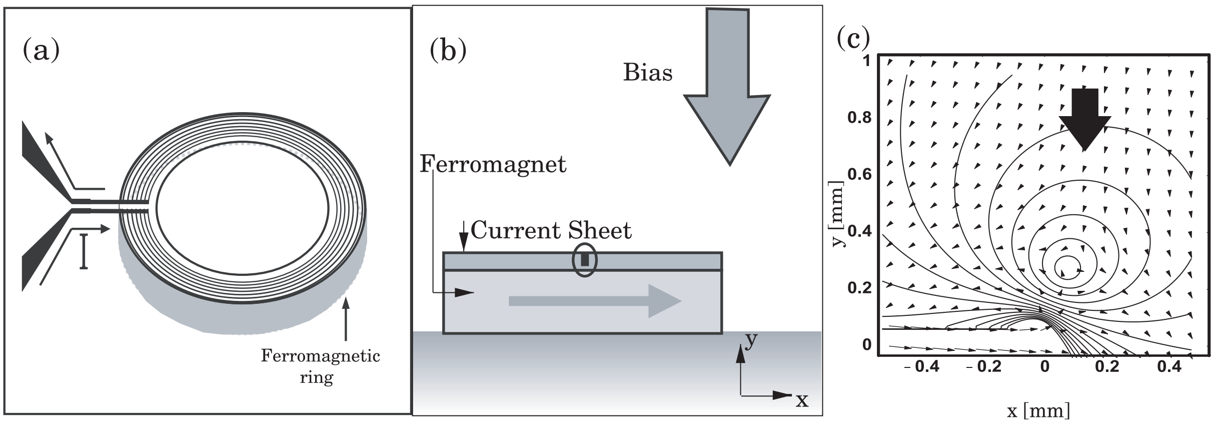

Fig. 1. (a) Schematic of the ring trap. The ferromagnetic ring has an inner and outer radius of 3 mm and 4 mm respectively. The typical thickness of the ferromagnetic sheet is 200 μm. The current sheet used to magnetize this ring is broken up into many discrete wires. This helps to magnetize the ring more homogeneously. (b) Cross-section of the ferromagnetic structure indicating the direction of magnetization and orientation of the current sheet and vertical bias fields. (c) Vector plot of the magnetic field illustrating the location of the magnetic field minimum (Figs. (b) and (c) are adapted from [9]).

of a hundred Hertz, much smaller than the temperature of the atoms. More recently, a tightly confining hybrid ring trap based on magnetic and electrostatic forces was proposed [8]. As was pointed out in this paper, the atoms are trapped very close (a few microns) to the substrate, and surface induced interactions could be significant.

In this paper, we describe a reciprocal magnetic trap based on soft ferromagnetic materials. The radial trap frequency can be as large as 50 kHz (2.5 μK) and the atoms can be trapped more than 100 microns above the substrate in order to minimize surface induced effects. Moreover, with the aid of a novel design, it is shown that the magnetic field inhomogeneities around the propagation path can be made arbitrarily small.

The schematic of the ring trap is shown in Figure 1. It consists of a microfabricated ring composed of a high permeability soft ferromagnet such as permalloy. A thin current sheet is deposited on the upper surface of this ring and serves to magnetize the ferromagnet. Typically, the ferromagnetic ring has an inner (outer) radius of 3 mm (4 mm), a width of 1 mm and a height of 200 microns. A thin layer of silicon dioxide insulates the current sheet from the ferromagnet.

For fields smaller than the saturation field of the ferromagnet (around 5 kG), the field of the ferromagnet is linearly proportional to the current through the current sheet. Thus, the magnetic field of this structure can be dynamically tuned to adjust the trap frequency and depth by varying the current. For the ferromagnetic atom chips fabricated thus far, the field of the ferromagnet is found to respond on the time scale of 20 μs to changes in the magnetizing current. This tunability is in contrast to the use of permanent magnets to generate the trapping potential. Also, the composition of the ferromagnet is chosen to minimize the remanent field when the current is switched off [9].

The behavior of the magnetic field of the ferromagnet in such a geometry has been described in detail in [9]. We summarize those results here. Due to the large aspect ratio of the ferromagnetic structure, the magnetization of the ferromagnet can be assumed to be uniform. In this case, it can be seen that the magnetic field curves around the ferromagnet. This field can be cancelled by a vertical bias field to create a quadrupole magnetic minimum. Since the external bias field is oriented perpendicular to the axis of the ferromagnet, crosstalk between the two fields can be minimized. The magnetization of the ferromagnet, the orientation of the bias field and the location of the magnetic trap are illustrated in Figure 1.

For a constant current through the current sheet, the location of the magnetic field minimum varies with the strength of the external bias field. This variation is shown in Figure 2. For small bias fields, the trap minimum is located far from the surface of the atom chip, with a small trap depth and oscillation frequency. Upon gradually increasing the strength of the bias field, magnetic traps with large trap frequencies are formed close to the surface of the atom chip. It can be seen that trap depths comparable to typical magneto-optic trap (MOT) temperatures ($\sim$100 μK) can be obtained a few millimeters away from the ferromagnet. The large trap depths and precise control over the trap location offers a mechanism to transfer atoms from a MOT into tightly confined ring traps with a large coupling efficiency.

Since the magnetic trap is formed by a combination of the ferromagnetic field and a vertical bias field, we can now consider bending the ferromagnet in the shape of a ring. To create a smooth, reciprocal ring trap, it is desirable to magnetize the ring uniformly. The current sheet that magnetizes the ferromagnet requires leads to couple current into and out of the sheet, necessarily creating an inhomogeneity in the magnetizing field. Thus, we need to consider the effect of this inhomogeneity on the ferromagnet. A number of strategies can be used to minimize this effect, and to create a smooth trap. Firstly, the use of the ferromagnet as the dominant contribution to the

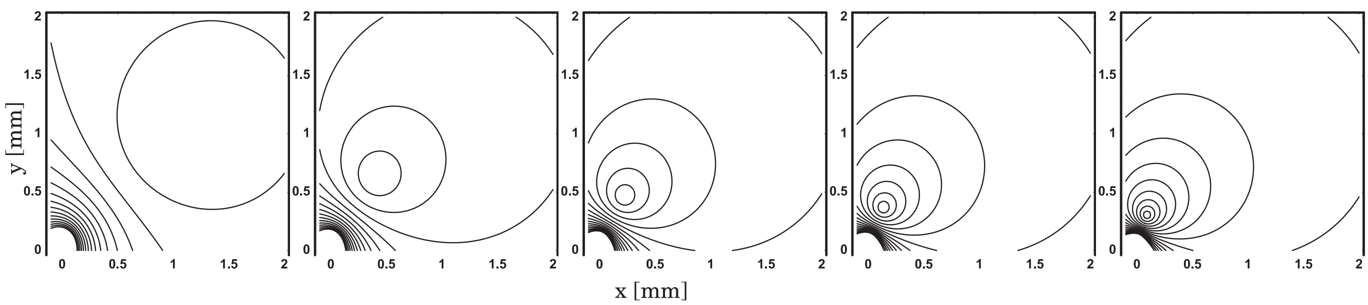

Fig. 2. Variation of the trap minimum as the strength of the bias field is increased. The large capture volume offers a way to transfer atoms from a cold source (such as a surface MOT) into the ring. The calculations were performed for a current of 5 A through the current sheet and vertical bias fields of 10 G, 20 G, 30 G, 40 G and 50 G. The contours are spaced 5 G apart (adapted from [9]).

magnetic field is in itself a large factor in "smoothing" over the magnetic field of the current sheet. In a crude sense, the ferromagnet in this context can be seen as a spatial low pass filter for the magnetic field of the current sheet.

Secondly, the current sheet can be suitably designed to ensure that the current density is relatively uniform across its breadth. For this, the gap in the current sheet is made as small as possible. In our simulations, we assumed a gap of 2 microns, well within the realms of current lithographic techniques. The edge of the current sheet is also recessed from the edge of the ferromagnet by around 200 microns. This helps to distance the gap in the current sheet from the location of the magnetic field minimum while not appreciably reducing the field of the ferromagnet.

Finally, the current sheet is broken up into many discrete wires. This has a marked effect on the homogeneity of the current density along the length of the current sheet, and thus on the resulting magnetization of the ferromagnet. Similar 'stranding' of current carrying conductors in linear atom guides has been proposed as a possible solution to fragmentation [10].

The magnetic field of this ring trap was calculated using a finite element electromagnetic simulation. In these simulations, the ferromagnetic ring had an inner (outer) radius of 3 (4) mm and a thickness of 200 μm. Calculations were performed for the case of (i) a current sheet with the same dimensions as the ferromagnet, (ii) a current sheet recessed 250 μm from the edge of the ferromagnet and (iii) a recessed current sheet that was broken up into discrete wires. In each case, the gap between the input and output leads of the current sheet was fixed to be 2 μm. For computational convenience, the current sheet in (c) was broken up into a maximum of eight wires. In practice, this number can be made much larger with a correspondingly smoother trap. It is feasible to consider the millimeter wide current sheet to be composed of a hundred wires a few microns wide.

Figures 3a, 3b and 3c indicate false color images of the current density in the current sheet for the three cases mentioned above. These images are magnified around the gap in the current sheet since this is expected to be the region with a large inhomogeneity in the magnetic field. It can be seen that stranding the current sheet leads to a homogeneous current distribution.

As was shown in Figure 2, the atoms are confined in a ring close to the inner edge of the ferromagnet. Thus, the variations of the magnetic field in this region are a good indication of the homogeneity of the trap. The magnetic field along a path corresponding to the inner circumference of the ferromagnet was sampled at different heights above the substrate. The results of these calculations are shown in Figures 3d, 3e and 3f. Since the currents in the input and output leads of the current sheet can also distort the trap, these were taken into account in the calculations. In the case of current sheet (i), it can be seen that there is a large dip in the magnetic field corresponding to the location of the gap. This dip becomes smaller at large heights above the substrate but is significant even around 300 μm above the ferromagnet. In contrast, the field of the recessed current sheet (ii) shows a significant improvement in the homogeneity of the field around the ring. This is indicative of the influence of the ferromagnet in "smoothing" the break in the current sheet. Stranding the current sheet leads to a dramatic improvement. Within the precision of the finite element calculation, the field around the ring appears homogeneous. The residual variations in the magnetic field are due to the discretization of the finite element mesh. These variations persist even in the ideal case of a uniformly magnetized ring.

The homogeneity of the magnetic trap can be measured in terms of the magnitude of the field dip near the current sheet as a function of the height above the substrate. At very large distances from the ferromagnet, this dip can be made negligibly small (corresponding to no field variations along the ring). Figure 4 shows the magnitude of the dip as a function of height above the substrate. It can be seen that the ferromagnet magnetized by the stranded current sheet is homogeneous even at heights of 50 μm.

The magnetic trap formed by the combination of the ferromagnet and the external bias field is quadrupole in nature. Hence, a small azimuthal magnetic field is required to protect the ultracold atoms from Majorana spin flips. This field can be provided by a wire aligned perpendicular to the plane of the ferromagnet.

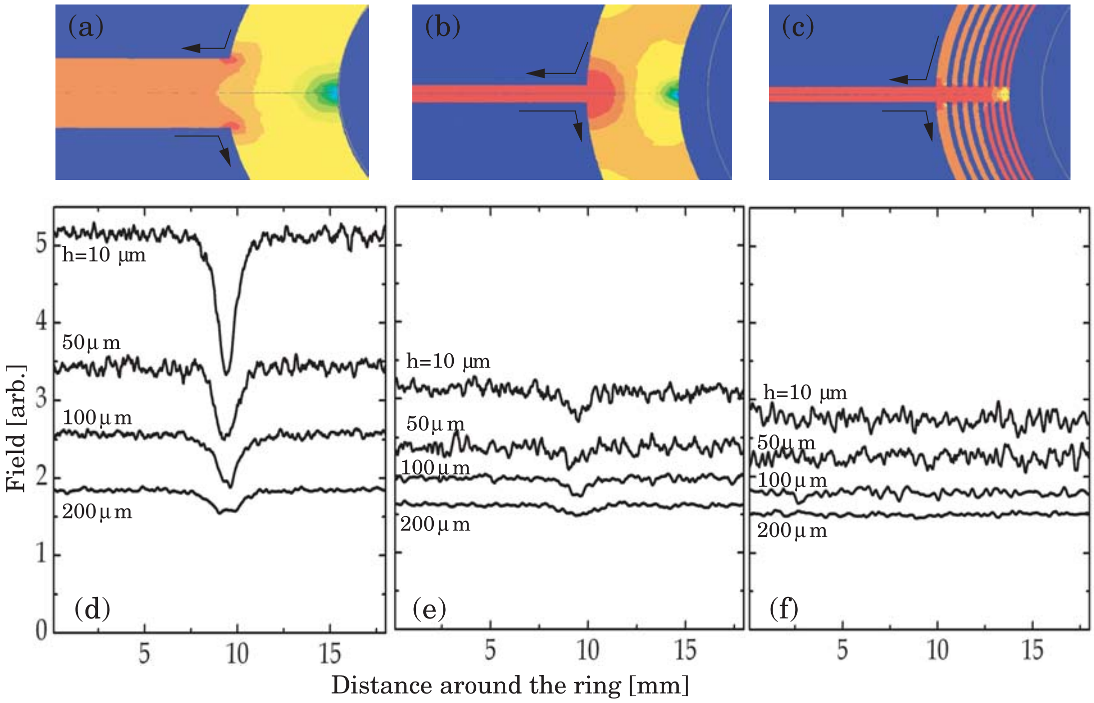

Fig. 3. Results of a finite element simulation of the ring trap. (a), (b) and (c) show false color images of the current density in the current sheet around the region of the input and output leads. The gap between the two leads was 2 μm. (d), (e) and (f) indicate the magnetic field along a circular path corresponding to the inner edge of the ferromagnet. As indicated, the magnetic fields are sampled at heights of 10 μm, 50 μm 100 μm, and 200 μm above the surface of the ferromagnet.The residual variations in the magnetic field (which are fairly large close to the ferromagnet) are an artifact due to the discretization of the finite element mesh. These variations are present even in the ideal case of a uniformly magnetized ring. A colour version of the figure is available in electronic form at `http://www.eurphysj.org`.

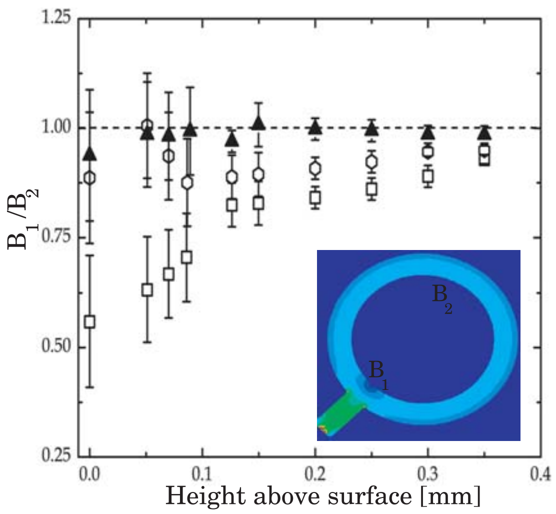

Fig. 4. The ratio of the magnetic fields sampled at the points closest to (B_1), and farthest from (B_2) the break in the current sheet at different heights above the ferromagnet. The symbols (□), (○) and (▲) correspond to the current sheets (a), (b) and (c) respectively. This ratio is an indication of the homogeneity of the trap, and is equal to 1 in the case of a homogeneously magnetized ring (no variation in the trap potential). It can be seen that the ferromagnet magnetized by the stranded current sheet approaches this ideal limit.

The fabrication of the ring trap begins with the thermal evaporation of a seed layer of copper (30 nm) on a silicon wafer. A thin layer of chromium (10 nm) is used as an adhesion layer. A thick photoresist is spin coated on this seed layer with the duration and spin speed suitably set to achieve a thickness of around 200 microns. Using conventional photolithographic techniques, rings of 1 mm width and a range of radii (2–5 mm) are patterned on the resist. After developing the resist, a mold for the ferromagnet is created. The ferromagnet is electroplated on the seed layer at room temperature using current densities of around 5–10 mA/cm^2. During electroplating, the bath is agitated and suitable additives are added to ensure an uniform and smooth deposition [11]. After the deposition of an insulating layer of silicon dioxide, the patterning of the current sheet is carried along similar lines i.e. deposition of a seed layer followed by resist patterning and electroplating. The thickness of the current sheet is on the order of 10 microns and the sheet is found to sustain steady state currents of 10 A without significant heating. Thus far, fabrication has been restricted to non-stranded current sheets. Techniques to realize highly stranded current sheets with similar current carrying capacities are being explored.

Due to the homogeneous nature of the magnetic field around the trap, the large trap frequencies, the ability to efficiently transfer ultracold atoms into the trap and the fact that atoms can be trapped far from the substrate, this trap is a promising candidate for integrated reciprocal atom sensors. It also seems feasible to consider the realization of strongly interacting lower dimensional systems (Tonks-Girardeau gases) [12] in such traps. This state is reached in the limit of very low temperatures and low densities. Also, the interaction strength in this regime is proportional to the radial trap frequency. Hence, traps of extremely large aspect ratio where the atoms are tightly confined in one dimension are well suited to the realization of such states. Using realistic parameters obtainable in this ring trap, one finds that the Tonks-Girardeau regime can be reached with a few thousand atoms. Measuring the energy distribution and coherence properties of such a small sample of tightly confined atoms presents a challenge. One possible scheme is examined in [13].

In conclusion, we have presented a proposal for a tightly confining reciprocal magnetic trap integrated on an atom chip. With the use of soft ferromagnets and a novel design for the current carrying conductors, we show that the magnetic field inhomogeneities around the ring can be made arbitrarily small despite the break in symmetry introduced by the wires. Thus, one can potentially combine the homogeneity of permanent magnetic traps with the dynamic tunability that is an attractive feature of current-based magnetic traps. This trap is well suited for integrated atom interferometers and the study of lower dimensional ultracold systems.

The authors are indebted to R. Conroy for valuable discussions. This work was funded by the Center for Ultracold Atoms and MURI.

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