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## Trapping atoms on a transparent permanent-magnet atom chip

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We describe experiments on the trapping of atoms in microscopic magneto-optical traps on an optically transparent permanent-magnet atom chip. The chip is made of magnetically hard ferrite-garnet material deposited on a dielectric substrate. The confining magnetic fields are produced by miniature magnetized patterns recorded in the film by magneto-optical techniques. We trap Rb atoms on these structures by applying three crossed pairs of counterpropagating laser beams in the conventional magneto-optical trapping geometry. We demonstrate the flexibility of the concept in creation and *in situ* modification of the trapping geometries through several experiments.

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Microfabricated devices for the trapping and manipulation of ultracold neutral atoms, known as atom chips [1–3], have been demonstrated to provide remarkable control of the internal and external atomic states [4–8], and in an essential way to simplify the production of Bose-Einstein condensates [8–12]. The magnetic-field patterns needed for trapping atoms on these chips are typically created by driving current through metal wires that are lithographically fabricated on the chip surface [13]. During the last few years, however, much attention has been paid to the development of atom chips based on selectively magnetized permanent magnets [14–18]. Such devices, in principle, allow one to get rid of the electric-power dissipation in the wires, avoid magnetic-field noise originating from temporal and spatial fluctuations of the currents, and reduce the near-field noise originating from the thermal motion of free electrons in the chip. Permanent magnets also make it possible to create novel geometries for surface traps, such as storage rings that can serve as miniature rotation sensors [19–22]. In view of future applications for atom chips, these developments have a great practical importance.

We introduce a different kind of permanent-magnet atom chip and demonstrate magneto-optical trapping of  $^{85}\text{Rb}$  atoms on the surface of this device. The chip is of optically homogeneous material and transparent to light at near-infrared and infrared wavelengths. Owing to this property we can make use of the ordinary magneto-optical trapping (MOT) geometry with three orthogonal pairs of counterpropagating laser beams to collect and trap atoms on the surface instead of using the reflection MOT configuration of the traditional atom chips. We routinely capture more than  $10^6$  atoms in a micro-MOT on a magnetized pattern at a distance of  $\sim 100\ \mu\text{m}$  above the chip surface. Being optically transparent, the device allows unimpeded control and probing of the on-chip atoms with laser light. Another important feature that makes our atom chip flexible and simple

to operate is the possibility and ease of *in situ* reconfiguration of its trapping potentials. The atoms are trapped above miniature magnetized patterns which can readily be remotely recorded and erased by means of conventional magneto-optical recording techniques, even in the presence of trapped atoms.

To fabricate the chip, a  $1.8\ \mu\text{m}$  thick film of magnetically hard ferrite-garnet,  $(\text{BiY}\text{TmGd})_3(\text{FeGa})_5\text{O}_{12}$ , was grown on a  $500\ \mu\text{m}$  thick substrate of gadolinium-gallium-garnet ( $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ ) [23]. The film only absorbs about 10% of the light at  $\lambda=780\ \text{nm}$ , which is the wavelength for trapping Rb atoms. The preferred direction of magnetization in the film is normal to the surface and the nearly squared hysteresis loop of the film is characterized by a saturation magnetization of  $\sim 20\ \text{mT}$  and coercivity of higher than  $10\ \text{mT}$ . We first magnetize the film uniformly and then create a desired magnetization pattern by locally heating the film with a scanned, focused cw laser beam at  $\lambda=532\ \text{nm}$ , at which wavelength 80% of the light is absorbed in the film. During the patterning, an external magnetic field of  $\sim 1\ \text{mT}$  is applied in the direction opposite to the initial magnetization of the film. By reversing the direction of the applied magnetic field, the patterns can be erased with the same laser beam. We have created patterns with dimensions down to the order of  $1\ \mu\text{m}$  with this technique [23]. Typically,  $10\ \text{mW}$  of power in the beam is needed to write  $10\ \mu\text{m}$  thick lines on the chip.

The film is placed in a rectangular UHV cell made of fused silica and connected to a vacuum system that keeps the pressure of  $\lesssim 10^{-11}$  mbars (see Fig. 1). The cell is located in the center of a set of six square-shaped magnetic coils of  $35\ \text{cm}$  dimension that are used to compensate the background magnetic fields and to create a uniform external magnetic field on the chip surface. By controlling the strength and direction of the external field, a quadrupole field structure can be created at the location of the magnetized surface pattern. Based on such a magnetic-field structure, a miniature magneto-optical atom trap at a short distance from the surface is then created by applying three orthogonal pairs of retro-reflected laser beams that are circularly polarized and

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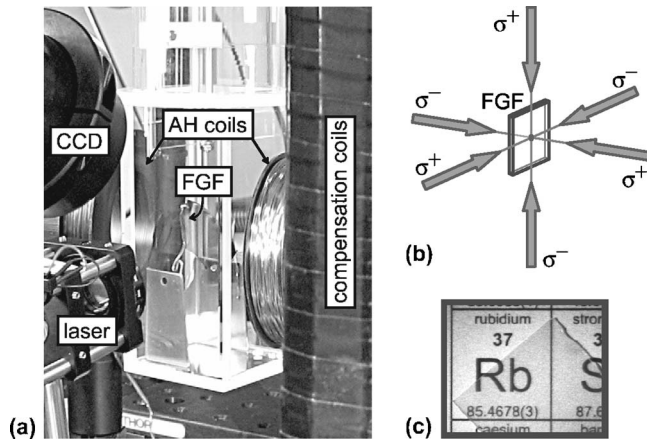


FIG. 1. Experimental setup. (a) CCD, CCD camera; FGF, ferrite-garnet film on gadolinium-gallium-garnet substrate; and laser, laser head that collimates and  $\sigma^+$ -polarizes the light from a fiber. Two anti-Helmholtz (AH) coils are positioned close to the right and left windows of the UHV cell. One pair of the cooling laser beams, the optical axis of the polarization imaging system, and the laser beam for magneto-optical patterning pass through the openings of the coils. (b) Cooling-beam alignment. (c) Transparency of the atom chip under illumination at 780 nm.

intersect on the chip surface at the location of a magnetized pattern. Two of the beam pairs propagate along the surface and the third one is let directly through the chip.

The cooling laser beams are produced by three separate single-frequency diode lasers that are injection-locked to a single home-built transmission-grating external-cavity diode laser [24]. The external-cavity laser is locked close to the  $|5^2S_{1/2}, F=3\rangle \rightarrow |5^2P_{3/2}, F=4\rangle$  transition of  $^{85}\text{Rb}$ . The light from the cooling lasers is delivered to the setup in three polarization-maintaining optical fibers. The maximum power in each of the beams is 20 mW and the  $1/e^2$  diameter of the beams in the cell is about 10 mm. The light frequency is tuned to the red from the atomic resonance by one atomic linewidth  $\Gamma$ . To obtain the repumping radiation, another laser locked to the  $|5^2S_{1/2}, F=2\rangle \rightarrow |5^2P_{3/2}, F=2\rangle$  transition is used. This radiation is guided to the cell in the same fiber as the light of one of the cooling lasers. The power in the repumping beam is several mW. The trapped atoms are observed from directions normal and parallel to the film by using two charge-coupled device (CCD) cameras, SSC-M370CE (Sony) and Pixelfly (PCO).

The atoms are collected to the micro-MOTs from rubidium vapor evaporated in the cell from a resistively heated Rb dispenser. The chip is positioned at a distance of 4 cm from the dispenser with the substrate side facing it. In all the experiments the dispenser is operated in at continuous mode.

To record and erase the magnetization patterns in the film, a simple mechanical beam-scanning system was built (see Fig. 2). A laser beam from a cw laser (Coherent Verdi-V10;  $\lambda=532$  nm) is focused onto the film by reflecting it from a mirror whose tilt angle is mechanically controlled via a computer. The beam spot size on the film is adjusted by shifting the lens ( $L$ ) along the beam axis. A mechanical shutter is used to switch the recording (erasing) beam on and off. The external field that defines the magnetization direction in the

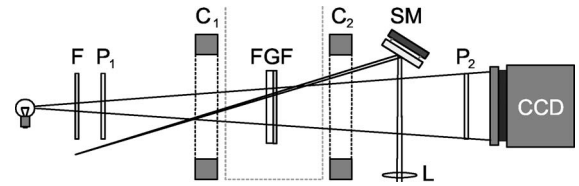


FIG. 2. Combined magneto-optical patterning and polarization imaging system. To record (erase) magnetization patterns in the film (FGF), the electric current in coils  $C_1$  and  $C_2$  (AH coils in Fig. 1) is switched on and a cw laser beam ( $\lambda=532$  nm) is reflected from a scanning mirror (SM) and focused with lens ( $L$ ) onto the film. The imaging system consists of a CCD camera, a tungsten halogen lamp, a color filter (F), and two nearly crossed polarizers ( $P_1$  and  $P_2$ ).

recorded pattern is produced by co-running currents in the anti-Helmholtz (AH) coils shown in Fig. 1. The setup includes a polarization-microscopy imaging system for *in situ* observation of the recordings. Faraday rotation in the film is made visible by observing the transmission of thermal light through the film and two nearly crossed polarizers placed in front and after the cell [23]. An image of the transmitted-light pattern is recorded with the same camera as is used to detect the trapped atoms. Figures 3(a) and 3(e) and e show two examples of the magnetization patterns visualized with this imaging system.

The magnetic field produced by a given pattern can be calculated by using the Biot-Savart law [23]. For example, the magnetic field strength at the center of the magnetized circular spot shown in Fig. 3(a) is equal to  $130 \mu\text{T}$ . By applying a uniform magnetic field of  $60 \mu\text{T}$  in the opposite direction one can obtain a localized quadrupole field above the pattern. The absolute value of the field,  $|B_q|$ , calculated as a function of distance  $z$  from the center of the spot along the normal to the surface, is plotted in Fig. 3(h). At  $z=200 \mu\text{m}$ ,  $B_q$  is zero and the gradient  $\partial B_q/\partial z$  is equal to  $3.5 \text{ mT/cm}$ . The gradients along the  $x$  and  $y$  directions are half of this.

For trapping atoms, the intensities of the cooling laser beams are carefully balanced at the position where the miniature magnetic quadrupole is created above a selected magnetized pattern. We first trap atoms in a large magneto-optical trap created with the aid of two external anti-Helmholtz coils placed close to the cell windows (see Fig. 1). Then the trap center is shifted towards the pattern by adjusting the positions of the coils, and the currents in the coils are gradually decreased to zero. Simultaneously, the number of atoms in the trap is optimized by readjusting the retroreflection angles of the cooling beams. When eventually the currents in the external coils are switched off, the atoms remain trapped in the surface trap. Figure 3(b) shows the fluorescence image of an atomic cloud above the pattern of Fig. 3(a). In the side view [Fig. 3(c)], the cloud is seen together with its reflection from the surface. The distance of the trap center from the surface is  $200 \mu\text{m}$ . The number of atoms in the trap is  $7 \times 10^4$ . In order to increase the number of trapped atoms, we increased the capture volume of the trap by superimposing on the steep quadrupole field of the surface trap a weaker quadrupole field of larger spatial extent produced by the two external anti-Helmholtz coils outside



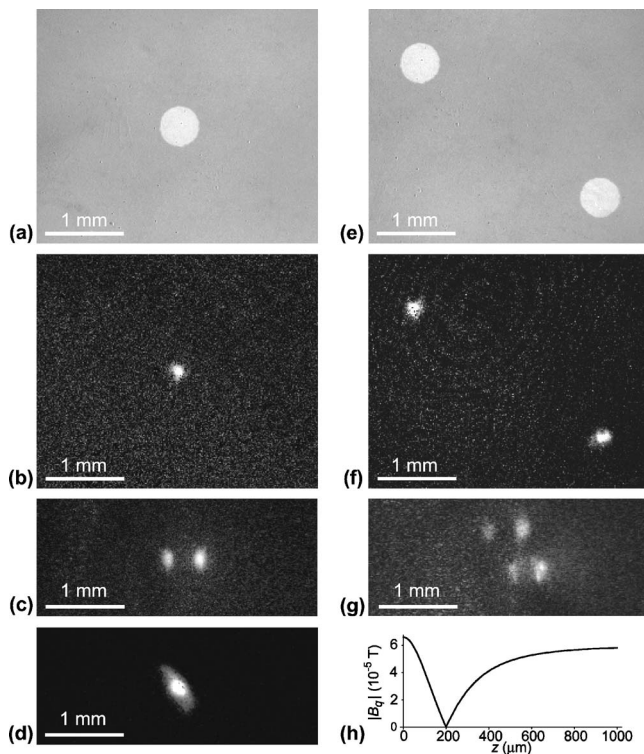


FIG. 3. Top row: Two different magnetization patterns on the chip. Second row: The front views of the resulting trapped atomic clouds. Third row: The side views of the same traps [in (g) the clouds are located at different distances from the side-view camera]. Bottom row: (d) The front view of an atomic cloud above the pattern (a) when the capture volume of the trap is increased by applying an additional large-extent quadrupole field; (h) the absolute value of the microscopic magnetic quadrupole field as a function of distance  $z$  from the center of spot (a).

the cell. The spatial gradient of this field was a few hundreds of  $\mu\text{T}/\text{cm}$ . As a result, the number of atoms in the trap exceeded  $10^6$ . This case is illustrated in Fig. 3(d). We then trapped atoms within two identical magnetized spots positioned at a distance of 3 mm from each other. The spots and the trapped atomic clouds are shown in Figs. 3(e)–3(g). The additional external quadrupole field was not used in this case. We note that such micro-MOTs could be created even further apart from each other if the cooling laser beams were made to have a larger diameter.

In order to demonstrate the *in situ* reconfigurability of the trapping potentials, we consecutively created and erased magnetization patterns within the same area of the film. Some of the patterns and the atoms trapped above them are shown in Fig. 4. In Fig. 4(b), a curved strip of reversed magnetization is added to the magnetized spot of Fig. 4(a), and the resulting L-shaped continuation of the MOT is filled with atoms. This structure was then erased and a square-shaped pattern was recorded in its place [see Fig. 4(c)]. The number of atoms in this trap is comparable to that in the trap of Fig. 4(a). We note that if the new pattern has similar dimensions and position as the previous one, it is not necessary to readjust the applied magnetic and optical fields for the new trap. The trap can be reconfigured even while atoms are confined in it. The array of micro-MOTs shown in Fig.

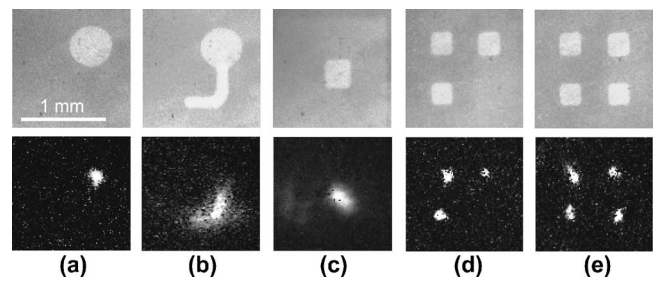


FIG. 4. Consecutively recorded and erased magnetization patterns (top row) and atomic clouds trapped within them (bottom row). The trap (d) was modified to obtain the trap (e) without significantly affecting the trapping of the atoms in the three original traps. A weak auxiliary quadrupole field centered in the middle of the structure was used to increase the trapping efficiency.

4(e) was obtained by modifying the array of Fig. 4(d) without destroying the functioning of the original micro-traps. The fourth square was magnetized purely optically, i.e., no additional writing magnetic field was applied. Even if the value of magnetization within this additional square is close to zero, the saturation magnetization of the surrounding area of the film is high enough for the creation of a micro-MOT. MOT arrays, similar to those shown in Figs. 4(d) and 4(e) but with somewhat larger dimensions, have been demonstrated previously by using ribbon UHV cables and applying the reflection-MOT principle [25].

The magneto-optical trapping efficiency turns out to be rather insensitive to the details of the magnetization-pattern geometry. It is, for example, possible to collect atoms within some part of a pattern and then guide the trap along the pattern's structure. This possibility could provide extra flexibility for the design and operation of atom-chip circuits. We recorded a toroidal pattern shown in Fig. 5(a) that, as a matter of fact, would be difficult if not impossible to realize using current-carrying wires. If a uniform magnetic field is applied in the direction opposite to the magnetization of the torus, the atoms settle in a ring-shaped MOT as shown in Figs. 5(b) and 5(c). The slightly uneven distribution of the atoms inside the torus is mainly explained by the interference and diffraction of the cooling laser beams at the position of the trap. We believe that this destructive effect can be substantially reduced by polishing the film and antireflection (AR) coating the surfaces of the device.

By periodically modulating the  $x$  and  $y$  components of a weak external magnetic field of the compensation coils with a mutual phase difference of  $\pi/2$ , we could drive the trap center into circular motion along the torus. The modulation is

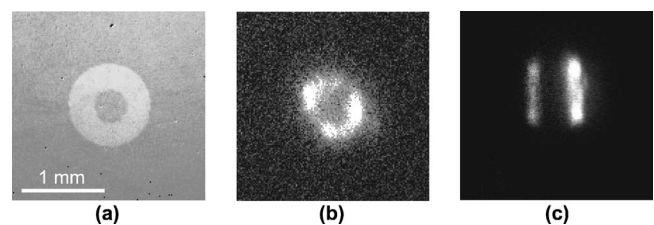


FIG. 5. A toroidal trap: (a) magnetization pattern, (b) front view, and (c) side view of the trapped atomic cloud.

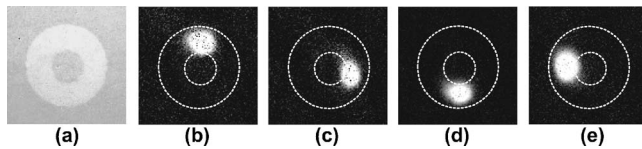


FIG. 6. A surface MOT translated along a toroidal magnetization pattern: (a) magnetization pattern and (b)–(e) a series of images of the trapped atomic cloud.

accomplished by modulating the currents in the 35 cm compensation coils. Figures 6(b)–6(e) show a sequence of images of the trapped atoms separated in time by a quarter of the modulation period. In this case, an auxiliary quadrupole field with a spatial gradient of  $300 \mu\text{T}/\text{cm}$  was added to increase the number of atoms. The modulation amplitudes were  $27 \mu\text{T}$ .

In conclusion, we have demonstrated magneto-optical trapping of atoms on a transparent permanent-magnet atom chip. This approach to the creation of atom chips can provide several advantages over conventional techniques based on current-carrying wires and over the other up-to-date techniques employing permanent magnets. Our traps are readily reconfigurable *in situ*. Essentially, free-format trap patterns can be realized as demonstrated by the example of a ring-shaped trap. Ring-shaped traps are particularly interesting due to the possibility of applying them in a Sagnac-type atom interferometer [19–22]. The device is transparent to

light, which provides unimpeded control of atoms with laser radiation. In particular, an ordinary MOT instead of a reflection MOT geometry was used to collect atoms close to the surface. The microscopic magneto-optical traps described in this work are formed at a distance of a few hundred micrometers from the surface and they contain more than  $10^6$  atoms. We also created surface-mounted arrays of micro-MOTs. Such an array can be used to prepare multiple atomic samples on the chip. Each of these samples can then be processed individually by using, e.g., a nearly resonant focused optical field.

There are no electric currents applied to the device. Consequently, there is no electric-power dissipation or temporal or spatio-temporal current fluctuation. Since the device is made of dielectric material, magnetic-field noise due to thermal electrons is insignificant at short distances from the surface [26]. Purely magnetic microtraps with a trap depth of up to 1 mK are realizable on an atom chip of this type [23]. Such traps can be loaded with atoms from the surface-mounted micro-MOTs described in this paper and be used for Bose-Einstein condensation and for experiments on atom interferometry.

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