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Preparation of a Bose-Einstein Condensate on a Permanent-Magnet Atom Chip

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Abstract. We describe an atom chip based on periodically magnetised videotape. Cold atoms are loaded into one of the microscopic magnetic traps formed by the videotape atom chip. Using forced evaporation we have produced a ^{87}Rb Bose-Einstein condensate in a permanent-magnet microtrap.

1. Introduction

Ultracold neutral atoms can be magnetically trapped and guided using small patterns of current carrying wire microfabricated on the surface of atom chips [1, 2]. However, magnetic storage media also provide a convenient way to manipulate clouds of cold atoms using patterns of permanent magnetisation. Magnetic mirrors for cold atoms have been demonstrated using audiotape, floppy disk and videotape [3]. Patterns of permanent magnetisation can also be used to from microscopic traps instead of mirrors [4, 5]. We have constructed an atom chip based on a piece of periodically magnetised videotape and loaded ultracold atoms into one of the microscopic traps formed by the videotape. On this chip we have produced a ^{87}Rb Bose-Einstein condensate in a permanent magnetic microtrap.

2. Permanent-Magnetic Microtraps

It can be shown [3] that a film of thickness b magnetised along the x direction with a wavelength λ and magnetisation M_0 produces a field at a distance y away from the surface with magnitude

$$B = \frac{1}{2}\mu_0 M_0 (1 - e^{-kb}) e^{-ky} = B_0 e^{-ky} \tag{1}$$

where $k = \frac{2\pi}{\lambda}$ and B_0 is defined as the field at the surface. An array of one-dimensional waveguides is formed by applying a uniform bias field, B_{bias}, in the x-y plane which cancels the field of the film at a height y_{trap} of

$$y_{trap} = \frac{1}{k} ln(\frac{B_0}{B_{bias}}) \tag{2}$$

as shown in Figure 1. The centre of each guide has a quadrupole structure with gradient $B' = kB_{bias}$.

To prevent the field going to zero at the centre of the waveguide an axial bias field, B_z, is applied in the z direction. The waveguides are harmonic for small amplitude oscillations with a radial frequency of

$$2\pi f_r = kB_{bias}\sqrt{\frac{\mu}{mB_z}} \tag{3}$$

where μ is the atomic magnetic moment and m is the atomic mass.

The videotape used in our experiment was recorded with a wavelength of $\lambda = 106 \pm 2\,\mu$m and a surface field of $B_0 = 11 \pm 1\,$mT. For ^{87}Rb atoms in the $|F = 2, m_F = 2\rangle$ ground state a bias fields of $B_{bias} = 0.1\,$mT and $B_z = 0.1\,$mT the traps form $80\,\mu$m from the surface with $f_r = 760\,$Hz.

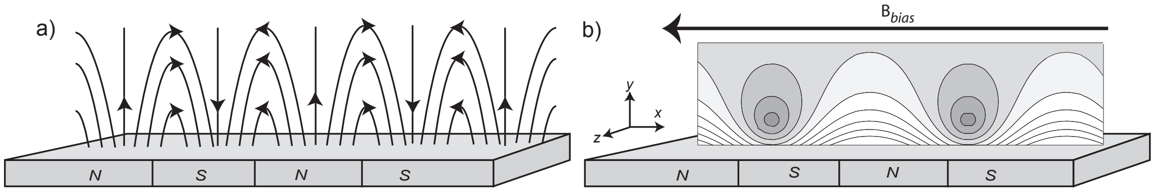

Figure 1. a) Magnetic field lines produced by a periodically magnetised film. b) Contours of constant field after applying a uniform bias field, B_{bias}.

3. The Videotape Atom Chip

Videotape was chosen as the basis of the atom chip because it is vacuum compatible, has high coercivity, high remnant magnetisation and can be recorded using commercial equipment adapted in the laboratory. The recorded videotape was glued to a glass coverslip and coated with 400 nm of gold to make the surface reflective for 780 nm light. This allows a mirror-MOT to collect atoms close to the surface of the videotape. Insulated wires run underneath the coverslip through channels cut in a steel block as shown in Figure 2b. One of these wires, the “centre” wire, runs along the z direction and is used to form a macroscopic magnetic trap for transporting atoms from the MOT into the videotape. Two “end wires” separated by 8.5 mm running in the x direction close off the ends of the traps by creating a field that rises to a maximum in the z direction above each wire. The remaining wires under the chip form an rf antenna used for evaporative cooling. The atom chip assembly is mounted at the centre of the vacuum chamber where a base pressure of 1×10^{-11} torr is achieved.

4. Preparing a Bose-Einstein Condensate

A low-velocity intense source of atoms (LVIS) is used to load the mirror-MOT continuously by passing 7.5 A through a rubidium getter for 20 s. Typically 10^9 atoms are collected by the mirror-MOT 4 mm from the surface of the chip. An external bias field then ramps the MOT to within 1 mm of the surface at which point the trap light is detuned to $-45\,$MHz from the D2($F = 2 \rightarrow 3$) transition for 15 ms to cool the cloud to $50\,\mu$K . The laser light and quadrupole field are switched off and the atoms are prepared in the $|F = 2, m_F = 2\rangle$ sub-level by optically pumping with σ^+ light on the D2($F = 2 \rightarrow 2$) transition for $400\,\mu$s.

A purely magnetic trap, formed by running 15 A through the centre wire and applying a 2 mT external bias field along x, recaptures the optically pumped atoms. Axial confinement with a frequency $f_z = 15\,$Hz is provided by passing current through the pair of end wires. The magnetic trap is compressed by increasing the bias field to 4.4 mT over 100 ms. A stage of rf

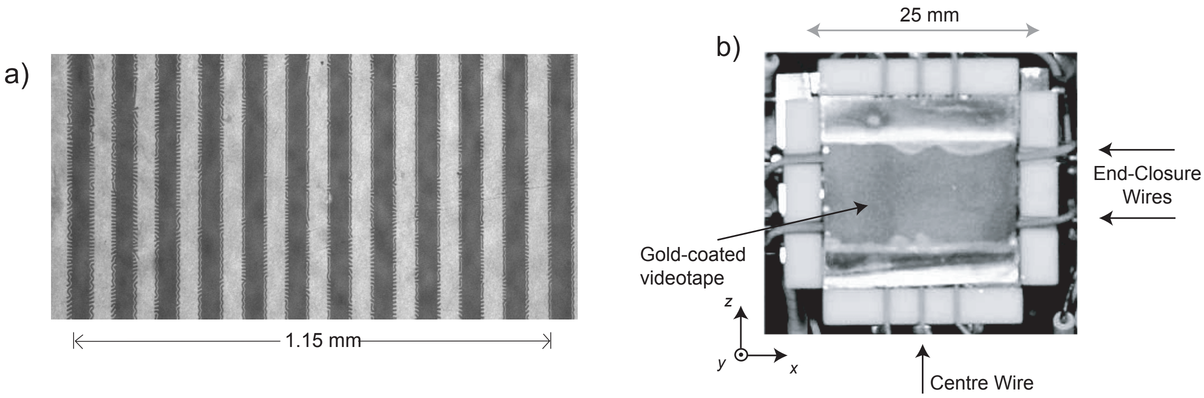

Figure 2. a)Optical microscope image of the recorded videotape revealing the reversals of magnetic field. A thin garnet film is placed over the surface and viewed with polarised light through a crossed analyser to produce this image. b)Photograph of the videotape atom chip.

evaporation in the wire magnetic trap cools the cloud to $10\,\mu$K by ramping the rf field from 30 MHz to 4 MHz in 6 s.

The pre-cooled cloud is then loaded into the videotape microtrap by reducing the current in the centre wire while holding the rf at 4 MHz. The bias field is simultaneously reduced to prevent the trap becoming too tight. The net effect is to draw the trapped cloud towards the surface and merge the potential of the wire trap with a videotape microtrap. At the end of the 4 s ramp the centre wire is turned off completely and cloud is trapped entirely by a videotape microtrap $90\,\mu$m from the surface.

Finally, a second stage of evaporation in the videotape trap lasting 2 s cools the cloud to BEC typically with a few times 10^4 atoms remaining.

The condensate is released and allowed to expand freely. Alternatively, the axial confinement is removed and the condensate is allowed to expand along the videotape waveguide. A $40\,\mu$s pulse of light resonant with the D2($F = 2 \rightarrow 3$) transition is used to image the cloud by optical absorption on a CCD camera. Figure 3 shows a freely expanded cloud after 14.7 ms of free expansion as the cloud for three different temperatures.

5. Properties of the Videotape Traps

Having produced BEC on the videotape atom chip it is interesting to compare the suitability of the permanent-magnet atom chip with its microfabricated-wire counterparts. The magnetic smoothness of the videotape potentials was investigated [4] and the trapped atom lifetime close to the surface was measured [6].

Some fragmentation of $1\,\mu$K clouds closer than $70\,\mu$m from the surface is observed, which can be attributed to surface defects in the magnetic tape. This effect is reminiscent of the fragmentation observed near current-carrying wires [7, 8, 9]. However, magneto-optical thin films [10], which have excellent surface quality, offer a promising alternative to videotape and should provide a smooth trapping potential to within a few micrometres from the surface.

The spin-flip lifetime of thermal atoms trapped less than $70\,\mu$m from the surface of the videotape, which is a dielectric material [11], compares very favourably with those measured close to conducting surfaces [12, 13]. The lifetimes were consistent with a spin-flip loss due to the gold layer on the chip [14], which could be reduced in future by making the gold thinner or using a dielectric coating.

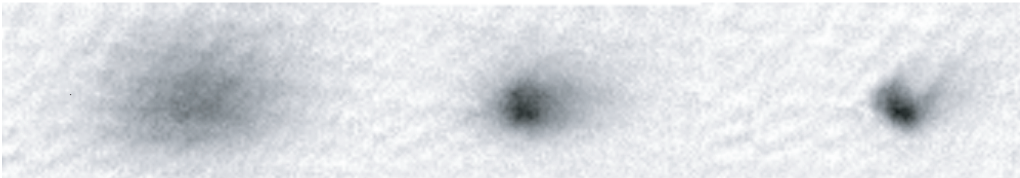

Figure 3. Absorption images taken after 14.7 ms of free expansion. As the final rf frequency f_0 is lowered the condensed component can be seen as a dense central peak.

6. Conclusion

In this article we have described an atom chip based on a piece of periodically magnetised videotape. Laser-cooled atoms were captured in a magnetic trap close to the chip and transferred into one of the videotape microtraps. Forced evaporation in the videotape microtrap cooled the cloud to Bose-Einstein condensation. The long-thin geometry of the microtraps makes videotape and other permanently magnetised materials suitable for studies of low-dimensional quantum gases [1]. In addition, long trap lifetimes close to the surface make permanent magnetic materials extremely promising for manipulation of atoms in applications such as quantum information processing and atom interferometry.

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