Reconfigurable atom chip on a transparent ferrite-garnet film

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Abstract. We introduce a new choice of material for the creation of microscopic magnetic potentials for the trapping and guiding of ultracold neutral atoms. The potentials are created above a ferrimagnetic, transparent $(BiYTmGd)_3(FeGa)_5O_{12}$ film by patterning the magnetic-domain structure in the film with a magneto-optical recording method. Patterns with linewidth down to 2 μm have been achieved, enabling trap frequencies of the order of 100 kHz for ^{87}Rb atoms in the state $|F = 1, m_F = -1\rangle$. The main advantages of the material are: 1) magnetic-field noise is suppressed due to the dielectricity of the material and the absence of electric currents, 2) trapped atoms can be addressed optically through the transparent film, and 3) the film can be repatterned, which enables different experiments with the same component.

PACS. 39.25.+k Atom manipulation (scanning probe microscopy, laser cooling, etc.) – 75.50.Ss Magnetic recording materials – 75.70.-i Magnetic properties of thin films, surfaces, and interfaces

1 Introduction

The concept of an atom chip, i.e., manipulation of ultra-cold neutral atoms with miniaturized magnetic potentials based on microfabricated current-carrying structures, is a promising technology for studying and applying quantum-mechanics on a new level [1]. The possibilities of this tool have been demonstrated by the on-chip creation of BEC and by various experiments showing delicate control of atomic motion [2–4]. Considerable research effort is being undertaken to realize devices on an atom chip, such as atom interferometers and realizations of quantum information processing.

An atom chip does not have to be based exclusively on current-carrying wires. The use of permanent magnets has been studied for the creation of magnetic potentials controlling the atomic motion. Experiments have been conducted using, e.g., audio- and videotapes [5–9], floppy disks and hard disks [10–13], patterned magnetic thin films [14–17], and self-organized domain patterns in bulk material [18].

On an atom chip, the control of the atoms on a length scale of their wave-packet extension requires the atoms to be trapped at a submicron distance from the field-creating structures. Recent experiments have shown the appearance of an unwanted effect related to the magnetic-field noise in the vicinity of conductors. Temporal fluctuation of the electric current, either of technical or of thermal origin, results in a noisy magnetic field, which in turn leads

to decoherence of the trapped atoms and to trap losses via spin flips [19–21]. The use of permanent magnets offer a convenient way of reducing the technical noise in the atom-trapping magnetic fields[1]. To our knowledge, however, all of the reported magnetic compounds have been *metallic* and hence not inherently preventing the harmful thermal electric currents (Johnson noise). In this article, we report on the fabrication and magnetic-domain patterning of a thin film of a *dielectric* ferrite garnet, $(BiYTmGd)_3(FeGa)_5O_{12}$ (referred to as FG in the following), as a promising technique to create microscopic trapping and guiding potentials for neutral atoms. In addition to being dielectric, the FG material is transparent to light at near-infrared and infrared wavelengths, which allows the use of laser light for the manipulation of atoms in the microtraps.

The trapping potentials are formed as the superposition of an external magnetic field and the stray magnetic field from the domain patterns in a FG thin film. The patterns of any desired 2D topology, within achievable resolution limits, can be created with a magneto-optical recording method, which allows one to reconfigure the atom chip in situ in the vacuum chamber.

In the following section we describe the fabrication process of thin films of the FG material and discuss their properties. The results of the magneto-optical patterning

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[1] Often one needs to create certain external bias fields with current-carrying coils, which introduces still some technical noise into the system.
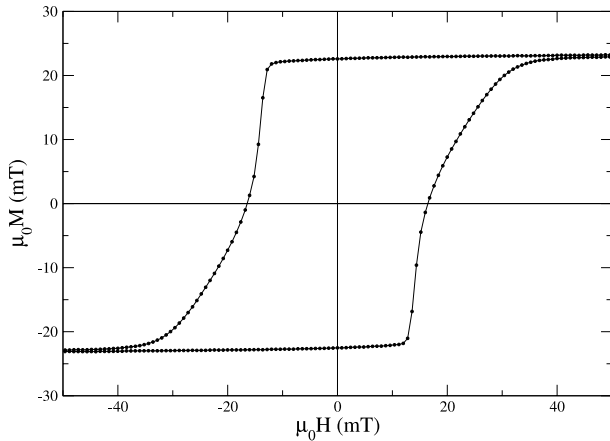
Fig. 1. Hysteresis loop of a FG film, measured perpendicularly to the film surface.

experiments are presented in Section 3. Some examples of simple trapping potentials based on domain patterns are described in Section 4 and the paper is concluded with a discussion of the results.

2 Ferrite-garnet films: fabrication and properties

Ferrite garnets have found their way to various technological applications because of their unique magnetic and optical properties. They have been actively investigated as materials for bubble-domain memories, in which cylindrical magnetic domains constitute bits which can be manipulated with external magnetic fields [22,23]. The Faraday-rotation in ferrite garnets has been used, e.g., in optical switches and isolators [24], and in magneto-optical imaging of superconductors where it recently has proved possible to observe the individual Abrikosov vortices [25].

Most of the applications of ferrite garnets rely on the magnetic "softness" of the material. Softness in this context refers to the very thin hysteresis loop, i.e., the domain structure responds very easily to changes in the external magnetic field. However, by appropriately choosing the composition of the material, a ferrite garnet can be made magnetically "harder" so that patterning of the domain structure will become possible.

We prepared the FG films with the liquid-phase epitaxy (LPE) method. The material to be grown is crystallized from a supersaturated liquid-phase solution onto a substrate. The substrate material $Gd_3Ga_5O_{12}$ (GGG) allows single-crystal growth of $(BiYTmGd)_3(FeGa)_5O_{12}$ with the desired magnetic properties. GGG is transparent and paramagnetic, and thus well suited for use in atom chips.

A hysteresis curve of a FG thin film we have grown is depicted in Figure 1. The film has a saturation magnetization of $\mu_0 M_S = 23$ mT. The fact that the magnetization remains at $\pm\mu_0 M_S$ within the external field range of $\mu_0 H = -15\ldots15$ mT reflects the stability of the domain structure at a microscopic level. This range gives
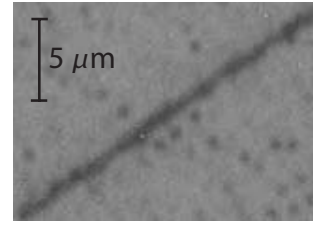

Fig. 2. A polarization microscope image of a line-shaped domain pattern in a FG film. The pattern was made with an ordinary magnetic-recording head. The Faraday rotation in the FG material enables imaging of the domains.
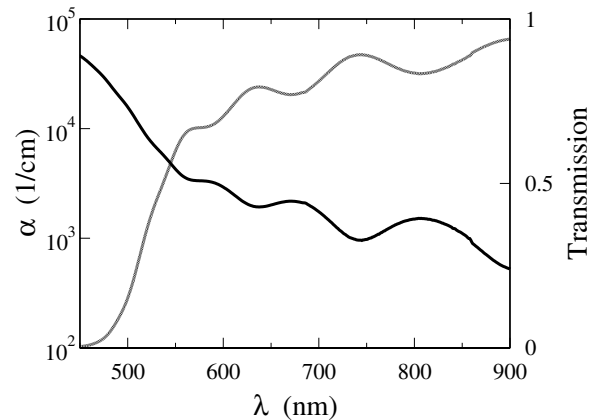

Fig. 3. Absorption coefficient α of a FG film (black line), and the transmission of the 1.2-μm-thick film without reflection losses (grey line).

the limits for the magnitude of the external field in the atom-trapping experiments. The FG films we made have uniaxial magnetic anisotropy. The preferred direction of magnetization is therefore normal to the surface. The minimum domain size is smaller than one micrometer, as illustrated by the line-shaped pattern in Figure 2. The pattern has been created with an ordinary magnetic recording head.

At near-infrared and infrared wavelengths the transparency of the FG material is high enough to allow laser access to the atoms through the film (see Fig. 3). On the other hand, increased absorption at shorter wavelengths allows for the magneto-optical patterning described in the following section. The thickness of the film is of the order of 1 μm, and the film area is $\sim 1 \times 1$ cm^2. We have tested our FG samples to be compatible with ultra-high vacuum and to withstand a baking temperature of about 200 °C.

3 Magneto-optical patterning

As indicated in the previous section, the patterning of a FG film can be done with a 1-μm resolution using an ordinary magnetic recording head. The magneto-optical patterning, on the other hand, enables simplifying the experiments with a FG atom chip: patterning can be straightforwardly extended to be done when the magnetic film already resides in a vacuum chamber, and thus the
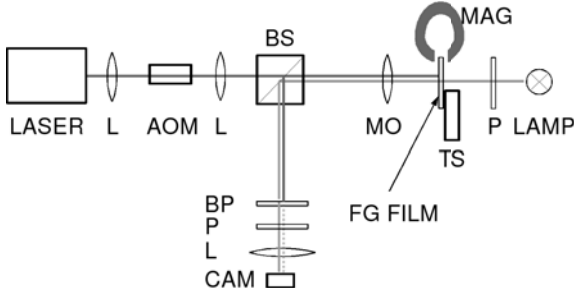
Fig. 4. Experimental setup for magneto-optical recording. Abbreviations: (L) lens, (AOM) acousto-optic modulator, (BS) beam splitter, (MO) microscope objective, (P) polarizer, (BP) band-pass filter, (MAG) permanent magnet, (TS) translation stage, and (CAM) camera.

FG film can be reconfigured at will to suit the needs of different experiments. Also the possibility to characterize the domain patterns remotely supports the feasibility of in situ patterning: due to Faraday rotation in the FG material the polarization of light is rotated in opposite directions in the two types of domains. Domains can thus be imaged using polarization microscopy.

The magneto-optical creation of domain patterns is based on the following process [26]: a laser locally heats up a small region of the film. The magnetic coercivity in the heated spot then decreases and a weak background magnetic field (~1 mT), pointing in the direction opposite to the initial magnetization, reverses the direction of magnetization in the heated region, while the unheated region of the film remains unaffected.

The experimental setup is shown in Figure 4. A frequency-doubled CW Nd:YVO laser ($\lambda = 532$ nm) was used to heat the FG film. An acousto-optic modulator was employed for the creation of 10-μs heating pulses. A U-shaped permanent magnet positioned in the vicinity of the film created the background magnetic field for flipping the magnetization of the heated-up region. Continuous domain patterns, such as lines, were created by applying successive laser pulses with a repetition rate of 1 kHz, and simultaneously moving the film slowly with a translation stage. The resulting domain patterns were imaged during the recording process with a polarization microscope integrated in the system. In our setup, we used a high-pressure mercury lamp for the sample illumination. A band-pass filter with the pass-band at $\lambda = 490$ nm was used to select the band at which the Faraday-rotation, and thus the contrast, is high, and on the other hand, to attenuate the back reflection of the heating-laser beam. With our patterning system we have been able to reach a linewidth of 2 microns. Polarization-microscope images of two different patterns created in the same film are shown in Figure 5.

4 Trapping potentials

The magnetic field of the patterned FG film can readily be modelled by considering the equivalent current densities
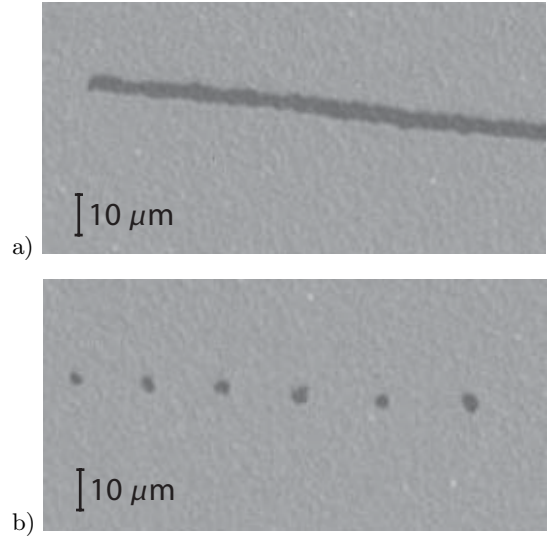

Fig. 5. Polarization microscopy images of patterns made with the magneto-optical recording method. The dots are made with single 10-μs heating pulses. The line-like pattern is created by applying successive pulses, which overlap each other partly.

at the domain boundaries [27]; at a boundary, where the magnetization $\boldsymbol{M}$ reverses its direction (from up to down or vice versa), the equivalent current density is given by $\boldsymbol{j} = 2\boldsymbol{M} \times \boldsymbol{n}$, with $\boldsymbol{n}$ being the unit normal to the boundary and the factor of 2 arising from the existence of magnetized regions on both sides of the boundary. Hence, the magnetic fields can be modelled as to be created by closed loops of current sheets having a height equal to the film thickness h and a total current of $I = 2Mh$. Integration according to the Biot-Savart law over the current sheets then gives the magnetic field. This model does not take into account the finite thickness of the transition region (domain wall) between the domains. However, a typical domain wall thickness in ferrite-garnets is only of the order of 100 nm [28], and thus the contribution from the walls can be neglected.

In the following we present two examples of employing the domain patterns for the creation of microscopic trapping potentials. These potentials are essentially single atom traps, since at a temperature of 100 μK and a peak density of 10^{14} atoms/cm^3 one expects the number of trapped atoms to be of the order of 10. A magnetization of $\mu_0 M = 23$ mT and a film thickness of $h = 1.2\,\mu$m are assumed throughout the calculations, and the trapped atoms are assumed to be ^{87}Rb in the state $|F = 1, m_F = -1\rangle$.

A configuration corresponding to the common Z-trap on an atom chip (Fig. 6) is formed by a 20-micron kink in the boundary between domains magnetized in opposite directions. Applying an external magnetic field of $\boldsymbol{B}_{ext} = (5\,\mathrm{mT}) \times \boldsymbol{u}_y$ ($\boldsymbol{u}_i$ denote the unit vectors along the three coordinate axes) results in a (non-zero) magnetic-field minimum above the center of the 20-micron-long domain boundary, at 1.2 μm from the film surface. The long domain boundaries extending in the $\pm y$-directions
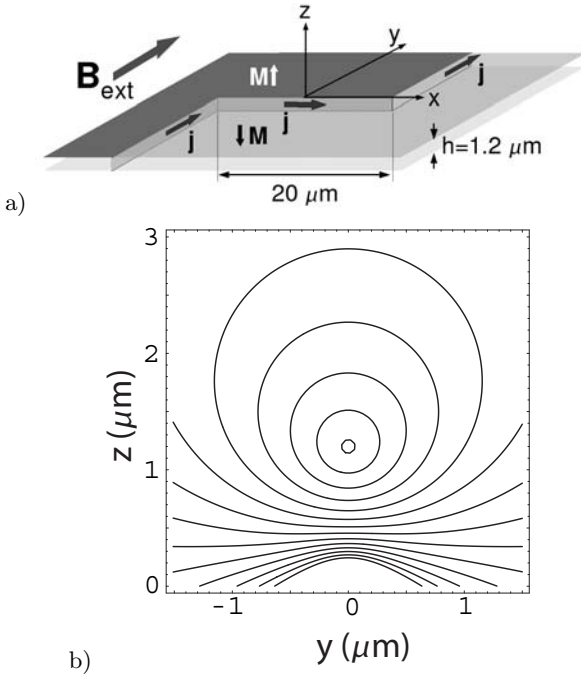
Fig. 6. A domain pattern creating a trapping potential corresponding the common Z-trap on an atom chip. (a) Schematic drawing of the configuration. $\boldsymbol{M}$ denotes the direction of magnetization in the region, $\boldsymbol{B}_{ext}$ shows the external field, and $\boldsymbol{j}$ stands for the equivalent current density at the domain boundaries. (b) Equipotential contours of the potential energy in the yz-plane for ^{87}Rb in the state $|F = 1, m_F = -1\rangle$. The contour spacing is 200 μK.

produce a field of strength of 150 μT at the trap center, which prevents the spin-flipping (Majorana) transitions [29]. The trap depth is 1.6 mK and the trap frequencies are $\omega_{y,z} = 2\pi \times 200$ kHz and $\omega_x = 2\pi \times 6$ kHz. The principal axes of the harmonic potential are slightly tilted, but this has been neglected, since the effect is small for traps with this high aspect ratio. We point out that such traps as the U-trap or, e.g., the doubled-wire trap can easily be created on a FG film using the same principles as in this example.

Another type of trap is formed with a cylindrical magnetic domain of diameter $D = 5\,\mu$m, with its direction of magnetization pointing to the $+z$-direction and surrounded by a domain magnetized in the opposite direction (Fig. 7). Note that such a trap configuration, where the equivalent current loop is closed, can be difficult if not impossible to create by using microfabricated current-carrying wires. Superposition with an external magnetic field of $\boldsymbol{B}_{ext} = (-2.5\,\text{mT}) \times \boldsymbol{u}_z$ results in a 800-μK-deep quadrupole-type trap with its center on the symmetry axis at a distance of 2.7 μm from the film surface. The field gradients of the quadrupole field are $\partial B/\partial x = \partial B/\partial y = 700$ T/m and $\partial B/\partial z = -1400$ T/m. In order to remove the zero at the trap center one can convert the quadrupole trap to the common TOP (time-averaged orbiting potential) trap by adding to the configuration a small-magnitude magnetic field B_0, which rotates in the
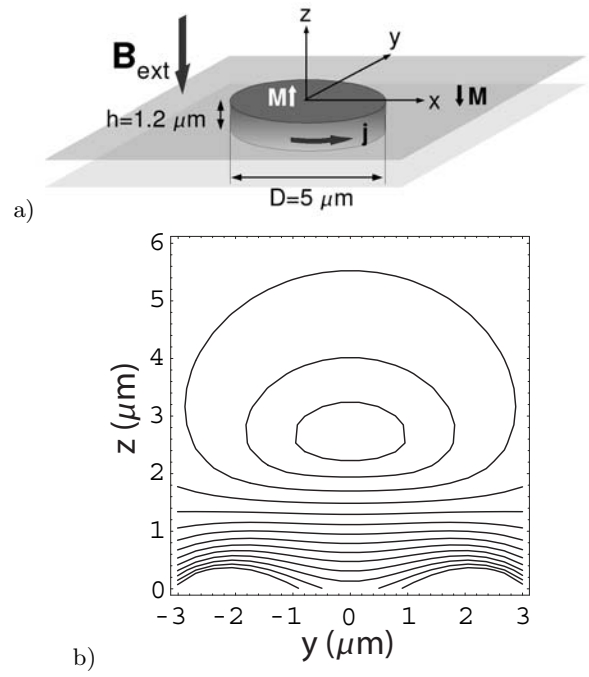

Fig. 7. A cylindrical domain pattern for the creation of a quadrupole-type magnetic trap. (a) Schematic illustration of the configuration. (b) Equipotential contours of the potential in the yz-plane. The contour spacing is 200 μK.

xy-plane [30]. With the choice of $B_0 = 100\,\mu$T one obtains a harmonic trap with frequencies $\omega_x = \omega_y = 2\pi \times 50$ kHz and $\omega_z = 2\pi \times 130$ kHz. The (time-averaged) magnetic field at the trap center, B_0, is again large enough to prevent spin-flipping transitions.

A microtrap on a FG film can be loaded with atoms from a MOT positioned at a distance of a few millimeters from the film. The atoms can be guided from the MOT to the microtrap, e.g., in a red-detuned laser beam focused at the position of the microtrap.

5 Conclusions

We have introduced a new choice of material for the creation of microscopic potentials for the trapping and guiding of ultracold neutral atoms. The creation of the potentials is based on the stray magnetic fields from the magnetic-domain patterns in a thin film of a ferrite garnet $(\text{BiYTmGd})_3(\text{FeGa})_5\text{O}_{12}$. We have shown that the trapping frequencies of the order of 100 kHz are achievable with this method. The ferrite garnet material is dielectric and transparent, hence suppressing the detrimental magnetic-field noise and allowing optical access to the atoms trapped in the vicinity of the film.

We have shown that the material can be patterned with micrometer resolution. The procedure contains experimental advantages such as the possibility to reconfigure the trapping potentials using a magneto-optical method, while the component resides in a vacuum chamber.

Transparency of FG-based atom chips allows more flexible loading of the microtraps with atoms compared to the traps on metallic permanent magnets, since one may use optical dipole potentials in the loading procedure, as suggested in [31].

We believe that the reconfigurable permanent-magnet patterns in a thin film of the FG on a dielectric, optically transparent substrate may provide a significant advance in the development of the concept of permanent-magnet atom chips.

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