Permanent magnetic atom chips

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Chapter 2

Opportunities and limitations of permanent magnetic atom chips

Confinement of cold atoms with magnetic field gradients is routinely used in magnetostatic traps. A new concept is to minimize confining magnetic structures on atom chips, using lithographically patterned current-carrying wires or magnetic materials, or a combination of them.

Here we present new atom-optical designs based on microstructured magnetic thin films for trapping the atoms. We describe the design principles and give examples of atom optical elements. These include waveguides, beam splitters, arrays of magnetic traps, and shift registers for manipulating atomic de Broglie waves under the surface of a substrate. Local dynamic control can be obtained by employing switchable external magnetic fields.

2.1 Permanent magnet field sources

The basic principle of magnetic atom optics is to confine spin-polarized cold atoms in a magnetic field using the magnetic dipole interaction $-\mu \cdot B$. The spin precession frequency of the total atomic dipole $\mu$ is usually sufficiently high to conserve the spin component in the direction of $B$. As the atom moves through the spatially varying field, the direction of its spin adiabatically follows the direction of the magnetic field. The potential energy is then proportional to the magnitude of the field, $B$. For the atom species that we use, $^{87}$Rb in the $|F = m_F = 2\rangle$ magnetic sublevel of the ground state, the potential is $U(r) \approx \mu_B B(r)$, with $\mu_B$ the Bohr magneton. These atoms therefore seek the minimum of the magnetic field $B$. Designing an atom chip is therefore essentially designing magnetic field minima.

In most atom chip experiments to date, the source of magnetic field is defined by a pattern of current carrying wires. The basic laws relating the magnetic induction $B$ to currents were initially established by Biot and Savart (1820) and
by Ampère (1820-1825) through experiments. The magnetic induction $\mathbf{B}$ of a line element $dl$, carrying a current $I$ is given by [16]

$$\frac{dB}{d\mathbf{l}} = \frac{\mu_0 I}{4\pi} \frac{d\mathbf{l} \times \hat{r}}{r^2}$$

(2.1)

where $r$ is the distance from the line element to the observation point and $\mu_0$ is the permeability of free space.

The experiments described in this thesis are based on permanent magnetic structures. In principle it is always possible to use the Biot-Savart law also for permanent magnets, by inserting the magnetization current. This works particularly well for films that are magnetized out of plane. For magnetic films that are in-plane magnetized the Biot-Savart approach is less intuitive. It is then conceptually easier to view the film as a collection of magnetic dipoles.

The current density due to a magnetization $\mathbf{M}$ is given by $\mathbf{J} = \nabla \times \mathbf{M}$. We restrict ourselves to the case where the material is uniformly magnetized. With this assumption, $\mathbf{J}$ is nonzero only at the edges of the material. If the film has a uniform thickness $d$, with magnetization $M$ perpendicular to the film (“out of plane”), the magnetization current has a value of $Md$ and runs along the perimeter of the film. For example, using typical values of $M = 500 \text{ kA/m}$, and $d = 0.2 \mu m$, we have an effective current $Md = 0.1 \text{ A}$, running along the perimeter of the film.

For an in-plane magnetized film the magnetization currents are given by current sheets, along the top and bottom surface of the film. In this case a more intuitive approach is to consider the field produced by the film as a superposition of dipole fields. Magnetization is the volume density of a magnetic moment, i.e. a volume element $dV$ with magnetization $M$ has a magnetic moment of $d\mathbf{m} = M dV$. An infinitesimal volume element $dV$ can be considered as a point dipole with magnetic dipole moment $d\mathbf{m}$. The field of a point dipole $\mathbf{m}$ is given by

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi r^3} (3(\mathbf{m} \cdot \hat{r})\hat{r} - \mathbf{m})$$

(2.2)

where $r$ is the vector to the position where the field is being measured. The total field is obtained by the volume integral over the structure. For a rectangular block of material this volume integral can be performed analytically. The resulting expression is too lengthy to reproduce here, but can be handled well using a symbolic computation program such as Mathematica [17]. The calculations in this chapter have been performed using two methods. Most numerical results were obtained using the Radia package [18] with Mathematica. Trapping frequencies were in most cases calculated using the mentioned analytical expressions.

### 2.2 Integrated magnetic atom optics

As a first class of integrated structures for magnetic atom optics we start by describing several methods to create waveguides for atoms. Waveguides are obvi-
ously a basic building block for creating propagating structures, including beam splitters and atom interferometers. At the same time a (short) waveguide structure can also be recognized in the prototypical design of a Ioffe-Pritchard trap.

Atom-optical structures can be divided into two categories: propagating (waveguide-based) and trapping structures, where the latter seems most useful for quantum computing devices.

2.2.1 Waveguides and derived structures

Waveguides

Guiding of atoms has attracted much attention in recent years and various guides have been realized using magnetic potentials [19, 20, 1].

The simplest method to create a magnetic waveguide is based on a single strip of magnetized material, in combination with a uniform external field. In Figure 2.1 (a) we show a vertically (out of plane) magnetized strip with a vertical bias field. Straight above, the strip produces a vertical field. This is canceled by the vertical bias at some height above the strip, yielding a line of zero field parallel to the strip. In the immediate vicinity of this line the field is a cylindrical quadrupole, with a field that increases linearly with the distance to the line of zero field. This is shown by the contour lines of equal \( B \). When the bias field is increased the waveguide will move closer to the chip and consequently the gradient will increase at the same time. This single strip waveguide is equivalent to a two-wire waveguide, using two wires carrying equal but opposite currents, as shown in Figure 2.1 [3].

In principle one could make a similar straight waveguide using in-plane magnetization and an opposing uniform bias field. However, there is a crucial difference: the out-of-plane guide can make turns in the plane while keeping the bias field in the right direction. For the in-plane magnetized guide this is not possible. Thus, in-plane magnetization will be unpractical for most propagating applications, except straight guiding.

For example a single \( 1 \times 0.2 \mu m^2 \) strip yields a gradient of \( \sim 5 \times 10^3 \) T/m at about 1 \( \mu m \) above the structure, for \( M = 500 \text{kA/m} \). When scaling down the wire dimensions, a regime is reached where the current density must be held constant. As soon as this happens, further reduction of the wire width does not lead to stronger gradients, because the maximum field gradient scales as the current density. The highest reported current densities are \( 10^{11} \) A/m\(^2\), leading to maximum gradients in the \( 10^4 \) T/m region [4, 21, 22].

One can also make the bias field on-chip, i.e. make the waveguide 'self-biasing'. For example, two separated magnetic strips produce a line of zero without the need of a bias field. Figure 2.1 (b) shows the magnetic field distribution for two perpendicularly magnetized strips. When a vertical bias magnetic field is added, the guide can be moved down or up, and made to merge with or separate from a
Figure 2.1: Cross sections of magnetic waveguides for atoms created by strips of magnetized material with a magnetization $M = 500$ kA/m. Contour lines have been drawn at 40 G intervals. a) one strip of magnetized material plus a uniform bias field $B_{bias} = 50$ G. b) A waveguide created by two magnetic strips, magnetized out of plane, with zero bias field. c) A waveguide created by two in plane magnetized strips, with zero bias field. No scales are given because the structures are scale invariant. The lower part of the figure shows the wire patterns that would produce the same fields.
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second quadrupole trap. Such a device can act as a beam splitter or recombiner for cold atoms, as is illustrated in Figure 2.2. This waveguide is equivalent to a four-wire waveguide, with wires carrying equal but alternating currents, as shown in Figure 2.1 [3].

Again, we can also create this waveguide with in-plane magnetized materials, as is illustrated in Figure 2.1 (c). Decreasing the distance between the strips lowers the center of the trap above the surface and increases the magnetic field gradient. This has the same effect as an increase of the bias field.

The maximum possible gradient formed above two strips can be optimized with the distance between them. For two infinite strips with width \( w \), thickness \( d \), and separation \( s \) (slit width), a waveguide is formed at \( z_0 = \frac{1}{2} \sqrt{d^2 + s^2 + 2sw} \).

The field gradient of the cylindrical quadrupole field is

\[
B' = \frac{\mu_0 M}{4\pi} \frac{16dw\sqrt{d^2 + s(s + 2w)}}{s(s + 2w)(d^2 + (s + w)^2)}.
\]  

(2.3)

In the thin film approximation: \( d \ll w, s, z_0 \), we get \( z_0 \sim \frac{1}{2} \sqrt{s(s + 2w)} \).

If we make a choice for the desired distance to the surface \( z_0 \), then the corresponding choice for the slit width is given by

\[
s = -w + \sqrt{w^2 + 4z_0^2}.
\]  

(2.4)

With this condition fulfilled, the maximum gradient in \( z_0 \) is reached for

\[
s = 2(-1 + \sqrt{2})z_0, \quad w = 2z_0.
\]  

(2.5)

With these choices, the value of the gradient is approximately

\[
B' = \frac{\mu_0 M 2d}{4\pi \frac{d^2}{z_0^2}}.
\]  

(2.6)

**Beam splitters and interferometers**

Beam splitters are key elements in interferometry and its applications. By combining two guides, it is possible to design potentials where at some point two different paths are available for the atom. This can be realized using various configurations. Two geometries have been demonstrated, one which distributes a trapped cloud in a Y-shaped pattern [23], and one which splits a guided beam using an X-shaped pattern [24]. In these configurations an additional potential minimum appears between the geometric splitting point of the wires and the splitting point of the potential, forming a fourth port, which induces a loss rate since atoms taking that route will hit the surface. This inconvenience could be overcome with permanent magnetic film guides.

A possible realization of a splitter with permanent magnetic materials is using two tracks that approach each other, as shown in Figure 2.2. A more detailed
Figure 2.2: A beam splitter, tunable via a bias field. The region between the merging positions $x = \pm 2.5 \, \mu m$ can be considered as a miniature interferometer. The bias field of 5 mT is perpendicular to the drawing. The contour plots have been drawn in the $yz$-planes (perpendicular to the track direction). Darker shading indicates lower potential, with contours at 1 mT intervals.

inspection of the contour plots at different points along the tracks reveals that the wave-guides merge at two positions, $x = \pm 2.5 \, \mu m$. Between these positions, two vertically separated wave-guides exist. Thus the structure essentially contains two beam splitters, which together form an interferometer. The merging points can be moved closer together or further apart by changing the bias field. Thus the beam splitters are tunable and can also form an interferometer. These devices could find applications in atom interferometry and in the study of decoherence processes close to a surface.

**Circular guides**

Another great opportunity offered by permanent magnet chips is the possibility to create circular guides with the absence of lead wires that would perturb the symmetry of the trap. A single ring of magnetized material with out-of-plane magnetization plus a bias field can create a circular guide for atoms, as shown in Figure 2.3 (a). Two or more concentric rings form (a set of) ring-shaped magnetic quadrupole fields with no need for a bias field, see Figure 2.3 (b). Ring structures are interesting for interferometry, for inertial sensing and for studies of low-dimensional gases. More about the usability of these type of traps can be found in [25].

**2.2.2 Traps, lattices and shift registers**

The simplest method to create magnetic traps is to create a point of zero magnetic field. In general such traps suffer from high loss rates due to Majorana spin flips.
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Figure 2.3: Circular guides, tunable via the bias field. a) One ring of magnetized material forming a circular guide by adding a perpendicular bias field, at \( z = 0.12 \) mm. b) More concentric rings forming waveguides, with zero bias field, at \( z = 0.08 \) mm. The contour plots have been drawn in the \( xy \)-planes (parallel to the track direction). Darker shading indicates lower potential.

Preferably the minimum field is nonzero in order to suppress spin flips. Ioffe-Pritchard (IP) traps are well known examples of magnetic traps with a non-zero minimum. The basic macroscopic configuration for an IP trap consists of four long bars with currents in alternating directions, two pinch coils and two nulling coils, both in Helmholtz configuration. Alternatively, microscopic wire patterns can be used to create IP traps. In conventional atom chips \( Z \)-shape wires are used for creating IP microtraps [2]. The \( Z \)-trap is shown in Figure 2.4 (a). In this configuration, the central part of the wire combined with the external field, produce a two dimensional quadrupole trap. The bent parts of the wire produce a field which is perpendicular to the external field. The \( x \) component of this additional field closes the trap along the \( x \) axis, while the \( y \) component merely causes a small displacement of the minimum. The two contributions add up so that the field in the trap center is nonzero.

A permanent magnetic version of a IP trap configuration can be made of two displaced magnetic strips, as shown in Figure 2.4 (b). Two in-plane magnetized strips produce a line of zero field above the gap between them. The additional field from the extra pieces added at the end has a component in the \( x \)-direction. Its purpose is to offset this minimum in order to avoid Majorana spin flips and to pinch off the ends.

In Figure 2.4 (c) we show a IP trap designed from an out-of-plane magnetized film. In this ‘horseshoe’ configuration the two long strips produce a line of zero field above the structure. The edge currents at the end of the strips, represented by the dark arrows around the material in Figure 2.4 (c), produce the axial and the pinching field. In both examples, in-plane as well as out-of-plane, the IP trap is self biasing.
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An important property of IP traps is their harmonic trapping frequency. Near the bottom of the trap the atoms see a three-dimensional harmonic trap. The oscillation frequency along the $i$-th eigen axis, ($i = 1, 2, 3$), of a harmonic potential $U$ is given by

$$\omega_i = \sqrt{\frac{1}{m} \frac{\partial^2 U}{\partial x_i^2}} = \sqrt{\frac{\mu_B g_F m_F}{m} \frac{\partial^2 B}{\partial x_i^2}}$$  \hspace{1cm} (2.7)

With permanent magnetic chips we can reach very high frequencies by going down in dimensions, even greater then 2 MHz in the radial direction. With a video tape atom chip [26] frequencies of 320 Hz in the radial direction and 15 Hz in the axial direction have been achieved. For current based chips, frequencies of over 1 MHz have been achieved using wire cross sections of $1 \times 1 \mu m^2$ [27]. Such extremely tight traps enable very fast thermalization, which may be used for rapid condensation on site aboard the chip. The trap depth is given by the bias field.

Magnetic microtrap lattices

It is straightforward now to extend the above designs to arrays of microscopic IP traps, as shown in Figure 2.5 and 2.6. The individual traps are anisotropic and cigar shaped. All have a nonzero minimum field. A possible application of such arrays is a shift register, an important application for quantum information processing. This allows controlled transport of trapped atoms along the array by manipulating an external magnetic field. Calculations for the geometry of Figure 2.5 show that if the bias field is rotated in the $xz$-plane, the entire array of traps, i.e. the magnetic field minima, moves along the $x$-direction. Reversing the sense of the rotation shifts the array backward. Rotating the bias field can be done using two orthogonal pairs of coils outside the vacuum.

Figure 2.4: Layout of a prototypical Ioffe-Pritchard magnetic trap - a) Classical Z-trap with a bias field made with current carrying wires, and two permanently magnetized traps that can form IP traps - b) two in-plane magnetized strips, and c) a horseshoe type trap, with the magnetization out of plane.
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Figure 2.5: An array of microtraps - an atomic shift register, made of out-of-plane magnetized material. The bias field is 2 mT and vertical (∥z). The contours were drawn at a height $z = 6.4 \mu m$ above the surface. A bias field rotating in the $xz$-plane moves the traps along the $x$-axis by one period per turn.

The geometry of Figure 2.6 has been produced in FePt film, see Chapter 4.

Lattices of cold atoms have so far only been created using optical fields [28], trapping atoms in the nodes or antinodes of an optical interference pattern, and using microlens arrays [29]. Whereas the period of optical lattices is on the order of the wavelength of the light used, the period of a magnetic lattice can be chosen at will while fabricating the structure. The period can be anywhere between a few 100 nm and $\sim 100 \mu m$. In addition one can fabricate quasiperiodic structures, superlattices, etc. Using lithographic techniques a vast number of microtraps can be integrated on a single chip. With further miniaturization it is possible to obtain $\sim 10^5$ traps/mm

Arrays of traps can be designed in many different geometries. We now describe a design for an in-plane magnetized film. The arrays consist of displaced strips, as one can see in Figure 2.7 and 4.7. In this design each array is characterized by roughly the same geometry. We vary the length and width ($w$) of the magnetic strips, the slit(s) between them, and the longitudinal displacement ($d$) of neighboring strips. All calculations are done with the same film thickness. By keeping the thickness constant and varying the other parameters we can achieve different trapping potentials at different heights above the surface with the possibility to reach trapping frequencies in the range of $10-100$ kHz. For example an array of strips with $w = 0.01 \text{ mm}$, slits of $s = 0.4 w$, lengths $40 w$, displacements $d = 4 w$, and 250 nm film thickness, produces traps with a radial frequency of 110 kHz. Higher frequencies could be achieved by a further reduction of the dimensions. For example for $w = 0.008 \text{ mm}$ and $s = 0.004 \text{ mm}$ the radial frequency is 230
Figure 2.6: An array of microtraps formed above an array of magnetic FePt strips - xy-plane. The film is in-plane magnetized.

Figure 2.7: Basic design of the arrays, with the geometry parameters: width (w), slit (s) and displacement (d).
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Double wells appearing in a lattice above the surface, formed by varying the longitudinal displacement.

If we also decrease the film thickness we can reach 2 MHz for the radial frequency. For example an array made from a film of 100 nm thick, \( w = 0.001 \) mm, \( s = 0.0004 \) mm can form traps with a radial frequency of 2.5 MHz and an axial frequency of 3 kHz.

If the distance between the strips is larger, the traps will form higher above the surface and will be shallower. By making longer strips we can form longer traps. For larger aspect ratios of all parameters the traps are shallower.

An interesting possibility emerges when the longitudinal displacement is increased. This allows the formation of a lattice of double-well potentials. Figure 2.8 shows a cut through the magnetic field forming the double-well in the \( xy \) plane taken along the axis of the double-well trap. In this example \( w \) is 0.01 mm, \( s = 0.004 \) mm, \( d = 6 \) \( w \), \( l = 20 \) \( w \) and the radial frequency is 96 kHz. Preliminary calculations show that by changing the strength of the bias field one can change the height of the barrier between the two wells. A gradual lowering of the bias field should also give rise to adiabatic cooling of the trapped atoms.

Such a device can be used for atom interferometry [30]. An atom chip-based interferometer may be formed with this device by coherently splitting and recombining the traps using the bias field to manipulate the barrier height [30]. Several other groups are also pursuing atom interferometry with BECs using microwire traps [31, 32, 33] and a few have demonstrated BEC splitting and the detection of interference fringes upon trap release [34, 35, 36].

Toward quantum computing

Arrays of traps have great potential as data registers for a quantum computer [37]. The vision is that each trap would contain an atom in a quantum superposition of two internal states, \( \alpha |0\rangle + \beta |1\rangle \), i.e. a qubit. In our case of \(^{87}\)Rb, we can use the two hyperfine ground states \( |F = 2, m_F = 1\rangle \) and \( |F = 1, m_F = -1\rangle \) as the qubit states. Transitions between these two states can be driven by a two-laser
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Raman pulse, which would implement a one-qubit gate operation. Alternatively, microwave plus rf two photon transitions can also be used.

In this context we envision an important application for a qubit shift register as described above. By shifting the array one could bring one particular qubit or pair of qubits in position for a quantum gate operation. One could also shift qubits to a detection region where their bit values are read out sequentially.

It is obvious that many technical problems have to be solved to build a practical quantum computer. Nevertheless, we think that arrays of magnetic microtraps should be considered as a promising candidate to implement and to test these ideas.

2.3 ‘Cold’ atoms near ‘hot’ surfaces

A source of concern about atom chip miniaturization is the presence of the ultracold atoms close to the room temperature substrate. For traps or guides in which the atoms are confined close to the surface of an atom chip, atoms experience magnetic field fluctuations which produce harmful effects such as spin-flip induced trap loss, heating and decoherence [38, 39]. Theoretical approaches [40, 41] predict dependence of the magnetic field noise on the temperature and resistivity of the metal chip elements in the limit of a large skin depth (low transition frequencies) [42]. Recent experiments measuring spin flip relaxation rates trapped near surfaces have demonstrated the importance of thermal field fluctuations [39, 43, 44]. This has promoted great interest in thin surfaces because they should generate less Johnson noise [45]. In [43] experimental values for the loss rate of $^{87}$Rb atoms, magnetically trapped near a thin surface (2 µm) are given. At distances greater than 7 µm from the surface, the loss rate is essentially constant and is due to collisions with the background gas. At shorter distances, the lifetime is reduced by thermally-induced spin relaxation. A comparison with theory [40] shows that the scaling laws are in good agreement for distances down to 3.4 µm. Below that, there seems to be a discrepancy, with observed lifetimes being substantially shorter than expected. This could be due to patch potentials on the surface.

The spin flip lifetime depends on three independent length scales [45, 46]: the substrate thickness $h$, the atom-surface distance $d$, and the skin depth $\delta$ of the substrate material, defined via the Drude relation [16]. For certain regimes of these parameters it is possible to approximate the lifetime. For thick films the lifetime exhibits a minimum at $\delta_{\text{min}} \approx d$, whereas for thin films it is at $\delta_{\text{min}} \approx \sqrt{hd}$. For example, with the atom placed at 50 µm above a thick slab, a skin depth of 100 µm leads to 10 s lifetime [45]. For the film thicknesses we use, with an estimated skin depth $\delta = 100$ µm at 2.1 MHz it should be possible to create long lived traps at $\geq 2$µm distance from the surface.

Another source of inhomogeneity and decoherence peculiar to microfabricated
atom chips is the fragmentation of the atom clouds [47, 48, 49, 8]. It was originally observed for ultracold atoms in magnetic microtraps located less than 100 µm from electroplated wires [50, 39]. This effect is due to small imperfections on the surface and edges of structures resulting in small modulation of the magnetic field. These modulations can break up the atom cloud. The same effect was recently observed with permanent magnetic materials [26, 51]. While the mechanisms that cause the fragmentation near current-carrying wires are currently well understood, it is unclear what mechanisms may cause fragmentation near permanent magnetic materials. An analysis of the requirements is in progress. The film we use has 50 nm roughness which is on the order of the nanocrystalline grain size. The edge roughness is slightly larger than the state of the art in current-conducting chips and can probably still be improved.

Recent research on multilayer thin films [13, 52] appears to offer a solution to the problem of the homogeneity of the magnetic layer. Films of few tens of angstroms could be made using this multilayer deposition with high magnetic anisotropy.

Significant reduction of the magnetic field noise can also be achieved by replacing the pure noble metal structures with dilute alloys. The alloy composition provides an additional degree of freedom which enables a controlled reduction of both magnetic noise and resistivity if the atom chip is cooled [42]. A non-monotonic behavior with either the skin depth or conductivity has also been pointed out by Rekdal and co-workers [46]. They demonstrate that conductors show only weak current fluctuations, while good conductors effectively screen the magnetic field. In this project we are using an FePt alloy which is not a good conductor.

2.4 Conclusions

In this chapter we have discussed few opportunities and limitations of the permanent magnetic atom chips. We have also shown some interesting designs for micro traps using permanent magnetic materials, such as waveguides, traps and lattices. These permanent magnetic chips have great potential because of the high gradients and intriguing geometries. Moreover, their naturally compact size is an advantage to system miniaturization and integration. The achievable gradients and curvatures, $10^7$ G/cm and $10^{10}$ G/cm$^2$, are comparable to those achievable in the tightest microwire traps, but without any power dissipation. Our magnetic material is suited to handle both in-plane and out-of-plane magnetization. The applicability of the first is better used for creating traps while the latter is more universal, e.g. curved guides and traps.

Atom chips are promising tools not just for quantum computation, but more in general for atom interferometry, as well as for miniaturized BEC production.

One obvious drawback of permanent magnets however is the relatively limited
degree of dynamic control available over the trapping potentials. As a result, the permanent magnet atom chips rely on externally controlled bias magnetic fields.