Combined chips for atom-optics

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We present experiments with Bose-Einstein condensates on a combined atom chip. The combined structure consists of a large-scale “carrier chip” and smaller “atom-optics chips”, containing micron-sized elements. This allows us to work with condensates very close to chip surfaces without suffering from fragmentation or losses due to thermally driven spin flips. Precise three-dimensional positioning and transport with constant trap frequencies are described. Bose-Einstein condensates were manipulated with submicron accuracy above atom-optics chips. As an application of atom chips, a direction sensitive magnetic field microscope is demonstrated.

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I. INTRODUCTION

Interest in phase coherent experiments with ultracold quantum gases has motivated numerous theoretical and experimental investigations into microscopic magnetic traps [1]. An intriguing feature of microtraps is the possibility of constructing complex potentials using the magnetic field of micro-structured conductors on a chip, as well as the precise spatial and temporal control of these potentials. Specific atom-optical experiments have been discussed, such as Bose-Josephson junctions in double well potentials [2], tunneling through a quantum dot in magnetic waveguides [3] or even scenarios for creating entangled pairs of atoms [4]. A central goal is the preparation of matter waves in microtraps with potential structures on the micron scale, comparable to the healing length of the condensate, which will allow for tunneling on experimentally viable timescales. Current experiments can readily produce Bose-Einstein condensates in magnetic microtraps [2, 3]; however, the potentials used to date have been too large scaled to reach the tunneling regime. To go beyond this, condensates must be moved closer to field generating elements, that is, to within a few microns of the chip surface.

With atom/conductor separations of a few microns, Johnson-noise induced spin-flip losses reduce the life time of the atomic cloud [5, 6]. Furthermore, at distances extending to several tens of microns, irregularities of the trapping potential, arising from geometrical imperfections of the conductor [7] and the corresponding spatial fluctuation of magnetic field [8], cause fragmentation of atomic clouds.

In this paper we present a way to overcome these limiting surface effects which allows one to work at micron distances from the surface. A smooth waveguide potential is produced by a large scaled “carrier chip” situated several hundreds of microns from the surface of further “atom optics chips”. At this distance, surface effects from the carrier are negligible [1]. The carrier chip is used for micro-positioning a condensate. Attached to the surface of the carrier, additional atom-optics chips based on micron scaled conductor patterns are used for steep and thin potential barriers. Due to the small amount of metal, Johnson-noise induced spin-flip rates are minimized even at close distances to the chip surface [12]. Since atoms are confined in a smooth waveguide and interact only with short sections of cross conductors at micron distances, stable conditions for coherent atom optics are achieved.

II. THREE-DIMENSIONAL CONFINEMENT ON A CHIP

When manipulating condensates with micron-sized electromagnets, the exact position of the atoms with respect to these elements becomes crucial. Previous microtraps have used large external electromagnets to generate the so called bias field that is essential for the microtrap concept [12]. Because of the uncertainties in their geometry, accurate calculation of the trap parameters and position becomes difficult. In order to overcome this, we have developed a chip which includes all field generating elements necessary for three-dimensional confinement and manipulation. The micro fabricated wire pattern defines a precise conductor geometry and the trap parameters and position can be computed with high accuracy. The conductor configuration was designed to provide three-dimensional positioning and transport of condensates, while keeping the trap frequencies constant.

A. Radial confinement and positioning

A magnetic waveguide potential can be realized by three parallel conductors as shown in Figure 1a and 1b. The magnetic field of the center conductor QP2, driven with a current of $I_{QP2}$, is superimposed with the bias field...
positive in -z direction. The central conductor QP1 and QP3. A waveguide is formed above the chip, as indicated by the magnetic field lines. Marked also is the thickness of the substrate \( s_0 = 250 \mu \text{m} \) as used for the carrier chip in our experiment. Conductor geometry for a microtrap with three dimensional confinement. A waveguide potential is generated by the conductors QP1, QP2, and QP3. The magnetic field of a pair of perpendicular conductors (“transport conductors”) can be used for an axial displacement. The geometry of conductors is marked: the distance between the QP wires \( d_{\text{QP}} \) is 750 \( \mu \text{m} \) and the distance between the transport wires is \( d_T = 650 \mu \text{m} \).

**B** \(_{L}\), generated by two other parallel conductors QP1 and QP3 (“quadrupole wires”).

The inhomogeneous bias field is given by

\[
B_{L} = \frac{\mu_0}{2\pi} \left( \frac{I_{\text{QP}1} y}{(d_{\text{QP}} + x)^2 + y^2} + \frac{I_{\text{QP}3} y}{(d_{\text{QP}} - x)^2 + y^2} \right) e_x
- \frac{\mu_0}{2\pi} \left( \frac{I_{\text{QP}1} (d_{\text{QP}} + x)}{(d_{\text{QP}} + x)^2 + y^2} - \frac{I_{\text{QP}3} (d_{\text{QP}} - x)}{(d_{\text{QP}} - x)^2 + y^2} \right) e_y .
\]

\( d_{\text{QP}} \) is the distance between the conductors QP1 and QP2, (and QP2 and QP3) and \( I_{\text{QP}i} \), \( i = 1, 2, 3 \) are the respective currents. The waveguide forms in a line, where the bias field and the field of the central conductor cancel each other. This requires the current in the outer conductors to be opposite in direction to the current in the central conductor. We follow the convention that \( I_{\text{QP}2} \) is positive for currents in +z direction, and \( I_{\text{QP}1/\text{QP}3} \) is positive in -z direction.

Applying the same current in QP1 and QP3, the \( y\)-component of the bias field vanishes along the \( y\)-axis, and the resulting bias field is

\[
B_{L} (x, y, 0) = \frac{\mu_0}{2\pi} \frac{y I_{\text{QP}1}}{d_{\text{QP}}^2 + y^2} e_x .
\]

The waveguide forms at a distance of

\[
y_0 = d_{\text{QP}} \sqrt{\frac{1}{2} \left( \frac{I_{\text{QP}1}}{I_{\text{QP}2}} + \frac{I_{\text{QP}2}}{I_{\text{QP}3}} \right) - 1}
\]

on the \( y\)-axis (Figure 1a). A trap is only formed if \( |I_{\text{QP}1}| \geq |I_{\text{QP}2}/2| \). The radial field gradient \( a_r \), in the trap center of the three-wire configuration is given by

\[
a_r = \frac{\mu_0}{2\pi} \frac{I_{\text{QP}2}}{y_0^2 \left( 1 + \left( y_0/d_{\text{QP}} \right)^2 \right)} .
\]

In the general case, the \( x, y\)-position of the waveguide is determined by the currents \( I_{\text{QP}1}, I_{\text{QP}2}, \) and \( I_{\text{QP}3} \):

\[
x_0 = \frac{d_{\text{QP}}}{2} \frac{I_{\text{QP}1} - I_{\text{QP}3}}{I_{\text{QP}1} + I_{\text{QP}2} + I_{\text{QP}3}}
\]

\[
y_0 = \frac{d_{\text{QP}}}{2} \frac{\left( I_{\text{QP}1} I_{\text{QP}3} - (I_{\text{QP}1} + 2 I_{\text{QP}2} + I_{\text{QP}3})^2 \right)^{1/2}}{I_{\text{QP}1} + I_{\text{QP}2} + I_{\text{QP}3}} .
\]

The trap can be positioned within a large area above the chip by changing the currents \( I_{\text{QP}1}, I_{\text{QP}3}, \) and \( I_{\text{QP}2} \). Figure 2 shows trajectories corresponding to a constant ratio of \( I_{\text{QP}1} \) and \( I_{\text{QP}3} \) (solid lines) and constant \( I_{\text{QP}2} \) (dashed lines) while keeping the sum \( I_{\text{QP}1} + I_{\text{QP}3} \) at a constant current of 2A. The values are realistic for experiments discussed later.

B. Axial confinement and translation of the trap center

The waveguide produced by the three conductors will suffer from Majorana spin flips [14] because the magnetic field vanishes in the center of the waveguide. However, a magnetic offset field \( B_{\text{off}} \) along the symmetry axis, stabilizes the trap against these losses. The nonzero absolute value of the magnetic field \( B_{\text{off}} \) in the trap center also changes the radial potential shape from linear to parabolic [14]. The radial confinement is then characterized by the oscillation frequency \( \omega_r = \sqrt{g_F \mu_B m_F / m_{\text{off}} \cdot a_r} \), with the Landé factor \( g_F \), the Bohr magneton \( \mu_B \), the magnetic quantum number \( m_F \), and in the mass of the atom. To allow for three dimensional confinement, an inhomogeneous offset field is generated by two conductors, T1 and T5 in Figure 1b, perpendicular to the waveguide (“transport wires”). The distance between T1 and T5 is \( 4d_T \). For identical currents \( I_T \) in T1 and T5, the magnetic field is described by its components

\[
B_x = 0
\]

\[
B_y = \frac{\mu_0}{2\pi} I_T \left( \frac{x_0 + y_0}{(x_0 + y_0)^2 + (2d_T + z)^2} - \frac{x_0 - y_0}{(x_0 + y_0)^2 + (2d_T - z)^2} \right)
\]

\[
B_z = -\frac{\mu_0}{2\pi} I_T \left( \frac{x_0 + y_0}{(x_0 + y_0)^2 + (2d_T + z)^2} + \frac{x_0 - y_0}{(x_0 + y_0)^2 + (2d_T - z)^2} \right).
\]
In our setup the transport wires are located at the back side of the substrate separated from the QP wires by $s_0$. The $B_z$ component provides the overall non-vanishing offset field for the waveguide. Near the minimum of $B_z$, between T1 and T5, the potential is approximately parabolic, with an axial oscillation frequency $\omega_a$ (Eq. 10) and an offset field value

$$B_{\text{off}} = \frac{\mu_0}{\pi} \frac{I_T(s_0 + y_0)}{(s_0 + y_0)^2 + 4d_T^2}. \tag{7}$$

The axial potential is plotted in Figure 1. The field component $B_y$ causes a small rotation of the waveguide about the $y$-axis. The rotation angle at the bottom of the trap is estimated by

$$\alpha \approx \frac{\mu_0 I_T}{\pi} \frac{y_0^2 - 4d_T^2}{a_r(y_0^2 + 4d_T^2)^2}. \tag{8}$$

The trapping potential generated by the five conductors QP1, QP2, QP3, T1, and T5 is characterized by the field curvatures $b_i$

$$b_{\text{axial}} = \frac{\mu_0}{2\pi} \frac{I_T(s_0 + y_0)}{y_0^2} \frac{48d_T^2 - 4(s_0 + y_0)^2}{((s_0 + y_0)^2 + 4d_T^2)^3},$$

$$b_{\text{radial}} = \frac{a_r^2}{B_{\text{off}}} = \frac{\mu_0}{2\pi} \frac{2I_{\text{QP2}}}{y_0^2} \frac{(s_0 + y_0)^2 + 4d_T^2}{I_T(s_0 + y_0)(1 + (r_0/d_{\text{QP2}})^2)^2}, \tag{9}$$

and the resulting trap frequencies $\omega_i$, $i=\text{axial, radial}$

$$\omega_i = \sqrt{\frac{ge^{\mu\text{FMB}}}{m} b_i}. \tag{10}$$

The above expressions assume infinite conductor lengths. The finite length of the conductors on the real chip (Figure 1) results in a deviation of the axial and radial trap frequencies by 5 and 4 percent, respectively.

The five-wire configuration achieves full, three-dimensional confinement of atoms using magnetic fields generated by the chip only. Precise control of the position $(x_0, y_0)$ and parameters of the trap is therefore possible. The $z$-position of the trap is controlled by further transport wires T1 - T8. A trap generated by T1 and T5 will have identical parameters to one generated by T2 and T6 (Figure 1). One trap can be continuously transformed into the other by reducing the current in one of the pairs while increasing it in the other. Thereby, the trap center shifts by $d_T$, the distance between two neighboring conductors $T_i$ and $T_{i+1}$. While in general the axial trap frequencies change during the transport, we have calculated an optimum trajectory of the currents $I_{T2}(I_{T1})$, the same as for $I_{T6}(I_{T5})$, so that the axial trapping frequency remains constant.

On our chip the transport wires $T_i$ are spaced by $d_T = 650\mu\text{m}$ (Figure 4). For a trap to be transported at constant height of about 300\,\mu m, the optimum currents, fitted to third order, are

$$\frac{I_{T2}}{I_T} = 1 - 2.39 \frac{I_{T1}}{I_T} + 2.31 \left( \frac{I_{T1}}{I_T} \right)^2 - 0.92 \left( \frac{I_{T1}}{I_T} \right)^3. \tag{11}$$

The axial displacement of the trap in terms of the currents is given by

$$z_0 = d_T \left( 1 - 1.49 \frac{I_{T1}}{I_T} + 0.49 \left( \frac{I_{T1}}{I_T} \right)^2 \right). \tag{12}$$

$I_T$ is the initial current in T1 and T5. Keeping the axial trap frequency and the height above the chip constant by changing the currents in the transport wires as described above, the offset field and correspondingly the radial trap frequency would vary by a factor of 1.14 and 0.94, respectively. The variation of the radial trap frequency, however, can be compensated by varying the radial gradient (Eq. 4) of the trap through matching the currents in the three quadrupole wires $I_{\text{QP1}} = I_{\text{QP3}}$ and $I_{\text{QP2}}$ while holding the ratio $I_{\text{QP1}}/I_{\text{QP2}}$ constant. The latter condition is necessary for the constant height (Eq. 4). On the other hand, the transport wires produce a non-vanishing $y$-component of the magnetic field at the trap center (Eq. 5), altering the $x$-position of the trap during the transport by $\pm 1.3\mu \text{m}$. This is in general a negligible effect, but can also be compensated by matching the currents $I_{\text{QP1}}$ and $I_{\text{QP3}}$ while keeping their sum constant. As a result, we are able to move the trap in the axial direction while keeping the radial and axial trap frequencies as well as the radial $(x, y)$ position of the trap constant. The axial trapping potential is plotted in Figure 5 during the optimized transport over a distance of $d_T$ (solid line). The curvature of the potential near the minimum does not change, while a small change in the offset field is visible. During transport, the axial trap depth reduces to almost half of its initial and final values. Nonetheless, this does not set any relevant restrictions on experiments which are operated with sufficiently cold ensembles.

On our atom chip, we have integrated a set of eight conductors T1-T8 which repeat periodically over the length of the chip (see next section). Transport of atomic clouds
is possible over a distance of 1.75 cm without any change of the trap frequencies or the radial position. The conveyor on our chip has been developed with respect to this scalability, allowing coherent transport of condensates over a large distance. A Bose-Einstein condensate of interacting particles is a nonlinear medium sensitive even to non-resonant excitations, e.g., through changes of the trap frequencies. Coherent, excitationless transport of the condensate thus requires constant trap frequencies as provided by the conveyor belt described in this article.

III. COMBINED CHIPS

In subsequent experiments, we have used a combined atom chip. This consists of a carrier chip, which operation principle has been outlined in the previous section, and several atom-optics chips.

A. Carrier Chip

The carrier chip is a dual-layer atom chip which produces the entire magnetic field for three-dimensional magnetic trapping and manipulation of Bose-Einstein condensates (Figure 4). It supports the QP and T wires described in the previous section. Additional wire patterns shown in Figure 4 between QP1 and QP2, as well as between QP2 and QP3 were deposited for further microtraps, however, these are not used in the present work.

The chip was produced by electroplating gold conductors on both sides of a 250 µm thick aluminum oxide substrate of size 15.7 mm x 55.7 mm. A tungsten-titanium alloy adhesive layer was used between the substrate and the gold wires. The conductors are 100 µm wide and 6 µm thick. Conductor lengths vary from 2.3 cm up to 6.5 cm.

A typical trap we use for the preparation and manipulation of condensates is shown in Figure 3 (left) for five displacements (0, 162.5 µm, 325 µm, 487.5 µm, 650 µm) during transport over $d_T = 650$ µm (solid line). Matching the currents in T1, T2, T4 and T5 (Eq. 11) results in a smooth transport without changing the trap frequencies. (Right) Absorption images of thermal clouds for the corresponding displacements. The dashed line shows the chip surface. In this experiment, the currents were driven linearly, resulting in a variation of the axial potential (dashed potential curves on the left).
ulation of Bose-Einstein condensates of $^{87}$Rb atoms in the $F=2$, $m_F=\pm 2$ hyperfine ground state is generated by the currents $I_{QP1} = I_{QP3} = 0.85A$, $I_{QP2} = 0.235A$ and $I_{T1} = I_{T5} = 0.6A$. This trap is located 300$\mu m$ above the surface of the chip, the trap frequencies are 140 Hz in the radial and 16 Hz in the axial direction. The trap depth is $87\mu K$ in the radial and $108\mu K$ in the axial direction. In this trap, no fragmentation of Bose-Einstein condensates is observed.

B. Atom-optics Chips

Our atom-optics chips consist of micron-scaled conductors deposited on silicon substrates. High quality 300nm thick gold conductors have been patterned using standard techniques of electron-beam lithography and dry etching. Figure 5a) and b) show the microscope image and connection scheme of two nested meandering current patterns. The 1$\mu m$ wide conductors are separated by 1$\mu m$ gaps. With 372 parallel conductor stripes, the structure has a total length of 743$\mu m$ and a width of 100$\mu m$. Driven with currents as indicated in Figure 5c), a magnetic lattice potential $[17, 18, 19]$ of 4$\mu m$ period is generated.

Atom-optics chips are attached to the carrier using ceramic glue (Figure 5a). The meandering current pattern sits approximately 250$\mu m$ above the surface of the carrier chip. The magnetic field of the meander can be superposed on the magnetic waveguide potential positioned above it.

Because of its large size, the carrier chip can host several atom optics chips, as depicted in Figure 5a. The electrical connection of atom-optics chips is realized by wire bonding to the carrier chip. Atomic clouds initially loaded into the magnetic potential of the carrier chip can be positioned over any of the atom-optics chips using the conveyor and the waveguide. Precise positioning of Bose-Einstein condensates on the atom-optics chips is described in section IV.

IV. EXPERIMENTS ON THE CARRIER CHIP

A. Transport on conveyor

A key feature of the carrier chip is its ability to achieve smooth transport over distances, limited only by the length of the chip, in our experiment to 17.5$mm$. Transport is demonstrated using a thermal cloud of $1.5 \cdot 10^6$ rubidium atoms at a temperature of 6$\mu K$. The cloud is initially loaded into a trap as characterized in the last paragraph of section III. A. We begin the transport by accelerating the cloud over 500ms to a velocity of $v_T = 2.6mm/s$. The acceleration is increased to a maximum value of $a_{\text{max}} = 8.2mm/s^2$ and subsequently reduced to zero, both with a sinusoidal characteristic shape. During the 500ms of acceleration, the trap moves by 650$\mu m$ along the $z$-axis. Then the cloud moves with a constant velocity of $v_T = 2.6mm/s$ and covers a distance of 650$\mu m$ in 250ms. In the experiment shown in Figure 6 the cloud was slowed down in 500ms using the inverse acceleration ramp. The cloud arrives at rest (without sloshing) after travelling a total distance of 1.95$mm$.

A thermal cloud is less sensitive to variations of the trap parameters so this transport was done with a simplified, linear relation between the currents $I_{T2} = I_T - I_{T1}$ instead of Eq. 11. The displacement is then approximated by a linear function of the currents in the transport wires, resulting in a relevant simplification of the computer program controlling the experiment. However, this simplification means that the trap parameters change during the transport: the radial trap frequency decreases by up to 7 percent and the axial frequency increases by up to 14 percent. The dashed line in Figure 8(left) shows the axial potential shape for the simplified transport with respect to the exact scheme, shown as a solid line. Nevertheless, the transport takes place without any heating, since the atoms can follow the frequency changes adiabatically. Absorption images of the cloud taken every 50ms for a total transport time of 1.25$s$ were fitted by a two dimensional gaussian function in order to determine the number of atoms, temperature and position. The five ab-
FIG. 6: Position of a thermal cloud during transport over a distance of 1.95 mm. The transport starts at $t = 0$. The atoms are accelerated to a velocity of $v_T = 2.6 \text{ mm/s}$ over 500 ms. For the next 250 ms the atoms move at constant velocity $v_T$ before they are decelerated within another 500 ms until they come to rest at $t = 1.25 \text{s}$. The solid line shows the expected position, calculated from the currents in the wires. The inset image shows the number of atoms estimated from the absorption images changing in time.

FIG. 7: Eliminating axial center-of-mass oscillations of a Bose-Einstein condensate. Axial position of a condensate, initially oscillating with $\omega = 2\pi \cdot (16.4 \pm 0.3) \text{ s}^{-1}$ and $A = (36.8 \pm 1.6) \mu\text{m}$, after 25 ms time-of-flight. The center off mass motion is stopped by a phase-matched displacement of the trap center using the conveyor. The phase and amplitude of the oscillation are detected after 25 ms time-of-flight (Figure 7). As the imaged cloud position depends on both its position and momentum at the time the trap is turned off, the data is fitted by the function

$$Z(t) = A \sin (\omega_\tau t + \phi) + A \omega_\tau \cos (\omega_\tau t + \phi) + z_0,$$

(14)
describing the position of the oscillating cloud after $\tau$ time-of-flight. The fit parameters $A = (15.8 \pm 0.8) \mu\text{m}$, $\omega = 2\pi \cdot (16.4 \pm 0.3) \text{ s}^{-1}$ and $\phi = (-0.014 \pm 0.09)$ are used to determine the magnitude and timing of the trap displacement required to stop the oscillation. Radial excitations are avoided if the displacement is applied on a time scale longer than the radial oscillation period. The displacement is initiated 5 ms prior to when the center of mass motion reaches its turning point. Within 10 ms the trap is displaced by 16 microns along $z$, and the cloud arrives at rest (Figure 7). Based on the accuracy of the current sources used for the experiment [20], it is in principle possible to calculate the trap position to a few nm [21]. The accuracy of our measurement however, is limited by the optical resolution of the imaging system which is approximately 5$\mu\text{m}$.

The time-of-flight position of a Bose-Einstein condensate is determined by the motion of the cloud after the trapping potential is turned off. Spin polarized atomic clouds in a magnetic field sensitive state are accelerated...
not only by gravity but also by magnetic field gradients. The method we describe for positioning Bose-Einstein condensates on the micron scaled atom-optics chips exploits the change in position of the condensate, after being exposed to the magnetic field of the micro-structured electromagnets, during the time of flight. The field adds to ambient stray magnetic fields in the laboratory and changes the trajectories of released clouds. In a series of experiments, the initial position of the condensate can be varied and the magnetic field of the atom-optics chip mapped out by comparing the position after ballistic expansion with and without current in the electromagnets.

The method is demonstrated for an atom-optics chip with a known meandering current pattern (Figure 5). Using the carrier chip, condensates were positioned at constant y- and z-, but different x-positions below the chip. At each horizontal position, the distance to the surface was calibrated by moving the condensate towards the chip surface, until it was lost due to atom-surface interactions. During positioning, the meandering current was turned off. For each initial x-position, the vertical position (y) of the condensate was detected after 25 ms time-of-flight with zero and ±1mA current in the meander. The current was applied during the first 5 ms of the ballistic expansion. Because the imaging beam propagates parallel to the x-axis, only displacements along y and z were detectable. Measurements in the center area of the meander reveal only vertical y-displacements. The displacements plotted in Figure 8 are relative to the time-of-flight position for zero current. Although the cloud was only shifted parallel to the imaging beam, we were able to accurately detect the 100 µm wide feature of the meander. Due to the finite width of the pattern (100 µm), the characteristics are dominated by the magnetic field of currents at the edge of the meander (see Figure 4 simplified wire array) while the contribution of the periodic pattern with alternating currents is negligible for distances larger than the period ¹µm. The asymmetry for positive and negative currents is due to ambient magnetic fields.

The data is compared to the numerical integration of the equation of motion for rubidium atoms in this magnetic field. The simultaneous fit to both data sets, for 1 mA and -1 mA, gives the center position of the meander structure to be shifted by 2x = 62.58±1.37µm relative to the origin which was defined to be the center of the conductor QP2 on the carrier chip. The fit also gives the distance to the chip surface y0 = 14.00±1.55µm and the ambient magnetic fields (Bx ≈ 0 G, By ≈ 1 G, Bz ≈ 1.9 G).

The same method is applicable for measuring the position of the meandering current pattern along the z-coordinate. Calibration curves such as in Figure 8 allow the ultra-precise, three-dimensional positioning of condensates on micron scaled atom-optics chips.

B. Direction sensitive magnetic field microscope

We now describe the principle of a magnetic field microscope based on the controlled translation of a well known magnetic potential. Bose-Einstein condensates are used as tiny probes, for measuring the difference between the applied and the actual potential. The microscope is demonstrated by mapping the magnetic field of a one micron wide test conductor.

The potential experienced by the condensate can be decomposed into a well known trapping potential U0(z) and an unknown potential U1(z) to be measured:

\[ U(z) = U_0(z) + U_1(z). \]  

The potential \( U_0(z) \) is related to the axial confinement of our waveguide on the carrier chip

\[ U_0(z) = \frac{1}{2} m \omega^2 (z-z_0)^2. \]  

At the minimum \( z_i \) of the potential \( U(z) \), the first derivative of \( U(z) \) vanishes and

\[ \frac{dU_1(z)}{dz} \Bigg|_{z_i} = - \frac{dU_0(z)}{dz} \Bigg|_{z_i} = -m \omega^2 (z_i-z_0) \]  

with \( z_0 \) being the minimum of \( U_0 \).

According to Eq. 16, the gradient of \( U_1(z_i) \) is proportional to the difference \( (z_i-z_0) \). From this difference, the magnetic field distribution of the sample can be derived. By translating the center \( z_0 \) of the well known potential
U₀(z) and detecting the position zi where a Bose-Einstein condensate is localized, the gradient of U(z) can be measured as a function of zi. Note, that the potential U(z) can have several minima zi, (i = 1, 2, ...). Integration of Eq. 17 over z gives the potential Uₐ(z).

The realization of this microscope requires the potential U₀(z) to be well known. It must also be possible to precisely shift its position which is possible with the micro structured conveyor belt of the carrier chip described in section II. Keeping the x- and y-coordinates constant is essential for the measurement. Keeping also the axial oscillation frequency ωₐ constant simplifies the analysis. The conveyor belt and manipulation schemes described in this article easily meet these requirements. Through the three-dimensional position control of Bose-Einstein condensates on the carrier chip, a three-dimensional, highly sensitive measurement of the independent magnetic field components is possible. This in turn allows the complete mapping of unknown magnetic potentials.

We demonstrate the microscope by measuring the z-component of a 1µm wide, 300µm long micro structured conductor aligned parallel to the x-axis. The conductor was patterned on the surface of an atom-optics chip, the same as used for the meandering pattern. Experiments were carried out 390µm away from the carrier chip in a smooth waveguide potential with an axial oscillation frequency of 16 Hz. Bose-Einstein condensates were positioned at different z-positions around the thin conductor, and the position z₀ was detected for a current of 1.2mA, and zi for a current zero, as shown in Figure 9. The position difference taken as a function of zi was integrated to find the magnetic field curve of the single conductor. The solid line is the calculated field of a finite length wire located 140µm below the condensate. The sensitivity of the microscope can be calculated with Eq. 17 and depends only on the trap frequency and the resolution of the imaging system. With a reasonably low trap frequency of 1Hz and an optical resolution of 1µm a sensitivity of about 6.2 · 10⁻⁵ G/cm should be possible. In our experiment with ωₐ = 2π · 16s⁻¹, and an optical resolution of 5 µm, the sensitivity was 0.08 G/cm.

VI. CONCLUSIONS

We have presented experiments using a combined atom chip which allows one to work a few microns from a surface. Fragmentation is avoided because the waveguide potential is formed by conductors at large distances from the condensate. Johnson-noise induced spin flip losses are greatly reduced as the only conductor in close proximity is a narrow wire aligned transverse to the cloud. The described methods here provide a route towards micron scale atom optics.

We have also performed experiments in which condensates were loaded into a magnetic lattice produced by the meandering current pattern. While interference following release from these traps was observed, the (exponential) height dependence of the lattice leads to a highly complex situation. This contrasts with optical standing waves where the lattice potential is homogeneous over the size of the condensate. It therefore remains an experimental challenge to engineer advanced atom-optical elements with magnetic potentials for extended clouds of Bose-Einstein condensates. Many of the proposed advantages of atom chips, however, such as precisely controlled tunnelling rates through potential barriers and in lattices should be attainable using smaller wave packets or single atoms.

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