Atom fiber for omnidirectional guiding of cold neutral atoms

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Received March 5, 2004

We present an omnidirectional matter waveguide on an atom chip. The guide is based on a combination of two current-carrying wires and a bias field pointing perpendicular to the chip surface. Thermal atoms are guided for more than two complete turns along a 25-mm-long spiral path (with curve radii as short as 200 μm) at various atom-surface distances (35−450 μm). An extension of the scheme for the guiding of Bose−Einstein condensates is outlined. © 2004 Optical Society of America

OCIS code: 020.7010.

The fast development of new tools for the precise control and manipulation of neutral atoms makes a great variety of novel experiments feasible. In particular, the adoption of microfabrication techniques for atom optics has lead to the implementation of atom chips.[1,2] The patterned surfaces allow trapping and guiding of atoms with the high accuracy given by the fabrication process. Possible applications of atom chips are abundant[1]: Interferometry, fundamental studies of degenerate quantum gases in low-dimensional potentials, and mesoscopic physics in small atomic ensembles are just a few prominent examples.

Here, we report on the implementation and experimental test of a key element for the controlled manipulation of matter waves on atom chips: an omnidirectional atom fiber, i.e., an atomic waveguide based on a potential that is independent of the guiding direction (Fig. 1). The use of such an element is inevitable when atoms are to be transported to individual trapping sites on the two-dimensional surface of the chip. Omnidirectional guiding is also crucial for guided matter wave interferometers that rely on spatially symmetric beam splitters, such as Mach−Zehnder and Sagnac interferometers.

Typically, wire guides are formed by superimposing the field of current-carrying wires with a bias field. Unhindered guiding in such a configuration is possible only if the value of the field at the potential minimum is constant along the guiding path. This implies that the angle between the (bent) guide and the bias field has to be constant. Omnidirectional guiding in a plane parallel to a chip surface therefore requires either precisely engineered bias fields or a bias field pointing perpendicular to the surface.

The simplest form of a magnetic wire guide is the side guide [Fig. 2(a)] formed by superimposing the field of a single current-carrying wire with a homogeneous external bias field. Atoms are guided in a potential tube along a line parallel to a straight current-carrying wire. For the minimum to be above the chip surface on which the wires are fabricated, the bias field has to have a component parallel to the surface. In this case the value of the potential at the minimum depends on the direction of the wire. The side guide is therefore only a single-directional guide.

For guides based on at least two current-carrying wires the bias field direction can be chosen to be exactly orthogonal to the wire plane. The potential of such a two-wire guide based on parallel counterpropagating currents is illustrated in Fig. 2(c). The currents together with the strength of the bias field determine the parameters of this omnidirectional guiding potential,[1,3] specifically the height of the guide above the wire plane. A guide based on two parallel wires carrying copropagating currents lacks this flexibility since in this case a bias field necessarily has a

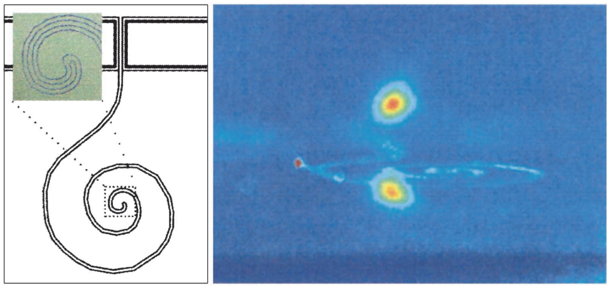

Fig. 1. Left, schematic drawing of the wire configuration used in the experiment. The black curves indicate current-carrying gold wires, the white areas are grounded parts of the chip surface. Inset, microscope image of a detail of the spiral wire guide. Here the 10-μm-wide grooves from which the gold has been removed to define the wires are shown as gray curves. Right, fluorescence of a magnetically trapped cloud and its reflection from the chip surface just before the guide is loaded. The guiding wires are visible through scattered imaging light.

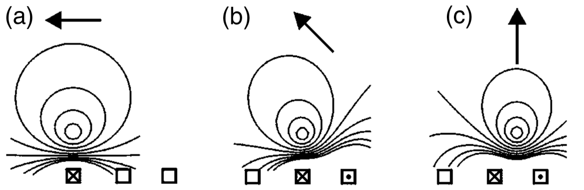

Fig. 2. Potential configurations during the transfer of atoms from (a) a single-wire guide with horizontal bias field to (c) a two-wire guide with vertical bias field. In each configuration an arrow points in the direction of the bias field and three squares represent the three wires. The current flow is indicated by the symbols in the squares. A dot (cross) corresponds to a current flow out of (into) the plane shown, and a blank square corresponds to zero current. (b) In the intermediate stage the currents run already exclusively through the two wires carrying counterpropagating currents while the bias field has been rotated by 45° with respect to the wire plane.

component parallel to the wire plane. However, even without a bias field, a potential minimum is formed in between the wires, i.e., very close to (in) the chip surface. Such guides have been employed to deflect atoms by small angles,[4] and atomic clouds have even been shown to circle a complete loop several times.[5] Guiding of a free-falling atomic cloud by a straight version of a two-wire guide carrying counterpropagating currents has been observed in a first experiment.[6]

In our experiment we set out to demonstrate deterministic loading and actual guiding of atoms confined in a bent two-wire guide with counterpropagating currents. For this purpose, we designed a spiral two-wire guide (Fig. 1). The two wires (width × height = 45 μm × 5 μm, center-to-center spacing of $2d = 115$ μm) are connected at the inner end of the spiral. This automatically leads to a counterpropagating current flow. The spiral shape was chosen to demonstrate the full flexibility of the guide by incorporating more than two full rotations with curve radii ranging from 200 μm to 3 mm along the 25-mm-long guiding path. The U-shaped wires (cross section of 200 μm × 5 μm) on either side of the straight beginning of the guide are used to form three-dimensional traps.[1]

The starting point of our atom-chip experiments is a reflection magneto-optic trap[7] that contains a cloud of typically 10^8 cold ^{7}Li atoms located a few millimeters above the chip surface. Assisted by a U-shaped wire underneath the chip, the atoms are brought closer to the surface and transferred to a purely magnetic trap.[8,9] The wire traps for cooling and transfer use single wires and horizontal bias fields. We load the atoms to the spiral two-wire guide by ramping down the current of the single wire after ramping up the counterpropagating currents in the two parallel wires of the guide. During this first step the bias field is only partially rotated so that the bending of the spiral wires still provides an end cap of the potential, thus confining the atoms in three dimensions. As depicted schematically in Fig. 2(b), this intermediate configuration is reminiscent of the simple side guide [Fig. 2(a)] with only a slight perturbation by the current in the extra wire. In the final step the rotation of the bias field is completed [Fig. 2(c)], and the atoms can expand freely along the spiral path of the guide.

Figure 3 shows a time sequence of the fluorescence signal of atoms in the guide.[10] Guiding of atoms was possible over a wide range of parameters. Varying bias field strength B from 1 to 50 G at a constant current of 1 A through both (connected) wires allowed us to scan the height of the potential tube above the surface from 450 to 35 μm. The corresponding gradients ranged from 40 G/cm to 8 kG/cm for atoms in the $|F = 2, m_F = 2\rangle$ state. The images and density profiles in Fig. 3 show the atom cloud expanding according to its temperature[11] and also moving as a whole along the guide. This center-of-mass motion is induced by a longitudinal field gradient produced by the current in the two leads from the beginning of the spiral wires to the connecting pads on the edge of the chip.[12]

For a quantitative understanding of the density profiles we performed Monte Carlo (MC) simulations of classical trajectories of particles in the guide. The results are depicted in Fig. 3 and show good agreement with the experiment. In particular, the reflections that occur when atoms reach the inner end of the guide are reproduced well. The effect of the reflection

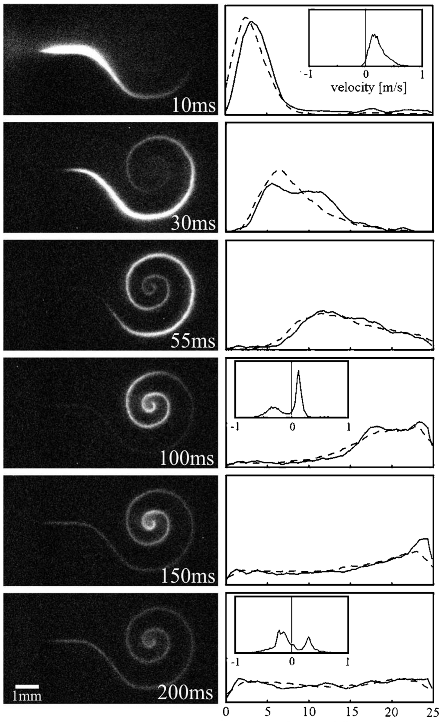

Fig. 3. Time sequence of atoms released from the reservoir trap into the spiral guide. Left, fluorescence images. Atoms that have reached the end of the guide (center of the spiral) are reflected from a potential barrier and propagate in the backward direction. Right, one-dimensional density distributions along the path of the spiral, extracted from the experimental data and MC simulations (solid and dashed curves, respectively). Insets, corresponding velocity distributions obtained by the same MC calculations. In these plots a clear signature of the reflection is visible, and the part of the cloud propagating backward is clearly separated from that propagating in the forward direction.

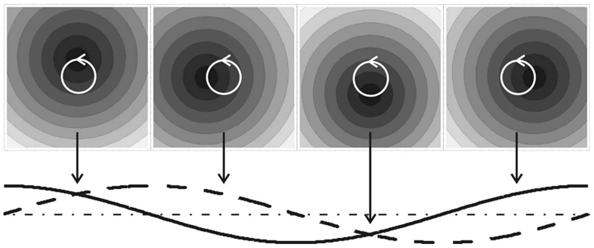

Fig. 4. Top, time sequence over one oscillation period of a time-orbiting guiding potential. Darker shading corresponds to lower potential. Bottom, each of the counterpropagating currents (solid and dashed curves) in two parallel wires is sinusoidally modulated around the steady current I_0 (dotted–dashed line). A relative phase difference of $\Delta\phi = \pi/2$ results in a quadrupole field zero circling around the minimum of the static situation (white arrows). With a proper choice of the modulation frequency, cold atoms are trapped in a time-averaged potential. Although the position of the potential minimum remains unchanged with respect to the static case, the atoms never encounter a magnetic field zero and thus do not undergo Majorana spin flips.

becomes most apparent in the plots of the velocity distributions extracted from the MC calculations (insets). The velocity classes for forward and backward motion in the guide are clearly separated.

For our guiding geometry to be truly universally omnidirectional, the homogeneous bias field has to be exactly perpendicular to the surface, resulting in a magnetic field zero in the center of the guide. For atoms much colder than in the presented experiment the vanishing field will lead to losses due to Majorana transitions. This problem can be overcome by use of a time-orbiting potential (TOP) technique, similar to the ones used for the creation of Bose–Einstein condensates.[13] A TOP configuration can be implemented by sinusoidal modulation of the currents according to $I(t) = I_0 + I_{\mathrm{mod}} \sin(\omega_{\mathrm{mod}} t + \phi)$ in the two guiding wires with a relative phase difference of $\Delta\phi = \pi/2$ (Fig. 4). The motion will be stable as long as modulation frequency ω_{mod} is slow with respect to Larmor frequency ω_{Lar} but fast with respect to transverse atomic oscillation frequency ω_{trap}. A TOP two-wire atom fiber with $\omega_{\mathrm{Lar}} = 2\pi \times 500$ kHz, $\omega_{\mathrm{trap}} = 2\pi \times 5$ kHz, and $r_0 = 1.4\ \mu$m could, for example, be obtained for a wire distance of $d = 20\ \mu$m with $I_0 = 100$ mA, $I_{\mathrm{mod}} = 10$ mA, and $B = 10$ G (^{87}Rb atoms in the $|F = 2, m_F = 2\rangle$ state).

To conclude, we have demonstrated the controlled loading and guiding of atoms in an omnidirectional guide that can be operated over a wide parameter range. Monte Carlo simulations reproduce the measured time-dependent atomic density profiles well. We have suggested a scheme involving time-dependent currents to modify the guide to lift the current restrictions to thermal atoms. Future applications range from the loading of two-dimensional trap arrays to the realization of circular and wide-angle matter wave interferometers.[14]

This work was supported by the European Union under contracts IST-2001-38863 (Atom Chip Quantum Processor), HPRI-CT-1999-00114 (Large Scale Facility), and HPRN-CT 2002-00304 (Field Atom Surface Training Network) and the Deutsche Forschungsgemeinschaft Schwerpunktprogramm Quanteninformationsverarbeitung. P. Krüger's e-mail address is krueger@physi.uni-heidelberg.de.

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10. The images are taken by exposing the atoms to a flash (100 μs) of near-resonant laser light. To avoid any disturbing reflections, the light enters the chamber from two directions parallel to the chip surface.
11. The clouds exhibit an anisotropic temperature profile (450 μK in the transverse and 50 μK in the longitudinal directions) due to a transverse compression during the loading without rethermalization.
12. By running a parallel current through another wire on the chip, we could even enhance this pushing effect.
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