Presently, the most common type of magnetic guides for neutral atoms are micro-fabricated structures on dielectric substrates \[^{[1]}\]. Due to requirements on the potential smoothness, such a guide needs to be fabricated with submicron precision \[^{[2]}\], which is still considered a challenge. Recently a partial solution to roughness suppression was demonstrated via rapid current modulation \[^{[3]}\]. Roughness can also be reduced by addition of many wires to compensate for finite size \[^{[4]}\]. The other disadvantage of the micro-chip is its close surface operation, which causes spin flips and thus atom loss \[^{[5]}\]. The short distance imparts the requirement for a chip to be placed inside a vacuum system and often integration of optical elements onto the chip itself thus limiting tuning capabilities of such systems \[^{[6]}\]. One alternative to the micro-chip guide is an Ioffe-type four-rods guide frequently used as a conveyor to transport atoms along its guiding direction \[^{[7]}\]. The major problem with such guides, however, is the requirement of a high current of a few hundred amps \[^{[8]}\], which requires water cooling, and the inability to smoothly translate atoms in the transverse direction. Another alternative is the use of an electromagnet-based guide with ferromagnetic materials \[^{[9]}\]. Because of field enhancement in ferro-foils the operational distance can be large; however, the hysteretic nature of ferromagnetic materials does not allow precise control over the magnetic field.

The goal of this effort is to create a magnetic guide with the reduced potential roughness and small field curvature capable of smooth translation of the atoms in the transverse direction. A flat potential along the guiding direction is required to achieve a long interrogation time for atom interferometers \[^{[10]}\]. To date, none of the demonstrated finite-size guides for atoms provide both the flat longitudinal potential and high gradient in transverse direction. In this work we present the design of such macroscopic guiding structure that utilizes symmetric geometry. An alternative geometry with low intrinsic field curvature although with low field gradient and no radial access is provided by a solenoidal geometry \[^{[11]}\]. Our guide is based on a parallel copropagating currents in a geometry similar to microscopic two-wire guides used as an atom conveyor \[^{[12]}\]. In addition such a guide allows precise cancellation of magnetic field and provides initial trapping potential for a surface magneto-optical trap (MOT). It is easily fabricated and does not require water cooling to generate large field gradients.

The guiding structure developed here is based on coils with macroscopic copper tape (Bridgeport Magnetics) wrapped around aluminum structures as shown in Fig. 1. Each coil has a 150 mm × 15 mm aluminum core and consists of 29 turns of double conductor tape (6.35 mm wide and 0.25 mm thick) with a 0.025-mm-thick layer of Kapton insulator on one side. The spacing between two coils \(h\) can be varied to accommodate vacuum cell of different sizes. We enclosed each coil in glass-epoxy dielectric retainers to insure that the coils are straight and parallel to each other. In the experiment, we place the guiding structure outside of an ultrahigh vacuum glass cell with square (4 × 4 cm) cross-section. The guide is mounted on two translational and two rotational stages that allow initial alignment of the guide axis with respect to the optical beams. In the stationary guide regime we use only one set of conductors from each coil, which are connected in series. Open air provides enough heat dissipation for the applied current of up to 50 A in the pulsed current regime. In the preliminary design we used similar coils in a counterpropagating current geometry to generate a minimum of the magnetic field above the coils plane. That macro guide, however, suffered significantly from the potential variation associated with the respective cur-

FIG. 1: (Color online) Photography of macroscopic symmetric magnetic guide structure, the inset picture shows the double tape conductor.
rent noise in two coils, which resulted in the short coherence
time of the atom interferometer.

The magnetic field properties of the symmetric guide are
shown in Fig. 2. In our setup the quadrupole guiding potential

![Diagram]

FIG. 2: (Color online) Symmetric guide configuration (a), and m mag-
etic field of the guide for current of 50 A: (b) contour plot of the
magnetic field vs position (x,z) (the separation between the lines is
16 G, the tape conductors from two coils and direction of the current
are shown for the reference); (c) magnetic field vs x; (d) magnetic
field vs y, which gives the curvature of the field near the axis.

is created along the symmetry axis between coils 2 cm away
from the outer turn of each coil. A peak current $I = 50$ A in
the guiding regime provides a field gradient of 80 G/cm and
a guide depth of $\approx 2.7$ mK for the $|F = 1, m_F = -1 >$
ground state of $^{87}$Rb. The magnetic field and radial gradient
of the field close to the symmetry axis scale with coils sep-
eration as $\propto 1/h^2$. Microscopic separation of the coils can
provide field gradients of the order of a few kG/cm, which
are highly desirable for ultracold atom experiments in low di-
dimensions [13]. Another advantage of our guide is favorable
field line orientation with respect to polarization of the optical
molasses beams in the mirror MOT regime that results in the
increased capture volume by a factor of five compared to the
electromagnets used in counterpropagating current geometry.
Figure 2(d) shows the field variation near the symmetry axis along the guiding direction, the estimated curvature of the
field $\partial^2 B/\partial y^2 \approx 8.7 \times 10^{-8}$ G/cm$^2$, which is many orders of
magnitude less than curvatures of the similar size guides in a
counterpropagating current geometries.

The typical experimental procedure is similar to the one
described for a ferro-foils guide in Ref. [14]. We first use
the guiding coils in a low current mode ($I_1 = 6 − 8$ A, \n$\nabla B \sim 12 − 16$ G/cm) to capture and cool atoms that are
optically transported from a source chamber along z-axis into
a mirror MOT that is generated by four 45°-oriented laser
beams bounced from a mirror in the inner surface of the glass
chamber. Atoms collected by the mirror MOT and Doppler-
cooled for 500 ms, after which the optical molasses beams are
gradually turned off and the atoms are optically pumped into
a low-field-seeking hyperfine magnetic sublevel, at the same
time the current in the coils is ramped up by the current regu-
lated power supply to the peak value of the guide. We experi-
mentally found that there is no need for the longitudinal bias
field since there is always a residual offset field present. We
estimate the transverse trapping frequency $\omega_\perp = 2\pi \times 40$ Hz
with the atoms temperature $T \approx 30 \mu$K. The loading effi-
ciency is maximized by monitoring the absorption of a weak
near-resonant probe beam propagating along the guiding di-
rection with the typical guide absorption of up to 90% that
corresponds to the optical depth of more than 20 along the
guide.

The main goal of our work is to develop a guide that al-
 lows us to enclose a large area in the atom-interferometer-
based rotational sensor by translating atoms over the large
distances [14]. In contrast to the early demonstration of the
translated guide, our guide allows fast translation over cm dis-
tances. Figure 3 shows translation of the guided atoms over
such macroscopic distance along z-axis. Unlike micro-chips

![Diagram]

FIG. 3: (Color online) Guide translation: (a) simulations of the field
contours show field minimum translation over 7 mm for $I_1 = 50 −$
$0 A, I_2 = 0 − 50 A (the tape conductors are shown for reference); (b)
experimental data of absorption images of guided atoms across the
resonant probe beam; the guided atoms are smoothly translated over
$\approx 2$ mm distance (from top to bottom) limited by the probe diameter.

used for atom transport above the surface, symmetry insures
that the atoms do not experience bumps in the x-axis direc-
tion over the course of travel. To get the absorption images
of guided atoms we direct a weak probe beam on-resonance to the $D_2 F = 1 \rightarrow F' = 2$ transition through the atoms along the guiding direction. The image of the probe cross-section and the absorbed atoms are taken by a fast CCD digital camera. Figure 3(b) shows a series of images for different values of a current in two sets of coils: $I_1 = 50$ A and $I_2 = 0 - 10$ A (from top to bottom); the respective guide translation is $\sim 2$ mm (as limited by the cross-section of the probe). The maximum translation is limited by the width of the tape conductors; in our case it can reach over 1 cm according to the current switching algorithm as shown in the simulation in Fig. 3(a). The other important application for such a guide would be heat-free coherent transport of guided atoms to a surface for atom-surface interaction studies [15]. To transport atoms over several cm distance a multiple-conductor tape can be used.

To demonstrate an application of the guided atoms in the macro-guide we carried out an atom interferometer experiment in a time domain similar to the free-space interferometer [16] and an interferometer with ferro-foils-guided atoms [14]. The interferometer scheme and preliminary results are presented in Fig. 4. The interferometer signal is detected by a heterodyne technique as a function of the interrogation time $T$. The guide tilt to horizon, and gravitational acceleration, respectively.

FIG. 4: (Color online) (a) Atom interferometer (AI) experimental scheme (here, PD is a photodiode, $Q$ is a grating vector); (b) experimental results with three pulse scheme in the symmetric magnetic guide: contrast of the interferometer vs. interrogation time; the inset shows the phase component, which is proportional to the gravitational acceleration component along the guiding direction; (c) experimental results with four-pulse scheme; the formula gives the linear fit, where $T_0$, $\alpha$, $g$ are the time separation between first and second pulses, the guide tilt to horizon, and gravitational acceleration, respectively.

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