Guiding neutral atoms around curves

with lithographically patterned current-carrying wires

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(March 31, 2022)

Laser-cooled neutral atoms from a low-velocity atomic source are guided via a magnetic field generated between two parallel wires on a glass substrate. The atoms bend around three curves, each with a 15-cm radius of curvature, while traveling along a 10-cm-long track. A maximum flux of $2 \times 10^6$ atoms/sec is achieved with a current density of $3 \times 10^4$ A/cm$^2$ in the 100 $\times$ 100-$\mu$m-cross-section wires. The kinetic energy of the guided atoms in one transverse dimension is measured to be 42 $\mu$K.

PACS numbers: 03.75.B, 32.80.P

Just as optical waveguides play a central role in many aspects of modern optics, from communications to integrated optics, atom waveguides are likely to be an enabling technology for future atom-optics-based science. In particular, well-characterized atom waveguides may make possible inertial and rotation measurements of exquisite sensitivity via large-enclosed-area atom interferometers [1]. One of the first guides for atoms was based on optical forces, where hollow glass fibers guide light, and the light in turn guides atoms [2,3].

Atom guiding using magnetic forces from current-carrying wires has been demonstrated more recently [4,5]. From the point-of-view of using atom-guides to pursue precision metrology goals [6] much benefit can be derived from patterning the waveguides on a rigid substrate. First, beamsplitters can be precisely and reproducibly fabricated. Second, the enclosed area of an interferometer can be precisely controlled. Third, the use of well-established lithographic techniques means that progress on individual optical elements (a beamsplitter, or a monochromator, for instance) can be rapidly extended to multi-component experiments. Mirrors based on micro-patterned wires have already been introduced [7]. We report magnetic guiding by a pair of parallel wires produced on a glass substrate by photolithography and subsequent electro-plating. Intricate two-dimensional guiding structures are easily produced by this manufacturing technique; in the present case, it allows us to demonstrate guiding around curves in a 10 cm long...
We guide weak-field-seeking atoms along a one-dimensional magnetic-field minimum. Our magnetic field is produced by two parallel wires with equal currents in the same direction. The track consists of two 100 × 100 µm wires spaced 200 microns from center to center, providing a 100 µm space between the wires. The resulting magnetic field is zero at the center between the wires and increases linearly outward. A small longitudinal field is applied to prevent the field magnitude from vanishing at the track center. The maximum transverse guiding potential increases linearly with applied current. The transverse magnetic-field gradient around the center is proportional to the track current and inversely proportional to the spacing between the wires. The wire spacing, applied wire current, and the longitudinal velocity of the guided atoms determine the minimum radius of curvature around which the atoms can be bent.

Our experimental apparatus consists of two chambers connected by a 2-inch-diameter steel tube that holds the substrate of the wire guide as shown in figure 1. The chambers are evacuated by separate ion pumps that maintain the pressure in each chamber typically at 10⁻⁹ Torr. The source chamber provides a beam of laser-cooled atoms, and the detection chamber houses a hot wire and channeltron electron multiplier to measure the atom flux.

A modified magneto-optical trap (MOT) in the source chamber produces the beam of laser-cooled atoms [9]. A diode laser in a master-oscillator power-amplifier configuration (MOPA) [10] provides 350 mW of single-frequency light tuned near the 5S₁/₂(F = 2) → 5P₃/₂(F' = 3) transition in rubidium for trapping and cooling in the MOT. This light is divided into three beams, which are directed into the chamber along orthogonal axes, and retro-reflected to supply cooling along all directions. A 30-mW external-cavity diode laser [11] supplies light tuned to the 5S₁/₂(F = 1) → 5P₃/₂(F' = 2) transition to repump atoms that fall into the F = 1 ground state back into the cycling transition. A 500-µm hole is drilled in the center of one of the retro-reflecting mirrors, and this mirror is placed inside the vacuum chamber. Thus, one of the six confining laser beams has a dark region in the center of its cross-section. The radiation-pressure imbalance for atoms in the MOT that enter into the shadow of the hole accelerates those atoms toward and then through the hole in the mirror. The resulting atomic beam is referred to as a low-velocity intense source (LVIS) [12]. Our observations show that 90% of the LVIS flux atoms are optically pumped into the F = 1 ground state by the MOT light. We observe that roughly 50% are in the m_F = 0 state and the rest of the atoms are roughly equally divided between the two m_F = ±1 sublevels. Therefore, only 25% of LVIS atoms are in the correct state to be guided. Typically, we measure an overall LVIS flux of \( \sim 5 \cdot 10^8 \) atoms/sec and a beam brightness of \( \sim 5 \cdot 10^{12} \) atoms/sr·sec. We estimate the transverse-velocity distribution entering our guide to be about \( v_t = 5.0 \pm 2.0 \)
A time-of-flight measurement found the longitudinal velocity of LVIS to be $v_l = 10.1 \pm 2.0 \text{ m/sec}$.

Our tracks were manufactured by Metrigraphics using photolithography and electro-plating techniques. A layer of photoresist is applied on top of a 3-µm-thick layer of copper deposited onto a 10 × 10 cm glass substrate (Fig. 2). This photoresist is then exposed through a mask and removed where the tracks will be grown. Using an electro-plating technique, the tracks are grown through the gaps in the photoresist to a height of 100 microns. The excess photoresist and 3-µm copper layer are removed, leaving behind a track structure. The final track structure extends 10 cm. We solder current-feeding wires to connection pads on the glass substrate.

The tracks are aligned with the mirror hole before the vacuum chambers are assembled. We define the track axis as the line joining the beginning and the end of the track (Fig. 2). The beginning of the track sits 1 mm behind the mirror hole and its axis is aligned parallel to the mirror axis (Fig. 1). The magnetic guide starts with a 1.2 cm straight region followed by a 1.9-cm-long curve to the right with a 15 cm radius of curvature (Fig. 2). The curvature is then reversed for a 3.8-cm-long left curve. This region is followed by a 1.9-cm-long right curve, completing the three alternating curves and leading back to the track axis. The three curves lead atoms around a bend, diverting their trajectory by 2 mm transverse to the track axis. After the bend, the guide confines atoms for another 1.2 cm to a straight trajectory before they exit the magnetic guide and travel 7 cm through free space to the detector hot wire. We place a glass barrier halfway along the track axis (Fig. 2) to block out direct LVIS flux. Guided atoms are led around this barrier by the magnetic guide and can be detected downstream. For our guiding experiment we run 35-msec-long current pulses of up to 4.5 A through the two wires. We choose short current pulses to prevent the substrate from overheating, allowing us to run larger guiding currents than continuous currents would allow.

After exiting the guide, atoms are ionized by the hot wire and the subsequent ions are then detected by the channeltron. The 70-µm-diameter hot wire placed ∼ 7 cm from the output of the magnetic guide intercepts a small fraction of the diverging atomic beam. We determine the total flux from our guide by integrating over the atom-beam profile. At a current of 3.0 A, we guide up to $2 \cdot 10^6$ atoms/sec.

Figure 3 shows the atom-flux dependence on the track wire current. For low currents (<0.7 A), the guiding potential should be sufficient to confine the initial transverse-velocity distribution, but it does not provide sufficient force to bend the atoms around the curve; hence no flux is observed at the detector (Fig. 3). Above the estimated centripetal track current threshold of 0.7 A, atoms with low longitudinal velocity are guided. At currents above 2.3 A, the flux saturates as we have sufficient magnetic gradient to guide all longitudinal velocities around the bend.
In our design, the magnetic-field minimum is 50 µm above the substrate. By lowering the position of the magnetic-field minimum, and thus the guiding center of the track, to near or below the substrate, we should be able to guide the atoms into the glass. We do this by applying a bias field transverse to the track and parallel to the substrate with a pair of Helmholtz coils. Depending on the polarity of our Helmholtz coils, the minimum is either raised or lowered. This variable bias field is set up at the final 1-2 cm stretch of our guide, after the atoms have negotiated the bend. We observe that for one polarity of the coils the guided flux changes by \( \sim 10\% \), but as the bias field polarity is reversed, the flux is completely eliminated (Fig. 4). In the first case, the bias field lifts the field minimum out of the tracks, but atoms still make it to the hot wire, although they are shifted vertically. In the second case, we lower the field minimum and atoms are guided into the substrate surface. Once atoms touch the substrate, they stick and can no longer be guided. As expected, larger track currents require larger bias fields to push atoms into the substrate (Fig. 4). The bias field required to entirely squelch the guided-atom flux is directly determined by the track current. The three track currents of 1.25, 2.0 and 3.0 A should correspond to squelching bias fields of 21, 33, and 49 Gauss, respectively. Our bias-field measurement shows that for the above track currents 21, 34, and 43 Gauss are necessary to cut off the flux, which is in good agreement with the estimates.

We measure the guided atoms’ transverse velocity profile by translating the hot wire to map out the spatial extent of the atom beam as it diverges from the exit of the track (Fig. 5). We calculate that the atoms’ emergence from the confining fields of the tracks is almost completely non-adiabatic—the transverse kinetic energy of the emerging beam should thus be a faithful reflection of the transverse kinetic energy in the guide. The virial theorem tells that the mean potential energy in the linear confining field should be twice the mean kinetic energy. The total mean energy per transverse dimension of the atoms in the guide should thus be three times the observed kinetic energy of the emerging atoms. At a track current of 2 A, we can determine that the guided atoms have \( 3 \times 42 \mu K = 126 \mu K \) total mean energy per transverse dimension (Fig. 5). This is smaller than the lowest point on the rim of the confining potential, which is 1.1 mK.

In the discussion above we apply a bias field parallel to the substrate and perpendicular to the track. Similarly, we can apply a transverse bias field in the vertical direction, perpendicular to the substrate. In this configuration the guided atom beam is moved close to one of the wires and the highest-energy component of the beam is "skimmed off". Figure 5 shows a case in which the mean energy in the corresponding direction has been reduced by a factor of 3.1 using a 43 Gauss bias field.
Due to the non-adiabatic loading into our tracks, atoms entering the center portion of the guide are more likely to be guided. The effective aperture through which atoms can enter the guide is consequently smaller than the physical wire separation. Comparing the estimated source flux to the number of atoms detected after the guide, we estimate that \( \sim 25\% \) of the \( m_F = -1 \) atoms that hit the \( 100 \times 100 \) \( \mu m \) opening are detected.

In summary, we have guided a beam of laser-cooled atoms between two \( 100 \times 100 \) \( \mu m \) wires. We are able to bend the atoms’ trajectory around 15-cm-radius curves. The guiding-current threshold agrees with our theoretical prediction to within our uncertainty from the atoms’ longitudinal velocity. We demonstrate that moderate current densities give guiding potentials of several milli Kelvin. No external cooling for the wires was necessary. Our magnetic guide design has great promise for applications in atom interferometers due to its versatility and simplicity. We tested the tracks with current pulses up to 8 A before substrate heating became a problem. This test indicates that we can reduce the radius of curvature by a factor of 4 to achieve a 3-4 cm track radius. In future experiments with larger currents, we hope to guide the atoms around a full 360 degree bend, which is an important step for a possible future Sagnac interferometer using magnetic-field confinement. Photolithographic technology will provide a reproducible method for producing an atom beamsplitter in future atom-interferometer applications.

The authors would like to thank Carl Wieman and Eric Abraham for helpful discussions. This work was made possible by funding from the Office of Naval Research (Grant No. N00014-94-1-0375) and the National Science Foundation (Grant No. Phy-95-12150).

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FIG. 1. Schematic of experimental setup. A beam of laser-cooled atoms generated in the source chamber (left) travels toward the magnetic guide between the source and detection chamber. Atoms enter the tracks and are guided around a barrier. After the guided atoms exit the tracks, they are ionized with a hot wire and ions are counted with a channeltron.

FIG. 2. Detail of magnetic guide. Atoms are guided over a 10-cm distance around three curves each with a 15-cm radius of curvature. A beam block in the middle of the guide blocks the center of the LVIS beam. The transverse scale of the track has been exaggerated for clarity.
FIG. 3. Flux versus current. As we increase the current in the guiding wires the magnetic field and its gradient between the wires increases and atoms are guided. For low currents ($< 0.7$ A), the longitudinal velocity of the atoms is too large to be bent around the curve. We increase the current, and the guiding flux increases until saturating ($> 2.3$ A), when all atoms between the wires are guided. Each data point represents the average of 50 current pulses; the statistical errors are typically smaller than the plotted symbols.

FIG. 4. Guided flux versus bias field parallel to substrate. When a bias field is applied parallel to the guide, the minimum of magnetic field is lowered toward the substrate. We lower the magnetic-field minimum until the atoms run into the track substrate and the flux is extinguished. The solid lines represent a linear fit to the data. Larger track currents require larger bias fields to cut off the flux.
FIG. 5. Transverse-velocity profile. We translate the hot wire across the guided-atom beam and measure the transverse-velocity distribution. A 43 Gauss bias field applied in the vertical direction moves the minimum of magnetic field toward one of the wires, and the highest-transverse-energy component is "skimmed off". We use the width of the Gaussian fit to determine the RMS transverse velocity $v_t$. 

Guided Atom Flux (in arbitrary units) 

Hot-Wire Position (mm) 

without bias field $v_t=9.0\ \text{cm/sec}$ 

with bias field $v_t=5.1\ \text{cm/sec}$