Guiding Neutral Atoms Around Curves with Lithographically Patterned Current-Carrying Wires

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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 2×10^6 atoms/sec is achieved with a current density of 3×10^4 A/cm^2 in the 100×100-μm-cross-section wires. The kinetic energy of the guided atoms in one transverse dimension is measured to be 42 μK.

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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].

Different atom guiding schemes using magnetic forces have been proposed [4] and some schemes using current-carrying wires or permanent magnets have been demonstrated [5–7]. From the point of view of using atom guides to pursue precision metrology goals [8] much benefit can be derived from patterning the waveguides on a rigid substrate. First, beam splitters 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 beam splitter, or a monochromator, for instance) can be rapidly extended to multicomponent experiments. Mirrors based on micropatterned wires have already been introduced [9]. We report magnetic guiding by a pair of parallel wires produced on a glass substrate by photolithography and subsequent electroplating. 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 guide [10].

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 μm 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 $\sim$10 G 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-diam steel tube that holds the substrate of the wire guide as shown in Fig. 1. 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 [11]. A diode laser in a master-oscillator power-amplifier configuration (MOPA) [12] provides 350 mW of single-frequency light tuned near the $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ 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 retroreflected to supply cooling along all directions. A 30-mW external-cavity diode laser [13] supplies light tuned to the $5S_{1/2}(F = 1) \rightarrow 5P_{3/2}(F' = 2)$ 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 retroreflecting 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) [14]. Our observations show that 90% of the LVIS flux atoms

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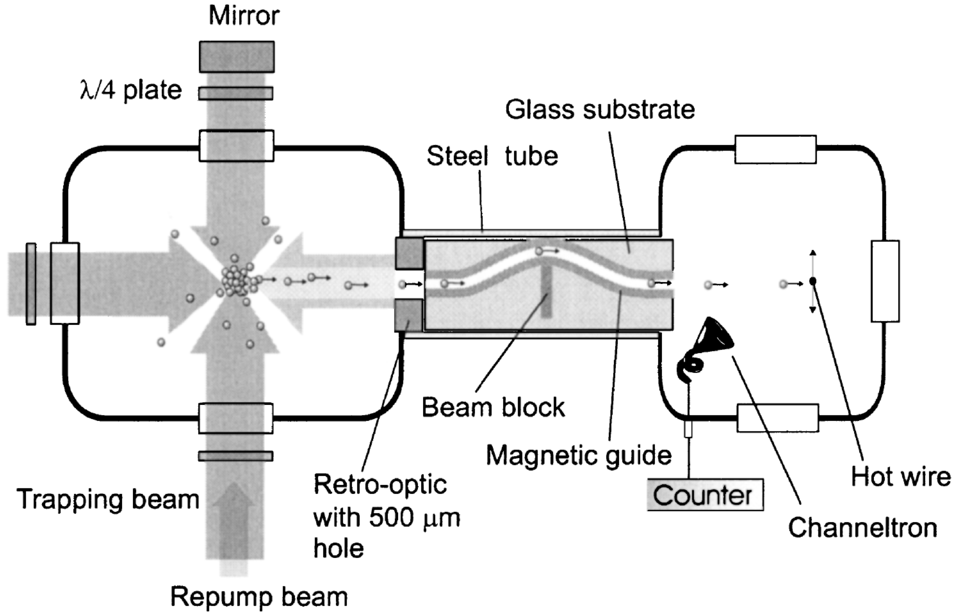

FIG. 1. Schematic of experimental setup. A beam of laser-cooled atoms generated in the source chamber (left) travels toward the magnetic guide between the source and the detection chamber. Atoms enter the tracks and are guided around a barrier. After the guided atoms exit the tracks, they are ionized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

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 $m_F = \pm 1$ sublevels with respect to a quantization axis in the direction of the atomic beam. Therefore, only 25% of LVIS atoms are in the correct state to be guided. Typically, we measure an overall LVIS flux of $\sim 5 \times 10^8$ atoms/sec and a beam brightness of $\sim 5 \times 10^{12}$atoms/sr sec. We estimate the transverse-velocity distribution entering our guide to be about $v_t = 5.0 \pm 2.0$ cm/sec [14]. A time-of-flight measurement found the longitudinal velocity of LVIS to be $v_l = 10.1 \pm 2.0$ m/sec.

Our tracks were manufactured by Metrigraphics [15] using photolithography and electroplating 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 electroplating technique, the tracks are grown through the gaps in the photoresist to a height of 100 μm. The excess photoresist and 3-μm copper layer are removed, leaving behind a track structure. The final track structure extends 10 cm.

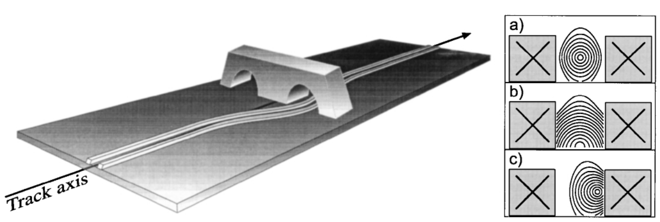

FIG. 2. Detail of magnetic guide. Atoms are guided over a 10-cm distance around three curves each with a 15-cm radius of curvature. A beam block in the middle of the guide blocks the center of the LVIS beam. Insets (a), (b), and (c) show the magnetic field contour lines for no bias, horizontal bias, and vertical bias, respectively.

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 at a 1 sec repetition rate 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-diam hot wire placed $\sim$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 2×10^6 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 [Fig. 2(b)]. 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%. In this 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. As we reverse the bias field polarity we can completely eliminate the flux (Fig. 4). In this 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, the 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 G, respectively. Our bias-field measurement shows that for the above track currents 21, 34, and 43 G 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 nonadiabatic—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 states that the mean potential energy in the linear confining field should be twice the mean kinetic energy. The mean total energy per transverse dimension of the atoms in the guide should thus be 3 times the observed kinetic energy of the emerging atoms. From the width of the upper curve of Fig. 5 we can determine that at a track current of 2 A the guided atoms have $3 \times 42\ \mu\text{K} = 126\ \mu\text{K}$ mean total 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 [Fig. 2(c)]. In this configuration the guided atom beam is moved close to one of the wires and the highest-energy component of

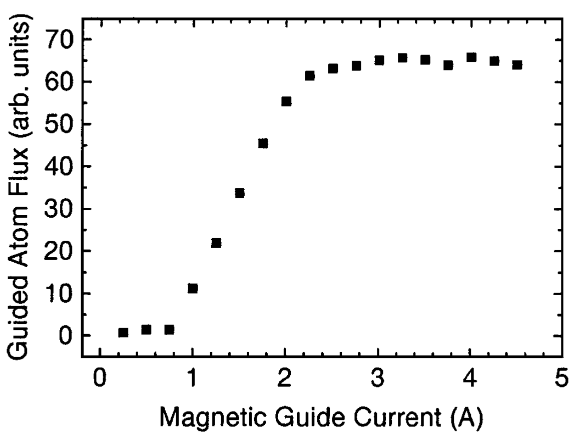

FIG. 3. Flux versus current. As we increase the current in the guiding wires the magnetic field and its gradient between the wires increases and atoms are guided. For low currents (<0.7 A), the longitudinal velocity of the atoms is too large to be bent around the curve. We increase the current, and the guiding flux increases until saturating (>2.3 A), when all atoms between the wires are guided.

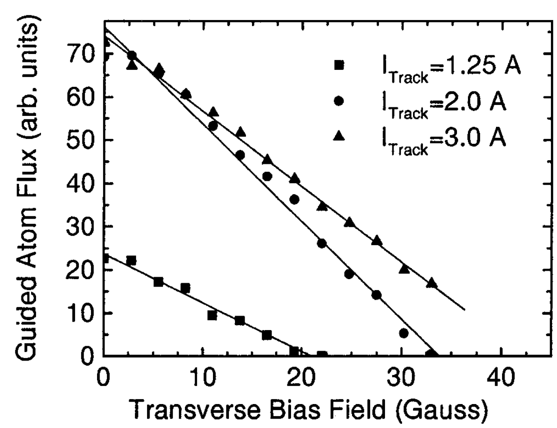

FIG. 4. Guided flux versus bias field parallel to substrate. When a bias field is applied parallel to the guide, the minimum of magnetic field is lowered toward the substrate. We lower the magnetic-field minimum until the atoms run into the track substrate and the flux is extinguished. The solid lines represent a linear fit to the data. Larger track currents require larger bias fields to cut off the flux.

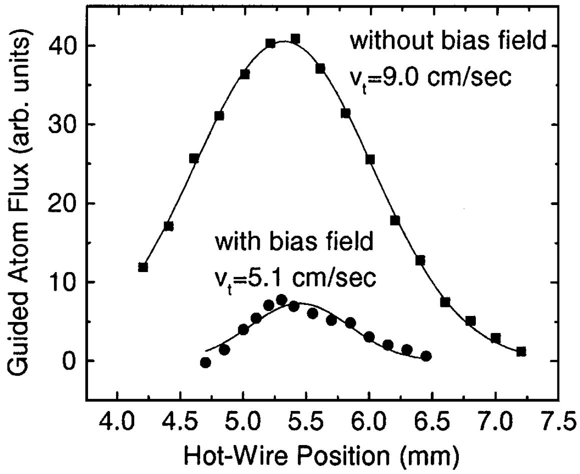

FIG. 5. Transverse-velocity profile. We translate the hot wire across the guided-atom beam and measure the transverse-velocity distribution. A 43 G bias field applied in the vertical direction moves the minimum of magnetic field toward one of the wires, and the highest-transverse-energy component is "skimmed off." We use the width of the Gaussian fit to determine the RMS transverse velocity v_t.

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 G bias field.

Because of the nonadiabatic 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 ~25% of the $m_F = -1$ atoms that hit the 100×100 μm opening are detected.

In summary, we have guided a beam of laser-cooled atoms between two 100×100 μm 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 millidegrees 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.

An ultimate goal for atom-guiding experiments is to create atom interferometers with very large enclosed areas. In such applications, the dephasing effects of transverse dispersion will wash out interference unless only a single transverse mode of the guide is occupied. It is widely believed that a very high transverse confinement frequency is a prerequisite for single-mode guiding. This is incorrect: while a high confining frequency will give the lowest-order mode a larger area in momentum space, it will lead to a correspondingly smaller area in coordinate space. The high confinement frequency will not facilitate loading a beam of atoms into the lowest-order mode, and it may well complicate the necessary "skimming" of atoms accidentally loaded into higher-order transverse modes. The fundamental issue in single-mode interferometry will be attaining a sufficiently bright atom source, one that can provide many atoms per second per transverse phase-space density. An evaporatively cooled source will probably be necessary, which means in practice one will likely wish to use a Bose-Einstein condensate (BEC). The use of a BEC reduces the problem of mode matching to a problem of adiabaticity–as long as the BEC is moved sufficiently slowly from its evaporation trap into the guide, the atoms will naturally enter the guide in its lowest-order transverse mode.

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