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Bidirectional propagation of cold atoms in a "stadium"-shaped magnetic guide

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We demonstrate the bidirectional propagation of more than 10^7 atoms (^{87}Rb) around a "stadium"-shaped magnetic ring that encloses an area of 10.9 cm^2, with a flux density exceeding 10^{11} atom s^{-1} cm^{-2}. Atoms are loaded into the guide from a two-dimensional (and higher) magneto-optical trap at one side of the "stadium." An optical standing wave pulse is applied to increase the propagation velocity of atoms along the waveguide. The atom sample fills the entire ring in 200 ms when counterpropagating atom sections of the original atom cloud recombine at their initial positions after a full revolution.

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INTRODUCTION

There is great interest in exploiting atom waveguides to improve precision measurements. In particular, fully reciprocal guided wave interferometers with large enclosed areas may be able to significantly increase both the accuracy and the sensitivity of atom-based rotation sensors. Rotation sensing requires that two halves of the initial wave packet propagate around a path that encloses an area. If the interferometer is rotating, then the Sagnac effect produces opposite phase shifts in the two wave packets, where the phase shifts are proportional to both the rotation rate and the area enclosed by the paths traversed by the wave packets. Measurements of the phase difference between the two wave packets can then be used to determine the rotation, where the sensitivity is proportional to the enclosed area.

In demonstrated atom interferometers, the area A enclosed by the two arms is typically $\sim$10 mm^2 (A=22 mm^2 in Ref. [1]), limited by the splitting angle of the atomic beam splitter. In contrast, in a guided wave interferometer the wave paths may be separated much more. Guided wave interferometers that permit the separated wave packets to traverse the reciprocal path should provide good common rejection of phase shifts associated with time-independent energy variations along the path of the interferometer. Time-dependent perturbations will also be cancelled if the time scale for the changes in the perturbation is longer than the time required for the wave packet to traverse the interferometer.

It has already been shown that guided atoms can circulate around a closed path with an effective area as large as 4400 mm^2 [2]. However, in that experiment the atom sample could not easily be split into two counterpropagating wave packets whose phase difference could be used to determine rotation. Indeed, a major experimental challenge in proposals for guided matter wave interferometers is the realization of coherent beam splitters [3–6]. As was suggested in [7,8], optical standing waves may be used instead of the more cumbersome method of using a bifurcation in the guiding potential. Matter wave interferometers using diffraction from optical standing waves as beam splitters have proved to be efficient and reliable in free space [9–11]. Such beam splitters may also coherently split the atom wave packets confined by waveguides. If the momentum impacted by the standing wave is along the propagating direction of the waveguide, the resulting atom sample can be used in guided atom interferometers.

It has been shown theoretically that single mode guided atoms can be split with an optical standing wave and interfere on a ring [7]. In that article, the authors carefully examined the influence of the atom-atom collisions, and pointed out that a reliable interference signal can be prepared from either fermions or bosons. For bosons the phase shift is complicated by the mean-field interaction in the limit of large density. However, the authors of Ref. [7] show that in the Tonks gas regime, the phase shift still faithfully represents rotation as a consequence of boson-fermion mapping theory. Similar interference is expected for a dilute atom sample that populates multimodes of the ring waveguide [12]. These proposals require an atom waveguide loop that can be combined with standing wave beam splitters.

In this paper, we demonstrate a type of magnetic waveguide ring that is compatible with the light pulse beam splitter. The magnetic waveguide ring is composed of two half-circles which are connected with two straight parts, thus composing a "stadium" shape (Fig. 1). The atoms are loaded into the waveguide from a two-dimensional (and higher) magneto-optical trap (2D$^+$ MOT) operated at one straight part of the "stadium," with the same technique described in Ref. [13]. After the transfer into the magnetic waveguide, an optical standing wave is applied to increase the velocity of atoms along the direction of waveguide. The atoms propagate in opposite directions around the waveguide ring and recombine at the original location. We expect that a similar device can be used for guided atom interferometry.

EXPERIMENTS WITH A MAGNETIC "STADIUM"

The same four waveguide-shaped foils that generate the magnetic field for the MOT, also generate the magnetic field for the magnetic waveguide that traps atoms in two dimensions and allows them to propagate around a closed loop. Specifically, four stadium-shaped rings with sorted size, each

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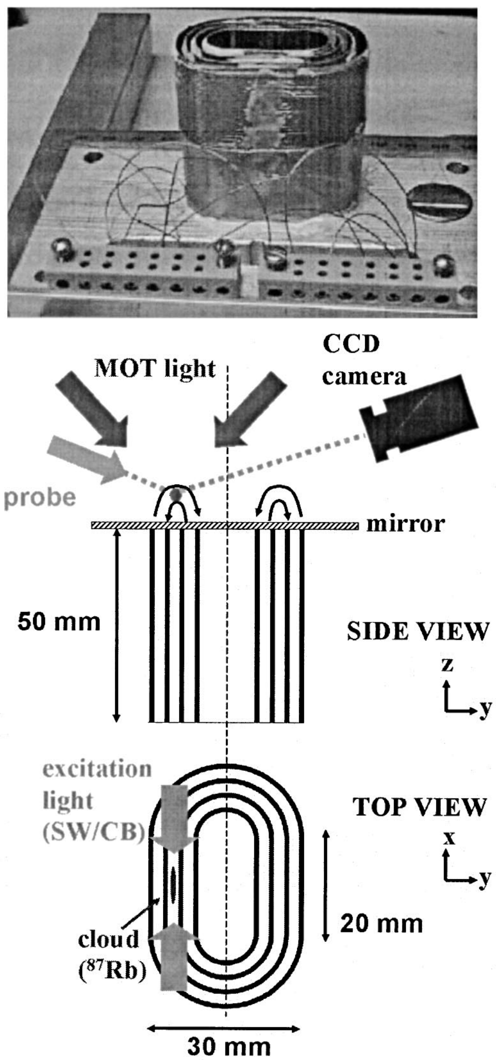

FIG. 1. (Color online) Top: photograph of the stadium assembly (without mirror). Kapton ® wires are wrapped around each foil and attached to the mu metal with Torr Seal glue ®. Bottom: top view and side view of the experimental setup. The same laser beam is used for standing wave (SW) operation ($\delta = +7\Gamma$) and as a cutting beam (CB, on-resonance).

individually wound with 42 turns of 400-μm-diam Kapton ® wire are assembled to form a closed loop (Fig. 1). The foils are 0.5 mm thick and spaced from each other by 3 mm. The foils are made of magnetizable material to create enough magnetic gradient for guiding at a distance ~1 mm from the surface [13,14]. Mu metal (CO-NETIC AA ® from the Magnetic Shield Corporation) is chosen since it can easily be poled by current carrying wires, and has negligible remnant magnetism when the current in the wires is switched off. A linear waveguide based on this type of four-foil magnetic structure has been discussed in [13], where we demonstrated that four-foil ferromagnetic structures can create 2D magnetic traps with a field gradient tunable from zero up to 1000 G/cm.

Figure 2 shows the calculated magnetic field strength $|B|$ for the structure. The boundary conditions for the simulation were measured directly with a Gauss meter while the currents were set to be the same as in an atomic experiment, and the calculation is confirmed by comparing the location of magnetic minimum in measurement and simulation. When the current is 800 mA through the smallest two coils and 1.68 A through the largest two coils, the B fields from the four mu-metal foils cancel approximately 2.5 mm above the foils
(2.2 mm above the mirror surface) near the top of the second (second largest) foil, with $d|B|/dr = 100$ G/cm at the straight parts. Alternatively, one may apply an external B field to cancel the B field generated by the smallest two foils, thus forming a 2D magnetic trap in only one straight section of the stadium. Experimentally we find the second configuration is more favorable for the operation of a $2D^+$ MOT. *In situ* loading of cold atoms from the MOT to the first configuration is realized by slowly ramping down the external B field, while increasing the currents for the four foils in proper ratio.

Infinitely long, straight waveguides possess translational symmetry along the direction of propagation, resulting in a magnetic potential that is perfectly smooth along the direction of propagation. Curved magnetic waveguides can be produced by making bent versions of structures that form straight waveguides; however, bending the structures breaks the translational symmetry. In most cases, including the stadium geometry considered here, this symmetry breaking results in variations in the potential along the direction of propagation; consequently, most bent magnetic waveguides have potentials that are not zero at the center of the guide and are not invariant along the guiding direction. An important exception is the case where a structure that forms a linear waveguide is bent into a perfectly circular ring, translational symmetry along the direction of propagation is preserved, and the resulting waveguide ring has a potential that is independent of position along the direction of propagation [14,15].

Figure 2 also shows a calculation of the magnetic field in the minimum of the magnetic guide. The calculation indicates that only at four points (the center of the straight sections and in the center of the curved sections) does the magnetic field cancel exactly, everywhere else we find a small magnetic field along the loop. This can be understood from symmetry considerations: only in these points, the integrated contribution to the tangential field from sources left of the symmetry plane cancel that of sources at the right-hand side. Also, the waveguide becomes “looser” for atoms entering the curved section (85 G/cm at the center of the curved parts, compared to 100 G/cm at the center of the straight parts). In addition, the minimum is slightly elevated in the curved parts (Fig. 2), and hence the atoms have to climb a gravitational potential while entering the curved parts. In the experiment we observe that atoms propagating towards the curved parts are partially scattered back from *both* sides (Fig. 3). It is possible to reduce the variations by going to smaller waveguide structures (corresponding to smaller separations of four-foils here) and carefully engineering the local magnetic structure (adjusting the separations of four-foils along the stadium here).

In the first stage of the experiment, a $2D^+$ MOT is created at one side of the stadium, where the 2D magnetic trap is

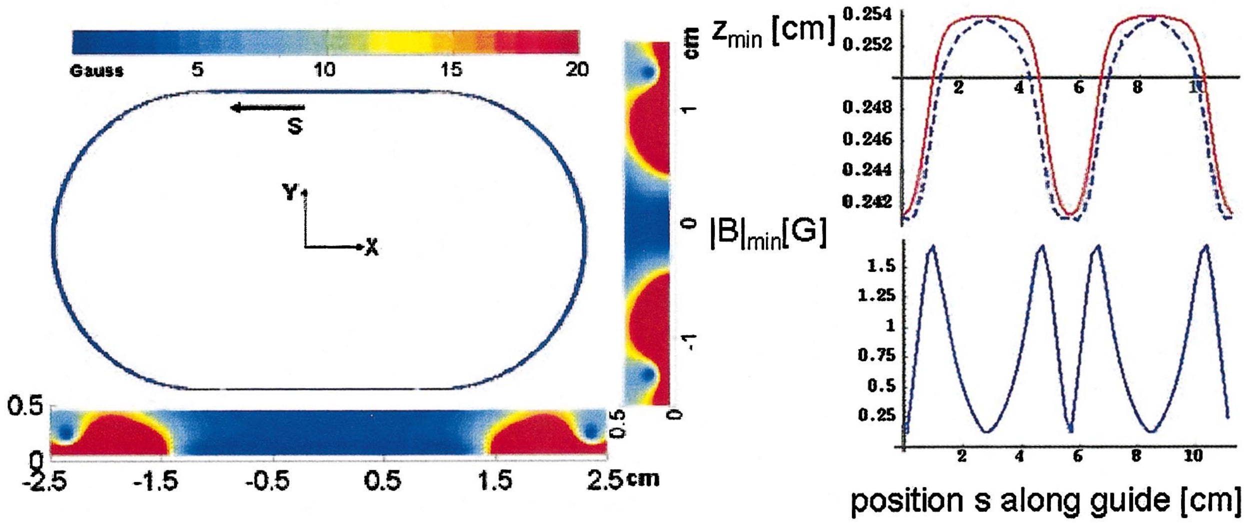

FIG. 2. (Color) Left: top view of the isopotential surface of calculated magnetic field strength $|B|=2$ Gauss for the stadium assembly. Field strength is also shown in $y=0$ and $x=0$ planes, coinciding with the long and the short axis of the stadium, respectively. Right: results of a numerical minimum search routine along the circumference s of the guide (see text). Top right: distance from mu-metal surface, solid line for the magnetic minimum, dashed line for the potential minimum including gravity, assuming $M_F=2$ atoms. Bottom right: field strength in the magnetic minimum along the guide.

generated by external magnetic field and the smallest two foils. The cooling light has detuning $\delta=-14$ MHz to the red of the $F\ .\ .\ .F'$. Three hyperfine transition in ^{87}Rb and repumping was provided by an additional laser locked on the $F=1 \rightarrow F'=2$ hyperfine transition of the $D2$ line. The $1/e^2$ beam diam of transverse and longitudinal laser beams are 2 cm and 1.5 cm, respectively. The laser intensities are 8 mW/cm^2 for each longitudinal beam and 5 mW/cm^2 for each transverse beam. During a period of 5 s 2×10^7 atoms are accumulated from the background vapor (3×10^{-9} mbar), producing a cigar-shaped sample of cold atoms that is 3 mm long and 0.5 mm wide. After that the currents for the four foils are ramped up, and the external B field is ramped down to zero in such a way that the magnetic minimum remains at about the same position, but the gradient increases from 5 to 100 G/cm. The compression is completed in 60 ms. During the first 30 ms the cooling light is kept on, but shifted from $\delta=-2.4\ \Gamma$ to $-4.5\ \Gamma$, and is then extinguished. A circularly polarized standing wave is pulsed for various durations after the cooling light is switched off. The evolution of the atom density along the guide is examined using resonant absorption imaging.

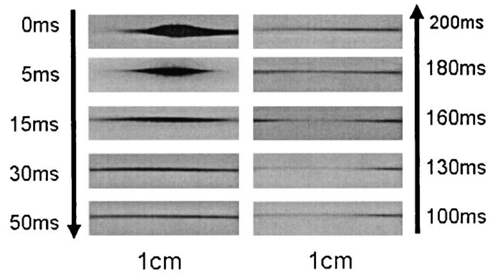

FIG. 3. Evolution of the atom cloud in the straight part of the stadium after loading at $t=0$ ms. Two groups of atoms which make 30% of the total atom number come back at around $t=160$ ms, due to backscattering from the curved parts.

Figure 3 shows a sequence of the absorption images at one side of the stadium, after a $\delta=+7\,\Gamma$ (blue detuned) standing wave with saturation parameter $s\sim5$ is pulsed for 300 μs (defined as time zero in the following discussion). The combination of a 0.1 Gauss plug field and the circular polarized standing wave optically pumps the atoms to the weak-field seeking states. From the absorption image we find that more than 10^7 atoms are transferred from 2D$^+$ MOT to the straight part of the magnetic waveguide, an efficiency of more than 50%. The transverse temperature of the magnetically trapped atoms is estimated from the extension of the atom sample in the waveguide to be about half the Doppler temperature. The mean longitudinal expansion speed of the sample is approximately 20 cm/s. The atom sample expands symmetrically, and moves beyond the imaging aperture in 30 ms. As shown in Fig. 4, a "stadium"-shaped atom distribution emerges after 200 ms of propagation inside the wave-

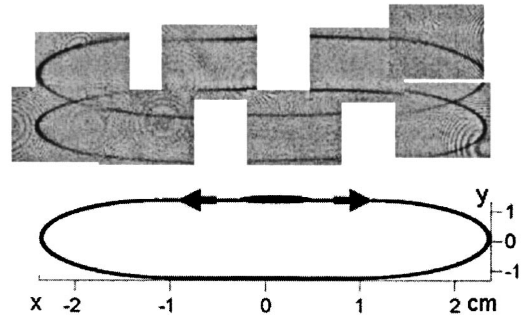

FIG. 4. (Color online) Top: sequence of absorption images of trapped atoms along the circumference of the stadium after 200 ms of free evolution. Observation angle (~18°), magnification (1:1) and grayscale of each image may vary slightly. Mirror image is also visible. Bottom: calculated isopotential surface of $|B|=2$ G, the observation angle is set to be 18°. The initial distribution and propagation directions of atom sample are also indicated.

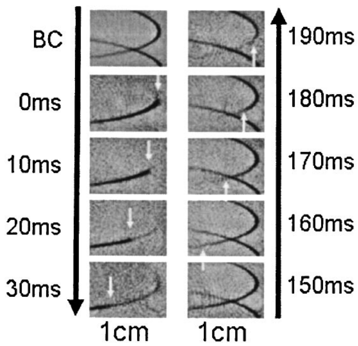

FIG. 5. Absorption images near the right curve of the stadium. "BC" = "before cut", taken 100 ms after SW operation. The images taken at $t' = t - 105$ ms (0 to 30 ms after cut) show the edge of the cloud propagating "down-left" (clockwise). The images from $t' = 150$ ms to 190 ms show the edge propagating "right-up" (counterclockwise). This indicates bidirectional propagation around the entire ring. White arrows were added to clarify the edge of the atom cloud.

guide. Since the CCD chip is 10 mm by 7.1 mm, we realign the absorption image system to observe atoms in different sections of the 11.2-cm-long loop while fixing the time delay at 200 ms. The images taken at different positions are then used to reconstruct the cloud over the full extension of the magnetic guide.

Figure 4 provides a static picture of atom distribution around the ring. To confirm that the atoms actually propagate around, we use an on-resonant light to "cut away" part of the atom sample, and observe the propagation of the "cut" via absorption images (Fig. 5). At $t = 100$ ms when the atom sample has filled over three-quarters of the stadium, an on-resonant standing wave ($1/e^2$ beam diameter: 0.8 cm) is pulsed for 5 ms so that the entire half of the stadium on the side where the atoms were originally loaded is depleted. Absorption images were then taken to study the propagation of the "cut" in time and position. The left column of Fig. 5 shows the edge of the atom cloud propagating clockwise towards the straight section of the waveguide, with a speed of approximately 25 cm/s. At $t' = t - 105$ ms $= 20$ ms after the cutting operation, a dilute trace blurs out the previously well-defined edges. At this time, the fastest atoms from the other curved section of the guide have arrived and start populating the empty region. As time advances, the other edge should start to appear moving counterclockwise. This is observed at $t' = 160$ ms (right column of Fig 5). Again, the edge is not sharp because by this time the fastest atoms that had originally started from the right have fulfilled an entire revolution and penetrated through the atoms from the left to blur out the edges. Nevertheless, the sequence of images shows clearly how the edge from the left moves upwards through the curved section of the guide, indicating that the atoms really perform an entire revolution. Notice that the atoms keep revolving in the closed waveguide, only limited by the lifetime of trapped atoms in vacuum, which presently is around 1 s.

A further step in our experiment would be using the light field along the waveguide to coherently manipulate and interrogate the guided motion of atoms. This would require confining potential variations to be much smaller than what we have in the current device. In addition, the initial atom sample should be further cooled along the waveguide for better control via the light and magnetic potentials. A quantitative discussion on this topic is beyond our experimental paper here, and will be given in Ref. [12].

To conclude, we have demonstrated the bidirectional propagation of 10^7 cold atoms in a magnetic waveguide ring enclosing a very large area (compared with the typical area enclosed by a free space atomic interferometer), where bidirectional propagation was induced by applying a standing light wave pulse to the guided motion of the atoms. If the bidirectional propagation is induced by a coherent optical beamsplitter, it should be possible to observe interference in a cold atom sample that is guided around a closed loop [10,11,16].

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is tight and the guided motion of atoms is adiabatic. A detailed discussion on the light pulse guided atom interferometer will be given in a future publication.

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