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A waveguide atom beamsplitter for laser-cooled neutral atoms

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Abstract

A laser-cooled neutral-atom beam from a low-velocity intense source is split into two beams while guided by a magnetic-field potential. We generate our multimode-beamsplitter potential with two current-carrying wires on a glass substrate combined with an external transverse bias field. The atoms bend around several curves over a 10-cm distance. A maximum integrated flux of $1.5 \cdot 10^5$atoms/s is achieved with a current density of $5 \cdot 10^4$Ampere/cm^2 in the 100-μm diameter wires. The initial beam can be split into two beams with a 50/50 splitting ratio.

Like their optical counterpart, atom beamsplitters are the pivotal element of atom-optical interferometers. While the original beamsplitter was perhaps the Stern-Gerlach apparatus[1], modern free-space beamsplitters are based on mechanical or light-based refractive elements.

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Such beamsplitters have been used with good success in Mach-Zehnder interferometers to measure the Sagnac-effect with high sensitivity[2,3]. Free-space beamsplitters are generally characterized by small splitting angles because the effective grating spacing is large compared to the atomic de Broglie wavelength.

A waveguide-based beamsplitter has the potential to provide arbitrary splitting angles. Furthermore, the confining potential of a waveguide also suppresses the beam divergence and gravitational sag to which free-space interferometers are subjected. Several atom-guiding schemes using magnetic forces have been proposed and demonstrated[4–10]. We recently demonstrated guiding a beam of laser-cooled atoms around a curve[11] using magnetic forces from photolithographically patterned current-carrying wires. The multimode-atom beamsplitter reported on here is a natural extension of our previously demonstrated guiding scheme. Like its fiber and integrated optical counterparts, our waveguide beamsplitter merges and then diverges two guiding regions.

We guide ^{87}Rb atoms in a weak-field-seeking state along a magnetic-field minimum. This magnetic guide leads atoms around several curves to a beamsplitter region. Our beamsplitter region consists of two such magnetic-field minima that merge to one field minimum and separate again into two minima. A variable fraction of atoms initially launched into one of the two magnetic field minima are guided and transferred into the second magnetic field minimum at the beamsplitter region.

For our atom source we prepare a laser-cooled beam of ^{87}Rb atoms with a modified vapor-cell magneto-optical trap (MOT)[12]. To generate our low-velocity intense source (LVIS)[13] we drill a 500-μm hole in the center of a retro-reflecting mirror placed inside our vacuum chamber [Fig. 1(d)]. We couple LVIS atoms into our magnetic guide by positioning the guide opening directly behind the mirror hole. The atom's internal state and velocity distributions are as measured previously[11,14].

We generate our one-dimensional guiding potential by adding an external transverse bias field to the magnetic field generated by a 100×100-micron current-carrying wire on a glass substrate[7,8,10]. The vector sum of the transverse bias field $\vec{B}_{bias}$ and the wire's magnetic field

$\vec{B}_{wire}$ becomes zero at a position outside the wire, if the bias field is smaller than the field generated by the wire at its surface [Fig. 1(a)]. As the bias field is increased (decreased) the position of the magnetic field minimum moves linearly toward (away from) the wire and the potential depth increases (decreases). Furthermore, when the wire's magnetic-field maximum is twice the transverse bias field, the magnetic field zero is 50-μm above the current-carrying-wire surface and the field magnitude increases linearly with displacement in the transverse directions. We generate the transverse bias field for the guide with an electromagnet placed near the substrate [Fig. 1(d)]. An additional ~14-G longitudinal bias field is applied to prevent the magnetic-field magnitude from vanishing at the field minimum. As the wire current and bias field are increased proportionally the magnetic-potential depth and gradient increase linearly, but the field-minimum position remains unchanged.

With current only in the wire positioned right behind the mirror hole, wire 1, and a 86-G external bias field applied we guide atoms and measure atom flux versus wire current for different bias fields. In this guiding experiment we run 35-msec-long current pulses of up to 5.5 A at a 1 sec repetition rate through wire 1. We choose short current pulses to prevent the glass substrate from overheating, allowing us to run larger wire currents than a continuous current would allow. After the atoms exit the guide, they are ionized by a hot wire and the subsequent ions are then detected by a channeltron. For each external bias-field value there is an optimum track current that maximizes the guided-atom flux [Fig. 2(a)]. For wire currents too large the magnetic-field minimum is shifted far away from the wire resulting in a reduced field gradient. This field-gradient reduction helps to couple atoms into the guide opening, but also leads to guiding losses as atoms can no longer be guided around the curves of the guide. When the track current is too low the generated magnetic-field gradient is sufficient to bend the atoms around the curve, but the field minimum is close to the wire surface and atom-surface interactions as well as a tighter guide opening result in a lower flux. Our guiding flux peaks when the condition for mode matching atoms into the guide opening and maintaining a sufficient gradient to bend atoms around the curves is optimized.

We measure the heating of guided atoms by comparing the transverse velocities before and after the guiding process. At a wire current of 5.0 A and a transverse bias field of $\sim$ 86 G we measure the guided-atoms' transverse-velocity profile by translating the hot wire transverse to the propagation direction to map out the spatial extent of the atom beam as it diverges from the guide exit [Fig. 2(b)]. The 70-μm-diameter hot wire is placed $\sim$ 2.5 cm from the output of the magnetic guide. We calculate that the atoms' emergence from the confining fields of the guide 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. From the width of the fit in Figure 2(b) we determine that the transverse-velocity distribution of the guided atoms is $v_t = 17.2 \pm 3.5$ cm/sec, in contrast to an initial transverse velocity of $v_t = 10.0 \pm 1.5$ cm/s of LVIS. We attribute the observed heating to the non-adiabatic loading of the LVIS atoms into the guide. An atom that enters the guide displaced from the magnetic field minimum experiences a sudden increase in its potential energy because it is not mode-matched to the guide. The additional potential energy increases its total energy inside the guide, which is converted into transverse kinetic energy once the atom leaves the guide. We believe this heating effect can be ameliorated by adiabatically loading the atoms into a tapered guide.

Once atoms are guided along the one-dimensional magnetic-field minimum we turn on our beamsplitter. As we increase the current running through wire 2 we observe that the flux from guide 2 increases and the flux out of guide 1 decreases. Figure 3(a) shows the flux of guided atoms coming out of each guide versus the current ratio between the two wires. As we change this current ratio we can tune the splitting ratio of our beamsplitter. We observe a dynamic range of the splitting ratio from 100/0 to 15/85. A 50/50 beamsplitter is achieved when the current in wire 2 is 85% of the current in wire 1. Aside from the current ratio there are two other parameters that determine the splitting ratio of our beamsplitter. First, as we change the applied transverse bias field we can vary the degree of overlap of the two magnetic field minima. For very large bias fields the two minima remain close to their respective wires and their overlap is small in the beamsplitter region. Second, the curvature of the guides in the beamsplitter region determines the manner in which the two magnetic-field minima merge. In our design the atoms are preferentially switched over into the secondary guide due to the wire curvature in the beamsplitter region. The guides bend with a radius of curvature of ∼30 cm into the splitter region and curve away with a radius of ∼70 cm. A calculation of our potential-minima trajectories shows that for this curvature the field minima follow straight lines that cross (Fig. 4). This means that atoms launched into guide 1, the primary guide of our beamsplitter, are more likely to switch over into guide 2, the secondary guide, than to continue along guide 1. This geometric feature of our beamsplitter is responsible for its bias toward coupling atoms into guide 2. Our experimental data shows that at a current ratio of 0.85 between guide 2 and guide 1 we compensate for the geometric bias of our beamsplitter and achieve 50/50 beamsplitting. As we increase the current in wire 2 to a current larger than in wire 1 the flux out of guide 2 peaks at a current ratio $I_{wire2}/I_{wire1} = 1.1$ and decreases again beyond this value. This decrease is analogous to the observation in 2(a) where we found a decrease in guided-atom flux for wire currents in a non-optimum B_{wire}/B_{bias}-ratio regime.

We sum the flux from the output of both guides and find the total flux to remain roughly constant. This observed flux conservation of our beamsplitter as shown in Figure 3(a) is a strong function of the transverse bias field applied. For a current in wire 1 of 5.0 A and a longitudinal bias field of 14 G a transverse bias field of $\sim$ 86 G is necessary to achieve a constant total flux as the current ratio is varied. This is 35% larger than the optimum bias field measured for maximum guiding efficiency when only one wire carries current. We postulate that the increased bias field separates the two magnetic field minima in the beamsplitter region making it easier for atoms to follow guide 1 instead of guide 2.

We model our beamsplitter design with a numerical simulation and find qualitative agreement with our measured data. The simulation calculates the classical trajectories of 2.5×10^6 atoms through our beamsplitter potential and records which guide each atom exits [Fig. 3(b)]. The test atoms' spatial initial conditions are spread over a 100×100-μm aperture centered 60 μm above the wire and their initial velocities match the LVIS-velocity distribution at the guide opening. We use constant bias fields of 100 G in the transverse and 14 G in the longitudinal direction for the simulation shown. In our experiment these values are not constant along the entire guiding region, which limits the accuracy of our simulation. The simulation shows that more atoms are coupled into guide 2 than remain in guide 1 when the currents in both wires are equal, which confirms our idea that the beamsplitter is biased toward guide 2 by its geometric design. Further, a 50/50 beamsplitting is shown at a current ratio of 0.75, which compares well within the errors of the simulation to the measured current ratio of 0.85. Our simulation also shows a decrease in flux out of both guides at the largest current ratios as observed in our experiment.

In summary, we have split a beam of laser-cooled atoms while guided in a magnetic-field potential. We are able to vary the ratio of atoms coupled into the secondary guide from 0 to ∼85% by varying the current in wire 2. We demonstrate that moderate currents give guiding potential depths of several millidegrees Kelvin. In the future the question of coherent beamsplitting will have to be addressed. While coherence has been well established for free-space atom interferometers it has yet to be demonstrated that our waveguide beamsplitter preserves coherence.

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REFERENCES

1. W. Stern and O. Gerlach, Z. Phys. **8**, 10 (1921).
2. A. Lenef, T. D. Hammond, E. T. Smith, M. S. Chapman, R. A Rubenstein, and D. E. Pritchard, Phys. Rev. Lett. **78**, 760 (1997).
3. T. L. Gustavson, P. Bouyer, and M. A. Kasevich, Phys. Rev. Lett. **78**, 2046 (1997).
4. J. Schmiedmayer, Phys. Rev. A **52**, R13 (1995).
5. M. Key, I. G. Hughes, W. Rooijakkers, B. E. Sauer, and E. A. Hinds, Phys. Rev. Lett. **84**, 1371 (2000).
6. J. Denschlag, D. Cassettari, A. Chenet, S. Schneider, and J. Schmiedmayer, Appl. Phys. **B 69**, 291 (1999)
7. J. Denschlag, D. Cassettari, and J. Schmiedmayer, Phys. Rev. Lett. **82**, 2014 (1999).
8. N. H. Dekker, C. S. Lee, V. Lorent, J. H. Thywissen, S. P. Smith, M. Drndic, R. M. Westervelt, and M. Prentiss, Phys. Rev. Lett. **84**, 1124 (2000).
9. J. Fortagh, A. Grossmann, C. Zimmermann, and T. W. Hänsch, Phys. Rev. Lett. **81**, 5310 (1998).
10. J. Reichel, W. Hänsel, and T. W. Hänsch, Phys. Rev. Lett. **83**, 3398 (1999).
11. D. Müller, D. Z. Anderson, R. J. Grow, P. D. D. Schwindt, and E. A. Cornell, Phys. Rev. Lett. **83**, 5194 (1999).
12. E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard Phys. Rev. Lett. **59**, 2631 (1987); C. Monroe, W. Swann, H. Robinson, and C. E. Wieman *ibid* **65**, 1571 (1990).
13. Z. T. Lu, K. L. Corwin, M. J. Renn, M. H. Anderson, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. **77**, 3331 (1996).

14. D. Müller E. A. Cornell, D. Z. Anderson, and E. R. I. Abraham, Phys. Rev. A **61**, 033411 (2000).

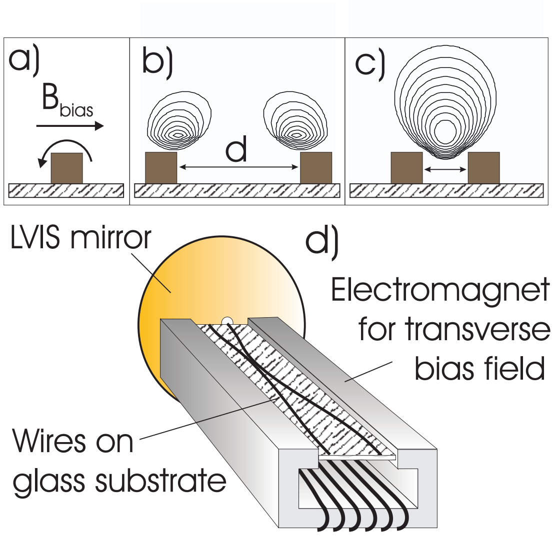

Fig. 1. Contour lines of magnetic-field potential and guide schematic. (a-c) We show a cross-sectional cut across the wires. When a bias field is applied transverse to the wires the magnetic field becomes zero just above the wire surface (a). For large track separations (d=300μm) the magnetic field minima do not merge (b). As the track spacing is reduced (d=100μm) the magnetic field minima merge to form one field minimum (c). The transverse bias field is generated with an electromagnet near the wire substrate (d). The LVIS mirror hole is aligned with one of the wires to couple the LVIS atoms into the guide.

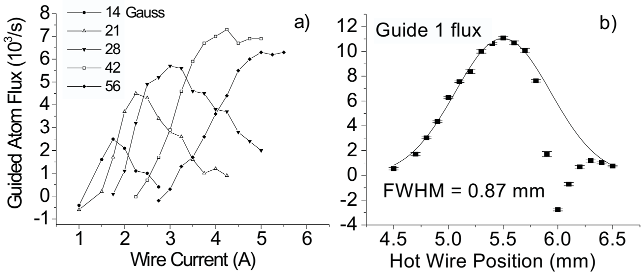

Fig. 2. Guided atom flux. We measure the guided atom flux versus the wire current at different transverse bias fields. For each bias field we observe an optimum wire current where the guided flux peaks (a). Figure 2(b) shows the guided-atom beam profile. We move the hot wire perpendicular to the propagation direction to map out the transverse-velocity distribution. We use the width of the Gaussian fit to determine the RMS transverse velocity to be $v_t = 17.2 \pm 3.5\mathrm{cm/sec}$. The dip in flux around 6 mm is an artifact due to some stray LVIS atoms that contaminate the guided-atom-beam profile. Those data points appear negative due to a background-subtraction procedure.

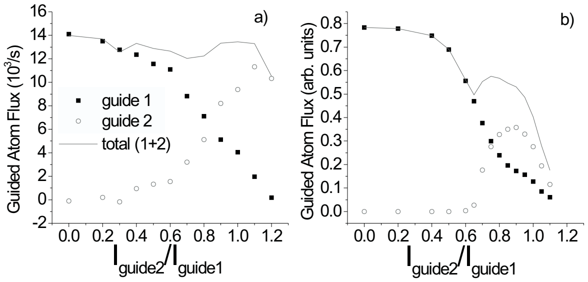

Fig. 3. Flux versus wire-current ratio. Figure 3(a) shows the experimental data and figure 3(b) a simulation of our beamsplitter. With no current in wire 2 all atoms coupled into guide 1 exit the same guide 1. As the current in wire 2 is increased the beamsplitter is turned on and atoms are transferred to guide 2. For the experimental (simulation) data the transverse-bias field, the longitudinal-bias field, and I_{guide1} are held constant at values 86 G (100 G), 14 G (14 G), and 5.0 A (5.0 A) respectively. The simulation shows good qualitative agreement with our experimental data.

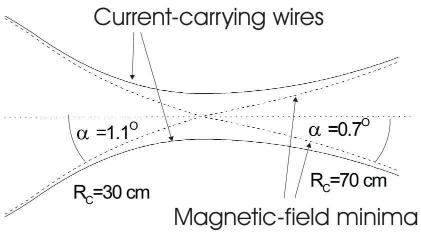

Fig. 4. Magnetic-field-minima crossing. For our curvature (R_c) and spacing the magnetic field minima cross in the center region with an angle α between the two trajectories. Atoms coupled into one guide are more likely to be transferred into the other guide when both wires carry equal currents, because of the tendency to shoot straight across the intersection.