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Time-orbiting potential trap for Bose-Einstein condensate interferometry

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We describe an atom trap for Bose-Einstein condensates of ^{87}Rb to be used in atom interferometry experiments. The trap is based on a time-orbiting potential waveguide. It supports the atoms against gravity while providing weak confinement to minimize interaction effects. We observe harmonic oscillation frequencies $(\omega_x, \omega_y, \omega_z)$ as low as $2\pi \times (6.0, 1.2, 3.3)$ Hz. Up to 2×10^4 condensate atoms have been loaded into the trap, at estimated temperatures as low as 850 pK. We anticipate that interferometer measurement times of 1 s or more should be achievable in this device.

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Atom interferometry with Bose-Einstein condensates has drawn a considerable amount of interest due to the potential for high-precision measurements [1]. The fundamental limit on the sensitivity of an atom-based Sagnac interferometer, for example, exceeds a photon-based interferometer by a factor of 10^{11}, for middle-weight atoms and optical-wavelength light. Sensor applications are also more numerous for an atom interferometer, given that atoms are affected by electric and magnetic fields while photons are not. This heightened sensitivity also amplifies the effects of environmental noise, imposing practical limits on the sensitivity that can be obtained. Nonetheless, the best gyroscope on record is an atom interferometer [2].

Using a Bose-Einstein condensate for interferometry is appealing because the intrinsic advantages of thermal atoms are considerably increased. Slow velocities and long coherence lengths allow condensates to exhibit greater sensitivity per atom than a thermal cloud with a similar number of atoms. Though producing and working with condensates remains challenging, several groups have demonstrated Mach-Zehnder or Michelson interferometers using condensates [3–10]. However, all these experiments have been limited to measurement times of roughly 10 ms or less. In this paper we discuss an atom waveguide that we expect will permit significantly longer measurement times.

In the design of a condensate interferometer, one must decide how the atoms will be transported through the device. The simplest method is to orient the axis of the device vertically, allowing the atoms to fall freely under the influence of gravity [3,6,8]. While this technique introduces no additional fields or dephasing effects, the measurement time is limited by the speed at which the condensate falls. However, Bose-Einstein condensate (BEC) experiments generically suffer from low production rates. This reduces the signal-to-noise ratio, since the statistical fluctuations in phase scale as $N^{-1/2}$ for number of atoms N. While thermal atomic beam experiments can produce 10^9 atoms/s, condensate production rates are more typically 10^5 atoms/s. In order to make up for these low numbers, long interaction times will be required so that the overall phase is increased. This makes interferometers based on falling atoms unattractive, though some of the difficulties might be circumvented using either a fountain geometry [11] or a magnetic levitation approach [12].

The alternative possibility is to use trapped atoms. Condensate interferometers using atoms confined by either magnetic [5,9,13] or optical [4,7,10] fields have been demonstrated. Measurement times in these devices have been limited for a variety of reasons, but a common concern is the effect of interatomic interactions, which can introduce phase noise and cause spatial distortions in the cloud [4,10,14]. Confinement also imposes severe geometrical constraints due to the need to avoid uncontrolled motional excitations [13,15]. To avoid these problems, one wants a trap capable of holding the atoms against gravity but otherwise as weakly confining as possible. Weak three-dimensional confinement has previously been observed [16], but in this paper we present a weakly confining waveguide that is particularly well suited for the demands of atom interferometry.

The waveguide is illustrated in Fig. 1. It is based on a four-wire linear quadrupole and uses the time-orbiting potential (TOP) technique [17–19]. Four current-carrying rods provide a linear quadrupole field, with the zero line at the center. A rotating bias field pushes the zero away from the atoms to prevent Majorana losses. We preferred the TOP to other options because of its noise-reduction effects. Our bias field rotates at about 10 kHz, and the atomic spins follow adiabatically. Because of this, any slowly varying magnetic fields or other environmental noise coupling to the spins will tend to average out. The atoms do become sensitive to noise near 10 kHz, but we have found that most of the magnetic noise in our laboratory has frequencies well below this.

Conventional TOP traps are not especially weak. The obvious way to reduce the confinement strength is to reduce the magnetic field amplitude, but we cannot lower the force below what is required to counter gravity. The solution we have found is to oscillate not only the bias field, but also the quadrupole field. With the appropriate choice of phase, this causes the field zero to oscillate back and forth above the atoms. The atoms are constantly attracted to the overhead zero, and we can weaken the confinement further than would otherwise be possible.

To understand this mechanism, suppose the oscillating quadrupole field is

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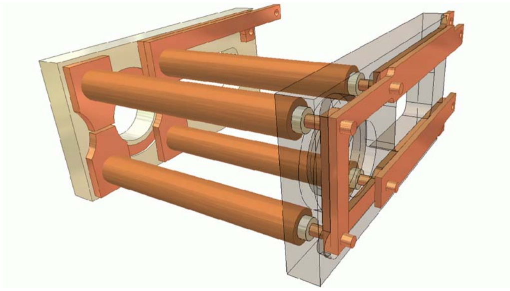

FIG. 1. (Color online) Scale drawing of the trap structure. The main fields are generated by the four horizontal rods, each of which is a coaxial pair. A pair consists of an outer conductor that is a 5-mm-diam, 1-mm-wall oxygen-free high-conductivity copper tube, an alumina insulator, and an inner conductor that is a 1.6-mm-diam copper wire. The rods are held by two boron nitride blocks, which also support the leads and circuit connections. The right block has been depicted as transparent in order to display the arrangement of the conductors. The rod centers form a square 15 mm on a side and the blocks are spaced 5 cm apart. The function of each of the conductors is described in Fig. 2.

$$\mathbf{B}_Q = B'_Q(x\hat{\mathbf{x}} - z\hat{\mathbf{z}})\cos \Omega t, \tag{1}$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ are the transverse directions and $\hat{\mathbf{y}}$ is along the axis of the waveguide. The $\hat{\mathbf{z}}$ direction is vertical. The bias field is

$$\mathbf{B}_0 = B_0(\hat{\mathbf{x}} \sin \Omega t + \hat{\mathbf{z}} \cos \Omega t) \tag{2}$$

with rotation frequency $\Omega = 11.9$ kHz. The resulting time-averaged field magnitude, to second order in the coordinates, is

$$\langle|\mathbf{B}|\rangle = B_0 - \frac{1}{2}B'_Q z + \frac{B'^2_Q}{16B_0}(3x^2 + z^2), \tag{3}$$

providing a total potential energy

$$U = \mu B + mgz = \mu B_0 - \frac{1}{2}\mu B'_Q z + mgz + \frac{1}{2}m(\omega_x^2 x^2 + \omega_z^2 z^2) \tag{4}$$

for atomic mass m, gravitational acceleration g, and magnetic moment μ. We set the gradient $B'_Q = 2mg/\mu$ to support the atoms against gravity and obtain trap frequencies

$$\omega_x = \left(\frac{3mg^2}{2\mu B_0}\right)^{1/2} \quad \text{and} \quad \omega_z = \frac{\omega_x}{\sqrt{3}}. \tag{5}$$

For a 10 G bias field, this gives trap frequencies $\omega_x = 2\pi \times 7$ Hz and $\omega_z = 2\pi \times 4$ Hz for Rb atoms in a state with maximum μ.

The waveguide is made of machined copper rods held inside a vacuum chamber, as shown in Fig. 1. Each of the four rods is a coaxial pair. As Fig. 2 illustrates, the four outer conductors are connected in one circuit that provides the quadrupole field while the inner conductors form two circuits used to generate the two components of the bias field. The end loops shown on the quadrupole circuit help minimize the axial quadrupole field.

The leads of the circuits do have an appreciable effect on the trap potential. For instance, any residual axial component causes the quadrupole field to become

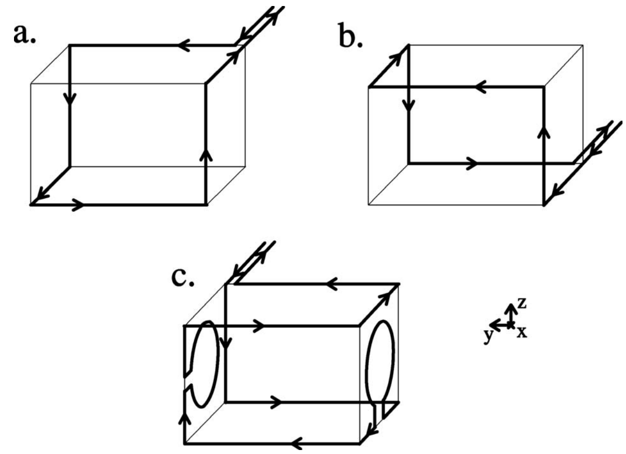

FIG. 2. Current flow through waveguide, indicated by thickened lines with directional arrows. The four rods in Fig. 1 are depicted here as the edges of a rectangular box. Circuits (a) and (b) refer to the current through the inner conductors, which provides the oscillating bias field. Circuit (c) is composed of the outer conductors, which supply the confinement quadrupole field. The end loops on circuit (c) help to minimize the axial quadrupole field.

$$\mathbf{B}_Q = (ax\hat{\mathbf{x}} + cy\hat{\mathbf{y}} - bz\hat{\mathbf{z}})\cos \Omega t \tag{6}$$

with $c = b - a$. A more accurate description of the potential requires the inclusion of many other first- and second-order terms in the magnetic fields. Categorizing all such terms is prohibitive, but we have found that in the relevant parameter range, the total average field magnitude is well approximated by

$$\langle|\mathbf{B}|\rangle = B_0 - \frac{1}{2}bz + \left(\frac{3}{16B_0}a^2 + \alpha B_0\right)x^2 + \left(\frac{1}{4B_0}c^2 + \gamma B_0\right)y^2 + \left(\frac{1}{16B_0}b^2 + \beta B_0\right)z^2 \tag{7}$$

which yields frequencies

$$\omega_x = \left[\frac{2\mu}{m}\left(\frac{3}{16B_0}a^2 + \alpha B_0\right)\right]^{1/2},$$
$$\omega_y = \left[\frac{2\mu}{m}\left(\frac{1}{4B_0}c^2 + \gamma B_0\right)\right]^{1/2}, \tag{8}$$
$$\omega_z = \left[\frac{2\mu}{m}\left(\frac{1}{16B_0}b^2 + \beta B_0\right)\right]^{1/2}.$$

Here a, b, and c are from Eq. (6) and α, β, and γ come from variations in the bias fields. We obtained this form by modeling the total field using the Biot-Savart law and the mechanical design of the leads. The model predicts $B_0/I_0 = 0.40$ G/A, $a/I_Q = -0.83$ G/(A cm), $b/I_Q = -0.86$ G/(A cm), $\alpha = -0.11$ cm^{-2}, $\beta = -0.061$ cm^{-2}, and $\gamma = 0.019$ cm^{-2}, where I_0 is the bias current amplitude and the I_Q is the quadrupole current amplitude. These values were coarsely verified using a gaussmeter, yielding $B_0/I_0 \approx 0.4$ G/A and $a/I_Q \approx b/I_Q \approx 0.8$ G/(A cm).

The three trap circuits have similar impedances, presenting a 10 $m\Omega$ resistive and 0.3 μH inductive load. The circuits are driven with an actively stabilized commercial audio amplifier, using transformers to match the amplifier's output impedance. The details of this drive circuit will be presented elsewhere. The trap is mounted on several copper blocks that deliver the current and remove heat. The measured thermal coefficient of the trap structure is 2 W/K. The quadrupole field requires a current of 38 A to cancel gravity and a bias field of 20 G requires $I_0=50$ A in both bias circuits, yielding a total temperature rise of about 16 K.

Our BEC system is based on the scheme described by Lewandowski *et al.* [20]. We have a single magneto-optical trap (MOT), separated from an ultrahigh vacuum science cell by a tube 30 cm long with diameter 1 cm. Our MOT contains 2×10^9 ^{87}Rb atoms at roughly 200 μK. We optically pump them into the $F=2$, $m=2$ ground state for magnetic trapping. We transfer the atoms to a spherical quadrupole trap, obtaining about 1.5×10^9 atoms at 900 μK with an axial field gradient of 387 G/cm. The atoms are transported to the science cell by a programmable motor, which moves the electromagnet coils at $v=0.8$ m/s.

Once in place within the waveguide structure, we evaporatively cool the cloud. The atoms are initially too hot for our TOP trap, so we start evaporating in the quadrupole trap. We evaporate on the spin-state transitions within the $F=2$ ground-state manifold. Once the cloud cools below 200 μK, we turn on the waveguide bias field and continue evaporating. The static spherical quadrupole field remains on to provide tight confinement. We achieve condensation with about 2×10^4 atoms at a temperature of 50 nK, using a 3.69 G bias field. From the evaporative cooling, we obtained a more accurate calibration of the bias field as 0.440 G/A times the current amplitude I_0.

Our final atom number is somewhat lower than typical. We believe this is because transferring the atoms from the quadrupole trap to the TOP trap is inefficient and we are exploring ways to improve this. Once the condensate is made, the waveguide quadrupole field is ramped on and the spherical quadrupole field ramped off. The centers of the main trap and the waveguide do not exactly coincide, so the fields are ramped with a 7 s time period to enable the atoms to move adiabatically to the new local B field minimum. We do not observe any losses in the transfer. Figure 3 shows snapshots of the cloud as the atoms are being transferred.

We measured the trap frequencies of the waveguide by observing either center-of-mass (for the x and z directions) or breathing mode (for the y direction) oscillations in the cloud. We perturbed the cloud by introducing a sudden change in the confining field and then recorded the subsequent behavior. These tests were done on a noncondensed cloud at temperatures of about 1 μK. From the periods, we determined the trap frequencies as a function of the applied currents.

We measured the frequencies over a range of bias fields from 3 to 16 G. From this data, we solved for the trap parameters in our model Eq. (8). Using a multivariable minimization, we found $|a|/I_Q=0.734$ G/(A cm), $|b|/I_Q=0.709$ G/(A cm), $\alpha=0.17$ cm^{-2}, $\beta=0.05$ cm^{-2}, and

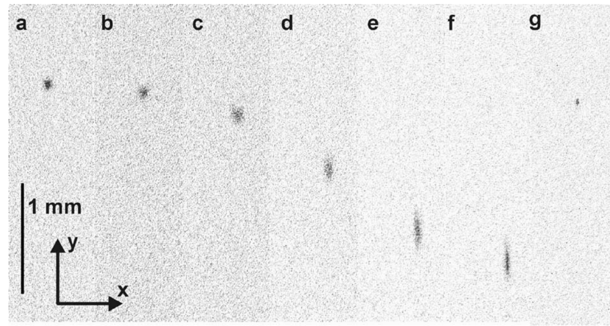

FIG. 3. Loading a Bose-Einstein condensate into the waveguide. The sequence of pictures show the trapped condensate as the static quadrupole field is gradually turned off: (a) 29 G/cm, (b) 19 G/cm, (c) 9.7 G/cm, (d) 3.9 G/cm, (e) 1.9 G/cm, and (f) 0 G/cm. During the loading, the cloud moves due to the centers of the external quadrupole and the waveguide not being aligned. The bias field here is 3.69 G, and the final trap frequencies are $\omega_x=2\pi\times 11$ Hz, $\omega_z=2\pi\times 6.2$ Hz, and $\omega_y=2\pi\times 0.6$ Hz. Panel (g) shows an atomic cloud after increasing the bias field to 20.5 G, with trap frequencies $\omega_x=2\pi\times 6.0$ Hz, $\omega_y=2\pi\times 1.2$ Hz, and $\omega_z=2\pi\times 3.3$ Hz. We estimate the temperature of this cloud to be 850 pK.

$\gamma=0.02$ cm^{-2}. The quadratic coefficients are rather different from our model predictions, though the order of magnitude is correct. Using the empirical coefficients, Eq. (8) reproduces the measured frequencies to an accuracy of about 0.1 Hz over the range of bias fields tested.

The weakest confinement we observed, at $B_0=20.5$ G, had $\omega_x=2\pi\times 6.0$ Hz, $\omega_y=2\pi\times 1.2$ Hz, and $\omega_z=2\pi\times 3.3$ Hz. By adiabatically expanding a small condensate into such a weak trap, we were able to obtain very low temperatures. Figure 3(g) shows an image of 1.6×10^3 atoms in the trap with this bias field. We estimate the temperature of this cloud to be 850 pK. Although lower temperatures have been observed in Na [16], this is the lowest temperature achieved for Rb atoms of which we are aware.

With the successful demonstration of our trap, we are now preparing to explore condensate interferometry. We plan to conduct experiments similar to those of Wang *et al.* [9], using a Bragg laser pulse to split and recombine condensate wave packets. The weak confinement of our guide should greatly reduce the limiting effects of interactions. For instance, the phase distortions discussed in [14] should have negligible effect for condensate numbers below about 1.5×10^4, and phase diffusion effects during the wave-packet propagation should not become important for interaction times less than about 1 s [21]. Using the current apparatus, we plan to study these and other limiting effects. With suitable modifications, our waveguide could be used to precisely measure electric polarizability, gravitational forces, rotations, and other phenomena [22]. We are hopeful that the trap design presented here will help condensate interferometry realize this potential.

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