Efficient optical guiding of trapped cold atoms by a hollow laser beam

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We present an experimental and theoretical study of efficient optical guiding of trapped cold atoms by a blue-detuned hollow laser beam. We have measured the atomic guiding efficiency with respect to the propagation direction of the hollow beam, which is in good agreement with numerical analysis. In particular, using a copropagating guide laser, we have obtained 20-fold enhancement of atom guiding with a guiding efficiency of 50%. Simulation shows that the efficiency can be increased to 80% with an improved hollow beam mode. The possibility of coherent atom guiding is also discussed.

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Recently, there has been much interest in atom guiding by optical dipole potentials produced by hollow-core optical fibers (HOF's) [1,2] and hollow laser beams (HLB's) [3–7]. Guidance of atoms by HLB's, in particular, has advantages over that by the evanescent waves in HOF's, since the van der Waals attraction due to the fiber walls can be ignored and collisions with background gas are much less probable. Moreover, a HLB configuration can be controlled more conveniently than that of a HOF. The development of efficient optical guiding of cold atoms is of much interest and importance for applications related to the transfer of trapped cold atoms to a region of dense atoms or a lower-dimensional space, which can be used for such experiments as high-resolution spectroscopy, atom lithography, atom microscopy, and atomic fountains.

In this article, we present quantitative experimental and theoretical studies of efficient optical guiding of trapped cold atoms by HLB's. We find that, when the HLB copropagates with the atoms, the guiding efficiency is higher than that due to a counterpropagating HLB, in particular at small laser detuning. Moreover, at large detuning, experimental results also indicate that a lower transverse atomic temperature is obtained. The experimental results show excellent agreement with two different theoretical analyses that have recently been developed from kinetic theory with the Fokker-Planck equation [4] and from the dressed-atom model [6]. We also discuss higher guiding efficiencies, with possible atom-optical applications such as optically guided atomic fountains as well as dipole traps using HLB's.

Figure 1 shows the experimental schematic for guiding cold ^{85}Rb atoms. The atomic guiding direction is downward along gravity ($+z$ direction), whereas the HLB propagates along the $-z$ direction in a counterpropagating scheme or along the $+z$ direction in a copropagating scheme. Note that an additional lens is used in the latter case to make the HLB approximately identical as experienced by the atoms, except for the propagation direction in the two cases. A Ti:sapphire laser is used as the guiding laser source with a maximum output power of 1.8 W. It is coupled to the core of a HOF with a coupling efficiency of about 30%. The typical HLB power used for guiding atoms is 250 mW. By using micro-collimation and microimaging techniques for the linearly polarized LP_{01} guided mode of the HOF [8], a HLB with a small dark spot can be conveniently obtained with a microscope objective. We have used a micrometer-sized HOF that has a hollow diameter of 4 μm, core thickness of 2 μm, and length of 25 cm. We have independently measured the intensity distribution of the HLB in both guiding schemes, and confirmed the identical radius of the maximum-intensity ring $\rho_m(z)$, which varies linearly with the distance z [$\rho_m(z) = \rho_m(0) - \alpha z$, where $\rho_m(0) = 1.4$ mm is the value at the trap center ($z=0$) and $\alpha = 1.27(4)\times 10^{-3}$].

We have used a standard vapor-cell magneto-optical trap of ^{85}Rb atoms in the stainless-steel vacuum chamber at a pressure of 10^{-9} Torr [4]. For cooling and repumping, we have used two injection-locked 70-mW diode lasers, which are frequency-stabilized to the red of the $F=3\rightarrow F'=4$ and the resonant $F=2\rightarrow F'=3$ transitions of the Rb D_2 line, respectively. Each laser has a diameter of 16 mm and an intensity of 3.3 mW/cm^2 per cooling beam and 0.5 mW/cm^2 for repumping. The number of trapped atoms is typically 2×10^7 and the trap diameter is about 1 mm, so that the loading efficiency of the trapped atoms into the HLB is 98%.

By time-of-flight measurement, the temperature of atoms in the MOT is found to be about 140 μK, which is further cooled down to 16 μK by polarization-gradient cooling. After the sub-Doppler cooling, the cooling and repumping lasers are blocked by mechanical shutters, and the HLB is simultaneously introduced to the atoms to guide their gravitational falling. The number and the temperature of guided atoms are detected by observing the probe-induced fluorescence with a photomultiplier. The probe laser beam is placed horizontally and tuned to the resonant transition $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F'=4)$. It has an intensity of 1 mW/cm^2 and a cross section of 1×2.5 mm^2, and is positioned at 105 mm below the trap center. An additional laser, having an intensity of 0.1 mW/cm^2 at the resonant line $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$, is overlapped with the probe for optical repumping.

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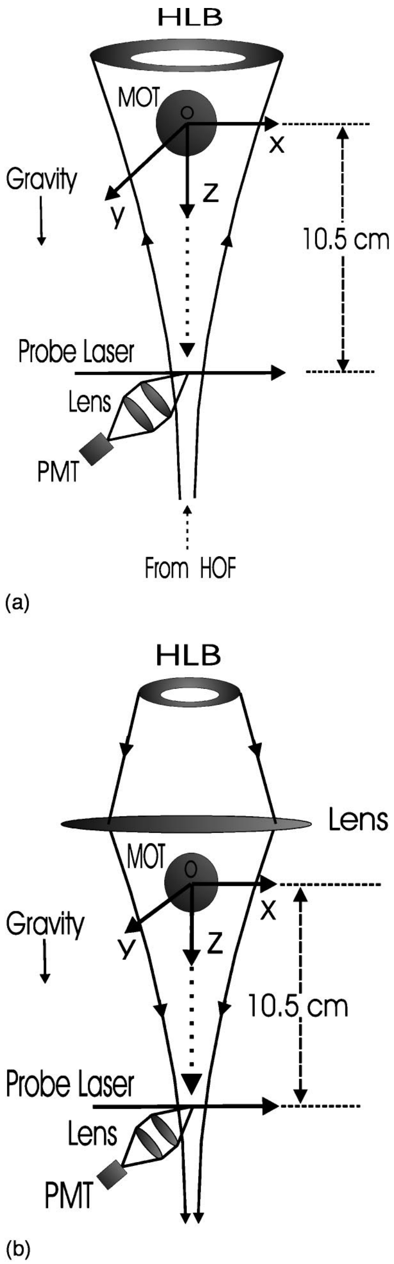

FIG. 1. Schematic diagram for HLB guiding of cold Rb atoms in (a) counterpropagating and (b) copropagating schemes. MOT denotes the magneto-optical trap and PMT the photomultiplier.

Figure 2 shows time-of-flight signals of guided cold atoms in both guiding schemes at various laser detunings δ_2 [$\delta_j = \omega - \omega_j$ $(j=1,2)$], where ω is the laser frequency, and ω_1 (ω_2) is the atomic transition frequency between the upper (lower) ground-state hyperfine level $|1\rangle$ ($|2\rangle$) and the excited state $|3\rangle$. For comparison, the signal detected without the HLB for the freely falling atoms is also shown. In particular, we observe that the number of atoms guided by the copropagating HLB is about 20-fold enhanced with respect to that without the HLB at 2 GHz detuning. In this case, the guided atoms also become faster along the $+z$ direction due to the increased radiation pressure at the small detuning [Fig. 2(a)]. In the counterpropagating case, on the other hand, the guided atoms are decelerated as the detuning is decreased [Fig. 2(b)].

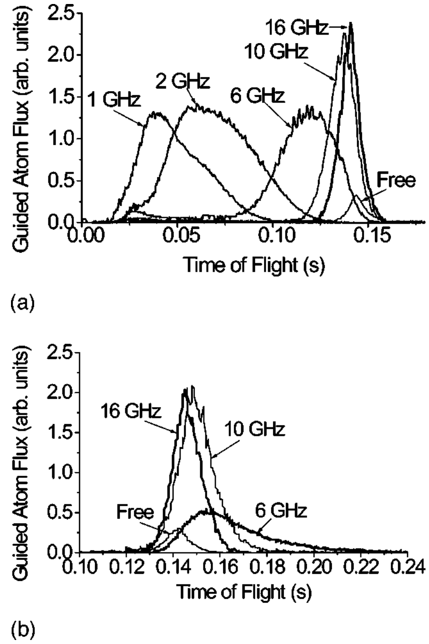

FIG. 2. Typical time-of-flight signals for atoms guided by a HLB. (a) In the copropagating scheme, the laser detuning δ_2 is 1, 2, 6, 10, and 16 GHz. (b) In the counterpropagating scheme, δ_2 is 6, 10, and 16 GHz. For comparison, the signal for freely falling atoms is also shown (''Free''). In all cases, the HLB power is 250 mW and the initial atomic temperature is 16 μK.

We have made a quantitative numerical analysis for HLB guiding using explicit expressions for the dipole force $\mathbf{F}_d$, radiation force $\mathbf{F}_r$, momentum-diffusion tensor D_{ii}, and dipole potential U_d, respectively, given by [4,6]

$$\mathbf{F}_d = -\frac{\hbar}{2}(q_1\delta_1 + q_2\delta_2)\frac{\nabla G}{C_0}, \qquad (1)$$

$$\mathbf{F}_r = \frac{1}{2}\hbar \mathbf{k}\Gamma\frac{G}{C_0}, \qquad (2)$$

$$D_{ii} = \frac{1}{12}\hbar^2 k^2 \Gamma \frac{G}{C_0}, \qquad (3)$$

$$U_d = \frac{1}{8}\hbar\Gamma^2(q_1\delta_1 + q_2\delta_2)\frac{G}{C_1}, \qquad (4)$$

where $C_0 = q_1/f_1 + q_2/f_2 + 3G/2 + 4C_1/\Gamma^2$ and $C_1 = q_1\delta_1^2/f_1 + q_2\delta_2^2/f_2$. Here f_i is the mean relative transition strength averaged over the ground-state hyperfine sublevels [6,7], and q_i is the mean branching ratio of the excited state $|3\rangle$ decaying to the ground state $|i\rangle$ when the state $|i\rangle$ is excited by the far-off-resonant HLB. For example, for ^{85}Rb atoms interacting with a linearly polarized HLB, by taking into account all the excited-state hyperfine levels, one can obtain $f_1 = f_2 = 2/3$, $q_1 = 0.741$ (0.185), and $q_2 = 0.259$ (0.815), for the excitation of $|1\rangle$ ($|2\rangle$). Γ is the natural width of the excited state, and G is the dimensionless satu-

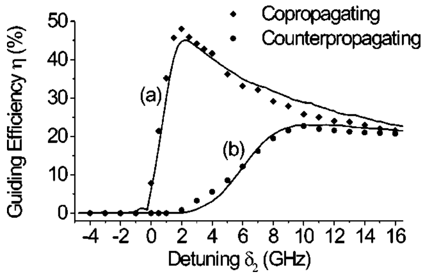

FIG. 3. The guiding efficiency as a function of the detuning δ_2 in the copropagating (a) as well as the counterpropagating (b) scheme, with the same HLB power and initial atomic temperature as in Fig. 2. The solid curves represent the numerical simulation results.

ration parameter given by $G=I/I_s$, where I is the intensity of the HLB and I_s is the saturation intensity. **k** is the wave vector of the HLB.

We find that the different characteristics of the two guiding schemes in Fig. 2 are mainly associated with the radiation-pressure force [Eq. (2)]. In the copropagating scheme, the amount of time that atoms stay in the HLB becomes shorter due to radiation-pressure-induced acceleration, and as a result the heating due to momentum diffusion [Eq. (3)] is reduced. Therefore the, guiding efficiency is mainly determined by the height of the mean potential barrier [Eq. (4)]. In the counterpropagating scheme, however, the radiation pressure decelerates the atoms at small detuning, and even reverses their velocities. The atoms then stay longer in the HLB, resulting in a higher temperature, and consequently the atoms can pass over the potential barrier and are lost more easily.

Figure 3 presents experimental and numerical guiding efficiencies versus detuning in the copropagating as well as the counterpropagating scheme. Note that in our simulation the HLB is assumed, to a good approximation, to be in the lowest Laguerre-Gaussian (LG_{01}) mode, given by $I=4P(x^2+y^2)\exp[-2(x^2+y^2)/w^2]/(\pi w^4)$, where P is the laser power and $w=\sqrt{2}\rho_m(z)$ is the beam waist at the position z. It can be seen that at small detuning, atoms are most efficiently guided in the copropagating scheme (for example, the maximum guiding efficiency is about 50% at a detuning of 2 GHz). Note that when atoms are released from the molasses without a HLB we detect only 2.5% of the initially trapped atoms. On the other hand, the counterpropagating guiding is generally less efficient as is clear in Fig. 3. However, for large detunings, the two schemes provide similar guiding efficiencies, and the maximum efficiency of 23% is obtained at 10 GHz detuning in the counterpropagating scheme.

We also observe that the guiding efficiency is increased with increasing laser detuning in the small-detuning region for the counterpropagating scheme, due to the decreasing contribution of the radiation pressure. Therefore, for a given HLB, there exists an optimum efficiency before the guiding is limited by the dipole-potential barrier, which decreases with increasing detuning [Eq. (4)]. The corresponding optimum detuning is the threshold beyond which the photon scattering is reduced at the expense of smaller guiding efficiency (of course, the efficiency can be enhanced by guiding colder atoms as discussed later). For example, in the counterpropagating case, it is about 10 GHz, and the maximum guiding efficiency is smaller than that in the copropagating case since the corresponding detuning value is larger. We have also checked that at small red detuning the time-of-flight signals vanish in both cases due to the high-intensity-seeking dipole force.

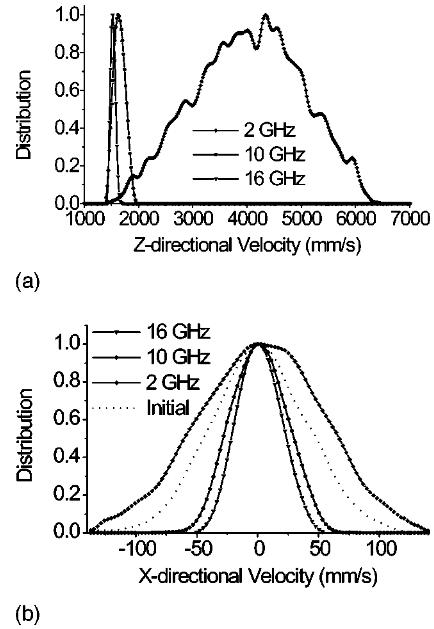

FIG. 4. The final velocity distributions of the atoms guided by the copropagating HLB at several detunings, which are calculated from the experimental data of Fig. 2(a): (a) longitudinal and (b) transverse distributions.

In Fig. 4, we present the final velocity distributions (longitudinal as well as transverse), which can be calculated from the experimental data in Fig. 2 by using a Monte Carlo simulation [6]. In the copropagating case, we find that the longitudinal velocity distribution becomes very broad in the small-detuning region. For example, at 2 GHz detuning, the velocity width is increased by a factor of 20 with respect to the initial width, and most of the atoms are heated considerably as shown in Fig. 4(a). Moreover, the transverse velocity distribution also becomes wider as shown in Fig. 4(b), where only the distribution in the x direction is shown due to the cylindrical symmetry.

However, for large detunings, whereas the longitudinal velocity distribution of the co-guided atoms is almost invariant with respect to that of the freely falling atoms, the transverse velocity distribution becomes non-Gaussian and narrower than the initial distribution. For instance, at 16 GHz detuning, while the longitudinal width is only a few percent larger than the initial value, the transverse width is decreased by a factor of 2. This indicates that the transverse temperature of the guided atoms is now 4 μK. This cooling effect can be attributed to velocity selection by the potential barrier and photon scattering as follows. Although atoms initially have average transverse energy lower than the potential barrier, those with higher transverse temperature can be more easily heated and lost during guiding as they can stay longer in the high-intensity region than those with lower transverse velocity. As a result, as the potential barrier decreases with the increase of HLB detuning, atoms having higher transverse temperature can escape more easily from the dark region, which leads to the lower transverse temperature for guided atoms. Note that this process occurs at the expense of the loss of guided atoms (or smaller guiding efficiency); for example, the number of atoms guided by the HLB at 16 GHz detuning is now only eight times larger than that without the HLB.

We have also calculated the final velocity distribution in the counterpropagating case and have obtained similar results: larger width at small detuning and smaller width at large detuning. Moreover, we have recently made a direct observation of such a lowered atomic temperature in an optical-dipole trap constructed with two crossed HLB's at large detuning (to be discussed elsewhere). This also indicates that the coherence of atoms may be preserved during optical guiding for an appropriate detuning of the HLB. In particular, having a comprehensive understanding of HLB guiding of cold atoms, one can also realize an optically guided atomic fountain that may improve the performance of the atomic clock based on the atomic fountain [9] (work currently in progress).

It is interesting to note that the efficiency of the copropagating guiding can be further enhanced with a higher power at a given atomic temperature (e.g., 60% with 500 mW at 16 μK) or with a lower atomic temperature at a given power (e.g., 75% with 1 μK at 250 mW). Moreover, if the quality of the HLB is improved by more careful fiber treatment and optical alignment for the LG_{03} mode, described by $I = 8P(x^2+y^2)^3\exp[-2(x^2+y^2)/w^2]/(3\pi w^8)$ with $w(z) = \sqrt{2/3}\rho_m(z)$, the numerical results indicate that the guiding efficiency will also be much enhanced. We find that the maximum guiding efficiency can be 80% (50%) in the copropagating (counterpropagating) scheme with all the conditions the same as shown in Fig. 3 except the HLB mode. In particular, the guiding efficiency at large detunings in both schemes can be increased by a factor of 2. Note that the overall behavior of the guiding efficiency versus the detuning is very similar to that in Fig. 3 and the optimum detunings are almost invariant for the two guiding schemes. Moreover, we also find that, if the coherence of guided atoms such as a Bose condensate is to be preserved, both schemes may be exploited with higher power, larger detuning and colder atoms. For example, simulation shows that when the HLB has 500 mW power and 220 GHz detuning, more than 30% of the atoms at 2 μK temperature can be guided over a distance of 30 cm without any spontaneous emission and with the average photon scattering rate much less than 1 s^{-1}.

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