Optical Guiding of Trapped Atoms by a Blue-Detuned Hollow Laser Beam in the Horizontal Direction *

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Optical guiding of ^{85}Rb atoms in a magneto-optical trap (MOT) by a blue-detuned horizontal hollow laser beam is demonstrated experimentally. The guiding efficiency and the velocity distribution of the guided atoms are found to have strong dependence on the detuning of the guiding laser. In particular, the optimum guiding occurs when the blue detuning of the hollow laser beam is approximately equal to the hyperfine structure splitting of the ^{85}Rb ground states, in good agreement with the theoretical analysis based on a three-level model.

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Since cold atoms can be guided to special regions where atoms can be experimentally used for an atom-interferometer,[1] integrated atom optics,[2,3] Bose–Einstein condensation (BEC),[4−7] and some other applications,[8,9] atom guiding opens intriguing new perspectives for experiments in atomic physics. Two kinds of techniques are often used for atom guiding. The first one is the so-called magnetic guiding which makes use of the interaction potential $V_{mag} = -\boldsymbol{u} \cdot \boldsymbol{B}$ between atomic magnetic moment $\boldsymbol{u}$ and the external magnetic field $\boldsymbol{B}$. In the previous four years, cold ^{87}Rb, ^{7}Li, and ^{52}Cr atoms have been guided in different shapes of magnetic guides.[10−15] This method only works for atoms with certain spin states. In addition, it is not a convenient choice to produce a magnetic field strong enough to confine the atoms. The second atom guiding technique is the so-called laser guiding. Atoms are confined by the guiding-laser induced dipole force (interaction potential $V_d = -\boldsymbol{D}\cdot\boldsymbol{E}$). Recently, atoms have been guided in hollow optical fibres (HOFs) by evanescent waves[16,17] and in hollow laser beams (HLBs).[18−22] Compared to HOF guiding, the advantages of the HLB guiding are that there are no van der Waals attraction due to the fibre walls, and the HLB configuration can be controlled more easily. To our knowledge, so far there has not been any report on the HLB guiding in horizontal direction. In this Letter, we investigate the horizontal HLB guiding with the HLB detuning as a variable parameter. The maximum guiding efficiency is observed when the HLB detuning is approximately equal to the hyperstructure splitting of the ground states. The velocity distribution of the guided atoms becomes narrower with larger detuning values.

The experimental setup and the timing sequences in the experiment are described first. Then the detected time-of-flight (TOF) signals of the guided atoms are used to analyse the guiding efficiency and to calculate the velocity distribution of the atoms. Finally, a quantitative interpretation to the experimental results is given by a simple three-level model.

Figure 1 shows the experimental schematics for guiding cold ^{85}Rb atoms. We use a specially designed and home-made ten-square vapour-cell magneto-optical trap (MOT)[23] which consists of three orthogonally counterpropagating laser beams and a spatially linearly varying magnetic field. The vapour cell is pumped by an ion pump down to a pressure of 10^{-9} Torr. A Ti:sapphire laser (Coherent CR-899-21) is used for laser cooling and trapping purpose and is locked to the frequency of the transition from the ground state $F = 3$ to the excited state $F' = 4$ of the ^{85}Rb D$_2$ line.[24] An external-cavity diode laser (DL100) used as the repumping laser is frequency stabilized to the resonant $F = 2 \rightarrow F' = 3$ transition.[25,26] The cooling laser beams have a diameter of 20 mm and an intensity of 6.8 mW/cm^2 and the repumping laser beams have a diameter of a 20 mm and an intensity of 2.8 mW/cm^2. The magnetic gradient is adjusted to 8 G/cm. The diameter of the trapped atomic cloud with a number of 10^8 in the MOT is about 3.5 mm. Another amplified external-cavity diode laser (TA100) with a maximum output power of 500 mW is used as the guiding laser. Using the TOF measurement, we know the trapped atoms temperature is about 240 μK when the cooling laser detuning is about −16 MHz. Then we turn off the magnetic field in 1 ms and shift the detuning to about −50 MHz in 5 ms. The intensity of the cooling laser is decreased to one-third value of the initial intensity at

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the same time. The trapped-atom temperature can reach 20 μK after the polarization gradient cooling (PGC) process.

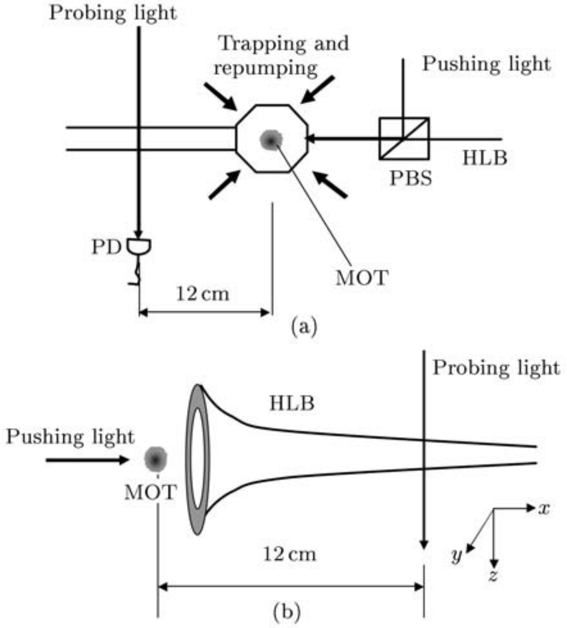

Fig. 1. Schematic of experimental setup for HLB guiding of cold Rb atoms. (a) Experimental scheme and the laser beams. (b) The HLB guiding and probing scheme. HLB: hollow laser beam; PD: photodiode; PBS: polarization beam splitter; MOT: magneto-optical trap.

As shown in Fig. 1, the z axis is taken in the gravity direction and the x axis is in the horizontal guiding direction. The HLB propagates parallel to the x-axis. In order to guide the trapped cold atoms in the horizontal direction, we need a pushing beam to give an initial momentum of the atoms. The pushing beam also comes from the Ti:sapphire laser whose frequency is controlled by a double-pass acoustic-optical modulator (AOM)[27] configuration. Using a polarization beam splitter (PBS), we overlap the pushing laser beam with HLB. Using a microscope objective, we can shape a well-defined HLB. The intensity of the HLB can be described as follows:

$$I(r,x) = I_0\frac{w_0}{w(x)}\exp[-r^2/w^2(x)], \quad r > \rho_m(x),$$

$$I(r,x) = 0, \quad r < \rho_m(x),$$

$$w^2(x) = w_0^2\Big(1+\frac{(x-b)^2}{x_R^2}\Big), \quad x_R = \frac{\pi w_0^2}{\lambda},$$

$$\rho_m(x) = \rho_m(0) - \alpha x, \quad r^2 = y^2 + z^2,$$

where $w(x)$ and w_0 are the beam waists at the distance x and at the focused point, respectively; and x_R is the Rayleigh length; $\rho_m(x)$ is the radius of the maximum-intensity ring, which varies linearly with distance x, where $\rho_m(0) = 3\,\text{mm}$ and $\alpha = 1.9 \times 10^{-3}$; b is the focused position with a value of 57 cm.

After sub-Doppler cooling, the trapping and repumping laser beam is turned off in 0.5 ms and the HLB is simultaneously introduced to the cold atoms. The pushing laser pulse is then switched on and delays for about 1 ms. A probing laser beam with an intensity of 0.6 mW/cm^2 and a cross section of $1\times 5\,\text{mm}^2$ is positioned at a distance of 12 cm from the MOT center and tuned to the resonant transition $F = 3 \rightarrow F' = 4$ of the D_2 line.

Figure 2 shows the TOF signals of the guided atoms without HLB guiding and with a 2.9 GHz blue-detuned HLB guiding. We can find that the number of the atoms (measured by the areas under the curves) guided by HLB is about 3-fold enhanced with respect to that without HLB. The atoms have a mean velocity of 20.0 m/s due to the pushing laser beam and the guided atoms with a mean velocity of 24.0 m/s become faster along the x direction because of the increased radiation pressure at the 2.9 GHz blue detuning. Figure 3 presents the TOF signals of the guided atoms with different blue detunings. The atoms become faster when the detuning turns smaller. For example, the mean velocity of the trapped atoms becomes 23.6 m/s, 24.0 m/s, and 24.3 m/s when the detuning changes to 5 GHz, 2.9 GHz, and 1.4 GHz. The guided atom numbers are 2.5, 3.0, 2.3-fold increased with respect to that without HLB, corresponding to 1.4 GHz, 2.9 GHz, and 5 GHz blue detuning. We also find that the time-of-flight signals disappear due to high-intensity seeking dipole force at small red detuning.

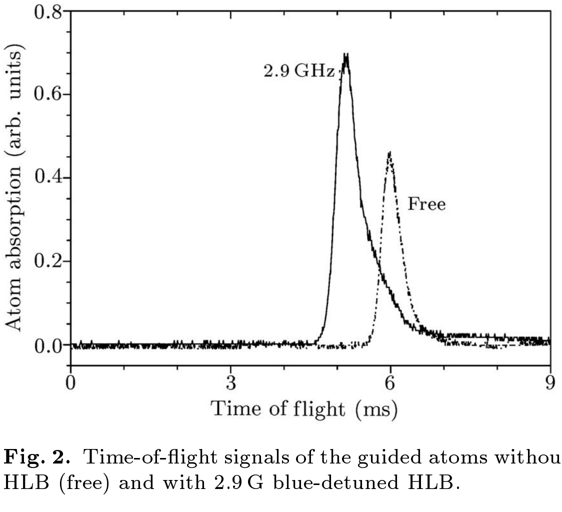

Fig. 2. Time-of-flight signals of the guided atoms without HLB (free) and with 2.9 G blue-detuned HLB.

Now, we give a theoretical analysis for the HLB guiding efficiency based on a three-level model. Figure 4 shows the energy-level diagram of a three-level Λ atomic interaction with a far-detuned single-mode laser beam. The energy-level includes two ground states $|g_1\rangle = |1\rangle$, $|g_2\rangle = |2\rangle$ and one excited state $|e\rangle = |3\rangle$. The detunings of the laser are $\delta_i = \omega - \omega_i$ $(i = 1, 2)$, where ω is the laser frequency and $\omega_1(\omega_2)$ is the atomic transition frequency between the ground state $|1\rangle(|2\rangle)$ and the upper exited state $|3\rangle$; $\delta_{hfs} = \omega_1 - \omega_2$ is the hyperfine structure splitting of the two ground states. The expressions for the dipole force F_d, radiation force F_r, momentum-diffusion tensor D_{ii} and dipole potential U_d were given in Ref. [21]:

$$F_d = -\frac{\hbar}{2}(q_1\delta_1 + q_2\delta_2)\frac{\nabla G}{C_0}, \tag{1}$$

$$F_r = \frac{1}{2}\hbar k \Gamma \frac{G}{C_0}, \tag{2}$$

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

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

where $C_0 = q_1/f_1 + q_2/f_2 + 3G/2 + 4C_1/\Gamma^2$ and $C_1 = q_1\delta_1^2/f_1 + q_2\delta_2^2/f_2$, f_i is the relative mean transition length from the ground states to the excited state,[21,22] and q_i is the mean relative spontaneous emission rate from the excited state to the ground states.[21,22] When ^{85}Rb atoms interact with a linearly polarized HLB, we can obtain $f_1 = f_2 = 2/3$, and for the excitation of the ground states $|3\rangle$. Γ is the natural linewidth of the excited state $|3\rangle$, G is the dimensionless saturation parameter given by $G = I/I_s$, and k is the wavevector of the HLB.

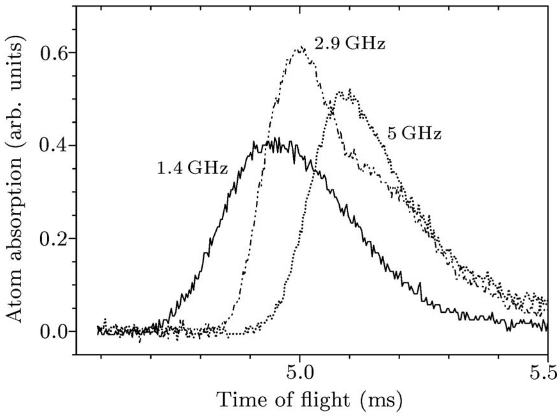

Fig. 3. Time-of-flight signals of the guided atoms for different blue-detuned HLBs. The detunings are 1.4 GHz, 2.9 GHz, and 5.0 GHz respectively.

The detected guided atoms flux is mainly determined by the following two parts: atoms loaded from the optical molasses into the guiding HLB and the guided atoms confined in HLB. The loading efficiency η_l and the guiding efficiency η_g are described as follows:

$$\eta_l = \frac{N_{\rm load}}{N_{\rm in}}, \tag{5}$$

$$\eta_g = \frac{N_{\rm guide}}{N_{\rm load}}, \tag{6}$$

where $N_{\rm in}$ is the initial atom number in the optical molasses, $N_{\rm load}$ is the number of atoms loaded into the HLB, and $N_{\rm guide}$ is the guided atoms number. The loading efficiency η_l mainly depends on the ratio of the size of the maximum-density ring of the HLB $\rho_m(0)$ to the radius of the initial trapped atom $r_{\rm in}$.[21] From the above description of $r_{\rm in}$ and $\rho_m(0)$ in our paper, the loading efficiency $\eta_l \approx \frac{\rho_m(0)}{r_{\rm in}} = \frac{3.0\,{\rm mm}}{3.5\,{\rm mm}} = 86\%$. When HLB copropagates with the guided atoms, the heating induced by momentum diffusion (Eq. (3)) is reduced because the guided atoms stay shorter time in HLB due to the radiation-pressure-induced acceleration (Eq. (2)). The guiding efficiency η_g will be increased by the confinement of the dipole force (Eq. (1)) and dipole potential (Eq. (4)). Considering the HLB intensity profile and the influence of the pushing beam on the guided atoms velocity, we can numerically calculate the relationship between the guiding efficiency and the laser detuning. The experimental results and the theoretical calculation are shown in Fig. 5. The maximum guiding efficiency appears at the position where the detuning of the HLB is nearly equal to the hyperfine ground structure splitting ($\delta_2 = 2.9$ GHz $\approx \delta_{hfs}$) ($\delta_{hfs} = 3.035$ GHz). When the detuning of the laser is larger or smaller than the hyperfine structure splitting of the two ground states, the dipole potential will decrease and the atoms with high velocity will more easily escape from the potential barrier. If we consider the momentum diffusion induced by the pushing beam, the theoretical calculation will agree well with the experimental results. In addition, the discrepancy between experiment and the calculation also comes from the reason that contribution of the radiation pressure force should be higher than that estimated by a simple three-level interaction model. Both our experimental results and calculation generally present the tendency of the guiding efficiency as a function of the laser detuning. Our further study also shows that lower initial trapped atom temperature and higher guiding power with large laser detuning give higher guiding efficiency.

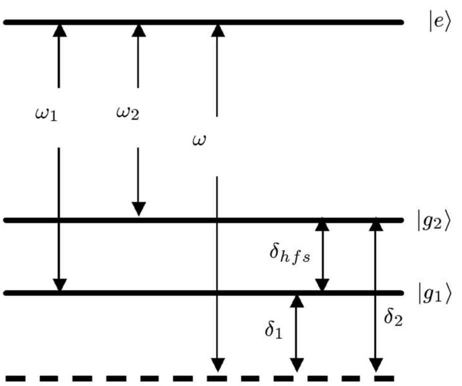

Fig. 4. Energy-level diagram of a three-level Λ-model of atomic interaction with a far-detuned single-mode laser beam.

Figure 6 shows the velocity distribution of the atom ensemble guided in HLB. We can find that longitudinal velocity distribution becomes narrower when the laser detuning turns larger. For example, when $\delta_2 = 1.4\,\mathrm{GHz}$, the full-width at half-maximum (FWHM) of the velocity distribution $\Delta V = 1.45\,\mathrm{m/s}$, and $\Delta V = 1.22\,\mathrm{m/s}$ for $\delta_2 = 2.9\,\mathrm{GHz}$, $\Delta V = 1.00\,\mathrm{m/s}$ for $\delta_2 = 5.00\,\mathrm{GHz}$. This gives us an opportunity to guide coherent atoms (for example, BEC) in a large blue-detuned HLB without deteriorating the atom coherence.

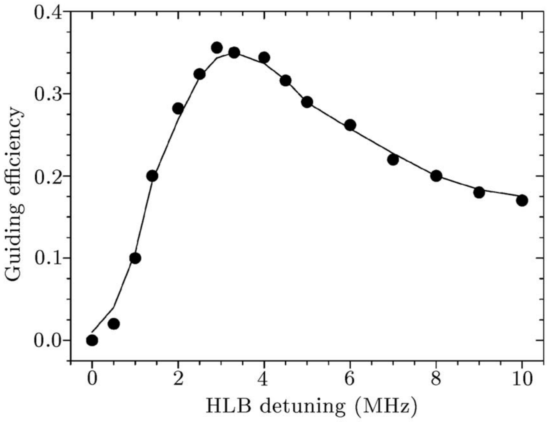

Fig. 5. The guiding efficiency as a function of the laser detuning δ_2. The solid curve indicates the theoretical calculation and the dots represent the experimental results.

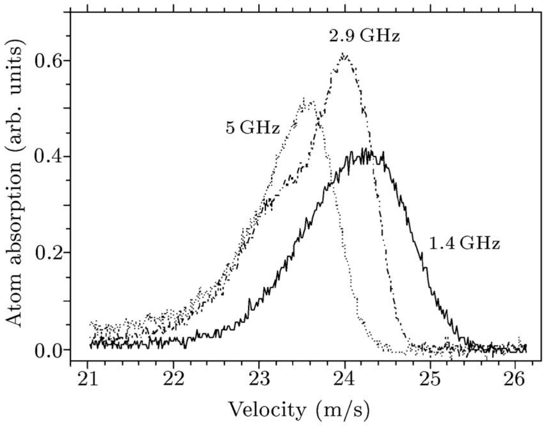

Fig. 6. The longitudinal velocity distribution of the guided atoms at different detunings of 1.4 GHz, 2.9 GHz, and 5.0 GHz.

In summary, we have realized atom guiding utilizing blue-detuned hollow beams in horizontal directions. To obtain the optimum guiding, the detuning of HLB should be set to be close to a value near the hyper-fine splitting of the ground states. On the other hand, the longitudinal velocity distribution becomes narrower at higher laser detuning values. A higher laser power with larger detuning are therefore preferred to preserve atom coherence while keeping a high guiding efficiency.

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