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Atom guiding and cooling in a dark hollow laser beam

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We propose and analyze theoretically a scheme for atomic guiding and cooling in a dark hollow laser beam generated from the collimated output beam of a LP_{01} mode in a micrometer-sized hollow optical fiber. In the scheme, cold atoms from a magneto-optical trap are loaded into the blue-detuned dark hollow beam, move down in the dark hollow beam, and experience transverse Sisyphus cooling induced by the dark hollow beam and a weak repumping beam. In the longitudinal direction, the guided atoms experience heating from the gravity field and cooling from the upward-propagating dark hollow beam and repumping beam. We estimate the transverse two-dimensional equilibrium temperature, the final longitudinal mean velocity, and the total loss of the guided atoms. Our calculations show that a transverse equilibrium temperature of $\sim 1.2\ \mu$K, a final longitudinal mean velocity of 0–4.41 m/s, and a guiding efficiency of 65–95 % may be obtained. [S1050-2947(98)06407-5]

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Atom guiding in hollow optical fibers (HOFs) has been a subject of recent studies [1–9] because of its potential applications in atom optics, such as the atom-fiber interferometer, atom-fiber cavity [10], atom-fiber laser [11], atom-fiber funnel [12], and atom-fiber deposition [13]. Two guiding schemes for thermal atoms in HOFs that use a red-detuned Gaussian laser beam [1,2] or a blue-detuned evanescent light [3–7] have been proposed [1,3,4] and demonstrated experimentally [2,5–7]. Recently, Balykin *et al.* proposed an atom guiding and cooling scheme with a convergent hollow optical waveguide [8]. Neglecting the effect of the scattering forces from the evanescent wave and the repumping laser beam on the longitudinal velocity of the guided atoms, they studied the evanescent-wave-induced cooling in a cylindrical- or curved-convergent-hollow fiber [9] and showed that a bright coherent source of cold atoms with a density near that of Bose-Einstein condensation may be obtained [8–9]. However, there are some shortcomings in the practical application of their cooling and guiding scheme because the grazing incident modes of the repumping beam in the hollow region of the micrometer-sized cylindrical HOFs [9] are leaky, which will limit the length of the HOFs to <3 cm [5,12]. For atom guiding and cooling in a convergent hollow optical waveguide [8], atomic loss will be considerable due to the multiple optical modes of the convergent hollow waveguide.

Recently, we produced a dark hollow laser beam (DHB) from the output beam of the LP_{01} mode selectively excited in a micrometer-sized HOFs by a Gaussian laser beam and proposed three atomic guiding schemes using blue-detuned DHBs [14,15]. We calculated the optical potential for atom guiding in a collimated DHB [15]. However, the cooling mechanism of the blue-detuned DHB and the heating effect from the gravity field were not discussed. Here, we analyze the spontaneous-emission induced heating, longitudinal gravity-induced heating, transverse Sisyphus cooling and longitudinal spontaneous-force cooling from the DHB and a weak repumping beam (RPB) in the DHB atom guide. We estimate the two-dimensional (2D) equilibrium temperature, the final longitudinal mean velocity, and the total atomic loss. Our results show that a bright coherent atomic source with a transverse temperature of $\sim 1.2\ \mu$K and a final longitudinal velocity of ~ 10 cm/s can be obtained in the DHB atom guide.

The scheme of atom guiding and cooling in a DHB is shown in Fig. 1. A blue-detuned dark hollow beam with a small divergent angle ($\alpha \sim 10^{-3}$ rad) is generated by the microcollimating technique (using a M-40$\times$ objective lens) for the output beam of the LP_{01} mode selectively excited by a Gaussian laser beam in a micrometer-sized HOF [14,15]. The coupling efficiency from the Gaussian beam into the DHB is typically $\sim 50\%$ (the Gaussian beam with an input power ~ 1 W can be converted into the DHB with an output power ~ 500 mW) [15]. The DHB propagates upwards in the Z direction and overlaps with a magneto-optical trap (MOT). When the MOT is turned off, the cold atoms are loaded into the DHB under the influence of the gravity. A near-resonant, weak repumping beam is also propagating along the Z direction and overlaps with the DHB. As the cold atoms bounce down inside the DHB, they experience efficient 2D Sisyphus cooling induced by the DHB and RPB (see discussion below), which is similar to the well-known Sisyphus effect in standing-wave laser fields [16,17], and is analogous to the evanescent-wave-induced Sisyphus cooling in a gravito-optical atom trap [18] and a hollow-fiber atom waveguide [8,9]. In the longitudinal direction, the guided atoms experience heating from the gravity field and cooling from the upward-propagating DHB and RPB, since the photon momentum of the DHB and RPB is opposite to the longitudinal momentum of the guided atoms.

The 3D intensity distribution of the linearly polarized DHB from the LP_{01} mode in a HOF can be simulated by a

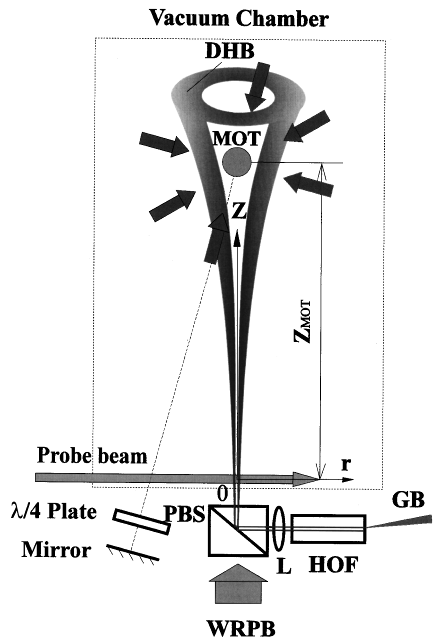

FIG. 1. Schematic diagram of atomic guiding and cooling in a dark hollow laser beam. DHB, MOT, PBS, L, WRPB, HOF, and GB stand for a dark hollow beam, magneto-optical trap, polarized beam splitter, lens (M-40× microscope objective), weak repumping beam, hollow optical fiber, and Gaussian beam, respectively.

simple theoretical mode, a modified TEM_{01}^{*} doughnut beam model [15], which is given by

$$I(r,Z)=\frac{2P_0}{\pi w^2(Z)}\,\frac{2r^2}{w^2(Z)}\,\exp\!\left(-\frac{2r^2}{w^2(Z)}\right), \tag{1}$$

where

$$w^2(Z)=w_0^2(1+kZ^2/Z_R^2),\qquad Z_R=\pi w_0^2/\lambda. \tag{2}$$

Here P_0 and Z_R are the power and Rayleigh length of the DHB, respectively. $w(Z)$ (w_0) is the beam waist at the distance Z ($Z=0$), and k is a fitting parameter. For a HOF with the hollow radius $a=3.5\ \mu$m, the core radius $b=7.3\ \mu$m, the refractive index of the core $n_2=1.45$, and the relative refractive index difference between the core and the cladding $\Delta n=(n_1^2-n_2^2)/2n_1^2=0.18\%$, we obtained $w_0=85\ \mu$m and $k=0.25$ for the DHB collimated by a M-40× objective lens. The corresponding far-field divergent angle α of the collimated DHB is about 10^{-3} rad. When $r^2(Z)=r_0^2(Z)=\frac{1}{2}w^2(Z)$, we have the maximum radial intensity, $I(r_0,Z)=I_{\max}(Z)=2P_0/e\pi w^2(Z)$. Here r_0 is defined as the beam radius of the DHB.

A detailed study of the optical potential for two-level ^{85}Rb atoms confined in the DHB is given in Ref. [15]. When the detuning $\delta=0.5$ GHz (0.1 GHz) and the power $P_0=500$ mW, the maximum height of the DHB potential barrier at $Z=Z_{\mathrm{MOT}}=1000$ mm is ~ 1 mK (~ 2.3 mK), which is more than sufficient to capture all of the cold atoms from a MOT with temperatures $\sim 120\ \mu$K. Under such conditions, the penetration depth r_{APD} of the cold atoms into the DHB is much smaller than the beam radius r_0, such that not more than one spontaneous transition occurs per reflection for the guided atoms in the DHB. For example, when $\delta=0.5$ GHz and $P_0=500$ mW, we obtain $r_{\mathrm{APD}}\approx 110\ \mu$m at $Z=500$ mm and ~ 80 nm at $Z=0$, which are sufficiently small to ensure that the saturation parameter $S=\omega_R^2/2\delta^2\ll 1$ (ω_R is the Rabi frequency) [18]. The corresponding divergent angle of the guided atomic sample in the DHB is $\theta\approx 2.3\times 10^{-4}$ rad. For guiding and cooling of three-level ^{85}Rb atoms [the two lower states are $5S_{1/2}$ $F=2$ and $F=3$ hyperfine ground states and the upper state is the $5P_{3/2}$ excited state, which are shown in Fig. 2(a)] considered here, the optical potentials of the two hyperfine ground states and the excited state are given by [12,18]

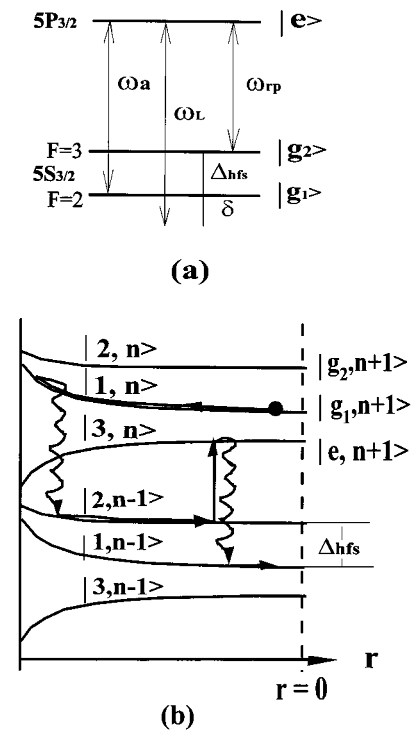

FIG. 2. (a) Energy-level diagram of a three-level ^{85}Rb atom interacting with a blue-detuned DHB and a near-resonant repumping beam. (b) Dressed-states picture of the three-level ^{85}Rb atom in the blue-detuned DHB. In (a) ω_a, ω_L, and ω_{rp} are the frequencies of the atomic transition $|g_1\rangle\leftrightarrow|e\rangle$, the DHB, and the repumping laser, respectively.

$$U_1(r,Z)=\frac{1}{12}\,\frac{\hbar\Gamma^2}{\delta}\,\frac{I(r,Z)}{I_S}, \tag{3}$$

$$U_2(r,Z)=\frac{1}{12}\,\frac{\hbar\Gamma^2}{\delta+\Delta_{\mathrm{hfs}}}\,\frac{I(r,Z)}{I_S}, \tag{4}$$

$$U_3(r,Z)=-\frac{1}{12}\,\frac{\hbar\Gamma^2(2+\Delta_{\mathrm{hfs}}/\delta)}{\delta+\Delta_{\mathrm{hfs}}}\,\frac{I(r,Z)}{I_S}, \tag{5}$$

where Δ_{hfs} is the level splitting between the two hyperfine ground states, and Γ and I_S are the neutral linewidth and the saturation intensity, respectively. For a ^{85}Rb atom, $\Delta_{\mathrm{hfs}}\approx 3$ GHz, $\Gamma=6.1$ MHz and $I_S=1.6$ mW/cm^2. When $\delta<\Delta_{\mathrm{hfs}}$, we calculated the optical potential $U_i(r)$ ($i=1,2,3$) around the dark center of the DHB and found that $U_1(r)$ of the lower hyperfine ground state is larger than $U_2(r)$ of the upper hyperfine ground state, which is a necessary condition for the efficient Sisyphus cooling [12,16–18] in the DHB.

Next, we discuss the cooling and heating of the guided atom in the DHB and the gravity field, which are similar to that of the alkali-metal atoms in an evanescent light [18]. A recent experiment demonstrated the evanescent-wave cooling and its results agree with the theoretical prediction [19]. We found that the radial intensity distribution of the linearly polarized DHB around the dark center can be approximated by a Gaussian beam:

$$I(\xi)=I_0\exp\left(-\frac{2\xi^2}{w_a^2}\right)\quad(r\ll r_0),\tag{6}$$

where $\xi=r-r_a$. I_0, r_a, and w_a are three fitting parameters. Because of the transverse Sisyphus cooling, the penetration depth of the guided atoms in the DHB decreases as the guiding distance increases, then r_a and w_a are dependent on Z. The total probability of an inelastic reflection of an atom due to the three decay channels in the dressed states, $|1,n\rangle\rightarrow|i,n-1\rangle$ [$i=1,2,3$ denotes the three dressed states that are the eigenstates of the interaction Hamiltonian including the three-level atom and the DHB; see Fig. 2(b)], can be calculated by [18]

$$p_{\rm sp}=1-\exp\left(-\int_{-\infty}^{\infty}\tfrac{1}{3}\Gamma S\ dt\right).\tag{7}$$

The relationship between the saturation parameter S and the time t can be derived from the conservation of energy in the normal motion. Using Eqs. (3) and (6), we obtain

$$dt=\frac{\sqrt{2}w_a}{4v_r}\frac{dS}{S\sqrt{\ln(S/b)(aS-1)}},\tag{8}$$

where

$$a=\hbar\delta/3E_r,$$
$$b=(I_0\Gamma^2/4I_S\delta^2).\tag{9}$$

Then, putting Eqs. (8) and (9) into Eq. (7), we derive

$$p_{\rm sp}=1-\exp\left(-\frac{mw_a\Gamma}{\hbar\delta}v_r\right).\tag{10}$$

If the mean transverse velocity and mean penetration depth of the guided atoms in the DHB are $\overline{v}_r$ and $\overline{r}_{\rm Apd}$, respectively, then the mean reflection rate of the atoms in the DHB is $\dot{n}=N/\tau_{\rm guid}=\overline{v}_r/(2\overline{r}_{\rm Apd})$. Here N and $\tau_{\rm guid}$ are the total number of reflections and the atom guiding time in the DHB, respectively. The time-averaged spontaneous-emission rate can then be estimated by

$$\gamma_{\rm sp}\approx\dot{n}\overline{p}_{\rm sp}=\frac{\overline{v}_r}{2\overline{r}_{\rm Apd}}\left[1-\exp\left(-\frac{m\overline{w}_a\Gamma}{\hbar\delta}\overline{v}_r\right)\right],\tag{11}$$

where

$$\overline{w}_a=\frac{1}{Z_{\rm MOT}}\int_0^{Z_{\rm MOT}}w_a(Z)dZ\tag{12}$$

is a mean fitting parameter. When the initial and final transverse temperatures of the guided atoms as well as the detuning and power of the DHB are given, the mean spontaneous-emission rate $\gamma_{\rm sp}$ is determined. Figure 3 shows the dependence of $\gamma_{\rm sp}$ on δ when the initial temperature of the guided atoms (i.e., the MOT's temperature) is $\sim120\ \mu$K and the final transverse temperature of the guided atoms is $\sim1.2\ \mu$K (see discussion below). As expected, the average spontaneous-emission rate decreases rapidly with the increase of δ. When $\delta=0.1$ GHz (1.0 GHz), we obtain $\gamma_{\rm sp}\approx1045\ {\rm s}^{-1}(323\ {\rm s}^{-1})$.

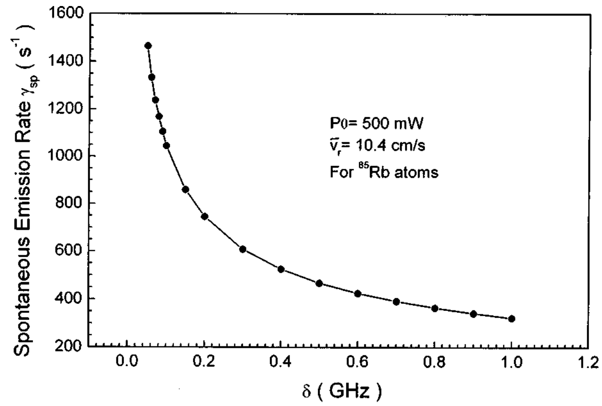

FIG. 3. Mean spontaneous-emission rate $\gamma_{\rm sp}$ versus the blue detuning δ of the dark hollow beam for the ^{85}Rb atom.

Because the divergent angle θ of the guided atomic sample in the collimated DHB ($\alpha\sim10^{-3}$ rad) is very small ($\theta\sim2.3\times10^{-4}$ rad), the transverse motion and longitudinal motion of the guided atoms in the DHB can be considered separately. In the transverse directions, the guided atoms experience the Sisyphus cooling and the recoil-induced heating. In the longitudinal direction, the guided atoms experience cooling from the scattering forces of the DHB and RPB, the recoil-induced heating, and heating from the gravity field.

The transverse Sisyphus cooling can be understood in terms of the dressed-atom picture shown in Fig. 2. An atom entering the DHB in the lower dressed state $|1,n\rangle$ may make a spontaneous transition to the less repulsive, upper dressed state $|2,n-1\rangle$. After the reflection from the DHB, the atom are pumped back to the original lower dressed state $|1,n-1\rangle$ by the weak repumping laser. In this inelastic reflection process, the atom lose their kinetic energy, and a closed and repeatable Sisyphus cooling cycle is formed. During the reflection, the atom may spontaneously decay to two other channels: $|1,n\rangle\rightarrow|1,n-1\rangle$ or $|1,n\rangle\rightarrow|3,n-1\rangle$. The heating induced by the latter can be neglected because its transition probability is very small [18], whereas the spontaneous emission of the former will result in a small heating of the reflected atom by one recoil energy (E_R). During the repumping process, each random recoil of a spontaneously emitted photon also leads to a small heating of the reflected atom by one recoil energy E_R.

Taking into the consideration of the spontaneous-emission heating and Sisyphus cooling, we derive an equation similar to that in Refs. [12,18] to estimate the final transverse (2D) equilibrium rms momentum of the guided atoms in the DHB:

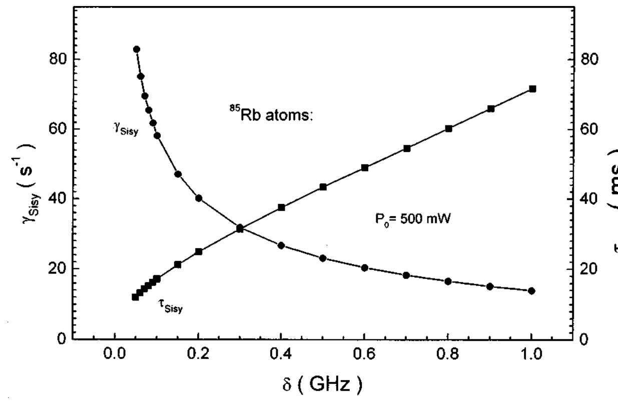

FIG. 4. Transverse Sisyphus cooling rate γ_{Sisy} and cooling time τ_{Sisy} versus the detuning δ of the DHB for the ^{85}Rb atom.

$$-\frac{2}{3}\frac{\Delta_{\mathrm{hfs}}}{\delta+\Delta_{\mathrm{hfs}}}\left(\frac{p_{\mathrm{rms}}}{\hbar k}\right)^2+\frac{1+q_r-q_{ev}}{q_r(1-q_{ev})}=0, \tag{13}$$

where q_r (q_{ev}) is the mean branching ratio into the lower hyperfine ground state from the excitation of the upper hyperfine ground state by the RPB (the average branching ratio of the spontaneous transition from $|1,n\rangle$ to $|1,n-1\rangle$). For the ^{85}Rb atom, $q_r=0.575$, and $q_{ev}=0.741$ [18]. When $\delta=0.5$ GHz, we obtain $p_{\mathrm{rms}}\approx 3.13\hbar k$. The corresponding transverse equilibrium temperature and transverse rms velocity of the guided atoms in the DHB are ~ 1.21 μK and ~ 1.88 cm/s, respectively.

Similarly, the Sisyphus cooling rate γ_{Sisy}, or cooling time τ_{Sisy}, can be estimated by [12,18]

$$\gamma_{\mathrm{Sisy}}=\frac{1}{\tau_{\mathrm{Sisy}}}\approx\frac{2}{3}\frac{\Delta_{\mathrm{hfs}}}{\delta+\Delta_{\mathrm{hfs}}}\frac{1-q_{ev}}{3}\gamma_{\mathrm{sp}}. \tag{14}$$

Figure 4 shows the Sisyphus cooling rate γ_{Sisy} and cooling time τ_{Sisy} versus the detuning δ. When δ increases from 0.05 to 1 GHz, γ_{Sisy} decreases rapidly from ~ 80 s^{-1} to ~ 15 s^{-1}, and the corresponding Sisyphus cooling time τ_{Sisy} increases from ~ 12 to ~ 67 ms.

In the longitudinal direction, the guided atoms experience gravity-induced heating and the DHB and RPB induced cooling because the atoms move downwards while both the DHB and RPB propagate upwards. Before the cold atoms in the MOT are released, their initial, mean longitudinal velocity is equal to zero (i.e., $\overline{v}_{z0}=0$). After the cold atoms from the MOT are loaded into the DHB at $t=0$, their longitudinal motion along the $-Z$ direction can be approximately treated as a free-falling-body motion with the initial velocity $\overline{v}_{z0}=0$ and a variable acceleration contributed by the gravity field and the scattering forces from the DHB and RPB. The longitudinal component of the gradient force of the DHB can be neglected (since $\theta\approx 2.3\times 10^{-4}$ rad). The longitudinal motion can then be described approximately by (setting $\overline{v}_{z0}=0$)

$$\overline{v}_z=(g-\overline{a}_{\mathrm{DHB}}-\overline{a}_{\mathrm{RPB}})\tau_{\mathrm{guid}},$$
$$Z_{\mathrm{MOT}}=\tfrac{1}{2}(g-\overline{a}_{\mathrm{DHB}}-\overline{a}_{\mathrm{RPB}})\tau_{\mathrm{guid}}^2. \tag{15}$$

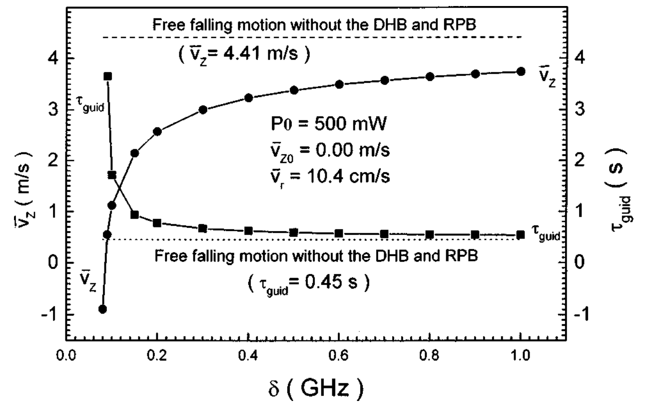

FIG. 5. Average guiding time τ_{guid} and final longitudinal mean velocity $\overline{v}_z$ of the guided ^{85}Rb atoms in the DHB atom guide versus the detuning δ of the DHB.

Here $\overline{v}_z$ and g are the final longitudinal mean velocity of the guided atoms and the gravity acceleration, respectively. $\overline{a}_{\mathrm{DHB}}$ $(\overline{a}_{\mathrm{RPB}})$ is the mean deceleration from the scattering force of the DHB (RPB).

If an atom makes a transition from $|1,n\rangle$ to $|1,n-1\rangle$ during the reflection, the velocity of the atom falling downwards will be slowed in the Z direction after it absorbs a DHB photon propagating upwards. From the momentum conversation, the change of atomic velocity per reflection is given by

$$\Delta v_{pZ}=\frac{\hbar k}{m}\approx 6.016(\mathrm{mm/s})\quad(\text{for }^{85}\text{Rb atom}). \tag{16}$$

Using Eq. (11), the total longitudinal velocity change of the atom after N reflections inside the DHB can be estimated by

$$\sum_i (\Delta v_{\mathrm{DHB}})_i=N\Delta v_{pZ}\approx\gamma_{\mathrm{sp}}\tau_{\mathrm{guid}}\Delta v_{pZ}. \tag{17}$$

The mean deceleration $\overline{a}_{\mathrm{DHB}}$ due to the absorption of the DHB photons is given by

$$\overline{a}_{\mathrm{DHB}}=\frac{1}{\tau_{\mathrm{guid}}}\sum_i (\Delta v_{\mathrm{DHB}})_i\approx\gamma_{\mathrm{sp}}\Delta v_{pZ}. \tag{18}$$

Similarly, the mean deceleration $\overline{a}_{\mathrm{RPB}}$ due to the absorption of the RPB photons can be estimated by

$$\overline{a}_{\mathrm{RPB}}=\frac{1}{\tau_{\mathrm{guid}}}\sum_i (\Delta v_{\mathrm{RPB}})_i\approx\frac{1-q_{ev}}{q_r}\gamma_{\mathrm{sp}}\Delta v_{pZ}. \tag{19}$$

Substituting Eqs. (18) and (19) into Eq. (15), we obtain the average guiding time τ_{guid} and final longitudinal mean velocity $\overline{v}_z$ of the guided atoms in the DHB. Figure 5 plots τ_{guid} and $\overline{v}_z$ versus the detuning δ. When $Z_{\mathrm{MOT}}=1000$ mm, $P_0=500$ mW, and $\delta=0.09$ GHz (0.5 GHz), we obtain $\overline{a}=\overline{a}_{\mathrm{DHB}}+\overline{a}_{\mathrm{RPB}}\approx 9.65$ m/s^2 (4.08 m/s^2). Using Eq. (15), we then obtain $\tau_{\mathrm{guid}}\approx 3.65$ s (0.591 s) and $\overline{v}_z\approx 54.8$ cm/s (3.38 m/s). The guiding time τ_{guid} is much longer than the Sisyphus cooling time τ_{Sisy} (<100 ms). If the longitudinal slowing effect from the DHB and RPB is neglected (i.e., setting $\overline{a}=0$), we obtain $\tau_{\mathrm{guid}}=0.45$ s and $\overline{v}_Z^*=4.41$ m/s when

$Z_{\mathrm{MOT}}=1000$ mm, which are the limits of atomic guiding time τ_{guid} and final longitudinal velocity $\overline{v_z}$ given by Eq. (15). It is clear that the influence of the DHB and RPB on the longitudinal motion of the guided atoms is important (it can sufficiently compensate, even completely cancel the acceleration effect of the gravity field). Therefore, the final longitudinal mean velocity of the atoms can be controlled by the detuning δ or the power P_0 of the DHB from ~ 10 cm/s (even near zero) to ~ 4 m/s, which may be useful in the study of the cold-atom collisions [20].

The tunneling loss of the guided atoms in the DHB can be neglected because of the high potential barrier (>1 mK) of the blue-detuned DHB. Collisions from the background thermal atoms in the vapor cell become the dominant loss mechanism. The atomic guiding efficiency in the DHB can then be estimated by

$$\eta_{\mathrm{guid}} \approx 1-2.31\times 10^{-2}\sigma_{\mathrm{Rb}}p\sqrt{1/mk_BT}\,\tau_{\mathrm{guid}}, \qquad (20)$$

where σ_{Rb} (p) is the collision cross section of ^{85}Rb atom in cm^2 (the vacuum pressure in Torr). T is the background temperature in kelvins. Figure 6 plots the guiding efficiency η_{guid} as a function of the DHB detuning δ. When $Z_{\mathrm{MOT}}=1000$ mm, $P_0=500$ mW, and $\delta=0.1$ GHz (0.5 GHz), we obtain $\eta_{\mathrm{guid}}\approx 83.6\%$ (94.4%).

In conclusion, we have presented an atomic guiding and cooling scheme using a collimated DHB, and analyzed the DHB-induced transverse Sisyphus cooling, spontaneous-emission heating, gravity-induced heating, the scattering-force-induced slowing effects from the DHB and RPB, and the loss mechanisms in the DHB atom guiding. We have also estimated the transverse equilibrium temperature, the mean guiding time, the final mean longitudinal velocity, and the atom guiding efficiency. Our results show that a low velocity, an intense atomic sample with a transverse temperature of ~ 1.2 μK (a transverse rms velocity of ~ 1.9 cm/s) and a final mean longitudinal velocity of ~ 10 cm/s can be obtained. The guiding efficiency and minimum spot size of the guided atoms in the DHB can reach $\sim 95\%$ and ~ 100 nm, respectively. Since the longitudinal velocity of the guided cold atoms can be adjusted by the detuning or the intensity of the DHB, this DHB guiding scheme may be used in the study of cold-atom collisions [20]. In particular, when the probe beam in Fig. 1 is replaced by a blue-detuned plug beam, a DHB gravito-optical trap based on the DHB-induced cooling is formed.

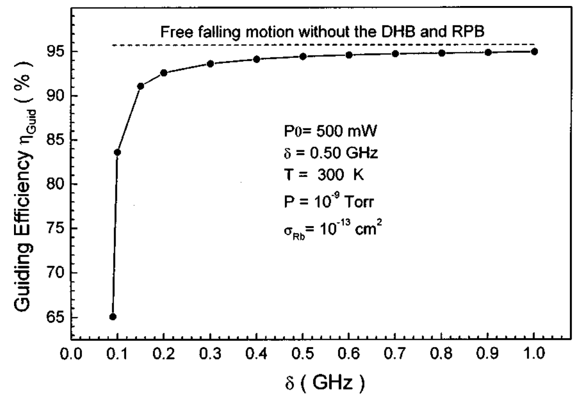

FIG. 6. Guiding efficiency η_{guid} versus the detuning δ for the cold ^{85}Rb atoms in the DHB atom guide.

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