

BFORT can enhance the oscillation frequency and hardly increases the light shift of atoms. This may help to bring the single atoms into the Lamb-Dicke regime through laser cooling single atoms in BFORT. After the above cooling process, we ramped up the doughnut beam over 10 ms and then implemented the above cooling process again. The LG potential height was about 3.9 mK and the oscillation frequency was about $\omega_{eff}/2\pi \sim 145$ kHz. Figure 7(b) shows the release and recapture experimental results after the laser cooling in the BFORT, together with the best-fit simulation results. This corresponds to a temperature of $15 \pm 1 \mu\text{K}$ for a BFORT with oscillation frequency 145 kHz. So the mean quantum number of the radial oscillator is about $\bar{n} = k_B T / \hbar \omega_{eff} \sim 1.65$ and gives the relation $\eta_{BFORT}^2 (2\bar{n} + 1) = 0.11$. This indicates that the quantum number of the atomic radial oscillator state in BFORT can be efficiently reduced by laser cooling and eventually satisfies the Lamb-Dicke criterion. This is a good starting point for implementing a proposed protocol to entangle two trapped atoms through the emission of a single photon by one of the atoms [19] or implementing Raman sideband cooling [20] or EIT cooling [21] to further cool the single atoms down to their ground state.

Furthermore, we can optimize our scheme by using diffraction-limited optics as in [8]. The diffraction-limited waist of NA=0.5 at $\lambda = 830$ nm is about $1.01 \mu\text{m}$. As proved by Eq. (6), in the case where $w_0^2/w_{10}^2 = 1$ the oscillation frequency of a single atom trapped in 0.5 mK red-detuned potential can be raised to 328 kHz by imposing a 4 mK blue-detuned potential, the corresponding ground state temperature would then exceed $7 \mu\text{K}$, a temperature that can be approached by the normal sub-Doppler cooling process. The corresponding root mean square spread of atoms is $\Delta x \approx 13 \text{ nm} \approx \lambda/60$ for $\lambda = 780$ nm, and effective trapping region is close to what could be achieved by an optical lattice. To our knowledge, this is hardly obtained by using a normal high numerical aperture objective to focus a simple red-detuned Gaussian beam and form a shallow FORT. Our scheme is a good candidate for implementing quantum logic gates by using coherent dipole-dipole interactions between two trapped ^{87}Rb atoms [22]. The two trapped atoms can be loaded efficiently into a red-detuned optical dipole trap by dynamically reshaping the trap with a spatial light modulator [23]. Our scheme is also suitable for compressing the radial direction of a 1-D optical lattice, in which a single atom has been cooled down to the ground state by microwave radiation [24], and results in 3-D strong confinement of single atoms.

6. Conclusion

In summary, we have proposed and experimentally demonstrated a tunable steep BFORT for single atoms. We have found that applying a blue-detuned doughnut beam increases the oscillation frequency of a single atom in a Gaussian FORT. The frequency enhancement is proportional to the square root of the ratio of blue-detuned potential depth to red detuned potential depth. The BFORT is an excellent scheme for enhancing the oscillation frequency of the single atom in any existing system, with the goal of further cooling to the ground state. Because the scattering rate of the same blue-detuned light mainly depends on the temperature of the atoms, it is reduced when the atoms are close to the ground state. We finally set the single atoms to be in the Lamb-Dicke regime by normal sub-Doppler laser cooling. Our work is in progress towards cooling atoms closer to the ground state for quantum information processing applications.

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