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Three-Dimensional Compensation for Minimizing Heating of the Ion in Surface-Electrode Trap *

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The trapped ions confined in a surface-electrode trap (SET) could be free from rf heating if they stay at the rf potential null of the potential well. We report our effort to compensate three-dimensionally for the micromotion of a single $^{40}Ca^{+}$ ion near the rf potential null, which largely suppresses the ion's heating and thus helps to achieve the cooling of the ion down to 3.4 mK, which is very close to the Doppler limit. This is the prerequisite of the sideband cooling in our SET.

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Surface-electrode traps (SETs)[1–6] are promising for many applications in quantum information processing, due to easy scalability and simple fabrication. For all the electrodes located in a single plane, they can be easily extended to more complex configurations such as the quantum charge-coupled device (CCD) as proposed in Ref. [7].

The ions confined in the SET are experiencing both a radio-frequency (rf) potential and a direct-current (dc) potential. Heating of the ions is mainly from the rf potential which produces the micromotion. To cool the ions down to the Doppler limit, we must minimize the heating effect by compensating the ions' micromotion, which could be achieved by pushing the ions to the rf potential null. To detect the micromotion, we normally employ the rf-photon correlation method,[8] which works, however, only for the compensation along the irradiation directions of the cooling lasers. In addition, if this method is applied in the case of the laser irradiation perpendicular to the surface, the compensation could not be accomplished well since the scattering light of the laser largely affects our observation. Alternatively, another method called the parametric excitation[9,10] is the option for this situation, in which the trapped ions are excited by modulating rf amplitude. Since the ions with larger distance from the rf null could be influenced more seriously by the modulation, we may acquire the information about the distance by the collected fluorescence from the ion's spontaneous emission.

In this Letter, we report our recent progress in the SET to cool a single $^{40}Ca^{+}$ ion down to 3.4 mK, very close to the Doppler limit, using an improved method of the parametric excitation to compensate the ion. As detailed later, we still employ the rf-photon correlation method to compensate the micromotion along x-direction and use the parametric excitation method to compensate along z-direction. For y-direction, we adopt a modified parametric excitation method, that is, compensate the ion's micromotion in y-direction by modulating rf amplitude at the secular frequency ω_x in x-direction by taking advantage of the couplings between different dimensions, due to nonlinearity in the SET.[11,12] Our method overcomes the shortcoming of the conventional rf-photon method that could not compensate three-directionally in SET system, due to the limitation of laser irradiation direction. Moreover, our method could be used for the SETs in which the trapped ions are very sensitive to the modulation signal. Furthermore, only one cooling laser is required to compensate the ion's three-directional micromotion in our method.

Our SET is a 500 μm-scale planar trap with five electrodes as shown in Fig. 1(a), where the electrodes labeled as EC and ME represent the end electrodes and middle electrodes, respectively, and SE represents four control electrodes. There are three horizontal electrodes as central electrodes, two of which (i.e., the rf electrodes) are applied by rf voltages and the middle one AE applied by a dc voltage works as a compensation electrode. We have found in our experiment that the rf-photon correlation method works less efficiently for compensating the z-directional micromotion even if the cooling laser have a component of z-direction. In addition, the ion is too sensitive to the modulation voltage when we try to compensate the micromotion along y-direction (i.e., the direction perpendicular to the surface). As a result, we have improved the implementation of the parametric excitation method in terms of the characteristic of our SET, and accom-

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plished a three-dimensional compensation of the ion's micromotion in combination with the rf-photon correlation method.

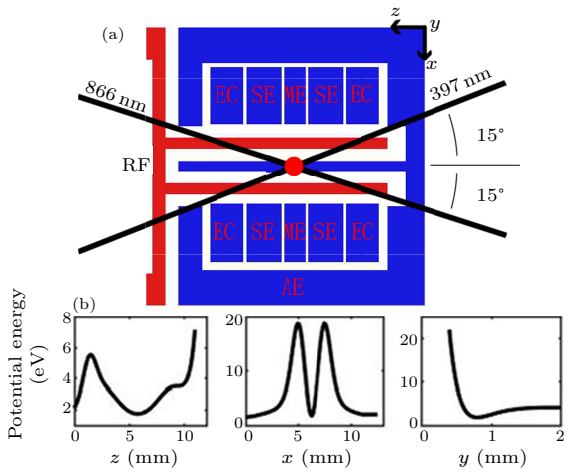

Fig. 1. (a) The SET in top view, where the electrodes are made of copper on a printed-circuit-board substrate. The scale of electrodes is 500 μm, the gaps between the electrodes are 20 μm. The voltages applied on the electrodes are $V_{\rm EC} = 40$ V, $V_{\rm SE} = V_{\rm ME} = V_{\rm AE} = 0$ V, $V_{\rm rf} = 400$ V. A signal source produces sinusoidal signal at the frequency $\Omega_{\rm rf}/2\pi = 22$ MHz with the power $P_{\rm rf} = 1.5$ W, and applies to rf electrodes after amplification by the helical resonator. The 866-nm and 397-nm lasers irradiate with respect to the z-direction by 15°, respectively. (b) Numerical simulation of the potential energy of the SET in three dimensions with respect to the coordinate axis set in the right top of (a).

The detail of our experiment system can be found in Ref. [13]. The SET is located in a vacuum chamber at room temperature with the pressure lower than 2.5×10^{-8} Pa. The secular frequencies of the SET are, respectively, $\omega_z/2\pi = 180$ kHz, $\omega_x/2\pi = 680$ kHz, and $\omega_y/2\pi = 1000$ kHz. We confine single $^{40}Ca^+$ ion in the SET, with 800 μm above the electrode surface. To understand the confinement, we simulate the potential wells in the three dimensions, as shown in Fig. 1(b). In our experimental implementation, we cool the ion by a 397-nm laser based on the $4S_{1/2} - 4P_{1/2}$ transition along with a 866-nm laser for repumping. These two lasers, as plotted in Fig. 1(a), are locked by the Pound–Drever–Hall technique to a cavity with fineness of 200. We monitor the ion along the y-direction by a 40 : 60 beam splitter, which sends the fluorescence signal, simultaneously, to a photomultiplier tube (PMT) and an intensified CCD (ICCD).

When the rf amplitude is modulated by a sinusoidal signal at the frequency ω with respect to the secular frequency ω_x in x-direction, the scattering rate of the ion is:[10]

$$R(t) = \frac{\Omega^2}{2\Gamma} - \frac{\omega\Omega^2 k A(\omega)}{\Gamma^2}\sin[\omega t - \theta(\omega)], \qquad (1)$$

where Ω is the Rabi frequency of the cooling laser (i.e., 397-nm laser in our system), Γ is the natural linewidth of the cooling transition, $k = 2\pi/\lambda$ is the wave number of the cooling laser, and λ is the wavelength. $A(\omega)$ and $\theta(\omega)$ are given by[10]

$$A(\omega) = \frac{F_{\rm d}/m}{\sqrt{(\omega_x^2 - \omega^2)^2 + 4\gamma^2\omega^2}}, \qquad (2)$$

$$\tan[\theta(\omega)] = \frac{2\gamma\omega}{\omega_x^2 - \omega^2}, \qquad (3)$$

where m is the mass of the $^{40}Ca^+$ ion, $F_{\rm d} = m(\kappa_{\rm trap}V_{\rm tickle}/\omega)^2 x_{\rm d}$ is the force on the ion from the modulation potential, $x_{\rm d}$ is the distance of the ion from the rf null, $\kappa_{\rm trap}$ is the geometric factor of the trap, $V_{\rm tickle}$ is the voltage regarding the modulation potential; and $\gamma = \hbar\Omega^2 k^2/2m\Gamma^2$ is the damping coefficient due to the Doppler cooling.

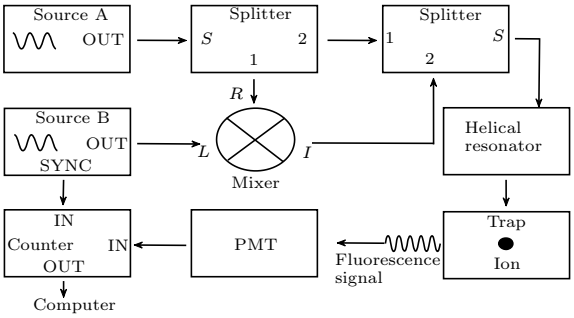

Fig. 2. Sketch of the apparatus for synchronous measurement. Source A (DS345 from Stanford Research Systems Company) outputs a sinusoidal signal at the frequency $\Omega_{\rm rf}/2\pi = 22$ MHz. The signal is divided by a splitter (ZFSC-2-4+ from Mini-Circuits Company) and the sideband $\Omega_{\rm rf} \pm \omega_{\rm resonance}$ is produced by a mixer (ADE-R6+ from Mini-Circuits Company) under the control of source B (DG4162 from Rigol Company). The sideband is then sent to the helical resonator by another splitter. Source B could send a square synchronization signal to the photon counter. Our photon counter is equipped with the Field Programmable Gate Array (Cyclone Ⅱ from Altrea Company), which can output simultaneously the synchronous and non-synchronous signals.

Seen from Eq. (2), $A(\omega)$ is proportional to $x_{\rm d}$. Therefore, if we want to know the distance of the ion from the rf null, we may measure $A(\omega)$ by monitoring the scattering rate $R(t)$. Experimentally, the ion's fluorescence signal is detected and then treated by integrating $R(t)$ over a duration. However, due to the symmetry of sine function with respect to zero, the integration of $R(t)$ over the entire duration of the fluorescence detection would be a constant. To avoid this unexpected case, we employ a practical method called synchronous measurement, as sketched in Fig. 2. Source B outputs both the modulation signal and the square synchronization signal respectively to the mixer and the photon counter. The photon counter, at the synchronous measurement mode, only records the fluorescence signal at the high level of the synchronization signal, which is called $C_{\rm S}$. The photon counter can also work in a non-synchronous measurement mode which records the fluorescence signal all the time, called $C_{\rm NS}$. Comparing $C_{\rm S}$ with $C_{\rm NS}$, we can acquire information about $A(\omega)$.

Experimentally, we sweep the modulation frequency regarding the resonance point (i.e., the ion's secular frequency) by the step of 0.2 kHz over the range of 10 kHz. At each step, we measure $C_{\mathrm{Si}} = C_{\mathrm{S}}$ and $C_{\mathrm{NSi}} = C_{\mathrm{NS}}$ ($i = 1$ to N with $N = 51$ because we have total 51 steps in one measurement). Despite the simple relation between C_{Si} and C_{NSi} theoretically, there are actually other factors in experimental operations, such as the excited vibration of the ion, causing changes of C_{Si} and C_{NSi}. To avoid this unexpected influence, we define the synchronous measurement parameter $\alpha_i = (2C_{\mathrm{Si}} - C_{\mathrm{NSi}})/C_{\mathrm{NSi}}$.[10] Then we calculate the fluctuation $Ft = \sqrt{\sum_{i=1}^{N}(\alpha_i - \alpha_{\mathrm{mean}})^2/N}$, where α_{mean} is the mean value of α_i. The smaller value of Ft implies the ion to be closer to the rf null because in this case α_i changes only slightly in the variation of the modulation frequency.

Practically, we make a rough compensation before implementing the parametric excitation method. When the modulation frequency is close to the resonance point, the ion would be largely excited, as monitored in the ICCD. With the ion approaching the rf null, however, due to a smaller x_{d}, the modulation voltage is required to be larger to acquire a large amplitude of vibration. From the exciting voltages (i.e., the voltages when the ion was exited obviously) at different compensation points, we could roughly determine the ion's position with respect to the rf null.

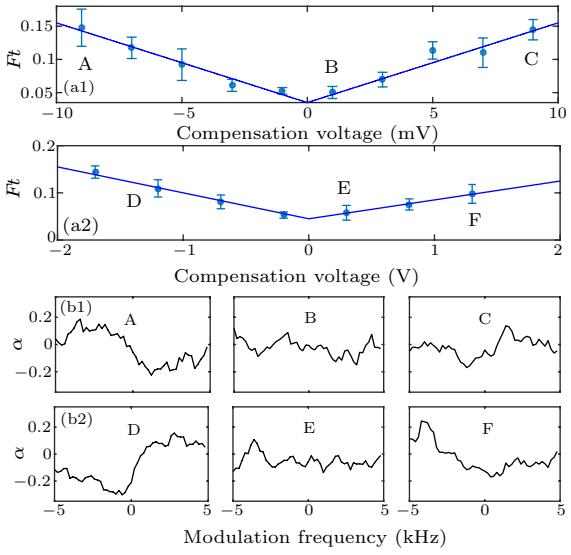

Fig. 3. (a) Fluctuation Ft with respect to the compensation voltage, where (a_1) shows the compensation along y-direction, (a_2) is for the compensation along z-direction. (b) The signals of α at the exemplified points in (a). (b_1) The points along y-direction. (b_2) The points along z-direction. The error bars indicate standard deviation containing statistical errors of five measurements for each data point.

The modulation frequency employed by the parametric excitation method[9,10,14–16] is the secular frequency of interest. For example, choosing ω_y as the modulation frequency when compensation is carried out along the y-direction. However, we have found in our system that the ion is too sensitive to the modulation frequency at ω_y due to the shallow potential along the y-direction. The ion is significantly excited, even if we select the minimum voltage; i.e., 2 mV of the source B as the modulation voltage. To solve this problem, we have to modify the original method of parametric excitation by utilizing the SET's nonlinear coupling between different dimensions. We first compensate the micromotion along x-direction by the rf-photon correlation method which works well in our case, then we compensate the y-directional micromotion of the ion by modulating ω_x. Due to the x–y coupling, the y-dimensional micromotion could be appropriately compensated by this way. For z-direction, we have found experimentally that the rf-photon correlation method works inefficiently. Thus, we compensate the z-directional micromotion of the ion by the parametric excitation method at modulating ω_z. Because the influence of the rf potential is weakest in z-direction, the micromotion in z-direction can be compensated after the compensation are achieved in other two directions. Therefore, in our implementation of three-dimensional compensation, we compensate the micromotion in such an order; i.e., first along x-direction, then y-direction, and finally z-direction.

In Fig. 3(a), we demonstrate the measurements of Ft with respect to the compensation voltages along y-axis and z-axis. The panels in Fig. 3(b) present signals of α corresponding to the points labeled in Fig. 3(a). The smaller Ft means the better compensation.

We add a small voltage from all dc electrodes to move the ion along y-direction, and control the ion offset along z-axis by the EC electrodes. The compensation effect could be checked from the ion's final temperature, which is obtained by measuring the linewidth Γ_{FWHM} (full width at half maximum) of the fluorescence signal by sweeping the detuning Δ of the 397-nm laser. Γ_{FWHM} includes the contribution from the natural linewidth Γ_{nature}, the Doppler broadening $\Gamma_{\mathrm{Doppler}}$ and the saturated broadening $\Gamma_{\mathrm{saturate}}$, where Γ_{nature} is 20.68 MHz. Since Γ^2_{FWHM} is a linear function of the laser's power, we can cancel the $\Gamma_{\mathrm{saturate}}$ by reducing the laser power in the measurement of Γ_{FWHM}, that is, $\Gamma_{\mathrm{saturate}}$ approaches zero when the laser power is vanishing. From $\Gamma_{\mathrm{Doppler}}$, we can straightforwardly calculate the ion's temperature by[17]

$$T = \frac{mc^2\Gamma^2_{\mathrm{Doppler}}}{8\ln 2\ k_{\mathrm{B}}\gamma_0^2}, \tag{4}$$

where c is the speed of light in vacuum, k_{B} is Boltzmann's constant, γ_0 is the transition frequency from $4P_{1/2}$ to $4S_{1/2}$.

To measure Γ_{FWHM}, we swept the 397-nm laser from the red detuning to the blue detuning with respect to the $4S_{1/2} - 4P_{1/2}$ transition. As suggested in Ref. [18] by switching the drive frequency and power

of acoustic-optic modulator(AOM) of 397-nm laser, we practically employed a laser with high intensity for cooling the ion and another laser with low intensity for measuring the Γ_{FWHM}. Figure 4(a) shows the measured Γ_{FWHM} with the low intensity of the laser as 1 μW. By this way, we have measured different temperatures as presented in Figs. 4(b) and 4(c), where the temperature $T_1 = 3.4 \pm 1.0$ mK indicates the best compensation we have achieved, and the temperature $T_2 = 5.9 \pm 0.7$ mK corresponds to a small offset in y-direction with respect to the best case. This comparison clearly manifests the effect of the compensation.

In comparison with our previous work,[19] we work here with the same SET and employ only a single cooling laser under almost the same conditions; i.e., the same detuning, irradiating direction and power. In our previous work, however, the rf-photon correlation method employed could not apply to the y-directional micromotion. In contrast, the three-dimensional compensate of micromotion here is accomplished much better by using the improved compensation method. Hence, we are able to cool the ion down to the lower temperature.

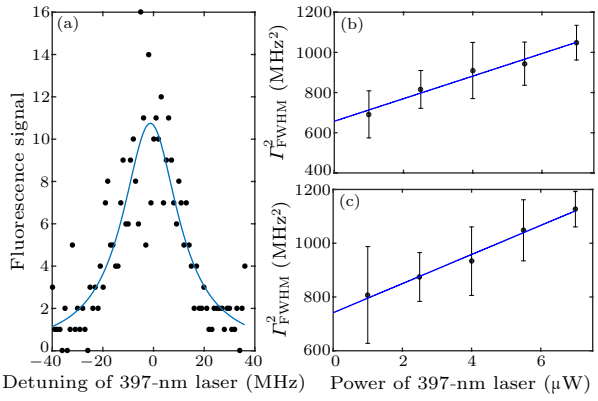

Fig. 4. (a) Fluorescence signal with respect to the detuning of 397-nm laser at power of 1 μW, where the points are experimental data and the curve is from the Lorentz fit. Each point is the accumulation of fifty measurements and each measurement takes 500 μs. (b) Γ^2_{FWHM} with respect to the power of 397-nm laser after the optimal compensation, where the final temperature T_1 is 3.4 ± 1.0 mK with the temperature uncertainty estimated by the linear fit. The error bars indicate standard deviation containing the statistical errors of ten measurements for each data point. (c) Γ^2_{FWHM} after a non-optimal compensation, where the final temperature T_2 is 5.9 ± 0.7 mK. The error bars indicate standard deviation containing statistical errors of five measurements for each data point.

Despite the same main idea involved, the parameter excitation method applied in our work is different from the previous publications[9,10,14–16] with the relevant operations. In fact, in those publications, the compensating operations are also different from each other due to different sizes and structures of the traps. Some of them[9,14–16] simply considered the fluorescence change of the ion, without the synchronous measurements. In order to have a better measurement accuracy, we consider the fluctuation Ft to compensate the micromotion, instead of the change of the synchronous measurement parameter α in Ref. [10].

In summary, by modifying parametric excitation method in combination with the rf-photon correlation method, we have accomplished a three-dimensional compensation of the ion's micromotion in a SET, leading to a cooling of the ion down to about 3.4 mK. In comparison with previously relevant work,[9,10,14–16] our SET works with a lower secular frequency, indicating that the ion confinement in our SET is more susceptible to the external disturbance. As a result, we have to modify the operations of the parametric excitation making use of the nonlinear characteristic of the SET to avoid direct excitation of the ion along y-direction. This work provides the prerequisite of the sideband cooling, which will be included in the work in the SET in near future.

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