Integrating a fiber cavity into a wheel trap for strong ion-cavity coupling

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We present an ion trap with an integrated fiber cavity, designed for strong coupling at the level of single ions and photons. The cavity is aligned to the axis of a miniature linear Paul trap, enabling simultaneous coupling of multiple ions to the cavity field. We simulate how charges on the fiber mirrors affect the trap potential, and we test these predictions with an ion trapped in the cavity. Furthermore, we measure micromotion and heating rates in the setup.

I. INTRODUCTION

In a quantum network, a coherent interface consists of a unitary interaction between light and matter that is much stronger than decay channels to the environment [1]. Recent experiments with a single trapped ion coupled to a fiber-based optical resonator have demonstrated a coherent coupling rate exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the atomic spontaneous-emission rate γ0 exceeding the 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RF electrodes

Compensation
electrode

RF electrode

Diamond wafer

(a)

(b)

Fiber

RF electrodes

Compensation

electrodes

1 mm

DC electrodes

with fiber mirrors

FIG. 1: a) Image of a wheel trap. b) Schematic of the ion-cavity system.

generates concave, near-spherical profiles on each fiber facet [13] [19]. The radii of curvature are 318(5) μm for the MM profile and 312(5) μm for the PC profile. The mirrors consist of alternating layers of SiO₂ and Ta₂O₅, applied to the fiber facets via ion-beam sputtering [20].

At a wavelength of 854 nm, the MM mirror has a transmission of 2(1) ppm, whereas the transmission of the PC mirror is 16(1) ppm. The cavity finesse is 9.2(2) × 10⁴ for a length of 507(8) μm, corresponding to a linewidth of κ = 2π · 1.61(3) MHz (half-width at half maximum). We calculate an ion-cavity coupling strength of g₀ = 2π · 20.3(3) MHz for the |3D₅/₂⟩ to |4P₃/₂⟩ transition of a ⁴⁰Ca⁺ ion [21]. The largest Clebsch-Gordon coefficient for transitions between Zeeman states of these manifolds is α = √2/3, so that the largest possible coupling strength is g = αg₀ = 2π · 16.6(3) MHz. The two relevant spontaneous emission channels are from |4P₃/₂⟩ to |3D₅/₂⟩, with a decay rate of γₚD = 2π · 0.67 MHz, and from |4P₃/₂⟩ to |4S₁/₂⟩, with a decay rate of γₚₚ = 2π · 10.74 MHz; both rates are half widths. Based on the values of g, κ, γₚD, and γₚₚ, we expect our system to operate in the strong coupling regime [21].

The ion-cavity system is located inside an ultra-high vacuum chamber at a pressure below 1×10⁻¹⁰ mbar, the lowest pressure value that can be determined from the ion-pump current. The DC electrodes with integrated fiber mirrors are glued on quartz v-grooves [22], each of which is glued on a shear-mode piezo [23], as shown in Fig. 2. The length of the cavity is stabilized by applying a Pound–Drever–Hall feedback signal to one of the piezos [24]. Each piezo is glued on a stainless-steel tilt-adjuster, with which the angle of each fiber mirror is aligned during the construction of the setup. Each tilt-adjuster is mounted on a 3D nanopositioning assembly [25], which allows positioning of each fiber mirror along three axes over a range of 12 mm with a resolution of 1 μm for relative movements. In practice, we translate the fiber mirrors over a range of at most 1 mm along each axis.

For loading ions, we use single laser pulses with pulse energies around 150 μJ at a wavelength of 515 nm to ablate neutral ⁴⁰Ca atoms from a target, which is mounted 2 cm from the trap along the line of sight (Fig. 2) [26]. Two objectives, each with a numerical aperture of 0.18, are mounted inside inverted viewports. The objectives collect the ion fluorescence, which is guided to an electron-multiplying CCD camera and to a photomultiplier tube.

III. SIMULATING THE ION-CAVITY SYSTEM

We now consider two means by which the harmonic potential of the Paul trap may be distorted. First, if surface charges are present on the fiber mirrors, their electric fields will shift the potential [10] [11]. Second, if the nanopositioning assemblies are used to displace the DC electrodes and integrated fiber mirrors, the potential minimum may be displaced, or the confinement strength may change [27] [28]. In this section, ion trap simulations are used to study both surface charges and electrode displacements.

A. Ion-trap potentials

The trapping potential at a position r = (x, y, z) has three components: the pseudopotential φRF generated by the RF electrodes, the potential φDC generated by the DC electrodes, and the potential φσ due to any charges on the fiber facets [29]:

φtrap(r) = φRF(r) + φDC(r) + φσ(r). (1)
FIG. 2: Rendered image of the ion-cavity system. a) Side view: To the left and right of the wheel trap, we see the DC electrodes with fiber mirrors, the quartz v-grooves, the shear-mode piezos, and the tilt-adjusters, all mounted on two 3D nanopositioning assemblies. b) Top view: An ablation target, along the line of sight of the wheel trap, is indicated in green. In this image, one of two inverted viewports is shown.

To simulate the trapping potential, we follow the steps outlined in Ref. [11]. We start by importing the geometry of the ion-cavity system as depicted in Fig. 1b into finite-element analysis (FEA) software [30]. We define our coordinate system to match the system indicated in Fig. 1b with the origin in the center of both the ion trap and the FFPC. The fiber-cavity length is set to 500 µm in this geometry. Unless otherwise mentioned, the trap
electrodes are grounded.

We now determine the contributions $\phi_{RF}$, $\phi_{DC}$ and $\phi_\sigma$ separately for a $^{40}$Ca$^+$ ion (mass $m = 40$ u, charge $e$), starting with $\phi_{RF}$. In experiments, $\phi_{RF}$ is generated by driving the wheel trap in one of two possible configurations. In the first configuration (RF-GND), we ground one pair of opposing RF electrodes and apply a driving signal with amplitude $V_{RF}$ and frequency $\Omega_{rf}$ to the other pair. In the second configuration (symmetric), we drive both RF electrode pairs such that the phase of the RF signal on one electrode pair is shifted by 180° relative to the signal on the other pair. To simulate the RF-GND configuration, we set a voltage $V_0 = 1$ V on one pair of RF electrodes. To simulate the symmetric configuration, we set a voltage $V_0 = 0.5$ V on one pair of RF electrodes and a voltage $-V_0$ on the other pair. For both configurations, the FEA software simulates the electric field $E(r)$, with which we calculate $\phi_{RF}$ from the expression \[ \phi_{RF}(r) = \frac{V_{RF} e^2 |E(r)|^2}{4 \mu_0 e t}. \]

Next, we set a voltage $V_{DC}$ on the DC electrodes and simulate $\phi_{DC}(r)$. Finally, to simulate $\phi_\sigma$, we set a homogeneous surface-charge density $\sigma$ on the facets of the fibers and assume the charges to be static. Since the fiber mirrors are located inside the DC electrodes, we do not consider charges on the sides of the fiber mirrors, in contrast to Ref. [11].

Following Eq. 1, we sum the three potentials to determine $\phi_{trap}$ over the trapping region. In Fig. 3a, $\phi_{trap}$ is plotted as a function of position along all three axes. Here, the symmetric drive configuration is used with $V_{RF} = 160$ V, $V_{DC} = 1$ V, and no charges present on the fiber mirrors. We fit a harmonic oscillator potential with offset $\phi_0$ to $\phi_{trap}$ in order to extract the ion position $r_0 \in \{ x_0, y_0, z_0 \}$ and the trap frequency $\omega_r$ along an axis $r \in \{ x, y, z \}$. This fit yields $x_0 = (0(1)) \mu$m, $y_0 = (1(1)) \mu$m, $z_0 = (0(1)) \mu$m, $\omega_x = 2\pi \cdot 3.134(2)$ MHz, $\omega_y = 2\pi \cdot 3.174(2)$ MHz and $\omega_z = 2\pi \cdot 1.041(1)$ MHz, where the uncertainties on the positions are set by the mesh resolution in the simulation.

In Fig. 3b, we compare $\phi_{RF}$ along the $z$ axis for the two drive configurations. Over a range of 200 $\mu$m around the trap center, the potential of the symmetric drive is constant at a value of approximately 1.22(8) meV. The potential of the RF-GND drive is harmonic with a minimum at $z = (1(1)) \mu$m and reaches a maximum value of 89.0(1) meV. In the symmetric case, the 180° phase shift of the two RF signals causes the electric field to vanish along the $z$ axis, while the asymmetric RF-GND configuration generates a vanishing field at only one point [9], meaning that ions displaced from this minimum will be subject to micromotion. This statement holds true for all linear Paul traps, but for typical centimeter-scale trap lengths, the curvature of $\phi_{RF}$ in the RF-GND configuration is negligible. However, for the 300 $\mu$m-long wheel trap, the curvature of $\phi_{RF}$ becomes significant, as we will see in Sec. IV A.

B. Influence of surface charges

We now include surface charges on the fiber facets in our simulations. The trapping potential is simulated for surface-charge densities $\sigma$ ranging from 0.1 to 50 $e/\mu$m$^2$, with $V_{RF} = 160$ V and $V_{DC} = 0$ V. In each simulation, the same value of $\sigma$ is used for both fiber facets. In this first simulation of charge densities, values less than or equal to zero are not considered, since they lead to unstable trapping without a voltage on the DC electrodes.
FIG. 4: a) Motional frequencies $\omega_x$, $\omega_y$, and $\omega_z$ plotted for surface-charge densities up to 50 e/µm$^2$ on the fiber mirrors. Error bars correspond to the standard deviation of the fit parameters and are too small to be visible. b) Voltage $V_{DC}$ corresponding to an axial trap frequency $\omega_z = 2\pi \cdot 1$ MHz as a function of the surface-charge density.

As in Sec. III A we determine the trap frequencies, with uncertainties given by the standard deviations of the fit parameters.

Figure 4a shows the trap frequencies along all three axes as a function of the surface-charge density. We observe that $\omega_z$ increases with increasing charge density while $\omega_x$ and $\omega_y$ decrease. This is the same effect that one observes when increasing $V_{DC}$ for a linear Paul trap, since the surface charges and the applied voltage play the same role. Here we highlight another advantage of using the wheel trap for an integrated fiber cavity: charges on the fiber mirrors are equivalent to DC voltages on the endcaps. In practice, it is difficult to add or remove surface charges in a controlled fashion [10] [11], but $V_{DC}$ provides a knob with which we can achieve the equivalent result.

As a proof of principle for this approach, we determine the value of $V_{DC}$ that results in an axial trap frequency of $\omega_z = 2\pi \cdot 1$ MHz for surface charge densities between $-10$ and 50 e/µm$^2$. These values are plotted in Fig. 4b. This range of densities corresponds to the range from experiments reported in Ref. [11]. The compensation voltage decreases linearly with increasing surface charge density. Note that the approach works for any value of $\omega_z$; $\omega_z = 2\pi \cdot 1$ MHz was simply chosen as a round number.

C. Influence of the cavity position

As a final consideration in our simulations, we vary the positions of the DC electrodes with integrated fiber mirrors in order to understand the effect on the trapping potential. In the experimental setup, it is necessary to adjust the relative positions of the electrodes so that the mirrors form a cavity. The laser-ablation process results in mirror profiles that are centered with respect to the fiber facets with an uncertainty of 0.9 µm [19]. Gluing the fibers into the DC electrodes results in a centering uncertainty of 30 µm. Thus, we require a positioning range of 31 µm. In addition, in order to position the cavity mode with respect to an ion, we will need to translate both mirrors and thus both electrodes.

We displace both fiber mirrors along the x axis for values $\delta_f$ between $-50$ µm and 50 µm and determine the position of the ion $r_0 = (x_0, y_0, z_0)$, which is plotted in Fig. 5 for the x axis. Again, we estimate a 1 µm uncertainty for the ion position from the resolution of the simulation mesh. Within the uncertainty, we observe no displacement of the ion, from which we conclude that it will be possible to position the fiber mirrors within our setup without affecting the ion position.
IV. EXPERIMENTAL TESTS

Prior to assembly of the ion-cavity system, we built an ion-trap test setup without integrated fiber mirrors. The DC electrodes described in Sec. IIIA are replaced by electrodes with 260(50) μm inner diameter and 410(20) μm outer diameter, separated by 3 mm. We perform two experimental tests with this setup: first, a measurement of the micromotion, and second, measurements of the motional heating rates. The heating rates quantify how much electric-field noise couples from the environment to the motion of the ion [33].

After assembling the ion-cavity system, we repeated the heating rate measurements. The earlier measurements without fiber mirrors allow us to distinguish between noise observed with the bare ion trap and noise due to the dielectric fiber mirrors, which are known sources of electric-field noise [34, 35]. Subsequently, we tested the predictions of Sec. IIIA regarding the influence of surface charges present on the fiber mirrors.

A. Comparison of micromotion in RF-GND and symmetric configurations

A symmetric configuration of the ion-trap drive leads to a vanishing electric field along the trap axis, as discussed in Sec. IIIA. Using the ion-trap test setup, we quantify the micromotion of a single ⁴⁰Ca⁺ ion for both symmetric and RF-GND configurations over a 20 μm range along the z axis. We measure Rabi oscillations on the $|{2S}_{1/2}, m_j = +1/2⟩$ to $|{2D}_{5/2}, m_j = +1/2⟩$ transition (qubit transition) and on the micromotion sideband of this transition. We determine the Rabi frequency $\Omega_Q$ of the qubit transition using a fitting model that assumes the Debye-Wallner coupling as the damping source [36]. For the micromotion sideband, this approach is not applicable, since the period of Rabi oscillations is longer than the 259(11) μs coherence time of the qubit. We instead extract the Rabi frequency $\Omega_M$ by fitting a damped sinusoidal oscillation. Error bars correspond to one standard deviation of the fit parameters.

For $\Omega_M < 1$ kHz, we are unable to resolve multiple oscillations of the ion’s state due to limitations in the experimental control hardware. For these Rabi frequencies, we estimate $\Omega_M$ from the first data point at which the excitation on the micromotion sideband overlaps with 0.5, and the error of $\Omega_M$ is given by the quantum projection noise. When displacing the ion along the z axis, the mean voltage on both electrodes is held constant in order to keep $\omega_z$ constant. At each ion position, before determining $\Omega_Q$ and $\Omega_M$, we minimize the micromotion using the compensation electrodes.

In Fig. 6, the modulation index $\beta \approx 2\Omega_M/\Omega_Q$ is plotted as a function of the ion position. The modulation index is proportional to the residual RF electric field and is thus a measure of micromotion [9]. The micromotion vanishes at a single point for the RF-GND configuration, as expected from the simulations in Sec. IIIA. In contrast, the micromotion vanishes over the full measurement range of 20 μm for the symmetric configuration. The setup has been designed to couple multiple ions to the fiber-cavity mode. As a typical ion–ion distance is around 5 μm, we see from Fig. 6 that it is not possible to confine two ions in the RF-GND configuration without excess micromotion. In contrast, in the symmetric configuration, it should be possible to confine at least five ions without excess micromotion.

The ion position in Fig. 6 is calibrated as follows: we take an image of the ion at $z = 0$ μm, displace the ion with the DC electrodes, and take an image of the displaced ion. From the two images, we calculate the ion displacement in units of pixels per volt. After measuring the micromotion, we load two ions into the trap and take a third image, from which we determine the distance $\delta z$ between the two ions in pixels. We also calculate $\delta z$ in meters with the relation [37]

$$\delta z = \left(\frac{e^2}{2\pi \epsilon_0 m \omega_z^2}\right)^{1/3},$$

thereby obtaining a conversion from pixels to meters. Combining both conversions yields the ion displacement in units of meters per volt. We obtain 1.28(16) μm V⁻¹ for the RF-GND drive with $\omega_z = 2\pi \cdot 1.517(1)$ MHz and 1.23(18) μm V⁻¹ for the symmetric drive with $\omega_z = 2\pi \cdot 1.650(1)$ MHz.

B. Heating rate measurements without fiber mirrors

We measure the ion heating rate using sideband thermometry [38]: the ion is Doppler-cooled for 5 ms, followed by optical pumping and 10 ms of sideband cooling. After a waiting time $t_w$, we drive the red motional sideband of...
FIG. 7: Mean phonon number extracted via sideband thermometry as a function of the waiting time between sideband cooling and interrogation pulse, without fiber mirrors integrated in the setup. The solid lines represent weighted fits corresponding to heating rates of $\dot{n}_z = 13(3)$ phonon s$^{-1}$ and $\dot{n}_x = 32(8)$ phonon s$^{-1}$. Error bars represent the standard deviation calculated from 20 samples.

the qubit transition for 2 ms. This sequence is repeated for the blue sideband. The phonon number is extracted from 100 of these measurements, and this process is then repeated 20 times for each waiting time in order to calculate the mean value and the sample standard deviation. For all measurements presented, we set the trap frequencies to $\omega_x = 2\pi \cdot 3.399(1)$ MHz, $\omega_y = 2\pi \cdot 3.229(1)$ MHz, and $\omega_z = 2\pi \cdot 1.517(1)$ MHz.

The phonon numbers of the axial mode and one radial mode are plotted in Fig. 7 for waiting times up to 50 ms. From a weighted least-squares linear fit, we extract the heating rates $\dot{n}_x = 32(8)$ phonon s$^{-1}$, $\dot{n}_y = 26(6)$ phonon s$^{-1}$ and $\dot{n}_z = 13(3)$ phonon s$^{-1}$. Similar rates have been measured with a $^{25}$Mg$^+$ ion in the original wheel trap [13, 14].

C. Heating rate measurements with fiber mirrors

After integrating the fiber mirrors into the experimental setup, we measure the heating rates again. The distance between the fiber mirrors is set to 550 $\mu$m and the axial trap frequency to $2\pi \cdot 1.636(5)$ MHz. We find that the red motional sideband is no longer suppressed by sideband cooling, so instead, the ion’s temperature is determined from fits to Rabi oscillations [35, 39–42]. The laser beam driving Rabi oscillations overlaps with all three motional modes, so we cannot determine the phonon number of each mode separately. As the contribution of the axial mode dominates by more than one order of magnitude, we express the mean phonon number $\bar{n}$ as a projection onto the $z$ axis, as described in Ref. [35]. Note that $\bar{n}$ approximates the mean phonon number $\bar{n}_z$ of the axial mode, but $\bar{n}_z$ is smaller than $\bar{n}$.

In Fig. 8 $\bar{n}$ is plotted for a variable waiting time $t_w$ before the interrogation pulse. From a linear fit, we determine a heating rate of $\dot{n} = 14(2)$ phonon ms$^{-1}$, three orders of magnitude larger than the rates in Sec. IV B. We attribute this higher rate to the presence of the fiber mirrors. We have recently developed a model for ion heating based on dielectric losses in the fibers, which is supported by further experiments that we have conducted with this setup [35].

D. Counteracting surface charges

As a final test, we return to the predictions of Sec. III B and adjust the trap electrode voltages to counteract the effects of surface charges on the fibers. Starting from $L = 507(8)$ $\mu$m, which is determined from a measurement of the cavity free-spectral range, we increase the length via the nanopositioning assemblies. For each value of $L$, we adjust the voltages on the DC electrodes such that the axial trap frequency is $\omega_z = 2\pi \cdot 1.6(1)$ MHz and the ion position remains fixed within 25 $\mu$m. Here, $V_{PC}$ and $V_{MM}$ are the voltages on the DC electrodes containing the PC fiber and the MM fiber, respectively. The uncertainties of $V_{PC}$ and $V_{MM}$ correspond to the precision of the voltage source. In Fig. 9, we plot $V_{MM}$ and $V_{PC}$ for fiber–fiber distances up to 1200 $\mu$m. Both voltages increase for increasing distance, but $V_{PC}$ is always positive, while $V_{MM}$ takes on both negative and positive values over a range that is three times higher. We attribute this difference to the presence of surface charges on the fiber facets. This measurement shows that despite surface charges, a trapped ion can be confined at a fixed position over a
FIG. 9: Voltages $V_{PC}$ and $V_{MM}$ applied to the DC electrodes in order to keep both the ion position and trap frequency fixed over a range of fiber–fiber distances $L$. Error bars are too small to be visible.

range of cavity lengths.

V. CONCLUSION

We have designed and constructed an ion–cavity system with integrated fiber mirrors. The system is designed such that strong coupling of multiple ions to the fiber cavity will be possible without excess micromotion. Simulations show that voltages on the DC electrodes compensate for surface charges on the fiber mirrors, and that translation of the fiber mirrors does not affect the ion position.

Prior to the assembly of the system, we built an ion-trap test setup without the fiber mirrors and measured micromotion and heating rates, both of which are consistent with values in state-of-the-art ion traps for quantum information processing. After integration of the fiber mirrors, we observed a heating rate that was three orders of magnitude higher, which we attribute to the presence of the fibers. This observation led to a recent study on the role of dielectrics in ion traps [35].

We have trapped an ion within the cavity for cavity lengths as short as $507(8)\mu m$, and we have confirmed that voltages on the DC electrodes compensate for surface charges. A next step will be to measure the coupling strength of single and multiple ions to the cavity field, followed by demonstrations of multi-ion protocols that have been previously implemented in macroscopic ion–cavity platforms, including quantum state-transfer [43] and optimized collective coupling [44]. Due to high coherent coupling rates and short cavity lifetimes, fiber-based systems may replace those bulkier setups, enabling scalable links between distributed ion-trap quantum computers.

All data presented and discussed in this article are available at Ref. [45]. The authors have no conflict of interest to disclose.

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