

Electric field distortions in surface ion traps with integrated nanophotonics

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The integration of photonic components into surface ion traps provides a scalable approach for trapped-ion quantum computing, sensing, and metrology, enabling compact systems with enhanced stability and precision. However, the introduction of optical apertures in the trap electrodes can distort the trapping electric field. This can lead to excess micromotion and ion displacement, which degrade the performance of quantum logic operations and optical clocks. In this work, we systematically investigate the electric field distortion in a surface ion trap with integrated waveguides and grating couplers that require apertures in the surface electrode using finite element method simulations. We analyze methods to reduce these distortions by exploiting symmetries and transparent conductive oxide materials.

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I. INTRODUCTION

Ion traps are a key technology for trapped-ion-based quantum computers, quantum simulators, quantum sensors, and quantum metrology [1–4]. Currently, the number of ions for these applications is limited by the trap technology and the laser optics that is needed for laser cooling, state control, and spectroscopy [5,6]. Integrating optics monolithically into ion traps is a viable way to make ion traps scalable to store larger numbers of qubits, reduce the size of the experimental setup, and at the same time enhance the pointing stability [7–16]. The stability and compactness make them particularly suitable for portable quantum sensors.

Recent advances in the fabrication of nanophotonics, especially for the blue and UV wavelength range [17,18], pave the way for the integration of all wavelengths needed to control many ion species. Optically integrated ion traps with waveguides and grating outcouplers [19] to deliver light to the ions have been demonstrated for single-ion addressing [11], excitation of optical clock transitions [11, 14–16], and multi-ion quantum logic operations [12,13]. For some demonstrators, increased heating rates have been measured [12–14].

Previous simulation-based studies have shown how integrated micro-optics and miniature optical cavities can perturb trapping fields in ion traps [20–22]. Motivated by these works, we systematically investigate, using finite element method (FEM) simulations, how the integration of nanophotonics with grating couplers distorts the trapping electric field of a surface ion trap. If the amplitude of the trapping rf field cannot be zeroed at the position of the ion due to this distortion, the residual rf field amplitude leads to excess micromotion (EMM). In an anharmonic trapping potential, EMM causes heating of the ion's secular motion [23,24]. In a harmonic trapping potential, the gradient of a residual rf field may result in increased heating rates [25,26] and heating during shuttling operations [13]. EMM also contributes to frequency shifts, such as time-dilation and AC Stark shifts, which often limit the accuracy of trapped-ion-based optical clocks [27]. Finally, the distortion can lead to ion displacement from the target position, causing the outcoupled beam to be misaligned with the ion.

In Sec. II, we introduce the electrode geometry of the surface ion trap with apertures for grating couplers and the simulation setup for analyzing the rf field distortion. Section III examines the design constraints imposed by the grating couplers. In Sec. IV, the simulation results of the rf field distortion caused by the aperture are presented. Approaches to mitigate the distortion through the application of symmetry principles and the use of transparent conductive oxide materials are then examined. In Secs. IVD 2 and IVD 3, the effect of a possible phase shift of the rf field is also discussed. Section V concludes by

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summarizing the effects of the aperture, offering design suggestions, and outlining future perspectives to mitigate distortion.

II. ELECTRODE GEOMETRY AND SIMULATION SETUP

For the discussions in this paper, we use a design of a surface ion trap from Ref. [28]. We modified the width of the center dc electrodes and rf electrodes to confine Yb^+ ions at a height of $100\text{ }\mu\text{m}$ above the surface on the trap axis, which is defined as the central axis of the trap in the z direction at the target ion height. Figure 1 shows a top view of the electrode geometry.

The height of $100\text{ }\mu\text{m}$ is selected to balance the trade-off between mitigating surface-induced heating [29,30] and maintaining sufficient trapping depth for stable ion confinement. The trapping field is generated by the application of an rf (radio-frequency) potential and dc (direct-current) potentials to the corresponding electrodes. Given an rf amplitude of $U_{\text{rf}} = 100\text{ V}$ and an rf frequency of $\Omega_{\text{rf}}/2\pi = 16\text{ MHz}$, we obtain a secular frequency of $\nu_{\text{sec}} = 1.9\text{ MHz}$ and a trapping depth of 103.01 meV for a $^{172}\text{Yb}^+$ ion. The relevant dimensions of the electrodes are detailed in Table I.

To integrate optical components into the surface trap, we adapted the layer stack-up from Ref. [12] in the design as depicted in Fig. 2. A waveguide layer with grating outcouplers is implemented beneath the electrodes. Light

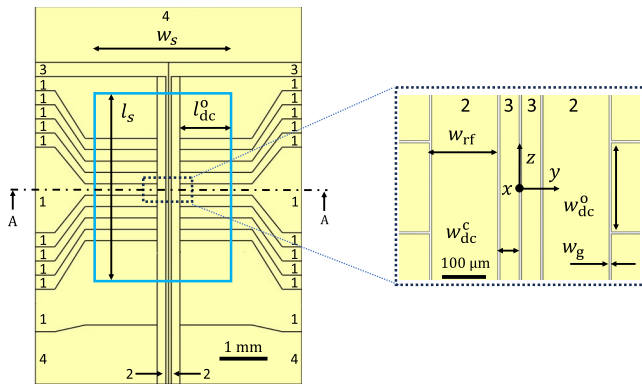


FIG. 1. Top view of the surface trap studied in the simulations. Label 1 identifies the outer dc electrodes, label 2 the rf electrodes, label 3 the center dc electrodes, and label 4 the ground electrodes. Only the region within the blue rectangle is considered in the simulation. The origin of the coordinate system (referred to as the trap center in the following discussion) is positioned at the center of the simulation region in the y - z plane, while in the x direction it is located on the surface of the gold electrode. Unless otherwise stated, all simulations shown in this paper use the same coordinate system as shown here. The trapping field is generated by applying an rf potential U_{rf} to the rf electrodes (2) and dc potentials U_{dc} to the dc electrodes (1, 3). The symbol A indicates a cutting plane for a cross-sectional view shown in Fig. 2(a).

TABLE I. Dimensions of the surface trap geometry and simulation setup.

Symbol	Value	Description
l_s	5 mm	Length of the simulation region
w_s	2.4 mm	Width of the simulation region
l_{dc}^o	1 mm	Length of the outer dc electrode
w_{dc}^o	$200\text{ }\mu\text{m}$	Width of the outer dc electrode
w_{rf}	$150\text{ }\mu\text{m}$	Width of the rf electrode
w_{dc}^c	$44.3\text{ }\mu\text{m}$	Width of the center dc electrode
w_g	$5\text{ }\mu\text{m}$	Width of the gap between electrodes
t_e	$6\text{ }\mu\text{m}$	Thickness of the gold electrode layer
t_d	$10\text{ }\mu\text{m}$	Thickness of the dielectric (SiO_2) layer
t_{gp}	$3\text{ }\mu\text{m}$	Thickness of the ground plane
t_c	$7\text{ }\mu\text{m}$	Thickness of the SiO_2 cladding
t_w	$525\text{ }\mu\text{m}$	Thickness of the wafer

is coupled into this layer, guided, and subsequently coupled out vertically by grating outcouplers through apertures in the gold electrodes. All apertures shown in the schematic figures throughout this paper are drawn for illustrative purposes only and are not to scale, as both their size and position are treated as variable parameters in the simulations.

The discontinuity arising from the aperture can introduce a distortion of the trapping field. We investigate the distortion of the trapping rf field using FEM simulations with the commercial software COMSOL Multiphysics 5.6. All simulations utilize square-shaped apertures. The target ion position for a single ion is $100\text{ }\mu\text{m}$ directly above the trap center. The ion's position in the radial direction (in the x - y plane), which is perpendicular to the trap axis, is determined by the minimum of the radial rf field $E_{\text{rf},r}$ in this plane, where $E_{\text{rf},r} = \sqrt{E_{\text{rf},x}^2 + E_{\text{rf},y}^2}$. This position is influenced by the electrode geometry and is independent of the magnitude of the rf field. Because of the finite length of the trap, a residual rf field exists along the trap axis. This residual field scales with the magnitude of the applied rf field. Accordingly, in the following discussion, we consider distortions in the radial and axial directions separately. In the radial direction, we analyze the displacement of the $E_{\text{rf},r}$ minimum from the target ion position, while in the axial direction we examine the residual rf field along the trap axis. To simplify the simulation of the trapping field, it is initially sufficient to consider the rf field at a fixed phase, which reduces the problem to an electrostatic analysis [31]. For the simulations presented in the following sections, we set $U_{\text{rf}} = 100\text{ V}$ and keep all $U_{\text{dc}} = 0\text{ V}$ unless otherwise stated. The ground plane is modeled as an equipotential surface held at 0 V . The silicon substrate is treated as a dielectric material, consistent with a high-resistivity Si substrate and the absence of a backside ground plane in the modeled geometry. The relative permittivities used in the simulations are $\epsilon_r = 3.9$ for SiO_2 and $\epsilon_r = 11.7$ for Si.

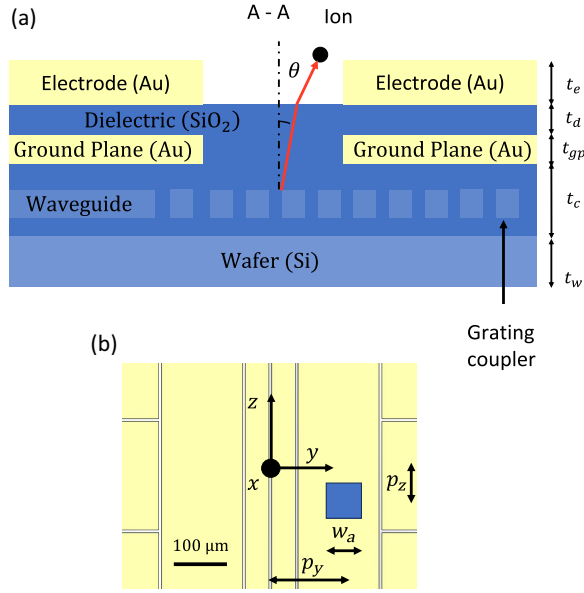


FIG. 2. (a) A cross-sectional view (A-A) of the surface trap reveals the layer stack-up of the photonic integrated ion trap chip. The cross-sectional view is schematic and not drawn to scale, and the layer thicknesses are given in Table I. A ground plane positioned $3 \mu\text{m}$ beneath the trap electrodes shields the silicon substrate from the rf trapping fields. The aperture in the ground plane has the same width as that in the electrode. The waveguide layer is embedded within the SiO_2 cladding layer on a silicon wafer. All the layers are taken into account in the simulations shown in this paper except the waveguide layer, as its contribution to the field distribution at the ion's position is negligible. The angle of the outcoupled laser beam relative to the surface normal (x axis) is denoted by θ . (b) Top view of a square-shaped aperture with a size of $w_a \times w_a$ in the gold electrode. Here p_z indicates the position of the center of the aperture, while p_y indicates the position in the y direction.

III. DESIGN CONSTRAINTS IMPOSED BY GRATING COUPLERS

The grating couplers constrain the position and geometry of the apertures in the trap electrodes. The light from the waveguide is coupled out at an angle θ by a grating coupler when the Bragg condition,

$$n_{\text{eff}} - \sin \theta = \frac{m\lambda}{\Lambda}, \quad (1)$$

is satisfied, where m is the diffraction order, λ is the wavelength, Λ is the period of the grating, and n_{eff} is the effective refractive index of the grating. The effective refractive index can be approximated as a weighted average of the refractive indices associated with the guided mode in the waveguide, n_{WG} , and the cladding region, n_{clad} , according to

$$n_{\text{eff}}^2 = f n_{\text{WG}}^2 + (1 - f) n_{\text{clad}}^2. \quad (2)$$

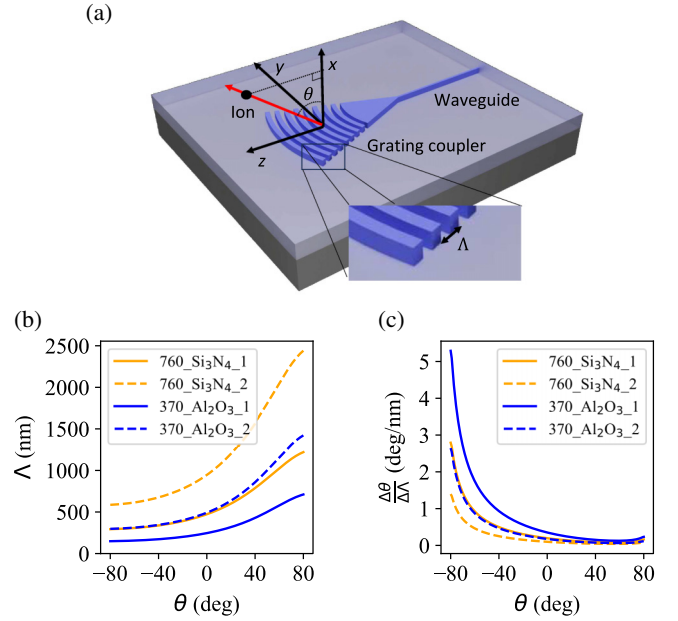


FIG. 3. (a) A grating coupler with period Λ couples light out from a waveguide at an angle θ onto an ion in free space. Here, a forward grating coupler with positive outcoupling angle θ is shown. (b) The grating period Λ and (c) the angle-to-period sensitivity $\Delta\theta/\Delta\Lambda$ for the first- and second-order beams as functions of θ . The first-order beams are represented by solid lines, while the second-order beams are shown with dashed lines. Data are shown for a Si_3N_4 grating with a wavelength of 760 nm and a thickness of 200 nm , and an Al_2O_3 grating with a wavelength of 370 nm and a thickness of 120 nm .

Here, the duty cycle f represents the fraction of the waveguide region within one grating period and is defined as $f = l_p/\Lambda$, where l_p is the length of the waveguide region and Λ is the grating period.

Figure 3(a) illustrates the structure of a grating coupler. A backward grating coupler emits in the direction opposite to the propagation of the guided light, resulting in a negative diffraction angle θ , while a forward grating coupler diffracts the guided light with a positive diffraction angle θ . As illustrated in Figs. 3(b) and 3(c), the grating period decreases as θ transitions from positive to negative values, while the absolute angle-to-period sensitivity $\Delta\theta/\Delta\Lambda$ increases. Additionally, shorter wavelengths require smaller grating periods and exhibit higher angle-to-period sensitivity. Another consideration for trap design is that backward grating couplers emit only first-order diffraction, while forward grating couplers can generate both first- and higher-order diffracted beams.

For example, for a forward Si_3N_4 grating coupler with a thickness of 200 nm at a wavelength of 760 nm , a first-order diffraction angle of $\theta = 20^\circ$ corresponds to a grating period of approximately 600 nm . At this period, the second-order diffraction condition is also satisfied, producing an additional beam at a backward angle of about -67° .

As the first-order diffraction angle θ increases, which corresponds to a further increase of the grating period, the emission angle of this second-order beam shifts continuously toward zero and can eventually become forward-directed. These higher-order beams can cause unwanted stray light in the ion trap. As a result, these considerations ultimately constrain the placement of apertures through the minimum grating feature size, the tolerance on the outcoupling angle, and the potential impact of stray light.

IV. RESULTS

Field distortions arising from apertures in the electrode in the context of surface-electrode ion traps with integrated grating couplers have been discussed previously in Ref. [32]. Here, we systematically investigate the dependence of these distortions on aperture type, position, and geometry, as well as strategies for their mitigation. In this section, we first discuss the rf field distortion resulting from a single aperture in different types of trap electrodes. Next, we examine how the position and geometry of an aperture, specifically in an rf electrode, affect this distortion. Following this, we investigate methods to reduce the distortion by utilizing symmetry and applying transparent conductive oxide materials. Throughout the discussion, the configuration without any aperture in the trap electrodes is treated as the reference configuration, providing a baseline to evaluate the effects of apertures on the rf field distortion.

A. Effect of a single aperture in the rf electrode, the center dc electrode, or the outer dc electrode

We begin by investigating the electric field distortion caused by a square-shaped aperture with width $w_a = 30 \mu\text{m}$ positioned in either the rf electrode, center dc electrode, or outer dc electrode (Fig. 4). These positions correspond to outcoupling angles θ ranging from 14° to 69° , encompassing the range of angles demonstrated in previously reported ion traps with integrated waveguides and grating couplers [11–16].

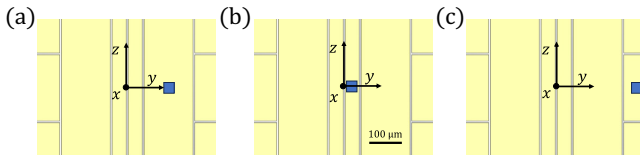


FIG. 4. Layout of an aperture with a size of $w_a = 30 \mu\text{m}$ positioned in (a) the middle of the rf electrode with $p_z = 0$ and $p_y = 126.8 \mu\text{m}$, (b) the middle of the center dc electrode with $p_z = 0$ and $p_y = 24.7 \mu\text{m}$, and (c) the outer dc electrode with $p_z = 0$ and $p_y = 257 \mu\text{m}$. These positions correspond to outcoupling angles θ of 52° , 14° , and 69° .

1. Shift of the rf field minimum in the radial direction

The unperturbed radial rf electric field $E_{\text{rf},r}$ ($E_{\text{rf},r} = \sqrt{E_{\text{rf},x}^2 + E_{\text{rf},y}^2}$) in the x - y plane for the reference configuration is illustrated in Fig. 5(a). When an aperture with

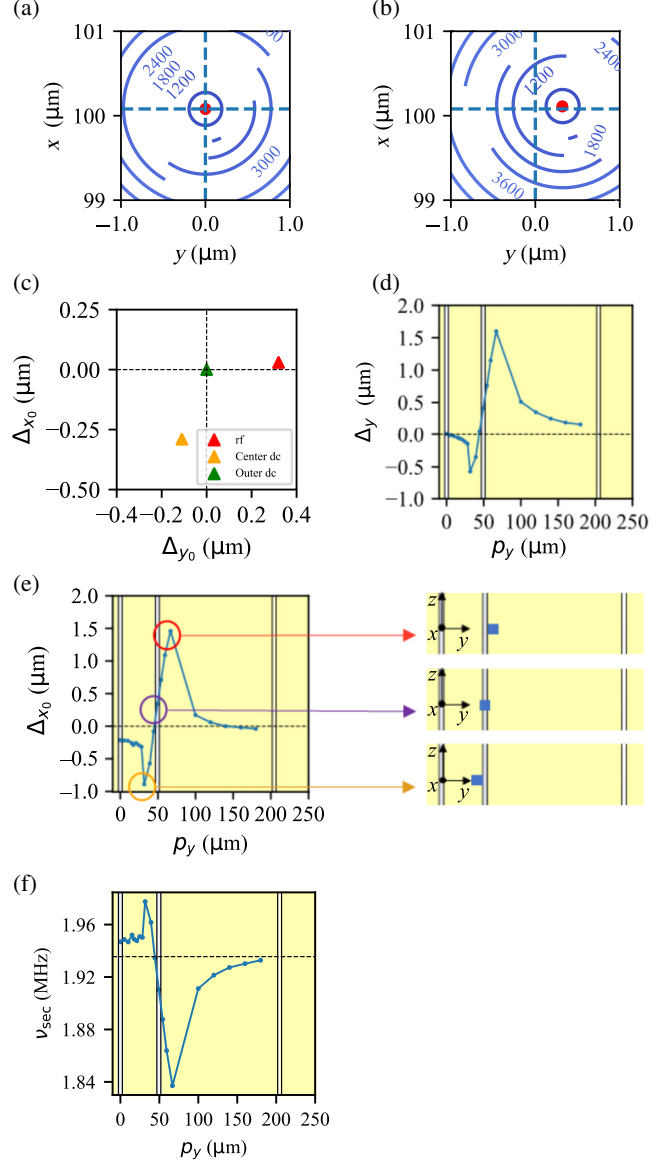


FIG. 5. (a) Radial rf field $E_{\text{rf},r}$ in the x - y plane. The values in the contour plot represent the amplitude of $E_{\text{rf},r}$ in V/m, the red dot indicates the field minimum. (b) Radial rf field $E_{\text{rf},r}$ in V/m in the x - y plane with an aperture in the rf electrode; see Fig. 4(a). (c) Displacement of the $E_{\text{rf},r}$ minimum for apertures located in the rf electrode, the center dc electrode, and the outer dc electrode, as shown in Figs. 4(a), 4(b), and 4(c). Subplots (d) and (e) show the displacement of the $E_{\text{rf},r}$ minimum in the x and y directions while moving an aperture in the y direction from the center dc electrode to the rf electrode, keeping $w_a = 30 \mu\text{m}$ and $p_z = 0 \mu\text{m}$. Subplot (f) shows the corresponding secular frequency ν_{sec} evaluated at the $E_{\text{rf},r}$ minimum for a $^{172}\text{Yb}^+$ ion. The black dashed line denotes the reference configuration without an aperture.

a size of $w_a = 30 \mu\text{m}$ is present in the rf electrode [see Fig. 4(a)], the radial electric field $E_{\text{rf},r}$ is shifted in the x - y plane, as illustrated in Fig. 5(b). The radial field $E_{\text{rf},r}$ minimum is displaced by 320 nm from the target ion position in y direction and 30 nm in the x direction.

Figure 5(c) provides a summary of the $E_{\text{rf},r}$ minimum displacements in both the x and y directions for an aperture in the rf electrode, the center dc electrode, and the outer dc electrode. When the aperture is in the outer dc electrode, the $E_{\text{rf},r}$ minimum experiences a less significant displacement compared to that in the rf or the center dc electrode. When an aperture is located in the rf electrode, the $E_{\text{rf},r}$ minimum mainly shifts in the positive y direction. In contrast, when the aperture is placed in the center dc electrode, the displacement reverses its direction, and the shift in the x direction becomes more prominent.

We resolve the transition of the displacement as the aperture is moved from the rf electrode to the center dc electrode, as depicted in Figs. 5(d)–5(e). The displacement reaches its absolute maximum when the aperture is located such that one side of the aperture coincides with the edge of the electrode. A zero displacement occurs when the aperture is positioned in the gap between electrodes due to a sign change in the displacement. As the aperture moves closer to the trap center, the displacement magnitude decreases. When the aperture is directly beneath the target ion position, the displacement magnitude in the x direction reaches a minimum of 200 nm, while in the y direction it vanishes due to the trap's symmetry with respect to the z axis.

In addition to the displacement of the rf field minimum, the presence of the aperture also modifies the curvature of the effective rf pseudopotential. We evaluate the radial secular frequency at the position of the $E_{\text{rf},r}$ minimum; see Fig. 5(f). The secular frequency increases when the aperture is located in the center dc electrode and decreases when it is located in the rf electrode. The magnitude of the frequency change follows the same trend as the displacement of the rf field minimum, reaching a maximum relative change of approximately 5% when the displacement is largest, i.e., when one side of the aperture coincides with the edge of the electrode.

2. Residual rf field on the trap axis

In the axial direction we evaluate the rf field along the trap axis, as shown in Fig. 6. For the reference configuration without apertures, the residual rf field arising from the finite length of the trap is weak and varies smoothly along the trap axis (black dashed line). Because of the symmetry of the ion trap with respect to the z axis, the y component vanishes along the entire trap axis. The x component exhibits a weak parabolic dependence, while the z component varies linearly and remains zero at the trap

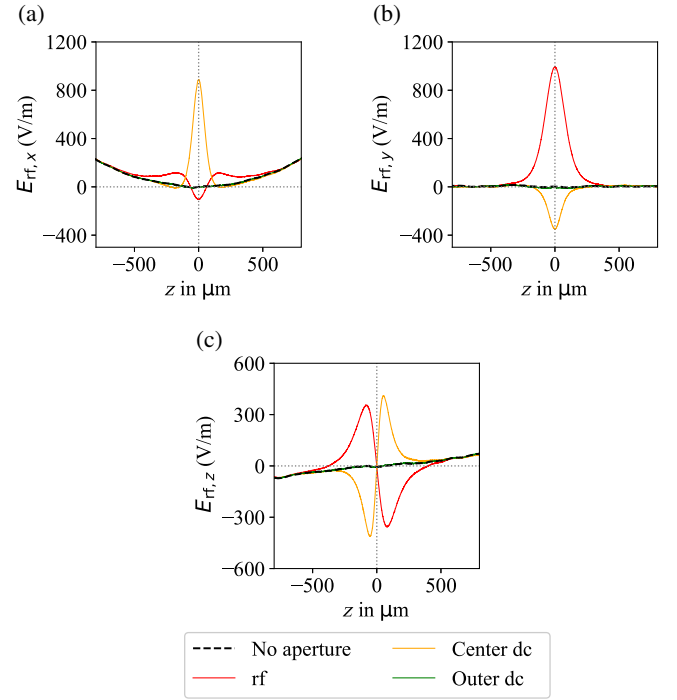


FIG. 6. Subplots (a)–(c) show the x , y , and z components of the rf field along the trap axis for different electrode configurations: the black dashed line represents the reference configuration, the red line represents a single aperture in the rf electrode as shown in Fig. 4(a), the orange line represents the aperture in the center dc electrode as shown in Fig. 4(b), and the green line represents the aperture in the outer dc electrode as shown in Fig. 4(c). The black and green lines overlap, which demonstrates the small impact of an aperture in the outer dc electrode.

center ($z = 0$), with gradients of the order of several tens of mV/mm^2 .

When an aperture is introduced in the rf electrode (see the red curve in Fig. 6), the residual rf field along the trap axis is strongly enhanced, with the dominant contributions appearing in the y and z components. The y component shows a pronounced peak at the trap center. In this case, the y component reaches a peak amplitude of 994 V/m at $z = 0$, with a gradient of $5.5 \text{ V}/\text{mm}^2$ at the FWHM, while the z component has a gradient of approximately $4.3 \text{ V}/\text{mm}^2$ at $z = 0$.

In contrast, when the aperture is located in the center dc electrode, the residual rf field is redistributed, and the dominant distortions occur in the x and z components. The x component shows a pronounced peak at the trap center, while the z component again displays an antisymmetric dispersive line shape. The resulting peak field amplitudes and axial gradients are of similar order to those observed for the y and z components when the aperture is placed in the rf electrode.

The differences in the radial components $E_{\text{rf},x}$ and $E_{\text{rf},y}$ at the target ion position ($z = 0$) explain the behavior of

the displacement of $E_{\text{rf},r}$ shown in Fig. 5(c). At the target ion position, for an aperture in the rf electrode, $E_{\text{rf},y}$ dominates over $E_{\text{rf},x}$, while for an aperture in the center dc electrode, $E_{\text{rf},x}$ becomes dominant. Additionally, both $E_{\text{rf},x}$ and $E_{\text{rf},y}$ change sign depending on the aperture's location. This explains why the $E_{\text{rf},r}$ minimum shifts in the positive direction, with the displacement more prominent in the y direction, when the aperture is in the rf electrode. For the case in which the aperture is in the center dc electrode, the displacement reverses direction, with the shift in the x direction becoming more pronounced.

To summarise the comparison of the three electrode types, placing the aperture in the outer dc electrode minimizes its effect on the trapping rf field due to the greater distance from the ion. However, this placement requires a large angle (approximately 70°) of the outcoupled beam. According to the Bragg condition for backward grating couplers, larger outcoupling angles correspond to higher angle-to-period sensitivity, making them more sensitive to fabrication tolerances. For example, a 200-nm-thick Si_3N_4 backward grating coupler at a wavelength of 760 nm exhibits an angle-to-period sensitivity of $1.4^\circ/\text{nm}$ at $\theta = -70^\circ$; see Fig. 3(b). Given a typical fabrication tolerance of 5 nm [33,34], this results in an angular deviation of 7° . Combined with the increased distance from the target ion position, this deviation leads to significant beam misalignment of the laser beam with the ion. Using forward grating couplers alleviates this issue by having smaller angle-to-period sensitivity at the same angle, making them less sensitive to fabrication tolerances. However, forward grating couplers operated at large angles generate higher-order beams, as shown in Fig. 3. These unintended beams contribute to stray light and optical crosstalk, introducing errors that degrade the performance of atomic clocks and quantum logic operations. Although the apertures in the center dc and rf electrodes displace the ion in opposing directions due to the sign change and the varying dominance of distorted rf field components, their effects on the trapping field are comparable. Therefore, in the subsequent sections, we focus on the aperture in the rf electrode.

While excess micromotion arising from a displacement of the rf field minimum can be compensated using static electric fields, the associated changes in the secular frequencies cannot be eliminated without perturbing the trapping potential. As shown in Fig. 5, the displacement of the $E_{\text{rf},r}$ minimum is nevertheless strongly correlated with the underlying distortion of the rf pseudopotential and with the corresponding changes in the secular frequencies. We therefore use the displacement of the $E_{\text{rf},r}$ minimum and the residual rf field along the trap axis as the primary indicators of aperture-induced distortion. An additional motivation for this choice stems from the integrated-optics approach, in which the optical beams are aligned to the geometric trap center. In such configurations, positioning the ion exactly at the rf-field minimum may not

always be practical without degrading the optical overlap. The dependence of the secular frequencies on the aperture width, where significant variations can occur, is discussed explicitly in the corresponding section.

B. Effect of aperture position and geometry

1. Effect of aperture position

In this section, we examine how the field distortion scales with the position of the aperture in the rf electrode. We first vary the position of an aperture in the z direction, p_z , in the rf electrode while keeping $w_a = 30\ \mu\text{m}$ and $p_y = 126.8\ \mu\text{m}$ (centered in the rf electrode), as shown in Fig. 7. Figures 7(b) and 7(c) present the impact on the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane by varying p_z from 0 to $600\ \mu\text{m}$.

The displacement of the $E_{\text{rf},r}$ minimum in the x direc-

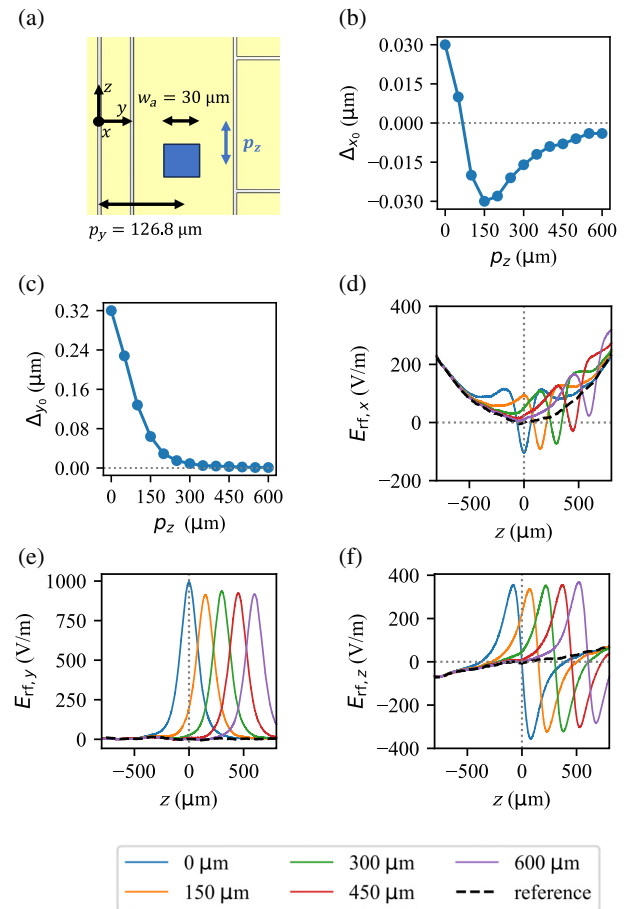


FIG. 7. (a) Varying p_z of an aperture in the rf electrode, with $w_a = 30\ \mu\text{m}$ and $p_y = 126.8\ \mu\text{m}$ (centered in the rf electrode). Subplots (b) and (c) illustrate the displacement of the $E_{\text{rf},r}$ minimum in x - y plane along the x and y directions as a function of p_z . Subplots (d)–(f) show the x , y , and z components of the rf field along the trap axis for p_z varying from 0 to $600\ \mu\text{m}$ and the reference case (black dashed line).

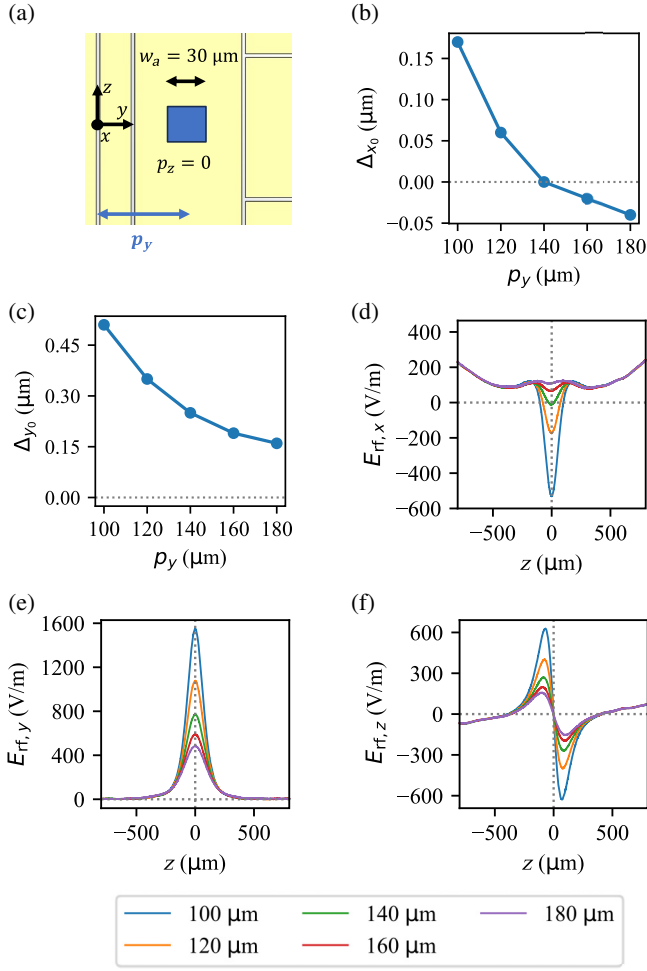


FIG. 8. (a) Varying p_y of an aperture in the rf electrode in the y direction, with $w_a = 30 \mu\text{m}$ and $p_z = 0 \mu\text{m}$. Subplots (b) and (c) illustrate the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane along the x and y directions as a function of p_y . Subplots (d)–(f) show the x , y , and z components of the rf field along the trap axis for p_y varying from 100 to 180 μm .

tion (Δ_{x_0}) shifts from positive to negative as p_z increases from 0 to 150 μm , with the displacement vanishing at $p_z = 75 \mu\text{m}$. As the aperture is placed farther from the trap center, the displacement approaches zero. In contrast, the displacement in the y direction (Δ_{y_0}) follows a monotonic trend, decreasing steadily and approaching zero as p_z increases. The analysis along the trap axis [Figs. 7(d)–7(f)] demonstrates that the rf field maintains its characteristic peak shapes, similar to those shown by the red line in Fig. 6, while undergoing a spatial shift that corresponds to the aperture position. When the aperture is moved farther away from the trap center, the amplitudes and gradients of the rf field at the target ion position converge to the case without any aperture (black dashed line), since the influence of the aperture on the rf field at the target ion position decreases.

We then vary the position of an aperture in the y direction (p_y) in the rf electrode while keeping $w_a = 30 \mu\text{m}$ and $p_z = 0 \mu\text{m}$ (on the y axis), as shown in Fig. 8. Figures 8(b) and 8(c) illustrate the effect on the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane as p_y is varied from 100 to 180 μm . The displacement of the $E_{\text{rf},r}$ minimum in the x direction (Δ_{x_0}) crosses from positive to negative as p_z increases, with the displacement vanishing at $p_z = 140 \mu\text{m}$, while the displacement in the y direction (Δ_{y_0}) follows a monotonic downward trend, approaching zero as p_y increases. Along the trap axis, as shown in Figs. 8(d)–8(f), the peaks in the x and y components of the residual field remain centered at $z = 0$ and increase in magnitude as p_y decreases. The z component maintains its dispersive line shape, with the gradient at $z = 0$ increasing significantly as p_y decreases.

To summarize the effect of the aperture position, simulations indicate that placing the aperture farther from the trap center reduces rf field distortion at the target ion position, as expected. However, this geometric relationship creates a trade-off: greater distances require larger outcoupling angles, which in turn demand wider apertures.

2. Effect of aperture size

The required aperture size for the outcoupled beam depends on the ion height, the angle of the outcoupled beam, the required beam waist at the target ion position, and the fabrication tolerances. The ion traps with integrated waveguides and grating couplers shown so far in Refs. [11–16] have aperture sizes ranging from 10 to 35 μm , with ion heights varying from 20 to 55 μm . In our study, due to our greater ion height of 100 μm , we examine rf field distortion by varying aperture width across a broader range, from 10 to 100 μm , while maintaining a fixed position in the rf electrode, as shown in Fig. 9.

Increasing the aperture size from 10 to 100 μm causes a displacement of the $E_{\text{rf},r}$ minimum in the x - y plane by up to 1.6 μm in the x direction and up to 12 μm in the y direction. Along the trap axis, the peaks of the x and y components of the residual field remain centered at $z = 0$ and become significantly larger as w_a increases. The x component reaches an amplitude of approximately 6 kV/m at $z = 0$ with a strong gradient of 64.2 V/mm² at the FWHM, while the y component reaches about 30 kV/m at $z = 0$ with a gradient of 163.3 V/mm² at the FWHM. The z component maintains its characteristic dispersive line shape, with the gradient at $z = 0$ increasing significantly as w_a increases, reaching 139 V/mm² for $w_a = 100 \mu\text{m}$.

We further investigate the change in the secular frequency as a function of the aperture width. As shown in Fig. 10, increasing w_a leads to a monotonic reduction of the radial secular frequency. For small apertures, this effect remains weak: for the reference aperture width $w_a = 30 \mu\text{m}$ used throughout this work, the secular-frequency

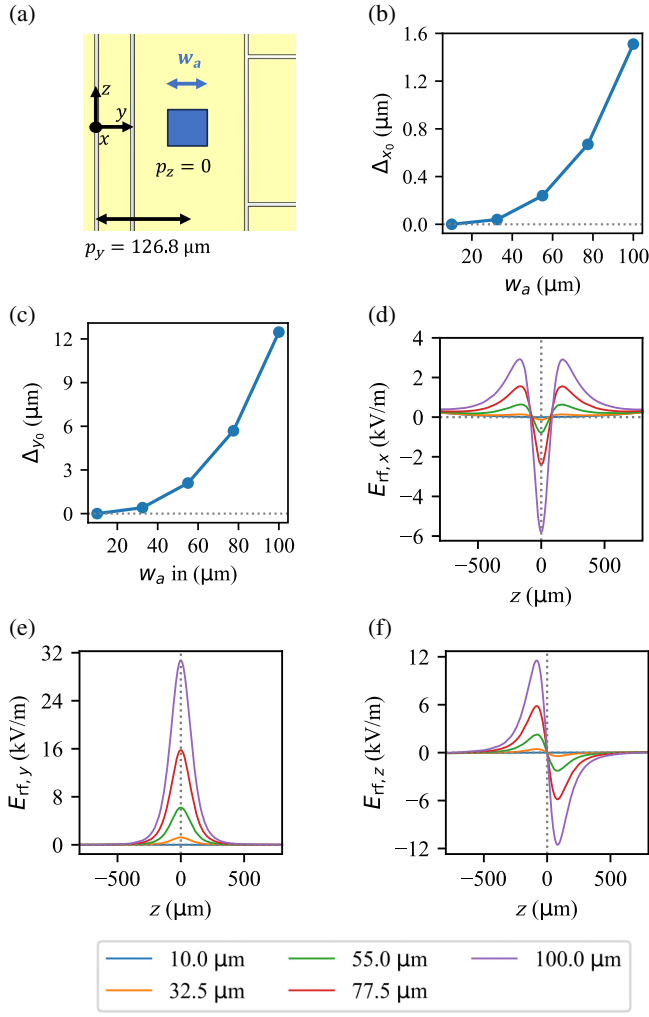


FIG. 9. (a) Varying w_a of an aperture in the rf electrode, with a fixed aperture position $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$. Subplots (b) and (c) illustrate the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane along the x and y directions as a function of w_a . Subplots (d)–(f) show the x , y , and z components of the rf field along the trap axis for w_a varying from 10 to 100 μm .

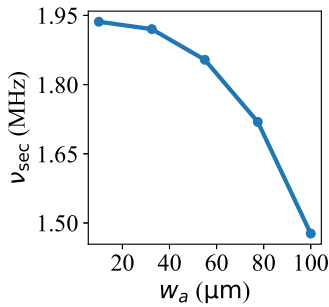


FIG. 10. Radial secular frequency ν_{sec} for a $^{172}\text{Yb}^+$ ion as a function of the aperture width w_a for an aperture in the rf electrode. The aperture position is fixed at $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$.

change is limited to about 0.7%. With increasing aperture width, however, the curvature distortion becomes substantial. In particular, increasing the aperture width from $w_a = 30$ to $100 \mu\text{m}$ results in a reduction of the radial secular frequency of up to approximately 20%.

In comparison to variations in location, altering the size of the aperture has a more pronounced effect on the electric field distortion. A larger distance of the aperture from the trap center reduces distortion but requires a larger aperture, which in turn introduces additional distortion. Therefore, a careful balance must be struck between the distance and the size of the aperture.

3. Effect of electrode thickness

Next, we study the effect of the electrode thickness on the field distortion, as presented in Fig. 11. Our results demonstrate that increasing the electrode thickness reduces

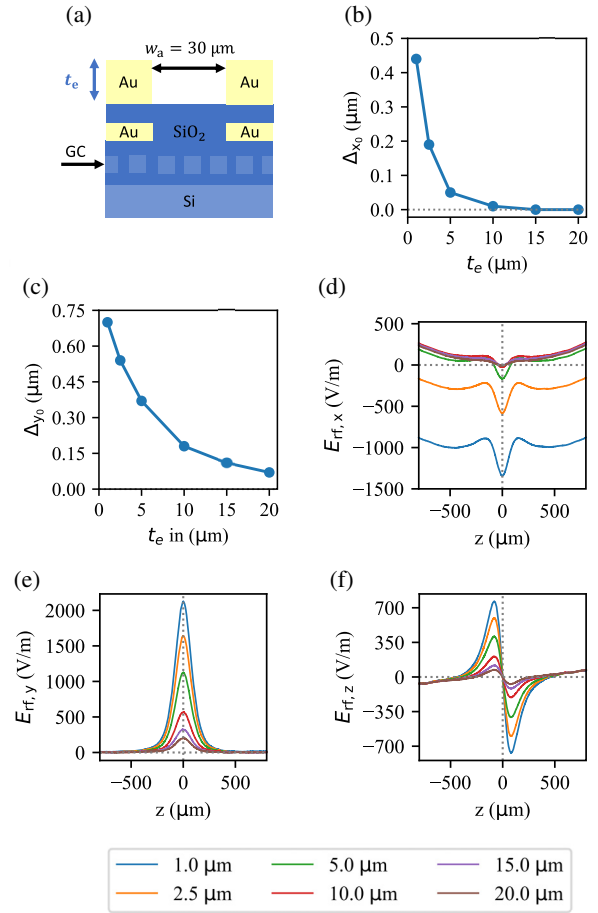


FIG. 11. (a) Varying t_e of the electrode around an aperture in the rf electrode, with $w_a = 30 \mu\text{m}$, $p_y = 126.8 \mu\text{m}$, and $p_z = 0 \mu\text{m}$. The layer stack is schematic and not drawn to scale. Subplots (b) and (c) illustrate the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane along the x and y directions as a function of t_e . Subplots (d)–(f) show the x , y , and z components of the rf field along the trap axis for t_e varying from 1 to 20 μm .

both the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane and the residual rf field along the trap axis. This improvement is due to the reduction of edge effects. Edge effects arise when the geometry of the electrode, such as sharp edges or boundaries, introduces nonuniformities in the electric field, especially near the edges. The aperture in a thinner electrode has a more pronounced field distortion at its edges because the field lines are less confined and can spread outward more easily, leading to larger variations in the trapping field. This behavior is similar to that seen in larger capacitors, where the influence of edge effects is diminished as the length of the capacitor (or, in our case, the thickness of the electrode) increases. However, increasing the electrode thickness also imposes geometric constraints, as excessively thick electrodes may obstruct the outcoupled laser beam, leading to a trade-off between reduced field distortions and optical access.

C. Effect of symmetry

When a single aperture is positioned off the symmetry axes (either y or z), as illustrated in Fig. 12(a), the $E_{\text{rf},r}$ minimum in the x - y plane is displaced from its target position. The asymmetry also leads to residual rf field amplitudes and gradients in all three components at the target ion position.

To address the displacement in the radial direction, we first introduce an additional aperture placed symmetrically with respect to the z axis, as shown in Fig. 12(b). The analysis along the trap axis [Figs. 12(d)–12(f), red line] demonstrates that this z symmetry cancels the y component of the rf field along the entire trap axis while simultaneously enhancing the peaks of the x and z components.

Next, to compensate the residual rf amplitude in the z component at the target ion position ($z = 0$), we introduce two additional apertures to create y symmetry, as depicted in Fig. 12(c). The analysis along the trap axis [Figs. 12(d)–12(f), orange line] shows that, while $E_{\text{rf},z}$ vanishes at $z = 0$ as expected, the introduction of the extra apertures creates additional peaks in the field. Furthermore, the x component exhibits a more complex line shape with additional peaks and a nonvanishing field amplitude at $z = 0$. Since surface ion traps are inherently two dimensional, exploiting x symmetry for further compensation is not feasible, meaning that the x component cannot be fully mitigated in this configuration.

D. Effect of using transparent conductive oxide coating

The use of transparent conductive oxides (TCOs) [35] in ion-trap experiments has been demonstrated in several recent works [14,36,37]. TCOs can be applied as thin-film coatings to cover the aperture, as shown in Fig. 13. These thin films are electrically connected to the electrodes, thus sharing their potential while allowing outcoupled light to pass through. In addition, the TCO covers dielectrics

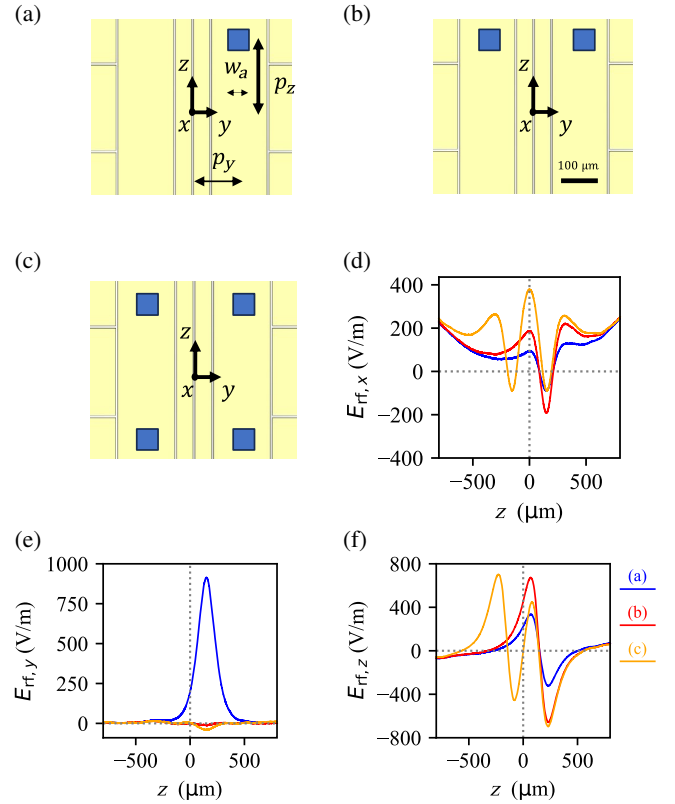


FIG. 12. (a) A single square-shaped aperture positioned asymmetrically, with a width of $w_a = 30 \mu\text{m}$, located at $p_y = 126.8 \mu\text{m}$ and $p_z = 100 \mu\text{m}$. (b) Configuration obtained by mirroring the aperture in subplot (a) with respect to the z axis. (c) Configuration obtained by mirroring both apertures in subplot (b) with respect to the y axis. Subplots (d)–(f) illustrate the x , y , and z components of the rf field along the trap axis, respectively. Blue, red, and orange lines indicate the configurations in subplots (a)–(c), respectively.

that could potentially charge due to laser-induced charging [38,39] and detrimentally affect the electric field at the ion location. A widely used TCO is indium tin oxide (ITO). In ITO films, the thickness is limited by a trade-off between electrical conductivity and optical transmittance. Increasing the thickness improves the conductivity but reduces the transmission due to increased absorption. For a 51-nm-thick ITO layer, Jansson *et al.* [40] reported a dc electrical conductivity at room temperature of approximately $1.7 \times 10^5 \text{ S/m}$, while maintaining high optical transmission of about 66% for a single ITO layer and about 80% when combined with an antireflection coating at 370 nm. At longer visible and near-infrared wavelengths, such as 760 and 935 nm, the optical transmittance exceeds 95%. Accordingly, we assume a TCO layer thickness of $t_{\text{TCO}} = 50 \text{ nm}$ in all subsequent simulations.

1. Effect of modified topography of the electrode

To account for the thickness difference in the trap electrode at the outcoupling aperture, we initially assume an

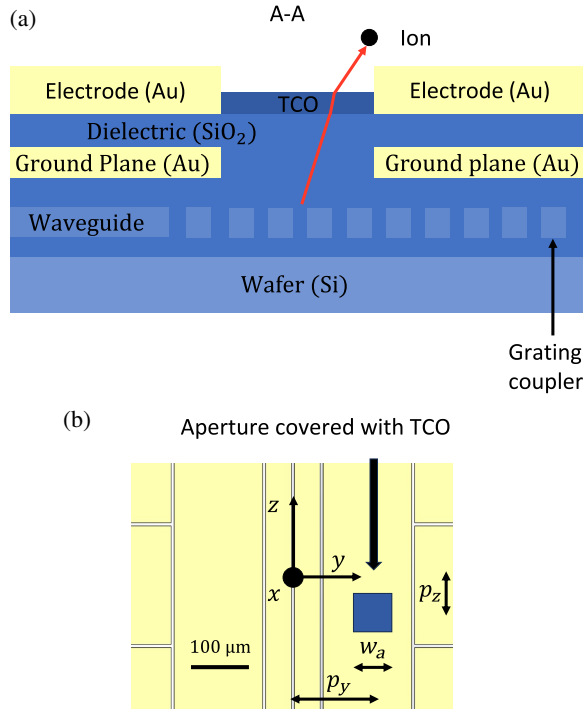


FIG. 13. (a) A cross-sectional view (A-A) illustrates that a transparent, conductive coating is applied to cover an aperture in the electrode. The cross-sectional view is schematic and not drawn to scale. (b) Top view of an aperture coated with TCO with a thickness of 50 nm in the gold electrode with $t_e = 6 \mu\text{m}$.

idealized TCO layer with a conductivity equivalent to gold ($4.5 \times 10^7 \text{ S/m}$), thereby ensuring that the layer shares the same electrical potential as the gold electrode.

The simulation results (see Fig. 14) indicate that, although the rf field along the trap axis is substantially reduced when TCO is applied (blue line) in comparison to the case without TCO (red line), a small residual rf field remains relative to the reference configuration (black). In the radial direction, the $E_{\text{rf},r}$ minimum in the x - y plane exhibits a residual displacement of approximately 30 nm in the y direction and no displacement in the x direction when the aperture is covered with TCO. Although the displacements are significantly smaller than in the case without the TCO coating [30 nm in the x direction and 320 nm in the y direction, as shown in Fig. 5(c)], they do not vanish entirely.

2. Effect of varying the conductivity of TCO

The conductivity of TCO is strongly influenced by its material composition and manufacturing process. To assess the effect of the TCO conductivity on rf field distortion, we vary the conductivity of the TCO layer and model the rf field by taking into account the current flow through both the gold electrode and the TCO. This simulation cannot be treated statically; therefore, we use the

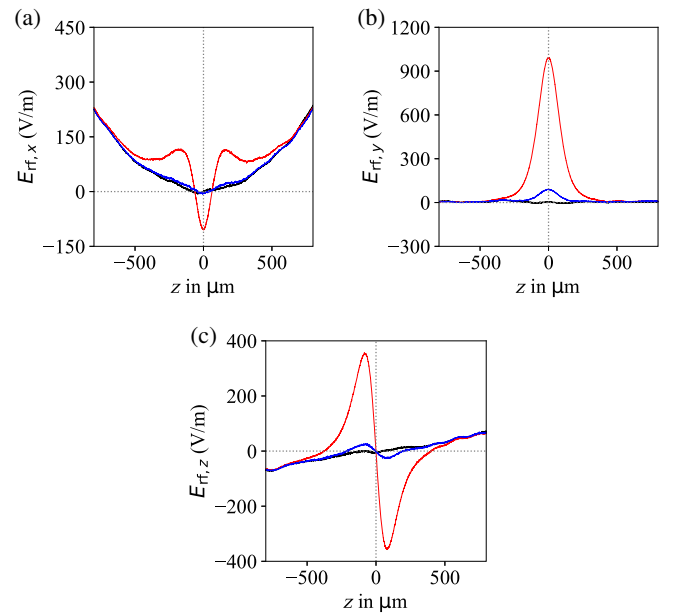


FIG. 14. Subplots (a)–(c) illustrate the x , y , and z components of the rf field along the trap axis: reference configuration (black line), a single square-shaped aperture with $w_a = 30 \mu\text{m}$, $p_y = 126.8 \mu\text{m}$, and $p_z = 0 \mu\text{m}$ in the rf electrode without TCO coating (red line), and the same aperture with an idealized TCO coating of $t_{\text{TCO}} = 50 \text{ nm}$ and conductivity equal to that of gold (blue line).

electric current module in COMSOL. A voltage source with a frequency of 16 MHz and an amplitude of 100 V is applied to the rf electrodes. All other dc electrodes are grounded. This method captures both the phase and potential distortions in the electrode, from which the rf field at the target ion position is calculated.

In the x - y plane, the displacement of the $E_{\text{rf},r}$ minimum decreases in both the x and y directions as the conductivity of the TCO increases, as shown in Fig. 15. The blue band indicates the region of typical conductivities of ITO, and the black line indicates the conductivity of gold. When the conductivity of the TCO matches that of gold ($4.5 \times 10^7 \text{ S/m}$), the displacement in the x direction vanishes, while a residual displacement of 30 nm remains in the y direction, which is consistent with results from the electrostatic simulation in Sec. IV D 1. A similar trend is observed in the axial direction as well. As the conductivity of the TCO increases to match that of gold, the rf field along the trap axis converges to the results shown by the blue line in Fig. 14.

3. Effect of the rf phase shift

The aperture in the rf electrode not only distorts the potential of the electrode, but also introduces a phase delay due to the differences in conductivity and thickness between gold and TCO. Such phase difference between the two rf electrodes can cause a nonzero $E_{\text{rf},r}$ minimum,

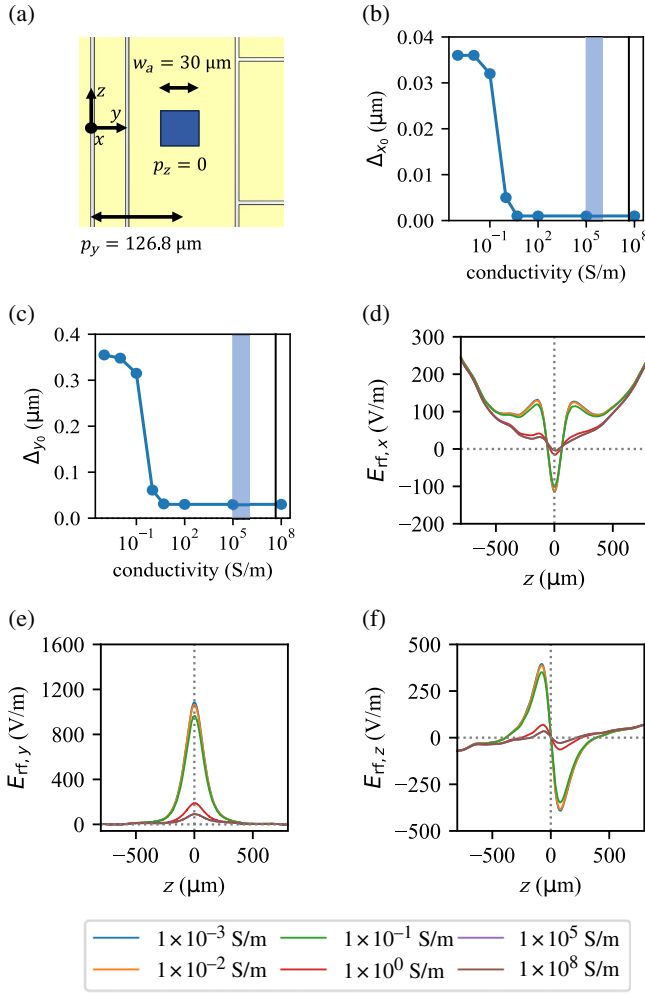


FIG. 15. (a) Variation of the conductivity of the TCO covering an aperture with a fixed width of $w_a = 30 \mu\text{m}$ and a constant position of $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$ in the rf electrode. Subplots (b) and (c) illustrate the displacement of the $E_{\text{rf},r}$ minimum in the x - y plane along the x and y directions as a function of the TCO conductivity; the black line indicates the conductivity of gold, and the blue band spans the region of typical conductivities of ITO. Subplots (d)–(f) show the x , y , and z components of the rf field along the trap axis for conductivities from 10^{-3} to 10^8 S/m. Notably, the purple and brown lines overlap.

resulting in excess micromotion that cannot be compensated [24].

Figure 16 shows the residual amplitude of $E_{\text{rf},r}$ at its minimum as a function of the TCO conductivity for varying aperture widths w_a . The residual amplitude exhibits distinct behavior across different conductivity regimes. At low conductivities (below 1 S/m) with $w_a > 50 \mu\text{m}$, $E_{\text{rf},r}$ exhibits a significant residual amplitude at its minimum. This arises from the mismatch in conductivity and thickness between the gold and TCO coatings, which induces a phase delay in the rf electrode and results in a nonvanishing field amplitude at the $E_{\text{rf},r}$ minimum. As the conductivity decreases further to 10^{-3} S/m, where the

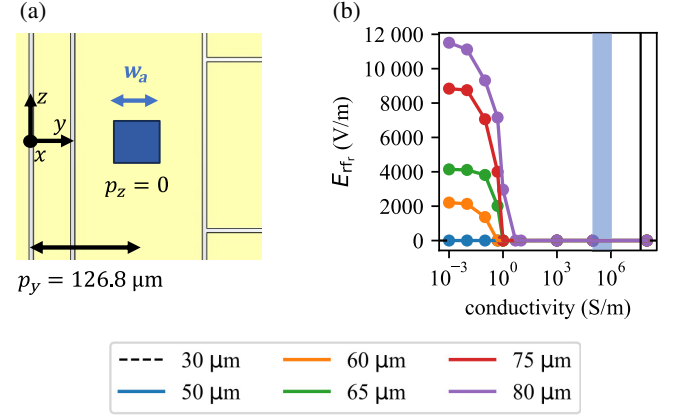


FIG. 16. (a) Variation of the conductivity of the TCO covering an aperture with varying widths (w_a). The position of the aperture is kept constant at $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$ in the rf electrode. (b) Amplitude of the $E_{\text{rf},r}$ minimum in the x - y plane as a function of the conductivity of the TCO for apertures with widths w_a varying from 30 to 80 μm . All lines converge to zero and overlap when the TCO conductivity exceeds 10 S/m. The black line indicates the conductivity of gold, and the blue band spans the region of typical conductivities of ITO.

aperture effectively behaves as if it had no TCO coating, the residual amplitude converges to a maximum. This indicates that the cut-through in the rf electrode created by the aperture introduces strong phase distortions (for $w_a > 50 \mu\text{m}$), resulting in a residual $E_{\text{rf},r}$ minimum that cannot be fully compensated. Conversely, increasing the TCO conductivity reduces the residual field amplitude. When the conductivity reaches the value of commonly used ITO or matches that of gold, the residual amplitude vanishes for all aperture widths. This indicates that the phase delay due to thickness differences between the TCO and gold is negligible.

To summarize the effect of TCO, our findings indicate that the effect of the conductivity of the TCO on the rf field can be neglected over a large range from 10 to 10^8 S/m. The observed conductivity threshold of the order of 10 S/m may be qualitatively interpreted by modeling the ITO patch as a resistance element embedded in a capacitive network formed by the surrounding gold electrodes and dielectric layers. Whether the ITO patch follows the rf potential of the surrounding gold electrode is governed by the effective charging dynamics of the ITO patch. For lower conductivity, this charging time becomes longer than the rf period, such that the patch cannot fully follow the rf drive, whereas for sufficiently high conductivity, the patch potential approximately follows the rf drive, thereby suppressing field distortions. However, a detailed quantitative analysis of the underlying impedance network is beyond the scope of the present work. The conductivity and thickness of commonly used ITO layers are adequate

to mitigate significant rf field distortion without introducing a phase shift in the rf electrode. However, the topography of the surface electrodes with apertures prevents a complete elimination of the rf field distortion.

V. CONCLUSION AND OUTLOOK

In this paper, we present a comprehensive analysis of the effects of apertures for vertically outcoupled laser beams from waveguides on the trapping field of a photonic-integrated surface ion trap. We find that placing apertures in the outer dc electrode is the optimal strategy to avoid significant trapping field distortion. However, this requires larger outcoupling angles. For backward grating couplers, larger angles necessitate smaller grating periods and result in higher angle-to-period sensitivity, making them highly sensitive to fabrication tolerances. In the case of forward grating couplers, higher-order diffraction is coupled out at larger angles. These effects become more pronounced at shorter wavelengths. For instance, given a typical fabrication tolerance of 5 nm, a 120-nm-thick Al_2O_3 backward grating coupler at a wavelength of 370 nm exhibits an angle-to-period sensitivity of $2.7^\circ/\text{nm}$ at $\theta = -70^\circ$, leading to an angular deviation of approximately 13.5° . Such a grating coupler requires a feature size of approximately 70 nm, which is critical for foundries [34].

When the aperture is located in the rf electrode, a trade-off emerges between the distance from the trap center and the size of the aperture. As the distance p_y increases, the distortion of the trapping field leads to a smaller displacement of the $E_{\text{rf},r}$ minimum. For distances from $p_y = 65 \mu\text{m}$ to $p_y = 180 \mu\text{m}$ in the rf electrode, the displacement reduces from $\Delta_{y0} = 1.5 \mu\text{m}$ to 150 nm in the y direction and from $\Delta_{x0} = 1.5 \mu\text{m}$ to 50 nm in the x direction. For a shift of the aperture position in the rf electrode in the z direction, a similar behavior is observed, with displacement on the same scale. However, the distortion and the resulting displacement also depend on the aperture size. While the displacement is $<1 \mu\text{m}$ for a square-shaped aperture of width $w_a = 30 \mu\text{m}$ at $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$, for a larger aperture with $w_a = 100 \mu\text{m}$ at the same position, the ion is displaced by $\Delta_{x0} = 1.6 \mu\text{m}$ and $\Delta_{y0} = 12 \mu\text{m}$. This large displacement is due to the highly distorted field, with the y component exhibiting a peak amplitude of 30 kV/m and a gradient of 164 V/mm^2 at the target ion position. Importantly, the aperture should not be placed at the edge of the gap between the center dc and rf electrodes, as this results in a larger ion displacement of $1.5 \mu\text{m}$ in both directions compared to when the aperture is fully surrounded by the metal electrode. When the aperture is positioned in the center dc electrode, the ion displacement Δ_{x0} can be minimized to 150 nm and Δ_{y0} can be zeroed by placing the aperture directly at the trap center.

In addition to the displacement of the $E_{\text{rf},r}$ minimum and the residual rf field along the trap axis, apertures

in the trap electrodes also modify the curvature of the rf pseudopotential and thereby the secular frequencies. Unlike micromotion, these secular-frequency changes cannot be compensated locally without modifying the trapping potential. For unfavorable aperture placements, relative secular-frequency changes of up to about 5% already occur for an aperture width of $w_a = 30 \mu\text{m}$. For larger apertures, this effect becomes substantially stronger, reaching changes of up to approximately 20% for $w_a = 100 \mu\text{m}$. These aperture-induced modifications of secular frequency therefore constitute an additional design constraint for photonic-integrated surface traps.

With a fixed aperture width, increasing the thickness of the electrode from 1 to 20 μm can reduce field distortions by 2 orders of magnitude due to the reduction of edge effects. However, care must be taken to ensure that the electrode does not obstruct the outcoupled laser beam, unless a technique is developed to shape the metal layer of the electrode at the angle of the outcoupled beam.

Arranging apertures symmetrically provides an effective strategy for compensating the displacement of the $E_{\text{rf},r}$ minimum and the phase difference between the rf electrodes. Nevertheless, this approach introduces stronger residual rf fields along the trap axis if additional apertures are required or if the aperture size must be increased to maintain symmetry. Independent of the presence of an aperture in an electrode, it is not possible to fully compensate the out-of-plane component (x) of the rf field at the target ion position due to the inherently two-dimensional geometry of planar surface traps.

The application of TCO coatings on apertures significantly reduces the potential and phase distortions on the electrodes, thereby strongly reducing rf field distortions at the target ion position, e.g., from $E_{\text{rf},y} > 900 \text{ V/m}$ to $E_{\text{rf},y} < 100 \text{ V/m}$. Only small residual rf field components remain due to the topography of the modified surface. Future technological developments could focus on leveling the topography of surface traps to reach a flat surface with TCO coating.

Although the present study is limited to simulated environments, the results provide a basis for anticipating challenges in real-world applications. We explore the implications of the simulation results for precision measurements and trapped-ion quantum technologies. For trapped-ion-based optical clocks, the time-dilation shift due to excess micromotion is one common contribution to the uncertainty. The fractional time-dilation shift due to EMM is given by [27]

$$\left| \frac{\Delta v}{v_0} \right|_{\text{TD}} = \left(\frac{eE_{\text{rf}}}{2mc\Omega_{\text{rf}}} \right)^2, \quad (3)$$

where e is the elementary charge, m is the ion mass, and c is the speed of light.

Besides excess micromotion, the field distortion caused by an aperture also leads to ion heating through rf noise.

The rf-noise-induced heating rate can be estimated using [25,26]

$$\dot{n}_i = \frac{e^4}{16m^3\Omega_{\text{rf}}^4\hbar\omega_{\text{sec},i}} \left(\frac{\partial}{\partial i} E_{\text{rf}}^2(\mathbf{r}) \right)^2 \frac{S_V(\Omega_{\text{rf}} \pm \omega_{\text{sec},i})}{U_{\text{rf}}^2}, \quad (4)$$

where S_V is the rf-voltage noise spectral density at $\Omega_{\text{rf}} \pm \omega_{\text{sec},i}$ and $\hbar$ is the reduced Planck constant.

As shown throughout this work, the aperture displaces the rf-field minimum from the geometric trap center. For a single ion, the residual rf field can be compensated by applying dc voltages to shift the ion to the rf-field minimum. In this case, the integrated outcoupling optics must be foreseen and designed to accommodate this displacement, ensuring alignment between the ion position and the optical beam. Table II summarizes the corresponding rf-minimum displacements for aperture widths of $w_a = 30$, 77.5, and 100 μm . For each aperture width, four configurations are considered: a single aperture and a symmetric two-aperture arrangement obtained by mirroring the aperture with respect to the z axis, each with and without an ITO coating.

If the micromotion cannot be compensated by shifting the ion to the rf-field minimum, the residual rf field results in a time-dilation shift and rf-noise-induced heating, which are also listed in Table II. The calculation is performed for a single $^{172}\text{Yb}^+$ ion, assuming a radial secular frequency of $\nu_{\text{sec},r} = 1.9$ MHz and an axial secular frequency of $\nu_{\text{sec},z} = 300$ kHz. The rf-noise-induced heating rate is estimated following the model and experimental observations reported by Kalincev *et al.* [25]. We assume a

resonant rf circuit with quality factor $Q = 542$ and inductance $L = 2.5$ μH , and a constant power spectral density of the input rf noise $S_P = 1.5 \times 10^{-14}$ W Hz^{-1} . The resulting rf-voltage noise spectral densities are 1.23×10^{-13} and 4.93×10^{-12} $\text{V}^2 \text{Hz}^{-1}$ for the radial and axial modes, respectively.

For single-ion addressing with a tightly focused beam, larger apertures without ITO coating lead to larger displacements, which can cause a significant mismatch between the ion position and the optical beam waist if not properly considered during the design phase. Symmetric aperture configurations do not fully cancel the residual rf field.

So far, we have considered single-ion addressing at the trap minimum. We now estimate the micromotion-induced fractional time-dilation shift $|\Delta\nu/\nu_0|_{\text{TD}}$ and the rf-noise-induced heating rates for a spatially extended linear ion crystal along the trap axis. Assuming the same secular frequencies as used in the single-ion calculation, we consider a crystal of ten $^{172}\text{Yb}^+$ ions with an axial length of approximately 35 μm . The equilibrium ion positions are calculated following the method of James [41]. As a representative example, we take the outermost ion at $z = 17.5$ μm and evaluate the residual rf electric field, the micromotion-induced fractional time-dilation shift, and the rf-noise heating rate at this position. The corresponding results are summarized in Table III.

For symmetric aperture configurations, the micromotion-induced time-dilation shift is not fully cancelled, but is reduced compared to the asymmetric case. Regarding

TABLE II. Electric field components, rf-minimum displacement at $z = 0$, micromotion-induced fractional time-dilation shift $|\Delta\nu/\nu_0|_{\text{TD}}$, and rf-noise heating rates along the three motional directions, evaluated at the target ion position ($x = 100$ μm , $y = 0$, $z = 0$). The position of the single aperture in the rf electrode is fixed at $p_y = 126.8$ μm and $p_z = 0$ μm . Four configurations are considered: (i) a single-aperture geometry; (ii) a single aperture with an ITO coating; (iii) a symmetric two-aperture geometry obtained by introducing a second aperture mirror-symmetric with respect to the z axis; and (iv) the symmetric configuration with ITO coating. All calculations assume a single $^{172}\text{Yb}^+$ ion with $\nu_{\text{sec},r} = 1.9$ MHz and $\nu_{\text{sec},z} = 300$ kHz.

Configuration	rf min. disp. ($z = 0$)			Evaluated at the target ion position						
	w_a (μm)	Δx_0 (μm)	Δy_0 (μm)	E_x (V/m)	E_y (V/m)	E_z (V/m)	$ \Delta\nu/\nu_0 _{\text{TD}}$	$\dot{n}_x$ (s^{-1})	$\dot{n}_y$ (s^{-1})	$\dot{n}_z$ (s^{-1})
single	30	0.03	0.32	-103.3	993.3	0	8.6×10^{-17}	7.0×10^{-2}	6.3×10^0	0
	77.5	0.68	5.69	-2402.5	15 796.4	0	2.2×10^{-14}	6.3×10^1	1.3×10^3	0
	100	1.50	12.47	-5794.8	30 722.4	0	8.5×10^{-14}	5.0×10^2	4.2×10^3	0
single + ITO	30	0.00	0.03	-4.2	89.3	0	6.9×10^{-19}	8.2×10^{-5}	5.1×10^{-2}	0
	77.5	0.05	0.32	-154.1	978.0	0	8.5×10^{-17}	1.6×10^{-1}	6.1×10^0	0
	100	0.13	0.64	-397.3	1960.7	0	3.5×10^{-16}	1.1×10^0	2.4×10^1	0
symmetry	30	0.07	0.01	-212.7	0	0	4.1×10^{-18}	2.7×10^{-1}	0	0
	77.5	1.74	-0.01	-4790.1	0	0	2.0×10^{-15}	1.2×10^2	0	0
	100	4.66	0.08	-11 564.9	0	0	1.2×10^{-14}	6.3×10^2	0	0
symmetry + ITO	30	0.01	0.01	-16.5	0	0	7.2×10^{-20}	7.3×10^{-4}	0	0
	77.5	0.01	0.01	-304.3	0	0	8.2×10^{-18}	5.5×10^{-1}	0	0
	100	0.01	0.01	-804.7	0	0	5.6×10^{-17}	4.8×10^0	0	0

TABLE III. Electric field components, micromotion-induced fractional time-dilation shift $|\Delta\nu/\nu_0|_{\text{TD}}$, and rf-noise heating rates along the three motional directions, evaluated at the outermost ion located at $z = 17.5 \mu\text{m}$ in a crystal of ten $^{172}\text{Yb}^+$ ions. All calculations assume radial and axial secular frequencies of $\nu_{\text{sec},r} = 1.9 \text{ MHz}$ and $\nu_{\text{sec},z} = 300 \text{ kHz}$, respectively. The position of the single aperture in the rf electrode is fixed at $p_y = 126.8 \mu\text{m}$ and $p_z = 0 \mu\text{m}$. Four configurations are considered: (i) a single-aperture geometry; (ii) a single aperture with an ITO coating; (iii) a symmetric two-aperture geometry obtained by introducing a second aperture mirror-symmetric with respect to the z axis; and (iv) the symmetric configuration with ITO coating.

Configuration	Evaluated at the target ion position							
	w_d (μm)	E_x (V/m)	E_y (V/m)	E_z (V/m)	$ \Delta\nu/\nu_0 _{\text{TD}}$	$\dot{\tilde{n}}_x$ (s^{-1})	$\dot{\tilde{n}}_y$ (s^{-1})	$\dot{\tilde{n}}_z$ (s^{-1})
single	30	-90.0	963.7	-131.8	8.3×10^{-17}	5.4×10^{-2}	5.9×10^0	9.3×10^{-4}
	77.5	-2213.7	15 363.4	-2106.9	2.1×10^{-14}	5.4×10^1	1.3×10^3	5.3×10^1
	100	-5412.8	29 916.9	-4061.3	8.1×10^{-14}	4.4×10^2	4.1×10^3	7.2×10^2
single + ITO	30	-0.9	85.9	-13.7	6.6×10^{-19}	2.1×10^{-5}	4.9×10^{-2}	1.1×10^{-7}
	77.5	-142.0	950.7	-134.5	8.2×10^{-17}	1.3×10^{-1}	5.8×10^0	8.0×10^{-4}
	100	-374.8	1911.0	-251.6	3.3×10^{-16}	9.5×10^{-1}	2.3×10^1	1.2×10^{-2}
symmetry	30	-167.7	0	-281.8	9.4×10^{-18}	1.7×10^{-1}	0	1.8×10^{-3}
	77.5	-4391.0	0	-4225.2	3.2×10^{-15}	1.0×10^2	0	1.0×10^2
	100	-10 784.5	0	-8150.3	1.6×10^{-14}	5.8×10^2	0	1.2×10^3
symmetry + ITO	30	9.0	0	-42.4	2.0×10^{-19}	7.6×10^{-4}	0	2.8×10^{-7}
	77.5	-258.0	0	-267.0	1.2×10^{-17}	4.1×10^{-1}	0	1.3×10^{-3}
	100	-749.7	0	-528.0	7.3×10^{-17}	4.0×10^0	0	1.4×10^{-2}

heating, the symmetric configuration cancels the rf-noise-induced heating in the y direction but increases the heating rates in the x and z directions.

Applying an ITO coating to the aperture significantly reduces the field distortion and thereby decreases the fractional time-dilation shift by approximately 2 orders of magnitude. The corresponding rf-noise-induced heating rates are reduced by 2–4 orders of magnitude, depending on the motional direction. This demonstrates that both the time-dilation shift and the rf-noise-induced heating arising from aperture-induced field distortions can be effectively mitigated by covering the apertures with ITO.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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