Laser-free trapped-ion entangling gates with simultaneous insensitivity to qubit and motional decoherence

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The dominant error sources for state-of-the-art laser-free trapped-ion entangling gates are decoherence of the qubit state and the ion motion. The effect of these decoherence mechanisms can be suppressed with additional control fields, or with techniques that have the disadvantage of reducing gate speed. Here, we propose using a near-motional-frequency magnetic field gradient to implement a laser-free gate that is simultaneously resilient to both types of decoherence, does not require additional control fields, and has a relatively small cost in gate speed.

I. INTRODUCTION

Trapped ions are a promising platform for quantum simulations and universal quantum computation due to their long coherence times, inherent uniformity, and high gate fidelities. The most common method for performing high-fidelity multi-qubit entangling gates, a requirement for universal quantum processors, relies on coupling the internal qubit “spin” states to collective motional degrees of freedom. Geometric phase gates—which create entanglement through closed, spin-dependent trajectories in motional phase space—are widely used because they are first-order insensitive to ion temperature (in the Lamb-Dicke limit). Geometric phase gates employing laser beams to create the required spin-motion coupling have been used to generate Bell states with fidelities ~ 0.999, with the main error arising from off-resonant photon scattering. Alternative laser-free schemes induce spin-motion coupling with static near-qubit-frequency or near-motional-frequency magnetic field gradients. While laser-free schemes eliminate photon scattering errors and do not require stable, high-power lasers, they can be more susceptible to other noise sources due to their typically longer gate durations.

Qubit frequency shifts or miscalibrations due to fluctuating field amplitudes are the primary sources of error in laser-free gates implemented with microwave field gradients. Recent work has shown that some of these shifts may be reduced passively through careful trap design. They can also be reduced actively by adding control fields to perform dynamical decoupling: to date, the best experimentally demonstrated Bell state fidelity using such a scheme is 0.997(1). Schemes which employ static magnetic field gradients to perform laser-free gates allow high-fidelity individual addressing of the ions in frequency space; however, this means that the microwave frequencies needed to realize an entangling gate are different for each ion, increasing the total number of drive tones necessary to implement such a gate.

Since laser-free geometric phase gates are typically slower than laser-based gates by an order of magnitude, the qubits spend more time entangled with the motional mode, and thus the gates are more sensitive to motional decoherence. Typically, after qubit frequency shifts, this is the next most important source of gate error. In the work reported here, we consider motional decoherence in three distinct regimes, depending on the timescale and nature of the decoherence: secular frequency shifts, motional heating, and motional dephasing.

In their original proposal, Sørenson and Mølmer pointed out that dividing a geometric phase gate into K loops decreases gate errors from heating and motional dephasing. Separately, decoherence from secular frequency shifts can be suppressed with Walsh sequences, or with phase modulation of gate fields. These techniques increase the gate duration in exchange for robustness. Polychromatic gates, geometric phase gates comprised of multiple simultaneously applied gate fields with optimized amplitudes, reduce the impact of all three types of motional decoherence and have a comparatively smaller increase in . This technique was recently demonstrated for both laser-based and laser-free gates. These gate implementations, however, remain sensitive to qubit frequency offsets, although they provide some dynamical decoupling for zero-mean fluctuations; their physical implementation also requires additional control fields, increasing experimental complexity. Similar robustness to motional errors can alternatively be achieved by smooth ramping of the gate field amplitude over the entire duration of the gate pulse.

In this work, we build upon Ref. to propose a gate that provides simultaneous robustness to qubit fre-
frequency shifts and to motional decoherence without requiring additional control fields, offering a combination of increased fidelity and decreased experimental overhead. The protection from qubit frequency errors extends to much larger frequency offsets than can typically be protected against using dynamical decoupling techniques, because the entangling gate commutes with these fluctuations, unlike all other laser-free entangling gates demonstrated previously.

The outline of the paper is as follows. In Sec. III we present a theoretical framework we use to analyze the qubit dynamics generated by a pair of microwave fields symmetrically detuned around the qubit frequency and a near-motional-frequency magnetic field gradient. In Sec. III we show how to tune these control fields to realize a geometric phase gate which is insensitive to qubit frequency shifts and robust to motional decoherence. We also characterize its performance with numerical simulations. In Sec. VII we analyze polychromatic gates that use multiple pairs of microwave fields and contrast them with the scheme presented here. Finally, we present conclusions and prospects for future work.

II. BICHROMATIC INTERACTION PICTURE FOR LASER-FREE GATES

We consider a Hamiltonian for laser-free gates between two trapped ions with identical qubit frequencies \( \omega_0 \), coupled to a shared motional mode with frequency \( \omega_r \). We apply a pair of microwave-frequency magnetic fields (symmetrically detuned around \( \omega_0 \) by \( \pm \delta \)), and a separate magnetic field gradient oscillating at \( \omega_g \), as shown in Fig. 1(a). Neglecting noise, the dynamics of this system are governed by the Hamiltonian

\[
\hat{H}_{\text{lab}}(t) = \frac{\hbar \omega_0}{2} \hat{S}_z + \hbar \omega_r \hat{a}^\dagger \hat{a} + 2\hbar \Omega_g \cos(\omega_g t) \hat{S}_z \left\{ \hat{a}^\dagger + \hat{a} \right\} + 2\hbar \Omega_g \hat{S}_x \left\{ \cos(\omega_0 + \delta) t + \cos(\omega_0 - \delta) t \right\}.
\]  

where \( \Omega_g \) is the magnetic field gradient Rabi frequency and \( \Omega_g \) is the microwave Rabi frequency. We define two-ion Pauli spin operators as \( \hat{S}_i = \hat{\sigma}_{i,1} + \hat{\sigma}_{i,2} \), with \( \gamma \in \{x, y, z, +, -\} \) and \( z \) as the qubit quantization axis. The shared ion motion has creation and annihilation operators \( \hat{a}^\dagger \) and \( \hat{a} \). This Hamiltonian can be generalized to multiple pairs of microwave tones or arbitrary gradient time dependence without significant complication (see Appendix A). Transforming into the interaction frame with respect to \( \hat{H}_0 = \hbar \omega_0 \hat{S}_z/2 + \hbar \omega_r \hat{a}^\dagger \hat{a} \) and ignoring terms that oscillate with frequencies near \( 2\omega_0 \) gives:

\[
\hat{H}(t) = 2\hbar \Omega_g \hat{S}_z \cos(\delta t) + 2 \hbar \Omega_g \cos(\omega_g t) \hat{S}_z e^{-i\omega_r t} + H.c.,
\]

The oscillating gradient at \( \omega_g \), in combination with the detuned microwaves, can give rise to two spin-motion-coupling sideband interactions, occurring when \( \delta = \omega_r \pm \omega_g \), respectively [28]. The proposed gate relies on this feature of the interaction, along with the fact that the bichromatic microwave pair combines to give an effective modulation of \( \Omega_g \). This scheme requires a magnetic-field-sensitive qubit transition instead of the magnetic-field-insensitive “clock” transitions typically preferred for their long coherence times. We envision storing quantum information in a clock qubit and transferring the state populations to a field-sensitive qubit only during times when an entangling gate is being carried out. Alternatively, microwave fields can be applied to field-sensitive transitions to create dressed-state clock qubits [31].

Typical experimental values of the amplitude \( \Omega_g/2\pi \) are in the few kHz regime, whereas \( \Omega_g/2\pi \) can be in the MHz regime [28]. It is therefore convenient to analyze the system dynamics in a frame that eliminates the large size disparity between the terms. This can be done by transforming into the interaction picture with respect to the bichromatic microwaves [27, 39, 40]:

\[
\hat{H}_I(t) = \hat{U}^\dagger(t) \hat{H}(t) \hat{U}(t) + i\hbar \hat{U}^\dagger(t) \hat{U}(t),
\]

where the frame transformation \( \hat{U}(t) \), given by

\[
\hat{U}(t) = \exp \left\{ -i \hat{S}_z \frac{\Omega_g \sin(\delta t)}{\delta} \right\},
\]

capsulates the dynamics of the microwave pair (see appendix). In the time-dependent transformed basis of this “bichromatic” interaction picture, the system dynamics between times \( t_i \) and \( t_f \), given by the propagator \( \hat{T}_I(t_i, t_f) \) of \( \hat{H}_I(t) \), appear simplified. Crucially, however,
if the microwave pair (as parameterized by $\Omega\mu$) can be turned on and off in such a manner that $\hat{U}(t_i) = \hat{I}$ and $\hat{U}(t_f) = \hat{I}$, where $\hat{I}$ is the identity operator, then the state evolution given by $\hat{U}_I(t_i, t_f)$ applies to the lab frame basis as well as the transformed basis in the bichromatic interaction picture. This condition on $\hat{U}(t_i)$ and $\hat{U}(t_f)$ can be achieved by ramping the microwave pair on and off slowly with respect to $1/\delta$, or by choosing the gate duration $t_G$ (during which the microwave pair is on) such that $t_G\delta$ is an integer multiple of $2\pi$. Either method can be used, with realistic parameters, such that the fidelity of the final state in the lab frame basis and the interaction frame basis differ by less than $10^{-4}$. While the first method would be used in experiments, we use the second method in this paper (unless otherwise specified) because it is simpler for the numerical simulations. Making the above transformation on Eq. (2) gives [27]:

$$\hat{H}_I(t) = \frac{2\hbar\Omega_g}{\delta} \sum_{n=1}^{\infty} J_{2n} \left( \frac{4\Omega_g}{\delta} \right) \cos(2n\delta t) + 2 \sum_{n=1}^{\infty} J_{2n-1} \left( \frac{4\Omega_g}{\delta} \right) \sin((2n-1)\delta t).$$

We also note that, for simplicity, we have assumed all single qubit operations implemented in this work are instantaneous and error-free.

### III. POLYCHROMATIC GATES

In this section, we discuss a protocol for tuning Eq. (1) to represent an entangling gate that is insensitive to motional and qubit decoherence. By setting the conditions

$$4\delta = (\omega_r - \omega_g) - j\Delta,$$

$$8\delta = (\omega_r + \omega_g) - (j + 1)\Delta,$$

where $j$ is an integer, and $\Delta = 2\pi/t_G$ is on the order of $\Omega_g$, the terms $\propto J_2$ and $\propto J_3$ become slowly varying in time with respect to all other terms in the sum. They will thus make the dominant contribution to the system dynamics, while the other terms that appear in Eq. (4) are significantly off-resonant, with contributions scaling as $(\Omega_g/\delta)^2$, where we note that $\Omega_g \ll \delta$. In the laboratory frame, the conditions in Eq. (6) are equivalent to setting $\delta$ and $\omega_g$ to predominantly drive both the $\omega_r - \omega_g$ and $\omega_r + \omega_g$ sidebands simultaneously, as shown in Fig. 3(c).

Keeping only near-resonant terms gives:

$$\hat{H}_I(t) \approx \hbar \Omega_g S_z \{ J_4 \left( \frac{4\Omega_g}{\delta} \right) \left( \hat{a} e^{-i\omega_r t} + \hat{a}^\dagger e^{i\omega_r t} \right) + J_8 \left( \frac{4\Omega_g}{\delta} \right) \left( \hat{a} e^{-i(j+1)\Delta t} + \hat{a}^\dagger e^{i(j+1)\Delta t} \right) \},$$

which resembles the form of the motional robust polychromatic gates discussed in Refs. [19, 37, 38]. This will generate a gate with $K$ loops if we choose

$$\Delta = 4\Omega_g K^{1/2} \left\{ \frac{(J_4(4\Omega_g/\delta))^2}{j} + \frac{(J_8(4\Omega_g/\delta))^2}{j+1} \right\}^{1/2}.$$  (8)

Since $J_4(4\Omega_g/\delta)$ and $J_8(4\Omega_g/\delta)$ are independent functions, we may optimize the amplitudes of their effective tones by setting the value of $\Omega_g/\delta$. For example, when $j = 1$, we can engineer a gate that is robust to gate duration errors when $J_8(4\Omega_g/\delta) / J_4(4\Omega_g/\delta) = -1$ [38], or the motionally robust gates of Refs. [19, 37] when $J_8(4\Omega_g/\delta) / J_4(4\Omega_g/\delta) = -2$ [37]. These gates are, unfortunately, still sensitive to time-varying qubit frequency shifts.

### IV. QUBIT DECOHERENCE

We model the effects of time-dependent qubit frequency shifts by adding a term $\hat{H}_{z,1}(t) \equiv (\hbar\varepsilon/2) \cos(\omega_z t) \hat{S}_z^{(1)}$ to the ideal Hamiltonian in Eq. (2). Here, we introduce an antisymmetric two-qubit Pauli operator $S_z^{(1)} \equiv \hat{\sigma}_{z,1} - \hat{\sigma}_{z,2}$ in order to represent a differential qubit shift. In the bichromatic interaction picture, keeping only near-resonant terms (assuming $\varepsilon, \omega_z \ll \delta$), $\hat{H}_{z,1}(t)$ can be written as:

$$\hat{H}_{z,1}(t) \approx \frac{\hbar\varepsilon}{2} J_0 \left( \frac{4\Omega_g}{\delta} \right) \cos(\omega_z t) \hat{S}_z^{(1)}.$$  (9)

Note that the above equation is valid for symmetric and antisymmetric Pauli operators. When the value of $\Omega_g/\delta$ is set to one of the zeros of the $J_0$ Bessel function, the expression in Eq. (9) goes to zero and the qubit frequency shifts do not contribute to the dynamics. The off-resonant terms dropped from Eq. (9) all oscillate at integer multiples of $\delta$, such that in the typical case where $\varepsilon, \omega_z \ll \delta$, their effect averages to zero; we refer to this phenomenon as intrinsic dynamical decoupling (IDD) [27]. By tuning $\delta$, $\omega_g$, and $\omega_z$ so that Eqs. (6) are met for a particular value of $j$, and setting $4\Omega_g/\delta \approx 8.65$, the third IDD point (i.e. the third zero of $J_0(4\Omega_g/\delta)$), we perform a gate such that $J_8(4\Omega_g/\delta) / J_4(4\Omega_g/\delta) \approx -1.22$ (see Fig. 4(c)); we will refer to this as the IDD-$j$ gate. The phase space trajectory of an IDD-2 gate is shown in Fig. 4(b). Figure 4(b) also compares the IDD-2 gate’s trajectory to that of a single-tone $\hat{\sigma}_z\hat{\sigma}_z$ gate corresponding to the $J_2$ resonance performed at the first IDD point (here referred to as IDD-single) [27]. While the phase space trajectories of IDD-single and IDD-1 gates are not completely centered on the origin, those of IDD-$j$ gates for $j \geq 2$ are, resulting in less time-averaged spin-motion entanglement, and consequently less impact of motional decoherence on gate fidelity. For all the calculations shown, we use experimentally achievable values of $\Omega_g/2\pi = 1$ kHz and $\omega_g/2\pi = 6.5$ MHz. Here $\omega_g/2\pi = 5$ MHz for the IDD-single gate; for the IDD-$j$ gates, $\omega_g$ is determined by solving Eqs. (6) and (9), giving $\omega_g \sim \omega_r/3$.

In addition to the intrinsic dynamical decoupling effect described above, the IDD-$j$ gates can also be made highly
insensitive to static qubit frequency shifts. These gates produce an effective interaction of the form $\sigma_z \sigma_z$, such that qubit frequency shifts as shown in Eq. (9) commute with the gate operation. As a result, the effect of static shifts can be removed (when $\varepsilon \ll \delta$) by performing a $K = 2$ loop gate with a qubit $\pi$ rotation in between loops (a Walsh modulation of index 1) [34]. Figures 2(a) and 2(b) show numerical simulations (including all terms in (a) Walsh modulation of index 1) [34]. Figures 2(a) and 2(b) show numerical simulations (including all terms in (b) Gate infidelity $1 - \mathcal{F}$ versus antisymmetric qubit frequency offset $\varepsilon$ for IDD-single (black dashed) and IDD-2 (solid red) gates with a given gradient strength $\Omega_y$.

FIG. 2. (a) Gate infidelity $1 - \mathcal{F}$ (plotted logarithmically) versus symmetric qubit frequency offset $\varepsilon$ for IDD-single (black dashed) and IDD-2 (solid red) gates with a given gradient strength $\Omega_y$. (b) Gate infidelity $1 - \mathcal{F}$ versus antisymmetric qubit frequency offset $\varepsilon$ for IDD-single (black dashed) and IDD-2 (solid red) gates with a given gradient strength $\Omega_y$. (c) Gate infidelity $1 - \mathcal{F}$ for the same gates versus the frequency $\omega_c$ of a symmetric qubit frequency shift, with $\varepsilon = \Omega_y/5$. Every simulated gate has two phase space loops with a global qubit $\pi$ rotation in between.

versus $\omega_c$, assuming a shift amplitude $\varepsilon = \Omega_y/5$. For $1 - \mathcal{F} \ll 1$, the infidelity scales as $\varepsilon^2$. The numerical simulations shown in Fig. 2 use a 20 $\mu$s Blackman envelope to shape the rising and falling edges of the gradient pulses and the microwave pulses [41]. We turn on the microwave pair first, ramping up the gradient after the microwaves reach steady state, and ramp down in the reverse order at the end of the pulses. This is done because the gate speed is linear in the gradient strength, while it depends on the microwave amplitude as the argument of the two Bessel functions $J_4$ and $J_8$ (see Eq. (7)), causing complicated undesired dynamics during the microwave ramp if the gradient is already present. The errors seen in Fig. 2(c) occur during the microwave rise and fall times, when $\Omega_y$ is not at the IDD point, such that the qubits are vulnerable to frequency fluctuations of the form in $\hat{H}_\mu(t)$. We note that qubit shifts that oscillate at or near $n\delta$ (for integer $n$) appear in the bichromatic interaction picture as static error terms $\alpha \hat{S}_z$ (for even $n$) or $\alpha \hat{S}_y$ (for odd $n$) [27]. Experimentally, qubit frequency fluctuations near $n\delta$ can arise from residual magnetic fields at $\omega_q$ from the currents generating the gradient. Choosing the $J_4$ and $J_8$ resonances to implement the gate makes $n$ even, and so the resulting errors are $\propto \hat{S}_z$ and can be removed as described above (see Sec. VI).

V. MOTIONAL DECOHERENCE

Gates with multiple blue and red sideband pairs, such as those presented in this work, have reduced sensitivity
to motional frequency offsets. For example, an IDD-\(j\) gate is a linear superposition of a \(j\) and a \(j+1\) loop IDD-single gate, each with amplitudes of opposite signs. A motional frequency offset \(\nu\) shifts the secular frequency such that \(\omega_r \rightarrow \omega_r + \nu\), resulting in a residual displacement in phase space at the end of the gate. With nonzero \(\nu\), the superposed gates experience opposite displacements in phase space which coherently cancel each other. As shown in Fig. 3(a), this results in reduced sensitivity to \(\nu\) [19, 38]. Fig. 3(b) shows that this coherent error cancellation can provide reduced sensitivity to \(\nu\) by increasing either the number of loops \(K\) or the order \(j\) of the gate. The infidelity due to an offset \(\nu\) will remain constant for an increased \(\nu\) if \(t_G\) is also increased proportionally; this remains true whether the increased \(\nu\) is associated with more loops \(K\) or larger values of \(j\). In Figure 3(b), we plot Bell state infidelity for a variety of different gates versus the dimensionless motional frequency offset \(\nu/\Omega_g\), normalized by the dimensionless gate duration \(t_G\Omega_g/2\pi\). With this normalization, the different gates fall on approximately the same curve of sensitivity to motional frequency offsets. As the gate-time-normalized motional frequency offset becomes larger, the IDD-\(j\) gates have higher fidelity than single tone gates following Walsh sequences, shown in Fig. 3(b) [24].

In Fig. 4, we show the increased robustness to heating and motional dephasing of the IDD-\(j\) gates. We treat these decoherence mechanisms as Markovian, using a Lindblad formalism [42]. Note that for these calculations, we use Eq. (7) to calculate the infidelity; this gives the same motional decoherence effect as the full integration of Eq. (2) (see appendix). Geometric phase gates can be made less sensitive to motional heating by performing more phase space loops, with \(1 - F\) scaling \(\propto 1/t_G\). Therefore, in order to make a relevant comparison to our polychromatic gates, Fig. 4(a) shows the infidelity due to a heating rate of \(\dot{\bar{\nu}} = \Omega_g/100\pi\), versus \(2\pi/\Omega_g t_G\), for the IDD-single, IDD-1, and IDD-2 gates. Similarly, in Fig. 4(b) we compare the same set of gates for a motional dephasing rate of \(\Gamma_g = \Omega_g/100\pi\). Both calculations in Fig. 4 show that, while better than the IDD-single, the IDD-1 gate is not as robust as the IDD-2; this can be understood because the IDD-1 trajectory is not centered on the origin of phase space. For \(j > 2\), however, we find that there is not a significant improvement of \(F\) versus \(t_G\) relative to \(j = 2\). This is because the phase space trajectories of the IDD-\(j\) gates with \(j > 1\) are all centered on the origin, thus saturating improvement to the time-averaged spin-motion entanglement.

VI. RESIDUAL MAGNETIC FIELD FROM GRADIENT

Generating a gradient that oscillates at \(\omega_g\) typically leads to a residual magnetic field that also oscillates at \(\omega_g\). We represent the Hamiltonian of this residual magnetic field as

\[
\hat{H}_z(t) = 2\hbar \Omega_z \cos(\omega_g t) \hat{S}_z,
\]

which adds to the full Hamiltonian, given by Eq. (2). To analyze this field’s effect on our gate, we make the transformation given by Eq. (4). This gives:

\[
\hat{H}_{z,t}(t) = 2\hbar \Omega_z \cos(\omega_g t) \times \left\{ \hat{S}_z \left[ J_0 \left( \frac{4\Omega_g}{\delta} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4\Omega_g}{\delta} \right) \cos(2n\delta t) \right] + 2\hat{S}_y \sum_{n=1}^\infty J_{2n-1} \left( \frac{4\Omega_g}{\delta} \right) \sin(2n-1)\delta t \right\}.
\]

Assuming \(\Omega_z \ll \delta\), we can simplify this equation by dropping far-off-resonant terms. By solving Eq. (8), we find that:

\[
\delta = \frac{\omega_g}{2} - \frac{\Delta}{4}.
\]

Keeping only the near-resonant terms gives:

\[
\hat{H}_{1,z}(t) \approx 2\hbar \Omega_z J_2 \left( \frac{4\Omega_g}{\delta} \right) \cos(\Delta t/2) \hat{S}_z.
\]

Since the residual term is \(\propto \hat{S}_z\), it commutes with the gate and its effect at the end of a single-loop gate, \(t_G = 2\pi/\Delta\), can be described by a unitary operator given by:

\[
\hat{U}_z(t) = \exp \left( -\frac{i}{\hbar} \int_0^{t_G} dt' H_{1,z}(t') \right) = \exp \left( -\frac{4i\Omega_z}{\Delta} J_2 \left( \frac{4\Omega_g}{\delta} \right) \sin(\pi) \hat{S}_z \right) = \hat{I}.
\]
Thus, a residual homogeneous magnetic field at $\omega_g$ (such that $\Omega_\mu \ll \delta$) does not impact the fidelity of the gate. For the gates described in this work, the $J_4$ and $J_8$ resonances were chosen specifically because the near-resonant ($\sim \omega_g$) contributions are $\propto \hat{S}_z$ (see Eq. 11). One could imagine a similar scheme using the $\omega_r \pm \omega_g$ sidebands, and the $J_2$ and $J_4$ resonances. This, however, results in an off-resonant term $\propto \hat{S}_x$ in $H_{I,z}$, as opposed to the term $\propto \hat{S}_z$ in the $J_4$, $J_8$ gate. Since this term does not commute with the gate, it would have to be nulled in order to not affect the fidelity, which would make the scheme significantly more difficult to implement.

VII. POLYCHROMATIC GATES WITH MULTIPLE MICROWAVE PAIRS

The gate presented in this work shows similar resilience to motional decoherence as the laser-free polychromatic gates successfully demonstrated by Webb et al. in Ref. [19], but it also has important advantages. In their experiment, Webb et al. implemented laser-free polychromatic gates by tuning two bichromatic microwave pairs close to the frequency of the sideband of a static gradient ($\omega_r = 0$). This scheme requires a total of 12 oscillating control fields plus a strong static magnetic field gradient [19], whereas the scheme presented here requires only two oscillating control fields, plus a strong, oscillating magnetic field gradient. Importantly, the scheme of Ref. [19] produces unavoidable errors outside the $\Omega_\mu/\omega_r \ll 1$ regime, which limits the achievable gate speed, while our gate scheme has no such limitation. We derive this result using our interaction picture formalism described in the appendix.

Outside of this regime, terms that are higher-order in $\Omega_\mu/\omega_r$, as seen in Eq. (C4), contribute to the dynamics and distort the phase space trajectory. In particular, the appearance of terms that oscillate at exactly $\omega_r$ prevent the motion from returning to its original state, leaving residual entanglement. This suggests that the implementation in Ref. [19] is limited to the weak microwave field regime. We illustrate this effect in Fig. 5 where we simulate the trajectory of Eq. (C4) for a static gradient with increasing values of $\Omega_\mu$, with no added noise. We can see that for the $\Omega_\mu/\omega_r \ll 1$ regime, the phase space trajectory follows the two-tone trajectory described in Ref. [37] and $F \rightarrow 1$. When $\Omega_\mu/\omega_r \sim 1$, however, the trajectory becomes distorted and the gate fidelity decreases. Since the speed of the gate in the $\Omega_\mu \ll \delta$ regime is $\propto \Omega_\mu$, this indicates that for a limited value of $\Omega_\mu$—typically the case in laser-free experiments—the maximum speed of a polychromatic gate performed via multiple pairs of microwave fields is slower than can be achieved with the oscillating gradient method presented here.

VIII. CONCLUSION

In this work, we described a new type of laser-free trapped ion entangling gate that can be tuned to be simultaneously robust to motional decoherence and qubit frequency shifts. The gate requires only two microwave magnetic fields and one near-motional-frequency magnetic field gradient. In addition to using analytic expressions, we numerically demonstrated this robustness. The design should enable higher gate fidelities for laser-free entangling gates without substantially increasing gate duration or the complexity of the required driving fields. We further demonstrated the advantages of our gate by showing that generating laser-free, polychromatic entangling gates using multiple pairs of microwave fields grows increasingly difficult when the microwave Rabi frequencies become comparable to the trap’s secular frequency.

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Appendix A: Laser-free Hamiltonian

We consider a general Hamiltonian for laser-free gates between two trapped ions with identical qubit frequen-
cies: 

\[ \hat{H}_{\text{lab}}(t) = \frac{\hbar \omega_i}{2} \hat{S}_z + \hbar \omega_r \hat{a} \hat{a} + 2 \hbar \Omega_g f(t) \hat{S}_j \{ \hat{a} + \hat{a}^\dagger \} \]

\[ + 2 \hbar \Omega_g \hat{S}_j \sum_n c_n \{ \cos(\omega_0 + \delta_n) t) \]

\[ + \cos([\omega_0 - \delta_n] t) \} \}, \]

(A1)

where \( i \in \{ x, y \} \) and \( j \in \{ x, y, z \} \). We define two-ion Pauli spin operators as \( \hat{S}_j \equiv \sigma_{r,1} + \sigma_{r,2} \). We have taken \( z \) to be the qubit quantization axis and \( \omega_0 \) to be the qubit frequency. Here we have assumed an ion crystal whose internal states are coupled via a motional mode of the same order of magnitude as \( \hbar \omega_r \) to Eq. (A2) when frequencies near \( 2 \omega_0 \) are dropped (see Eq. [A1]). Furthermore, we make the rotating wave approximation to eliminate terms oscillating with frequencies near \( 2 \omega_0 \). This gives the interaction Hamiltonian:

\[ \hat{H}(t) = 2 \hbar \Omega_g \hat{S}_j \sum_n c_n \cos(\delta_n t) \]

\[ + 2 \hbar \Omega_g f(t) \hat{S}_j \{ \hat{a} e^{-i \omega_r t} + \hat{a}^\dagger e^{i \omega_r t} \} \],

(A2)

which is Eq. (2) from the main text when \( i = x \) and \( j = z \). Note that when \( j \in \{ x, y \} \), \( f(t) \) changes from Eq. (A1) to Eq. (A2) when frequencies near \( 2 \omega_0 \) are dropped (see Ref. [27] for more details).

**Appendix B: Bichromatic interaction picture**

For completeness, we summarize an analysis of geometric phase gates for large microwave magnetic fields \( \Omega_\mu \sim \omega_r \) demonstrated originally in Ref. [27]. Assuming a Hamiltonian that takes the form of Eq. (2), representing a system with a bichromatic magnetic field pair and a (static or oscillatory) magnetic field gradient, we obtain:

\[ \hat{H}(t) = \hat{H}_\mu(t) + \hat{H}_g(t) \]

\[ = 2 \hbar \Omega_g \hat{S}_j \sum_n c_n \cos(\delta_n t) + 2 \hbar \Omega_g f(t) \hat{S}_j \{ \hat{a} e^{-i \omega_r t} + \hat{a}^\dagger e^{i \omega_r t} \} \}, \]

(B1)

where we have dropped the subscript of \( \delta \), since there is only one microwave pair. In order to exactly account for the dynamics caused by the larger of the two terms in this equation (\( \hat{H}_\mu(t) \), the bichromatic field term), we note that the time propagator for this field alone is exactly solvable:

\[ \hat{U}(t) = \exp \left( - \frac{2 i \hbar \Omega \hat{S}_j \int_0^t dt' \cos(\delta t') \right) \]

\[ = \exp \left( - \frac{2 \hbar \Omega \nu}{\delta} \sin(\delta t) \hat{S}_j \right). \]

(B2)

We can then transform into the interaction picture with respect to the bichromatic microwave term:

\[ \hat{H}_I = \hat{U}(t) \hat{H}_g(t) \hat{U}^\dagger(t) \]

\[ = 2 \hbar \Omega_g f(t) \{ \hat{a} e^{-i \omega_r t} + \hat{a}^\dagger e^{i \omega_r t} \} \hat{U}^\dagger(t) \hat{S}_j \hat{U}(t). \]

(B3)

Applying the Jacobi-Anger expansion (see Ref. [27]),

\[ \hat{U}^\dagger(t) \hat{S}_j \hat{U}(t) = \{ \hat{S}_j \left[ J_0 \left( \frac{4 \Omega_\mu}{\delta} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4 \Omega_\mu}{\delta} \right) \cos(2n \delta t) \right] \]

\[ - 2 \epsilon_{ijk} \hat{S}_k \sum_{n=1}^\infty J_{2n-1} \left( \frac{4 \Omega_\mu}{\delta} \right) \sin[(2n - 1) \delta t] \}, \]

(B4)

giving

\[ \hat{H}_I(t) = 2 \hbar \Omega_g f(t) \{ \hat{a} e^{-i \omega_r t} + \hat{a}^\dagger e^{i \omega_r t} \} \{ \hat{S}_j \left[ J_0 \left( \frac{4 \Omega_\mu}{\delta} \right) \right] \]

\[ + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4 \Omega_\mu}{\delta} \right) \cos(2n \delta t) \}

\[ - 2 \epsilon_{ijk} \hat{S}_k \sum_{n=1}^\infty J_{2n-1} \left( \frac{4 \Omega_\mu}{\delta} \right) \sin[(2n - 1) \delta t] \}. \]

(B5)

This shows a series of resonances corresponding to \( \sigma_z \sigma_z \) and \( \sigma_x \sigma_x \) (Mølmer-Sørensen) gates when the sideband frequency is an even or odd integer multiple of \( \delta \), respectively.

**Appendix C: Polychromatic gates with multiple pairs of microwaves**

The Hamiltonian for the system containing multiple microwaves pairs used in [19] is given by:

\[ \hat{H}(t) = \hat{H}_{\mu,1}(t) + \hat{H}_{\mu,2} + \hat{H}_g(t) \]

\[ = 2 \hbar \Omega_{\mu,1} \hat{S}_c \cos(\delta t) + 2 \hbar \Omega_{\mu,2} \hat{S}_c \cos(\delta_2 t) \]

\[ + 2 \hbar \Omega_g \hat{S}_z \{ \hat{a} e^{-i \omega_r t} + \hat{a}^\dagger e^{i \omega_r t} \}. \]

(C1)
It is helpful to study the dynamics in the interaction picture with respect to both of the microwave field terms, which are exact. This gives:

\[ H_1(t) = \hat{U}_1(t) \hat{U}_2^\dagger(t) \hat{H}_g(t) \hat{U}_2(t) \hat{U}_1(t), \tag{C2} \]

where

\[ U_j(t) = \exp \left( - \frac{i}{\hbar} \int_0^t dt' H_{\mu,j}(t') \right) = \exp \left( - \frac{2i\Omega_c}{\delta_j} \sin(\delta_j t) \hat{S}_x \right). \tag{C3} \]

Focusing on the Pauli operators, and using Eq. (B4) twice we obtain:

\[ \hat{U}_1(t) \hat{U}_2^\dagger(t) \hat{S}_z \hat{U}_2(t) \hat{U}_1(t) = \]
\[ \hat{S}_z \left\{ \left[ J_0 \left( \frac{4\Omega_c}{\delta_1} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4\Omega_c C_1}{\delta_1} \right) \cos(2n\delta_1 t) \right] \right. \]
\[ \times \left[ J_0 \left( \frac{4\Omega_c}{\delta_2} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4\Omega_c C_2}{\delta_2} \right) \cos(2n\delta_2 t) \right] \]
\[ - 4 \sum_{n,n'=1} \left[ J_{2n-1} \left( \frac{4\Omega_c C_1}{\delta_1} \right) J_{2n'-1} \left( \frac{4\Omega_c C_2}{\delta_2} \right) \right] \]
\[ \times \sin([2n-1] \delta_1 t \sin([2n'-1] \delta_2 t) \right) \}
\[ + 2 \hat{S}_y \left\{ \sum_{n=1}^\infty J_{2n-1} \left( \frac{4\Omega_c C_1}{\delta_1} \right) \sin([2n-1] \delta_1 t) \right\} \]
\[ \times \left[ J_0 \left( \frac{4\Omega_c}{\delta_2} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4\Omega_c C_2}{\delta_2} \right) \cos(2n\delta_2 t) \right] \]
\[ + \sum_{n=1}^\infty J_{2n-1} \left( \frac{4\Omega_c C_2}{\delta_2} \right) \sin([2n-1] \delta_2 t) \right] \}
\[ \times \left[ J_0 \left( \frac{4\Omega_c}{\delta_1} \right) + 2 \sum_{n=1}^\infty J_{2n} \left( \frac{4\Omega_c C_1}{\delta_1} \right) \cos(2n\delta_1 t) \right] \}. \tag{C4} \]

This equation can be simplified for the case considered by Webb et al. 19, where \( \Omega_\mu \ll \omega_r, \delta_1 = \omega_r - \Delta, \delta_2 = \omega_r - 2\Delta. \) Here \( \Delta \) is of the same order as \( \Omega_g. \) Noting that \( J_n(x) \rightarrow (\frac{C}{x})^n / n! \) as \( x \rightarrow 0, \) and keeping only the terms that are first order in \( \Omega_\mu/\omega_r, \) we obtain:

\[ \hat{U}_1^\dagger(t) \hat{U}_2^\dagger(t) \hat{S}_z \hat{U}_2(t) \hat{U}_1(t) \]
\[ \approx \hat{S}_z + \frac{4\Omega_c}{\omega_r} \hat{S}_y \left\{ c_1 \sin(\omega_r - \Delta t) + c_2 \sin(\omega_r - 2\Delta t) \right\}, \tag{C5} \]

which, if we neglect the terms oscillating at frequencies on the order of \( \omega_r, \) we get an interaction picture Hamiltonian:

\[ \hat{H}_I(t) = \frac{4\hbar \Omega_c}{\omega_r} \hat{S}_y \left\{ \hat{a}^\dagger (c_1 e^{i\Delta t} + c_2 e^{2i\Delta t}) - \hat{a} (c_1 e^{-i\Delta t} + c_2 e^{-2i\Delta t}) \right\}, \tag{C6} \]

giving the form of a polychromatic gate 37. This means that in the \( \Omega_\mu \ll \omega_r \) limit, as is the case in Ref. 19, this is a valid technique for performing laser-free polychromatic gates. If terms in Eq. (C1) that are higher-order in \( \Omega_\mu/\omega_r \) contribute, terms that oscillate at exactly \( \omega_r \) appear, such as

\[ J_1 \left( \frac{4\Omega_c C_2}{\omega_r} \right) J_2 \left( \frac{4\Omega_c C_1}{\omega_r} \right) \sin(\omega_r - 2\Delta t) \cos(2(\omega_r - \Delta) t) \]
\[ = J_1 \left( \frac{4\Omega_c C_2}{\omega_r} \right) J_2 \left( \frac{4\Omega_c C_1}{\omega_r} \right) \left\{ \sin(3\omega_r - 4\Delta t) - \sin(\omega_r t) \right\}. \tag{C7} \]

These terms, as discussed in the text, prevent the trajectory from returning to the origin in phase space.

**Appendix D: Decoherence due to Bath Coupling**

In this section, we show that for the system described in the paper, we can calculate the infidelities due to Markovian heating and motional dephasing by numerically calculating the (significantly less computationally intensive) master equation for \( \hat{H}_I \) (neglecting terms rotating near \( \omega_r \)) rather than the full Hamiltonian given by Eq. (2). This is because the unitary transformation given by Eq. (B4) commutes with the Lindblad operators that represent heating and motional dephasing. The full master equation for the time evolution of the full Hamiltonian, Eq. (2), including heating and motional dephasing, is:

\[ \dot{\hat{\rho}}(t) = -\frac{i}{\hbar} \left[ \hat{H}(t), \hat{\rho}(t) \right] + \dot{\gamma} \left\{ \hat{a} \hat{a}^\dagger \hat{\rho}(t) \hat{a}^\dagger + \hat{a}^\dagger \hat{a} \hat{\rho}(t) \hat{a} \right. \]
\[ - \frac{1}{2}(\hat{a}^\dagger \hat{a}^\dagger + \hat{a}^\dagger \hat{a}) \hat{\rho}(t) - \frac{1}{2} \hat{\rho}(t)(\hat{a}^\dagger \hat{a}^\dagger + \hat{a}^\dagger \hat{a}) \}
\[ + \Gamma_d \left\{ (\hat{a}^\dagger \hat{a}) \hat{\rho}(t) \hat{a}^\dagger \hat{a} - \frac{1}{2} (\hat{a}^\dagger \hat{a})^2 \hat{\rho}(t) - \frac{1}{2} \hat{\rho}(t)(\hat{a}^\dagger \hat{a})^2 \right\}, \tag{D1} \]

where \( \dot{\gamma} \) is the heating rate of the system and \( \Gamma_d \) is the motional dephasing rate. Making the unitary transformation defined by Eq. (B4), we can solve for the density matrix in the interaction picture:

\[ \hat{\rho}_I(t) = \hat{U}_I^\dagger(t) \hat{\rho}(t) \hat{U}_I(t). \tag{D2} \]

Since the above transformation commutes with both the heating and motional dephasing operators, the interaction picture master equation is simply:

\[ \dot{\hat{\rho}}_I(t) = -\frac{i}{\hbar} \left[ \hat{H}_I(t), \hat{\rho}_I(t) \right] + \dot{\gamma} \left\{ \hat{a} \hat{a}^\dagger \hat{\rho}_I(t) \hat{a}^\dagger + \hat{a}^\dagger \hat{a} \hat{\rho}_I(t) \hat{a} \right. \]
\[ - \frac{1}{2}(\hat{a}^\dagger \hat{a}^\dagger + \hat{a}^\dagger \hat{a}) \hat{\rho}_I(t) - \frac{1}{2} \hat{\rho}_I(t)(\hat{a}^\dagger \hat{a}^\dagger + \hat{a}^\dagger \hat{a}) \}
\[ + \Gamma_d \left\{ (\hat{a}^\dagger \hat{a} \hat{\rho}_I(t) \hat{a}^\dagger \hat{a} - \frac{1}{2} (\hat{a}^\dagger \hat{a})^2 \hat{\rho}_I(t) - \frac{1}{2} \hat{\rho}_I(t)(\hat{a}^\dagger \hat{a})^2 \right\}. \tag{D3} \]
The fast rotating terms in $H_f$ can be dropped with an effect scaling $\propto (\Omega_f/\omega_r)^2$. This is demonstrated by the calculations of the full numerical Hamiltonian shown for the pure state systems in this work. Numerically integrating Eq. (2) allows us to calculate $\hat{\rho}_f(t_G)$, where $t_G$ is the gate duration, while accurately including the effects of Markovian heating and motional dephasing. As with the pure state calculations, when $\hat{U}(t_G) \rightarrow \hat{I}$, $\hat{\rho}_f(t_G) \rightarrow \hat{\rho}(t_G)$, meaning that our reduced calculation gives the same answer as would performing the full numerical integration of Eq. (11), as long as the pure state calculation is also valid.

[1] J. I. Cirac and P. Zoller, “Quantum computations with cold trapped ions,” Phys. Rev. Lett. 74, 4091 (1995).
[2] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, “Demonstration of a fundamental quantum logic gate,” Phys. Rev. Lett. 75, 4714 (1995).
[3] M. A. Nielsen and I. L. Chuang, Quantum computation and quantum information (Cambridge University Press, 2010).
[4] H. Häffner, C. F. Roos, and R. Blatt, “Quantum computing with trapped ions,” Phys. Rep. 469, 155 (2008).
[5] R. Blatt and D. J. Wineland, “Entangled states of trapped atomic ions,” Nature 453, 1008 (2008).
[6] T. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guindon, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas, “High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit,” Phys. Rev. Lett. 113, 220501 (2014).
[7] C. J. Ballance, T. P. Harty, N. M. Linke, M. A. Sepiol, and D. M. Lucas, “High-fidelity quantum logic gates using trapped-ion hyperfine qubits,” Phys. Rev. Lett. 117, 060504 (2016).
[8] J. P. Gaebler, T. R. Tan, Y. Lin, Y. Wan, R. Bowler, A. C. Keith, S. Glancy, K. Coakley, E. Knill, D. Leibfried, and D. J. Wineland, “High-fidelity universal gate set for $^{9}\text{Be}^{+}$ ion qubits,” Phys. Rev. Lett. 117, 060505 (2016).
[9] D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof, “Experimental issues in coherent quantum-state manipulation of trapped atomic ions,” J. Res. Natl. Inst. Stand. and Technol. 103, 259 (1998).
[10] K. Mølmer and A. Sørensen, “Multiparticle entanglement of hot trapped ions,” Phys. Rev. Lett. 82, 1835 (1999).
[11] A. Sørensen and K. Mølmer, “Entanglement and quantum computation with ions in thermal motion,” Phys. Rev. A 62, 022311 (2000).
[12] D. Leibfried, B. DeMarco, V. Meyer, D. M. Lucas, M. Barrett, J. Britton, W. M. Itano, B. Jelenković, C. Langer, T. Rosenband, and D. J. Wineland, “Experimental demonstration of a robust, high-fidelity geometric two-ion-qubit phase gate,” Nature 422, 412 (2003).
[13] R. Ozeri, W. M. Itano, R. B. Blakestad, J. Britton, J. Chiaverini, J. D. Jost, C. Langer, D. Leibfried, R. Reichle, S. Seidelin, J. H. Wesenberg, and D. J. Wineland, “Errors in trapped-ion quantum gates due to spontaneous photon scattering,” Phys. Rev. A 75, 042329 (2007).
[14] F. Mintert and C. Wunderlich, “Ion-trap quantum logic using long-wavelength radiation,” Phys. Rev. Lett. 87, 257904 (2001).
[15] A. Khromova, Ch. Piltz, B. Scharfenberger, T. F. Gloger, M. Johanning, A. F. Varón, and C. Wunderlich, “Designer spin pseudomolecule implemented with trapped ions in a magnetic gradient,” Phys. Rev. Lett. 108, 220502 (2012).
[16] K. Lake, S. Weidt, J. Randall, E. D. Standing, S. C. Webster, and W. K. Hensinger, “Generation of spin-motion entanglement in a trapped ion using long-wavelength radiation,” Phys. Rev. A 91, 012319 (2015).
[17] J. Randall, S. Weidt, E. D. Standing, K. Lake, S. C. Webster, D. F. Murgia, T. Navickas, K. Roth, and W. K. Hensinger, “Efficient preparation and detection of microwave dressed-state qubits and qutrits with trapped ions,” Phys. Rev. A 91, 012322 (2015).
[18] S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, “Trapped-ion quantum logic with global radiation fields,” Phys. Rev. Lett. 117, 220501 (2016).
[19] A. E. Webb, S. C. Webster, S. Collingbourne, D. Breault, A. M. Lawrence, S. Weidt, F. Mintert, and W. K. Hensinger, “Resilient entangling gates for trapped ions,” Phys. Rev. Lett. 121, 180501 (2018).
[20] C. Ospelkaus, C. Langer, J. M. Amini, K. R. Brown, D. Leibfried, and D. J. Wineland, “Trapped-ion quantum logic gates based on oscillating magnetic fields,” Phys. Rev. Lett. 101, 090502 (2008).
[21] C. Ospelkaus, U. Warring, Y. Colombe, K. R. Brown, J. M. Amini, D. Leibfried, and D. J. Wineland, “Microwave quantum logic gates for trapped ions,” Nature 476, 181 (2011).
[22] T. P. Harty, M. A. Sepiol, D. T. C. Allcock, C. J. Ballance, J. E. Tarlton, and D. M. Lucas, “High-fidelity trapped-ion quantum logic using near-field microwaves,” Phys. Rev. Lett. 117, 140501 (2016).
[23] S. Wolk and C. Wunderlich, “Quantum dynamics of trapped ions in a dynamic field gradient using dressed states,” New J. Phys. 19, 083021 (2017).
[24] H. Hahn, G. Zarantonello, M. Schulte, A. Bautista-Salvador, K. Hammerer, and C. Ospelkaus, “Integrated $^{9}\text{Be}^{+}$ multi-qubit gate device for the ion-trap quantum computer,” New J. Phys. Quantum Information 5, 70 (2019).
[25] G. Zarantonello, H. Hahn, J. Morgner, M. Schulte, A. Bautista-Salvador, R. F. Werner, K. Hammerer, and C. Ospelkaus, “Robust and resource-efficient microwave near-field entangling $^{9}\text{Be}^{+}$ gate,” Phys. Rev. Lett. 123, 260503 (2019).
[26] J. Chiaverini and W. E. Lybarger, “Laserless trapped-ion quantum simulations without spontaneous scattering using microtrap arrays,” Phys. Rev. A 77, 022324 (2008).
[27] R. T. Sutherland, R. Srinivas, S. C. Burd, D. Leibfried, A. C. Wilson, D. J. Wineland, T. C. Allcock, D. H. Slichter, and S. B. Libby, “Versatile laser-free trapped-ion quantum logic gates using trapped-ion hyperfine qubits,” Phys. Rev. A 77, 022324 (2008).
D. H. Slichter, “Trapped-ion spin-motion coupling with microwaves and a near-motional oscillating magnetic field gradient,” Phys. Rev. Lett. 122, 163201 (2019).
[29] L. Viola and S. Lloyd, “Dynamical suppression of decoherence in two-state quantum systems,” Phys. Rev. A 58, 2733 (1998).
[30] L. Viola, E. Knill, and S. Lloyd, “Dynamical decoupling of open quantum systems,” Phys. Rev. Lett. 82, 2417 (1999).
[31] N. Timoney, I. Baumgart, M. Johanning, A. F. Varón, M. B. Plenio, A. Retzker, and C. Wunderlich, “Quantum gates and memory using microwave-dressed states,” Nature 476, 185 (2011).
[32] A. Bermudez, P. O. Schmidt, M. B. Plenio, and A. Retzker, “Robust trapped-ion quantum logic gates by continuous dynamical decoupling,” Phys. Rev. A 85, 040302 (2012).
[33] M. Johanning, A. Braun, N. Timoney, V. Elman, W. Neuhauser, and C. Wunderlich, “Individual addressing of trapped ions and coupling of motional and spin states using rf radiation,” Phys. Rev. Lett. 102, 073004 (2009).
[34] D. Hayes, S. M. Clark, S. Debnath, D. Hucul, I. V. Inleik, K. W. Lee, Q. Quraishi, and C. Monroe, “Coherent error suppression in multiqubit entangling gates,” Phys. Rev. Lett. 109, 020503 (2012).
[35] T. J. Green and M. J. Biercuk, “Phase-modulated decoupling and error suppression in qubit-oscillator systems,” Phys. Rev. Lett. 114, 120502 (2015).
[36] P. H. Leung, K. A. Landsman, C. Figgatt, N. M. Linke, C. Monroe, and K. R. Brown, “Robust 2-qubit gates in a linear ion crystal using a frequency-modulated driving force,” Phys. Rev. Lett. 120, 020501 (2018).
[37] F. Haddadfarshi and F. Mintert, “High fidelity quantum gates of trapped ions in the presence of motional heating,” New J. Phys. 18, 123007 (2016).
[38] Y. Shapira, R. Shaniv, T. Manovitz, N. Akerman, and R. Ozeri, “Robust entanglement gates for trapped-ion qubits,” Phys. Rev. Lett. 121, 180502 (2018).
[39] D. Jonathan, M. B. Plenio, and P. L. Knight, “Fast quantum gates for cold trapped ions,” Phys. Rev. A 62, 042307 (2000).
[40] C. F. Roos, “Ion trap quantum gates with amplitude-modulated laser beams,” New J. Phys. 10, 013002 (2008).
[41] R. B. Blackman and J. W. Tukey, “The measurement of power spectra from the point of view of communications engineering part i,” Bell Syst. Tech. J 37, 185 (1958).
[42] H. Breuer and F. Petruccione, The theory of open quantum systems (Oxford University Press on Demand, 2002).