High-fidelity laser-free universal control of trapped ion qubits

Universal control of multiple qubits—the ability to entangle qubits and to perform arbitrary individual qubit operations—is a fundamental resource for quantum computing, simulation and networking. Qubits realized in trapped atomic ions have shown the highest-fidelity two-qubit entangling operations so far. Universal control of trapped ion qubits has been separately demonstrated using tightly focused laser beams or by moving ions with respect to laser beams, but at lower fidelities. Laser-free entangling methods may offer improved scalability by harnessing microwave technology developed for wireless communications, but so far their performance has lagged the best reported laser-based approaches. Here we demonstrate high-fidelity laser-free universal control of two trapped-ion qubits by creating both symmetric and antisymmetric maximally entangled states with fidelities of and per cent confidence level, corrected for initialization error. We use a scheme based on radiofrequency magnetic field gradients combined with microwave magnetic fields that is robust against multiple sources of decoherence and usable with essentially any trapped ion species. The scheme has the potential to perform simultaneous entangling operations on multiple pairs of ions in a large-scale trapped-ion quantum processor without increasing control signal power or complexity. Combining this technology with low-power laser light delivered via trap-integrated photonics and trap-integrated photon detectors for qubit readout provides an opportunity for scalable, high-fidelity, fully chip-integrated trapped-ion quantum computing.

In trapped-ion systems, the entangling interactions required for universal control typically rely on an effective qubit–qubit coupling mediated by the shared motion of the ions’ zero-point motion (usually a few nanometres), commonly generated using laser light with wavelengths of a few hundred nanometres. Laser light can also be tightly focused to illuminate specific ions, providing individual qubit control. Universal control of two trapped-ion qubits by creating both symmetric and antisymmetric maximally entangled states with fidelities of and respectively (68 per cent confidence level), corrected for initialization error. We use a scheme based on radiofrequency magnetic field gradients combined with microwave magnetic fields that is robust against multiple sources of decoherence and usable with essentially any trapped ion species. The scheme has the potential to perform simultaneous entangling operations on multiple pairs of ions in a large-scale trapped-ion quantum processor without increasing control signal power or complexity. Combining this technology with low-power laser light delivered via trap-integrated photonics and trap-integrated photon detectors for qubit readout provides an opportunity for scalable, high-fidelity, fully chip-integrated trapped-ion quantum computing.

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interaction. We use this universal control to create antisymmetric Bell states—which requires individual qubit control—with a fidelity of 0.9977±0.0013, corrected for initialization error, which is, to the best of our knowledge, the highest so far in any qubit platform.

The entangling operation relies on control signals at three frequencies, as shown in Fig. 1a. A strong magnetic field gradient with amplitude 152(15) T m⁻¹ oscillating at frequency ωₐ = 2π × 6.9 MHz, close to the frequency ω₀ of one of the ions’ out-of-phase radial (transverse to the trap axis) motional modes at ω₀ = 2π × 6.9 MHz, is combined with two additional weaker microwave magnetic fields, symmetrically detuned by δ from the qubit frequency ω₀ = 2π × 1.326 GHz, which is shifted from its nominal value of ω₀ by residual magnetic fields oscillating at ω₀. Previous laser-free entanglement demonstrations have required two high-power signals at gigahertz (rather than megahertz) frequencies to generate large gradients, or eight microwave fields (four per qubit) along with a strong static magnetic field gradient.

Choosing δ = (ω₀ − ωₐ)/2 + Δ/2, where |Δ| ≪ |ω₀ − ωₐ| is a small offset frequency, the slowly rotating terms generate the interaction (Supplementary Information)

\[
\hat{H}_{\text{int}}(t) = \hbar \Omega / 2 \frac{4 \Omega / \delta}{\Omega / 2} (\hat{b}_1 - \hat{b}_2)(\hat{a}e^{i\delta t} + \hat{a}^\dagger e^{-i\delta t}),
\]

which is used to implement a geometric phase gate, entangling the ion states via their shared motion with an effective δ.a₂ coupling. Here Ωₚ and Ωₚ are proportional to the amplitude of the radiofrequency gradient and the microwave fields, respectively. The nth order of the first kind, the Pauli operator δₐ acts on ion i, δ.∆ is the annihilation (creation) operators for the ions’ selected motional mode, h is the reduced Planck’s constant, and t is the interaction duration. By tuning the amplitude Ω of the two microwave fields to an appropriate value (an ‘intrinsic dynamical decoupling’ or ‘IDD’ point), the qubits are dynamically decoupled from dephasing noise at frequencies well below δ, without requiring any additional control fields. The microwave fields modulate the qubit state such that the effect of low-frequency dephasing noise on the qubit is multiplied by a prefactor of Jₚ(4Ω/δ); the IDD points occur when Jₚ is set such that Jₚ(4Ω/δ) = 0. We can also interleave the application of the interaction in equation (1) with a sequence of global qubit π pulses. These pulses suppress errors due to static or slowly varying (relative to 1/Δ) qubit frequency offsets, which are proportional to δₐ and thus commute with the entangling interaction (see Supplementary Information). These same π pulses simultaneously implement Walsh modulation, which provides robustness to static offsets and slowly varying (relative to 1/Δ) drifts in the motional frequency or in the control field amplitudes (Supplementary Information). This combination of techniques yields an entangling interaction with substantial protection against decoherence of both the qubit and the ion motion, as well as experimental miscalibrations. Although our method can also generate an effective δₐδₐ interaction with a different choice of δ, such an interaction would not commute with δₐ errors and is therefore less desirable.

The experimental setup is similar to that in ref. 41, with radiofrequency and microwave control currents, as well as trapping voltages, applied to electroplated gold electrodes on a surface-electrode trap as shown in Fig. 1b. The trap is cooled to about 15 K, and we perform our operations on two ²⁵Mg⁺ ions held approximately 30 μm above the trap surface. We use the |F = 3, m_F = 3⟩ ≡ |↓⟩ and |F = 2, m_F = 2⟩ ≡ |↑⟩ states within the ions’ magnetic ground-state hyperfine manifolds as our qubit states, where F is the total angular momentum and m_F is its projection along the quantization axis defined by a 21.3 μT static magnetic field. We present complete details of the experimental setup in the Supplementary Information.

Our scheme requires a magnetic-field-sensitive qubit transition, so the qubit coherence time is limited by magnetic field fluctuations. We investigate the performance of IDD, which should reduce the impacts of such fluctuations, by observing the qubit coherence of a single ion in a spin-echo experiment without applying the oscillating gradient. We compare two cases: either no fields are applied during the spin-echo arms, or we apply two microwave fields, symmetrically detuned about the qubit frequency by δ, during both arms of the spin echo. The amplitudes of these fields are set to the IDD point Ω / δ = 6.01, where Jₚ(4Ω / δ) = 0 and the effects of low-frequency dephasing noise are thus suppressed. Figure 2a shows that including IDD during the spin-echo arms increases the spin-echo coherence time by more than an order of magnitude. As the gradient at ωₐ is not being applied, these microwave fields realize IDD but do not drive qubit-motion coupling.

Our entangling operation ideally transforms the initial state |↑ + i⟩ to the symmetric |(↑↑⟩ + |↓↓⟩)| Bell state. We generate this entangling operation by applying the gradient and microwave fields as shown in Fig. 1a, using a sequence of eight pulses of simultaneously applied radiofrequency and microwave currents, interleaved with five qubit π pulses, and a π/2 pulse at the beginning and end of the sequence (Supplementary Fig. 2). This entire operation has a total duration of 740 μs (Supplementary Information). To achieve the highest fidelities, we sideband-cool both the motional mode used for the entangling operation and the out-of-phase axial mode beforehand (Supplementary Information).
The fidelity of the prepared state is determined by a parity analysis method\(^{44}\) (Supplementary Information). We measure the probabilities \(P_0, P_1\) and \(P_2\) of finding 0, 1 or 2 ions in \(\uparrow\rangle\), respectively, either immediately after the entangling sequence, or after a subsequent \(n/2\) analysis pulse with a variable phase. In the latter case, we determine the parity \(P_0 + P_2 - P_1\) as a function of the analysis pulse phase as shown in Fig. 3a. We use these data to determine the Bell-state fidelity using maximum likelihood estimation.

To characterize the performance of the entangling operation, we seek to estimate the fidelity with which the operation could create a Bell state from a pure unentangled input state. As the experimental input states were not perfectly pure, we correct our reported Bell-state fidelities for initialization outside the \(\{\uparrow\rangle, \uparrow\rangle\}\) manifold that occurs with probability 3.5(2) \times 10^{-1} per qubit (Supplementary Information). Owing to statistical uncertainty in both the raw fidelity estimate, which is constrained to be between 0 and 1 and the estimate of the state initialization error, it is possible to calculate a corrected fidelity greater than 1, in which case we truncate the estimate to the physical maximum of 1. We recorded multiple independent datasets while adjusting experimental parameters to optimize the fidelity. To avoid selection bias in choosing which dataset to report, we divided each dataset in half deterministically and used the extracted fidelity of one half as a ‘trigger’. The fidelities reported here are determined by selecting the dataset with the highest ‘trigger’ fidelity and reporting the fidelity estimated only from the other half of that dataset. To characterize the uncertainty in the estimated fidelity, we performed bootstrapping of the data. Analysis details are presented in the Supplementary Information.

The estimated fidelity of the state produced (ideally \(|\Phi\rangle\)) for the dataset with the highest ‘trigger’ fidelity, corrected for the initialization error, was 1. From the distribution of bootstrapped fidelities, we determined a 68% confidence interval on the fidelity of [0.9983, 1] and a median bootstrap fidelity of 1. As an additional cross-check, we calculated the fidelity using an unbiased linear estimator instead of the maximum likelihood parity analysis, obtaining consistent results (Supplementary Information). In Fig. 3b, we compare the Bell-state fidelity and confidence interval to those of the highest-fidelity entangled states generated by laser-based\(^{24}\) and laser-free\(^{30,39}\) methods. We estimate that the leading sources of infidelity are decoherence of the ion motion such as motional dephasing, motional frequency drifts and motional heating, giving a total estimated infidelity of approximately 7 \times 10^{-5}, on the basis of independent calibrations and numerical simulations (Supplementary Information). These errors are consistent with the experimental results given the uncertainty in the fidelity estimate. The motional errors could in principle be reduced further by increasing the interaction strength, performing a gate sequence with more phase-space loops or by using more complicated phase-space trajectories\(^{41}\). Future work will aim to reduce the uncertainty in the fidelity estimate and to characterize the entangling interaction using randomized benchmarking\(^{42,43}\).

We also investigate the entangling operation’s robustness to qubit frequency offsets that cause errors of the form \(\sigma_x \epsilon\), which commute with the interaction in equation (1). The pulses in the gate sequence and the IDD should both provide protection against such errors. To characterize this effect, we intentionally add a common offset to the frequencies of the detuned microwave fields with respect to the qubit frequency, then perform the entangling interaction and measure the Bell-state fidelity, keeping all other parameters constant. As shown in Fig. 2b, the Bell-state fidelity remains below 10^{-3} for frequency offsets up to \pm 200 kHz.

This insensitivity to qubit frequency offsets enables individual addressing of the ions in frequency space without compromising entanglement fidelity. Individual addressing of trapped ion qubits has been demonstrated previously using tightly focused laser beams\(^{21,22,30}\), and without lasers using static magnetic field gradients\(^{36,39,48}\) and oscillating magnetic field gradients\(^{40,49}\) at gigahertz frequencies. In our system, the currents at \(\omega_r\) in the three-qubit control electrodes give rise to a magnetic field with a strong spatial gradient, but nearly zero field amplitude along the quantization axis, at the ion positions. The residual magnetic field at \(\omega_r\) induces an a.c. Zeeman shift on the qubit transition frequency (Supplementary Information). We apply static electric fields to rotate the ion crystal slightly with respect to the trap axis (Fig. 1b, inset), such that the two ions experience different a.c. Zeeman shifts when the drive at \(\omega_r\) is applied; we choose the ion positions to produce a differential shift of approximately 20 kHz (we use this same ion crystal configuration when performing entangling operations). The differential a.c. Zeeman shift generates differential phase evolution of the two qubits, enabling universal control when combined with global control pulses. For example, we can flip the spin of one of the two qubits using a spin-echo sequence of approximately 70 \mu s duration (Supplementary Information). With this individual control of our qubits, we transform the symmetric entangled state \(|\Phi\rangle\) into an antisymmetric entangled state \(|\Psi\rangle\):

\[
|\Phi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\uparrow\rangle) \quad \Rightarrow \quad |\Psi\rangle = \frac{1}{\sqrt{2}} (|\downarrow\rangle + |\uparrow\rangle).
\]

After creating the antisymmetric state \(|\Psi\rangle\), we measure the ion populations and parity as before. As \(|\Psi\rangle\) is invariant under global rotations,
we observe a constant parity as a function of the analysis pulse phase, as shown in Fig. 3a. We use the same ‘trigger’ technique as before to choose the reported dataset, which has a(\Psi^+) Bell-state fidelity of 0.9977, again corrected for the initialization error on |\uparrow\rangle; to the best of our knowledge, this is the highest reported fidelity in any platform for such an antisymmetric Bell state. Bootstrapping yields a 68% confidence interval for the Bell-state fidelity of [0.9964, 0.9987], with a median bootstrap (Supplementary Information) fidelity of 0.9976. We do not correct for any error in the individual addressing operation in this fidelity estimate. Imperfect calibration of the required duration and phase of the individual addressing operation, an effect that could be mitigated by use of a composite pulse sequence, may account for the reduced fidelity compared with our symmetric entangled state.

Our results highlight the potential of laser-free techniques for universal control of trapped ion qubits for quantum computing and simulation. This technology offers potential advantages for scaling of trapped-ion quantum processors by enabling entangling operations to be carried out simultaneously in multiple trapping zones\(^{50}\) in a multizone ion trap\(^{16,11}\), as the control currents can produce the necessary gradients and fields in multiple zones at the same time. The entanglement of any particular group of ions could be enabled simply by adjusting the trap confinement in that zone with static potentials applied to local trapping electrodes, shifting the motional mode frequency of each zone in or out of resonance with the entangling interaction. The ability to perform many entangling operations simultaneously may reduce or eliminate the speed penalty relative to laser-based operations, which are often performed serially on different sets of ions due to laser power constraints. The tolerance of our laser-free method to drifts or offsets in driving parameters, as well as other sources of decoherence, relaxes the requirements for the fields to be exactly the same across all zones, and the scheme does not rely on carefully tuned trap electrode dimensions to achieve high fidelity\(^{20,21}\). Changes in the local trapping potentials can also be used to select which ions are temporarily frequency-shifted for individual qubit control. Entanglement between qubits in different ion species could be achieved by adding another pair of weak microwave tones for each different qubit frequency; any magnetic-field-sensitive Zeeman or hyperfine qubit transition can be used. These features may enable a large-scale, multizone ion-trap quantum computing architecture using a two-ion-species qubit/helper design, where all qubit operations aside from ion loading are carried out with radiofrequency or microwave signals, along with microwatt-scale laser beams for the helper species. These laser beams could be delivered efficiently to all zones using integrated optics\(^{21,22}\). With the addition of trap-integrated photon detectors for qubit readout\(^{21,23}\), and trap-integrated circuitry to generate confining potentials\(^{13}\), it may be possible to realize a large-scale, fully integrated, high-fidelity trapped-ion quantum processor with no need for free-space optical access and dramatically reduced electrical interconnect requirements. Laser-free mixed-species entanglement may also be useful for molecular\(^{20}\) or highly charged ions\(^{35}\), or trapped electrons\(^{57}\) or positrons, where suitable optical transitions for quantum logic operations may not be readily available.

Online content

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1. Barenco, A. et al. Elementary gates for quantum computation. Phys. Rev. A 52, 3457–3467 (1995).
2. Joza, R. In The Geometric Universe: Science, Geometry, and the work of Roger Penrose (eds Huggett, S. A, Mason, L. J., Tod, K. P., Tsou, S. T. & Woodhouse, N. M. J.) 369 (Oxford Univ. Press, 1998).
3. Georgescu, I. M., Ashhab, S. & Nori, F. Quantum simulation. Rev. Mod. Phys. 86, 153–185 (2014).
4. Kimble, H. J. The quantum internet. Nature 453, 1023–1030 (2008).
5. Ballance, C. J., Harty, T. P., Linke, N. M., Sepiol, M. A. & Lucas, D. M. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Phys. Rev. Lett. 117, 060504 (2016).
6. Gaebler, J. P. et al. High-fidelity universal gate set for 81Rb ion qubits. Phys. Rev. Lett. 117, 060505 (2016).
7. Clark, C. R. et al. High-fidelity Bell-state preparation with 40Ca+ optical qubits. Preprint at https://arxiv.org/abs/2105.05828 (2021).
8. Harty, T. P. et al. High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit. Phys. Rev. Lett. 113, 220501 (2014).
9. Schmidt-Kaler, F. et al. Realization of the Cirac–Zoller controlled-NOT quantum gate. Nature 422, 408–411 (2003).
10. Debnath, S. et al. Demonstration of a small programmable quantum computer with atomic qubits. Nature 536, 63–66 (2016).
11. Wright, K. et al. Benchmarking an 11-qubit quantum computer. Nat. Commun. 10, 5464 (2019).
12. Erhard, A. et al. Characterizing large-scale quantum computers via cycle benchmarking. Nat. Commun. 10, 5347 (2019).
13. Barrett, M. D. et al. Deterministic quantum teleportation of atomic qubits. Nature 429, 737–739 (2004).
14. Ruster, T. et al. Entanglement-based dc magnetometry with separated ions. Phys. Rev. X 7, 031050 (2017).
Data availability
Source data are provided with this paper. All other data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

Code availability
All simulation code or analysis code that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions
R.S. and H.M.K. carried out the experiments, assisted by S.C.B., D.T.C.A and D.H.S.; D.H.S., R.S., H.M.K., A.K. and R.T.S. analysed the data and performed numerical simulations, with support from E.K. and S.G., D.T.C.A., D.H.S., R.S., S.C.B. and H.M.K. built and maintained the experimental apparatus, R.S. wrote the manuscript with input from all authors; A.C.W., D.L., D.H.S. and D.J.W. secured funding for the work, and D.H.S. and D.T.C.A. supervised the work with support from A.C.W., D.L., S.G., E.K. and D.J.W.

Competing interests
The authors declare no competing interests.

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