nature portfolio

Peer Review File

Individually Addressed Entangling Gates in a Two-Dimensional Ion Crystal

Corresponding Author: Professor Luming Duan

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Summary:

The authors demonstrate entangling gates on a 2D ion crystal using a cross-AOD Raman scheme. The gates are done on a 4 ion crystal on all possible pairs with fidelities ranging from 98-99%. The authors simulate contributing errors and introduce a new scheme to reduce the error due to crosstalk from the cross-AOD configuration. Added micromotion seems to have no effect on the gate fidelity, suggesting possible extension of the scheme to many more ions in the future.

Impact and importance:

The authors claim the cross-AOD scheme will work for thousands of qubits. I believe this statement needs to be backed up with more detailed consideration of factors such as bandwidth and other AOD specifications, optical access, micromotion for edge ions, gate sequence length for low crosstalk, coupling distant ions, etc. Why were more ions not loaded to show control in a larger crystal? Without a detailed analysis of the scalability or demonstrated fidelities exceeding state of the art, it is unclear the impact this prototype will have.

The alternating gate sequence to reduce crosstalk is an interesting new approach. The length of the gate sequence will only scale linearly with the number of ions in the gate, or if parallel gates are used it will scale with the number of simultaneous gates. This scaling does not seem deadly. This technique may become useful in the field.

The manuscript is lacking reference to other cross-AOD demonstrations in ions and atoms e.g. Pogorelov et al. “Compact Ion-trap quantum computing demonstrator” PRX Quantum 2, 020343 2021, and S. Kim, R. R. McLeod, M. Saffman, and K. H. Wagner, “Doppler-free, multiwavelength acousto-optic deflector for two-photon addressing arrays of rb atoms in a quantum information processor”, Appl. Opt. 47, 1816 (2008). The existence of these other demonstrations makes this approach derivative. The new part of the design to include individually addressed beams from both sides, using the AODs common focal length to cancel frequency shifts in the Raman configuration is much more interesting and novel. However, the details are not written here and are instead buried in a patent. The same design is also advertised in the IonQ Forte system.

Technical questions:

It seems that the 4 ms laser dephasing time is quite short (100x other report AOM based systems e.g. Egan et al. Nature 2021). Is this a fundamental issue with the overall AOD design?

Why is performance of UD pair worse than LR pair?

Fig 3c uses a linear fit to the fidelity decay of the LU gate. However, it seems a cosx or 1-x^2 would be more appropriate, suggesting a dominant coherent error. I do not see any such errors included in the error analysis. The simulation also suggests the gate error would be much larger than what is measured. These inconsistencies make me doubt the validity of the error budget.

Reviewer #2

(Remarks to the Author)
The manuscript by Hou, Yi, Wu et al. describes the first demonstration of individual addressing and 2-qubit quantum gates in a small 2-d crystal of trapped ions. This represents a significant result and in conjunction with the application of laser intensity recalibration to compensate for the effects of excess micromotion allowing scaling up to larger crystal geometry makes this technique of general interest to the trapped ion and quantum information community. We believe that the novelty of this approach makes the manuscript suitable for publication in Nature Communications.

The paper is well written, providing enough technical details for the results to be reproduced in other research laboratories. The supplemental information addresses the very important question of scalability of this 2-qubit gate design, showing theoretically that sufficiently high 2-qubit gate fidelity can be achieved with a limited number of laser pulses.

From a technical perspective, the demonstrated results suffer from poor state readout/high measurement error due to cross talk between adjacent ions. However, this deficiency derives from limitations of the imaging system employed and does not reflect any fundamental limitation of the 2D crystal/gate design. As such, this does not detract from the novelty and strength of the approach outlined in the paper.

Finally, the paper could benefit by an expanded attention played to the developments in 2D ion crystals for quantum information using Penning trap platforms. Although differences between RF trap and Penning trap designs mean these two approaches each face certain unique challenges, many common problems apply to both implementations and significant work has been made in recent years on Penning trap devices. Some brief discussion of contemporary Penning trap work would improve the scope and context provided by the authors.

We have outlined several additional specific notes and comments below:

Abstract:
"Two-dimensional (2D) ion crystals have become a promising way to scale up qubit numbers for ion trap quantum information processing."
It would be better to say ‘may represent a path to scale up…’ as no large scale 2D ion traps have been used to execute deep quantum circuits to date.

Introduction
"However, the number of qubits in the commonly used one dimensional (1D) configuration of ion crystals is seriously limited."
The paper could benefit from a brief description of the factors which limit 1D trap qubit number scaling (buckling, motional mode crowding) and in what manner 2D crystals either avoid or are also susceptible to these major barriers to scaling.

"However, its performance is restricted by the relatively low efficiency for ion-photon entanglement generation and connection."
The use of the term ‘connection’ here is ambiguous. Perhaps it would be better to say something like ‘qubit-qubit connectivity’ if the authors are referring to the lack of direct all-to-all entangling capacity between distributed traps in most photonic interconnect implementations.

"Despite the site-resolved single shot measurement capability, previous experiments are still restricted to global quantum manipulations, while individually addressed single-qubit and two-qubit quantum gates have not yet been realized."
It may be worth citing work which proposes individual addressing schema such as the article ‘Individual qubit addressing of rotating ion crystals in a Penning trap’.

"Fundamentally, the inevitable micromotion of ions in a 2D crystal seems to affect the gate fidelity, although theoretical works already show that the micromotion is a coherent process and can in principle be included into the gate design."
Seems as an ambiguous word choice here. The authors should clarify: is fidelity affected or not?

Effects of micromotion section:
Some of this discussion here, including the contents of Fig. 4, may be more suited to the supplemental material than the main body of the article. This is just a suggestion, though, and we let the authors to decide.

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)
The manuscript "Individually Addressed Entangling Gates in a Two-Dimensional Crystal" is focused on the challenges associated with creating a trapped ion quantum information processor where the ion qubits are arranged in two spatial dimensions. A 2D architecture could substantially increase the number of qubits that can be manipulated in each volume compared to the conventional 1D chains that are used in most trapped ion quantum information processors today. Owing to the way that entangling gates are performed and the nature of the radiofrequency (RF) ion traps that are usually used, this goal poses several challenges that are not present in the 1D architecture.

The authors address two of the main challenges in operating quantum gates on a 2D ion crystal.

The first challenge is to individually control the qubits and entangle arbitrary pairs, for example, by spatially addressing each qubit with different laser beams. The authors do this by employing a crossed acousto-optic deflector (AOD) scheme similar to an optical architecture that is successfully used in many Rydberg atom apparatuses and demonstrate adequately low crosstalk for performing well-isolated single-qubit operations. To execute the entangling gates, the authors make an important and creative observation: even though previous experiments have always illuminated qubit pairs simultaneously to achieve an entangling operation, this is not an intrinsic requirement. In fact, for their setup it is not feasible to illuminate certain pairs simultaneously without unwanted light leaking onto other ions. The authors show experimentally that qubit pairs can be entangled with high fidelity using a stroboscopic scheme that alternates which qubit is illuminated.

The second challenge for 2D ion processors is that RF traps can have only a single line or axis where the amplitude of an RF electric field is zero. As a result, 2D ion crystals experience significant "micromotion", where off-axis ions experience driven oscillations at the RF drive frequency. The authors show that their entangling gates can be modified to have similar fidelities with and without the presence of micromotion, accounting only for the change in effective Rabi frequency in the presence of micromotion.

We find this work interesting, clearly presented, and an important advance in the field of trapped ion quantum computing. The entangling technique, though particularly useful for the 2D ion crystals being studied, could also be used in other trapped ion systems, and opens the possibility of investigating alternative optical architectures (for example, rapidly steering a single laser beam between ions instead of creating multiple laser beams). We recommend its publication subject to some minor clarifications.

The micromotion compensation for the entangling gates depends on calculating the displacement of the ions from the RF null. How was the displacement of the ions from the RF null determined in this experiment?

Given that an important potential advantage of 2D ion crystal architectures is that they offer a pathway to scaling up the number of ion qubits in each ion trap module, an estimate on the practical limit of the entangling gates presented in this paper would illuminate the potential impact of this work. How many ions can be addressed and controlled with this technique? How does gate fidelity change with the number of ions in the crystal?

Finally, including legends on the plots presented in this work to distinguish would increase the legibility of the data. Currently, the reader must closely examine the captions of the plots to determine what each data series (color) represents on each plot. The same colors are sometimes (but not always) used to represent different data series in different plots, increasing confusion.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors address many of my technical concerns, except for the overestimation of the error. I think that the recently published paper [1] is a good comparison. In [1], the authors present a detailed noise simulation based on independent measurements that is within one sigma of the experimental result. This simulation based on independent measurements is common in many trapped ion gate demonstrations (e.g. refs 4, 5, 10), and the mismatch in this manuscript is below the standard for this journal.

I believe for a technical demonstration to be suitable for Nature Communications, it should be based on a more novel scheme and closer to state-of-the-art. Looking at the discussion by the authors, it is a simple technical summary of the result, with no discussion of implications or ingenuity. On this note, [1] also makes a good comparison. What they did could also be called a technical demonstration, however, in this case the qudit-qudit entanglement is (was at publication) state-of-the-art and uses a novel native scheme that shows clear scaling advantages.

Let me be clear, I think what the authors present here is new and interesting. I just do not think it is new and interesting enough, nor is the analysis presented of high enough quality for Nature Communications.

[1] Hrmo, P., Wilhelm, B., Gerster, L. et al. Native qudit entanglement in a trapped ion quantum processor. Nat Commun 14, 2242 (2023). https://doi.org/10.1038/s41467-023-37375-2)

Reviewer #4

(Remarks to the Author)
I would like to thank the authors for their careful discussion of the points raised in review. I am satisfied with the provided changes and recommend the revised article for publication.

Reviewer #5

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reply to reviewers

Reviewer #1:

Comment:

Summary:

The authors demonstrate entangling gates on a 2D ion crystal using a cross-AOD Raman scheme. The gates are done on a 4 ion crystal on all possible pairs with fidelities ranging from 98-99%. The authors simulate contributing errors and introduce a new scheme to reduce the error due to crosstalk from the cross-AOD configuration. Added micromotion seems to have no effect on the gate fidelity, suggesting possible extension of the scheme to many more ions in the future.

Reply: We thank the referee for carefully reading through our manuscript and for the detailed summary of its main contributions. Below we address the comments of the referee point by point.

Comment:

Impact and importance:

The authors claim the cross-AOD scheme will work for thousands of qubits. I believe this statement needs to be backed up with more detailed consideration of factors such as bandwidth and other AOD specifications, optical access, micromotion for edge ions, gate sequence length for low crosstalk, coupling distant ions, etc. Why were more ions not loaded to show control in a larger crystal? Without a detailed analysis of the scalability or demonstrated fidelities exceeding state of the art, it is unclear the impact this prototype will have.

Reply: We thank the referee for this important comment. The reason why we do not load more ions to directly show the control in a larger crystal is that in this experiment our trap is operating at the room temperature, which restricts its capability to stably trap large 2D ion crystals as we show in Nature 630, 613 (2024). On the other hand, although the cryogenic ion trap that we use in Nature 630, 613 (2024) can hold large 2D crystals, it currently lacks the individual addressing system which is required in this experiment. Therefore, for a proof-of-principle experiment to demonstrate the 2D individual addressing under micromotion, we choose to use the current setup and a small 2D crystal.

Following the suggestion of the referee, we have added more discussions in Sec. II of Supplementary Information about the bandwidth and other AOD specifications, optical access and micromotion for edge ions as follows:

"To apply our 2D addressing scheme to larger ion crystals, it is necessary to consider many technical factors like the number of resolvable spots of the AODs and the optical access of the imaging system. The number of resolvable spots is given by $N=\Delta f\cdot D/v$ where Δf is the bandwidth of the AOD, D the aperture, and v the acoustic velocity. For the AODs we use in this experiment (ISOMET, D1384-aQ170-7), about 100 resolvable spots can be obtained with a switching time $\tau=D/v$ of about one microsecond. Suppose we separate the ions by at least twice the diffraction limit for the crosstalk of the Raman beams to be below 10^{-4}, the number of ions that can be addressed along each direction can be estimated to be $N/2 = 50$. Allowing slower switching speed, the number of resolvable spots can be further increased. Also note that the individual addressing of above 50 ions by an AOD has already been demonstrated in the experiment [Science 376, 720 (2022)].

The above analysis suggests that a 2D array with about $50^2 = 2500$ sites can be addressed by the crossed AODs. The required deflection angle of the laser is also given by $50/2 = 25$ ions from the center in each direction, thus within the available optical access of the current trap design. However, as we describe in the main text, for a 2D ion crystal in a Paul trap, another restriction to the addressing system comes from the micromotion of the ions. To avoid the crosstalk when controlling adjacent ions, we may want the micromotion amplitudes to be smaller than the ion spacing. Therefore, to maximize the available qubit number, we may arrange the trap potential to hold the 2D crystal in the shape of an ellipse with its major axis aligned in the axial direction without micromotion. An example with 512 ions has been demonstrated in [Nature 630, 613 (2024)]. For a trap with a Mathieu parameter $q = 0.13$ and a typical ion spacing of about $d = 5\ \mu\text{m}$ on the edge, we thus limit the length of the minor axis to be at most $r = 15d$ for the micromotion amplitude $A = qr/2$ to be smaller than d. A rough estimation of the available ion number can be given by $2 \times 15 = 30$ rows, each with 50 ions, thus totally $30 \times 50 = 1500$. Another way is to assume a triangular lattice and to count the number of elementary triangles in the total area of the ellipse. Note that each elementary triangle contains $3/6 = 1/2$ ions on average. This gives an estimation of $\pi \times 25 \times 15/(\sqrt{3}/4) \times 1/2 = 1360$ ions."

As for the gate sequence length, we show an example of the gate design for 100 ions in Sec. I of Supplementary Information and note that the required number of degrees of freedom is already smaller than the number of phonon modes to be decoupled. We have added a sentence in this section to discuss the scalability "As shown in [Europhysics Letters 86, 60004 (2009); Phys. Rev. A 100, 022332 (2019)], utilizing the locality in the spatial or the frequency domain, many distant ions or phonon modes can be neglected, allowing efficient gate design for even larger ion crystals." As for the coupling to distant ions, all-to-all coupling in a 1D chain of 30 ions has been reported in [arXiv.2308.05071], and high-fidelity gate design for 2D ion crystals can be performed in similar mathematical form as we show in Sec. I of Supplementary Information. However, this may come with the cost of longer gate time and more complicated pulse sequences. Following the suggestion of the referee, we have added "Finally, note that we may not need to achieve all-to-all coupling for all the ions. (For more distant ion pairs, this may be achieved at the cost of longer gate time and more complicated pulse sequences.) Just achieving direct two-qubit entangling gates for ion pairs within a constant distance, say, 5 to 10 ion spacings, already supports universal quantum computation while largely reducing the overhead for compiling the quantum circuit compared with the nearest-neighbor connectivity."

Comment: The alternating gate sequence to reduce crosstalk is an interesting new approach. The length of the gate sequence will only scale linearly with the number of ions in the gate, or if parallel gates are used it will scale with the number of simultaneous gates. This scaling does not seem deadly.

This technique may become useful in the field.

Reply: We thank the referee for the evaluation that the alternating gate sequence is an interesting new approach and that it may be useful in the field.

Comment: The manuscript is lacking reference to other cross-AOD demonstrations in ions and atoms e.g. Pogorelov et al. "Compact Ion-trap quantum computing demonstrator" PRX Quantum 2, 020343 2021, and S. Kim, R. R. McLeod, M. Saffman, and K. H. Wagner, "Doppler-free, multiwavelength acousto-optic deflector for two-photon addressing arrays of rb atoms in a quantum information processor", Appl. Opt. 47, 1816 (2008). The existence of these other demonstrations makes this approach derivative. The new part of the design to include individually addressed beams from both sides, using the AODs common focal length to cancel frequency shifts in the Raman configuration is much more interesting and novel. However, the details are not written here and are instead buried in a patent. The same design is also advertised in the IonQ Forte system.

Reply: We thank the referee for this helpful comment. The referee is correct that crossed AODs have been used in previous experiments in ions and atoms [PRX Quantum 2, 020343 (2021); Appl. Opt. 47, 1816 (2008)]. However, we would like to mention that in these previous experiments, the crossed AODs are used for 1D addressing where the frequency shift due to the +1 diffraction of the first AOD is cancelled by that of the -1 diffraction of the second AOD such that the overall laser frequency is uniform for any target ions. In comparison, in this experiment we are performing 2D individual addressing and the crossed AODs are only used for controlling the orientation of the laser beams. As noted by the referee, we use the additional symmetric Raman configuration to cancel the resulting frequency shift from the crossed AODs. Although similar Raman configuration is also used by the IonQ Forte system [arXiv.2308.05071, we have also described this addressing method in a 2021 patent [40]], there the 1D addressing rather than 2D is considered. Therefore, we believe that there are sufficient differences between our work and the previous works.

Considering the comment of the referee, we have added these two references into the main text "Also note that previously the crossed AODs have been used for 1D individual addressing along the diagonal direction where the frequency shift due to the +1 diffraction order of the first AOD can be compensated by that of the -1 diffraction order of the second one [PRX Quantum 2, 020343 (2021); Appl. Opt. 47, 1816 (2008)]", following the detailed description of our addressing system "We use two pairs of symmetrically placed crossed AODs for individual addressing of the 355 nm Raman laser beams. By tuning the driving frequencies on the horizontal or vertical AODs, the addressing beam can be scanned along the z or x directions, respectively. The objectives for the two addressing beams have the same focal length so that the two pairs of crossed AODs have equal driving frequencies when addressing the same target ion. In this way, the frequency shift introduced by the AODs can be cancelled in the Raman transition."

Comment:
Technical questions:

It seems that the 4 ms laser dephasing time is quite short (100x other report AOM based systems e.g. Egan et al. Nature 2021). Is this a fundamental issue with the overall AOD design?

Reply: The currently short laser dephasing time is not a fundamental limit of the crossed AOD addressing system. We think it is mainly caused by the relatively long optical path of our Raman beams whose optical components are located on several layers. The relative vibration of these optical components can thus lead to the dephasing of the Raman lasers. We have added this into the "Gate error sources" section in Methods: "The laser dephasing time is measured to be $\tau_s = 4$ ms by fitting the exponential decay of the Ramsey fringes under the counter-propagating Raman $\pi/2$ pulses, and is mainly caused by the vibration of optical components in the relatively long optical path consisting of multiple layers."

Comment: Why is performance of UD pair worse than LR pair?

Reply: The experimentally measured performances for the LR and the UD pairs are actually close to each other within the error bars (Bell state fidelity as 99(1)% vs 98(2)% and a fitted gate infidelity from multiple MS gates as 1.4(2)% vs 1.6(1)%). On the other hand, our theoretical model does suggest slightly better performance for the LR pair than the UD pair. As shown in Fig. 2c, this is mainly due to the motional dephasing effect. Specifically, for the gate parameters we describe in the main text including the laser detuning and the pattern of the phonon modes, for the LR pair, the contributions from two neighboring modes (Mode 2 and Mode 3) will add up, allowing lower laser intensity to realize the maximally entangled gate. In comparison, for the UD pair, the contributions from two neighboring modes (Mode 3 and Mode 4) have opposite signs, requiring stronger laser intensity for the maximally entangled gate. Therefore, the gate for the UD pair has stronger phonon excitation during the pulse sequence, thus is subjected to stronger motional dephasing error. We have added in the main text "The theoretical fidelity is lower than that of the LR pair because of a stronger laser intensity and thus larger motional excitations during the gate sequence, leaving the gate more sensitive to the motional dephasing error as shown in Fig. 2c."

Comment: Fig 3c uses a linear fit to the fidelity decay of the LU gate. However, it seems a cosx or 1-x^2 would be more appropriate, suggesting a dominant coherent error. I do not see any such errors included in the error analysis. The simulation also suggests the gate error would be much larger than what is measured. These inconsistencies make me doubt the validity of the error budget.

Reply: We thank the referee for this suggestion. We tried to fit the data with $100\cos(Ax)$ and $100 - Ax^2$, and obtained the R^2 values of 0.86 and 0.85, much lower than the $R^2 = 0.99$ for the linear fitting $100 - Ax$. This suggests that the gate fidelity (note that it is described by the green dots in Fig. 3c) is better fitted by the linear model as we used in the manuscript. The appearing curvature in the parity data (orange dots), which may be the reason why the referee suggests a quadratic fitting, may instead be explained by the error bar of the data at the large number of MS gates due to the parameter drift in the system. Therefore, we think that our error model, which is dominated by the incoherent errors, is reasonable for the current experiment. Besides, if there are significant coherent errors which should be fitted by a quadratic function, then our linear fitting will lead to overestimation of the gate infidelity. Then it can still act as an upper bound for the achieved gate infidelity.

Also, we agree with the referee that our estimation of the error budget is systematically larger than the measured values by about 50% and we have acknowledged this in the manuscript that it can be due to an oversimplified white-noise model. However, as mentioned above, the measured gate fidelity seems to follow the predicted linear scaling with the gate number. This error model also correctly predicts the relative magnitudes of the gate infidelities for different ion pairs. Therefore, we believe that using this simplified model can still provide useful information to understand the dominant error sources.

Reviewer #2:

Comment: The manuscript by Hou, Yi, Wu et al. describes the first demonstration of individual addressing and 2-qubit quantum gates in a small 2-d crystal of trapped ions. This represents a significant result and in conjunction with the application of laser intensity recalibration to compensate for the effects of excess micromotion allowing scaling up to larger crystal geometry makes this technique of general interest to the trapped ion and quantum information community. We believe that the novelty of this approach makes the manuscript suitable for publication in Nature Communications.

The paper is well written, providing enough technical details for the results to be reproduced in other research laboratories. The supplemental information addresses the very important question of scalability of this 2-qubit gate design, showing theoretically that sufficiently high 2-qubit gate fidelity can be achieved with a limited number of laser pulses.

From a technical perspective, the demonstrated results suffer from poor state readout/high measurement error due to cross talk between adjacent ions. However, this deficiency derives from limitations of the imaging system employed and does not reflect any fundamental limitation of the 2D crystal/gate design. As such, this does not detract from the novelty and strength of the approach outlined in the paper.

Reply: We thank the referee for carefully reading through our manuscript and for the positive evaluations that it “represents a significant result”, be “of general interest to the trapped ion and quantum information community”, “well written, providing enough technical details for the results to be reproduced in other research laboratories”, and “suitable for publication in Nature Communications”. We also thank the referee for the comment that our current state readout error “does not detract from the novelty and strength of the approach outlined in the paper”.

Comment: Finally, the paper could benefit by an expanded attention played to the developments in 2D ion crystals for quantum information using Penning trap platforms. Although differences between RF trap and Penning trap designs mean these two approaches each face certain unique challenges, many common problems apply to both implementations and significant work has been made in recent years on Penning trap devices. Some brief discussion of contemporary Penning trap work would improve the scope and context provided by the authors.

Reply: We thank the referee for this helpful suggestion. We have added the following sentence with references into Introduction "Two-dimensional (2D) ion crystals have long been used for quantum simulation in Penning trap [Nature 484, 489 (2012); Science 352, 1297 (2016)] with individual addressing scheme also being proposed [Phys. Rev. Research 4, 033076 (2022)]."

Comment: We have outlined several additional specific notes and comments below:

Abstract:
"Two-dimensional (2D) ion crystals have become a promising way to scale up qubit numbers for ion trap quantum information processing."
It would be better to say 'may represent a path to scale up…' as no large scale 2D ion traps have been used to execute deep quantum circuits to date.

Reply: We thank the referee for this suggestion and have revised this sentence into "Two-dimensional (2D) ion crystals may represent a promising path to scale up qubit numbers…" We would like to mention here that by "quantum information processing" we mean not just the universal quantum computation which requires the execution of deep quantum circuits, but also other NISQ algorithms like quantum simulation and quantum annealing which may work with global operations.

Comment: Introduction
"However, the number of qubits in the commonly used one dimensional (1D) configuration of ion crystals is seriously limited."
The paper could benefit from a brief description of the factors which limit 1D trap qubit number scaling (buckling, motional mode crowding) and in what manner 2D crystals either avoid or are also susceptible to these major barriers to scaling.

Reply: We thank the referee for this suggestion. We have added "To avoid the buckling of the ions into a zigzag pattern, the axial trap frequency needs to be decreased as the ion number increases, making the system sensitive to the low-frequency electric field noise" following this sentence. The 2D crystals are also susceptible to such buckling into 3D multi-layer patterns, but the number of ions that can be held in 2D is much larger than that in 1D before the buckling occurs.

Comment: "However, its performance is restricted by the relatively low efficiency for ion-photon entanglement generation and connection."

The use of the term ‘connection’ here is ambiguous. Perhaps it would be better to say something like ‘qubit-qubit connectivity’ if the authors are referring to the lack of direct all-to-all entangling capacity between distributed traps in most photonic interconnect implementations.

Reply: Here by “connection” we mean the entanglement connection (entanglement swapping) via Bell measurement of the photons. To generate ion-ion entanglement between two ion traps, one first needs to generate ion-photon entanglement for ions in both traps, and then to perform the Bell measurement for the two photons to project the corresponding ions into an entangled state. To avoid confusion, we have revised this sentence into “… ion-photon entanglement generation and ion-ion entanglement connection via Bell measurement of photons”.

Comment: "Despite the site-resolved single shot measurement capability, previous experiments are still restricted to global quantum manipulations, while individually addressed single-qubit and two-qubit quantum gates have not yet been realized."
It may be worth citing work which proposes individual addressing schema such as the article ‘Individual qubit addressing of rotating ion crystals in a Penning trap’.

Reply: We thank the referee for this suggestion. This sentence mainly considers ion crystals in a Paul trap, for which the addressing techniques are different for those in a Penning trap. Considering this comment and a previous comment of the referee, we think it is more suitable to cite the mentioned reference together with the introduction of the background about Penning trap: “Two-dimensional (2D) ion crystals have long been used for quantum simulation in Penning trap [Nature 484, 489 (2012); Science 352, 1297 (2016)] with individual addressing scheme also being proposed [Phys. Rev. Research 4, 033076 (2022)].”

Comment: "Fundamentally, the inevitable micromotion of ions in a 2D crystal seems to affect the gate fidelity, although theoretical works already show that the micromotion is a coherent process and can in principle be included into the gate design."
Seems as an ambiguous word choice here. The authors should clarify: is fidelity affected or not?

Reply: We thank the referee for this suggestion and have revised this sentence into “Fundamentally, the inevitable micromotion of ions in a 2D crystal seems to affect the gate performance, although theoretical works already show that the micromotion is a coherent process and can in principle be included into the gate design, still allowing high gate fidelity.”

Comment: Effects of micromotion section:
Some of this discussion here, including the contents of Fig. 4, may be more suited to the supplemental material than the main body of the article. This is just a suggestion, though, and we let the authors to decide.

Reply: We thank the referee for this suggestion. We think the results of this section, namely that the micromotion effect can be compensated by a rescaling of the laser intensity without affecting the gate fidelity, is an important result for the scalability of our scheme to large 2D ion crystals. It is also related to the gates demonstrated in previous sections where the "U" and "D" ions already have micromotion. Therefore we think it is better to keep this section in the main text.

Reviewer #3:

Comment: I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reply: We thank the referee for co-reviewing our manuscript and for all the helpful suggestions.

Reviewer #4:

Comment: The manuscript "Individually Addressed Entangling Gates in a Two-Dimensional Crystal" is focused on the challenges associated with creating a trapped ion quantum information processor where the ion qubits are arranged in two spatial dimensions. A 2D architecture could substantially increase the number of qubits that can be manipulated in each volume compared to the conventional 1D chains that are used in most trapped ion quantum information processors today. Owing to the way that entangling gates are performed and the nature of the radiofrequency (RF) ion traps that are usually used, this goal poses several challenges that are not present in the 1D architecture.

The authors address two of the main challenges in operating quantum gates on a 2D ion crystal.

The first challenge is to individually control the qubits and entangle arbitrary pairs, for example, by spatially addressing each qubit with different laser beams. The authors do this by employing a crossed acousto-optic deflector (AOD) scheme similar to an optical architecture that is successfully used in many Rydberg atom apparatuses and demonstrate adequately low crosstalk for performing well-isolated single-qubit operations. To execute the entangling gates, the authors make an important and creative observation: even though previous experiments have always illuminated qubit pairs simultaneously to achieve an entangling operation, this is not an intrinsic requirement. In fact, for their setup it is not feasible to illuminate certain pairs simultaneously without unwanted light leaking onto other ions. The authors show experimentally that qubit pairs can be entangled with high fidelity using a stroboscopic scheme that alternates which qubit is illuminated.

The second challenge for 2D ion processors is that RF traps can have only a single line or axis where the amplitude of an RF electric field is zero. As a result, 2D ion crystals experience significant "micromotion", where off-axis ions experience driven oscillations at the RF drive frequency. The authors show that their entangling gates can be modified to have similar fidelities with and without the presence of micromotion, accounting only for the change in effective Rabi frequency in the presence of micromotion.

We find this work interesting, clearly presented, and an important advance in the field of trapped ion quantum computing. The entangling technique, though particularly useful for the 2D ion crystals being studied, could also be used in other trapped ion systems, and opens the possibility of investigating alternative optical architectures (for example, rapidly steering a single laser beam between ions instead of creating multiple laser beams). We recommend its publication subject to some minor clarifications.

Reply: We thank the referee for carefully reading through our manuscript, the detailed summary of its main contributions, and the positive evaluations that it is "interesting, clearly presented, and an important advance in the field of trapped ion quantum computing" and that "the entangling technique, though particularly useful for the 2D ion crystals being studied, could also be used in other trapped ion systems, and opens the possibility of investigating alternative optical architectures". We thank the referee for recommending publication. Below we address the comments of the referee point by point.

Comment: The micromotion compensation for the entangling gates depends on calculating the displacement of the ions from the RF null. How was the displacement of the ions from the RF null determined in this experiment?

Reply: We thank the referee for this important question. The displacements of the ions are read from the image on the CCD camera as $0.88\mu m/\text{pixel}$, which is computed from the CCD pixel size of $16\mu m$ and the magnification of the imaging system of 18.24. To clarify this, we have added "(read from the image on the CCD camera as $0.88\mu m/\text{pixel}$)" in the caption of Fig. 4. Also we would like to clarify that although theoretically the micromotion compensation for the entangling gates requires computing the displacement of the ions from the RF null, experimentally this compensation can directly be performed by calibrating the Rabi rates of the laser on the ions as shown in Fig. 4b. Therefore the ion displacement does not need to be measured very accurately.

Comment: Given that an important potential advantage of 2D ion crystal architectures is that they offer a pathway to scaling up the number of ion qubits in each ion trap module, an estimate on the practical limit of the entangling gates presented in this paper would illuminate the potential impact of this work. How many ions can be addressed and controlled with this technique? How does gate fidelity change with the number of ions in the crystal?

Reply: We thank the referee for this helpful suggestion. Following this comment and a related comment from Reviewer #1, we have added Sec. II of Supplementary Information to discuss the ion number that can be addressed and controlled with this technique:

“To apply our 2D addressing scheme to larger ion crystals, it is necessary to consider many technical factors like the number of resolvable spots of the AODs and the optical access of the imaging system. The number of resolvable spots is given by $N = \Delta f \cdot D/v$ where Δf is the bandwidth of the AOD, D the aperture, and v the acoustic velocity. For the AODs we use in this experiment (ISOMET, D1384-aQ170-7), about 100 resolvable spots can be obtained with a switching time $\tau = D/v$ of about one microsecond. Suppose we separate the ions by at least twice the diffraction limit for the crosstalk of the Raman beams to be below 10^{-4}, the number of ions that can be addressed along each direction can be estimated to be $N/2 = 50$. Allowing slower switching speed, the number of resolvable spots can be further increased. Also note that the individual addressing of above 50 ions by an AOD has already been demonstrated in the experiment [Science 376, 720 (2022)].

The above analysis suggests that a 2D array with about $50^2 = 2500$ sites can be addressed by the crossed AODs. The required deflection angle of the laser is also given by $50/2 = 25$ ions from the center in each direction, thus within the available optical access of the current trap design. However, as we describe in the main text, for a 2D ion crystal in a Paul trap, another restriction to the addressing system comes from the micromotion of the ions. To avoid the crosstalk when controlling adjacent ions, we may want the micromotion amplitudes to be smaller than the ion spacing. Therefore, to maximize the available qubit number, we may arrange the trap potential to hold the 2D crystal in the shape of an ellipse with its major axis aligned in the axial direction without micromotion. An example with 512 ions has been demonstrated in [Nature 630, 613 (2024)]. For a trap with a Mathieu parameter $q = 0.13$ and a typical ion spacing of about $d = 5$ μm on the edge, we thus limit the length of the minor axis to be at most $r = 15d$ for the micromotion amplitude $A = qr/2$ to be smaller than d. A rough estimation of the available ion number can be given by $2 \times 15 = 30$ rows, each with 50 ions, thus totally $30 \times 50 = 1500$. Another way is to assume a triangular lattice and to count the number of elementary triangles in the total area of the ellipse. Note that each elementary triangle contains $3/6 = 1/2$ ions on average. This gives an estimation of $\pi \times 25 \times 15/(\sqrt{3}/4) \times 1/2 = 1360$ ions.”

As for the scaling of the gate fidelity, as we show in Sec. I of Supplementary Information, the theoretical gate fidelity can be designed to be very high using a polynomial number of segments. However in practice there can be many error sources like the laser and motional dephasing considered in the main text, and we expect the gate error to increase as one attempts to entangle more distant ion pairs using longer gate time. Nevertheless, previously high-fidelity entangling gates have already been demonstrated for up to 30 ions in 1D with all-to-all connectivity [arXiv.2308.05071], so there seems to be no fundamental limitation. We have added some discussions in Sec. I of Supplementary Information: “As shown in [Europhysics Letters 86, 60004 (2009); Phys. Rev. A 100, 022332 (2019)], utilizing the locality in the spatial or the frequency domain, many distant ions or phonon modes can be neglected, allowing efficient gate design for even larger ion crystals” and “Finally, note that we may not need to achieve all-to-all coupling for all the ions. (For more distant ion pairs, this may be achieved at the cost of longer gate time and more complicated pulse sequences.) Just achieving direct two-qubit entangling gates for ion pairs within a constant distance, say, 5 to 10 ion spacings, already supports universal quantum computation while largely reducing the overhead for compiling the quantum circuit compared with the nearest-neighbor connectivity.”

Comment: Finally, including legends on the plots presented in this work to distinguish would increase the legibility of the data. Currently, the reader must closely examine the captions of the plots to determine what each data series (color) represents on each plot. The same colors are sometimes (but not always) used to represent different data series in different plots, increasing confusion.

Reply: We thank the referee for this helpful suggestion. We have added legends to Figs. 2d, 2e, 3c, 4b and 4d.

Reply to reviewers

Reviewer #1:

Comment:

The authors address many of my technical concerns, except for the overestimation of the error. I think that the recently published paper [1] is a good comparison. In [1], the authors present a detailed noise simulation based on independent measurements that is within one sigma of the experimental result. This simulation based on independent measurements is common in many trapped ion gate demonstrations (e.g. refs 4, 5, 10), and the mismatch in this manuscript is below the standard for this journal.

I believe for a technical demonstration to be suitable for Nature Communications, it should be based on a more novel scheme and closer to state-of-the-art. Looking at the discussion by the authors, it is a simple technical summary of the result, with no discussion of implications or ingenuity. On this note, [1] also makes a good comparison. What they did could also be called a technical demonstration, however, in this case the qudit-qudit entanglement is (was at publication) state-of-the-art and uses a novel native scheme that shows clear scaling advantages.

Let me be clear, I think what the authors present here is new and interesting. I just do not think it is new and interesting enough, nor is the analysis presented of high enough quality for Nature Communications.

[1] Hrmo, P., Wilhelm, B., Gerster, L. et al. Native qudit entanglement in a trapped ion quantum processor. Nat Commun 14, 2242 (2023). https://doi.org/10.1038/s41467-023-37375-2)

Reply: We thank the referee for the evaluation that we have addressed many of their technical concerns. As for the overestimation of the gate error, we would like to emphasize that the main contribution of this work is the first demonstration of individually addressed two-qubit entangling gates in 2D trapped ion crystals under micromotion. To enable such an entangling gate, we also develop a novel scheme where the addressing laser is switched between two target ions alternatingly rather than being shined on them simultaneously. Reviewers #2, #3, #4 and #5 all recommend its publication in Nature Communications. We agree with the referee that having a better theoretical explanation to the experimental errors within one standard deviation can further improve the manuscript technically, but we would like to mention that it is not the main focus of this work. Besides, the main reason for this deviation is known and has been discussed in the manuscript. In the previous version, we had a paragraph on page 3 discussing why we had an overestimation of the gate error. We have revised it into "However, note that these theoretical analyses are based on a white-noise model, which seems to systematically over-estimate the gate error by about 50% as the actual noise can be dominated by the low-frequency part" to acknowledge the current limitation in the error model and to point out that it still gives the correct tendency. Also in Discussion section we add "Also a more complete noise model with an experimentally measured noise spectrum may be used for better consistency between the theoretical prediction and the experimental gate fidelity, and for further optimization of the gate performance [55]".

Reviewer #4:

Comment: I would like to thank the authors for their careful discussion of the points raised in review. I am satisfied with the provided changes and recommend the revised article for publication.

Reply: We thank the referee for being satisfied with our replies and revisions, and for recommending our manuscript for publication.

Reviewer #5:

Comment: I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reply: We thank the referee for co-reviewing our manuscript.