

Algorithms and Architectures for Quantum Computers

RLE Group

Quanta Research Group

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Overview

This research group seeks to understand and develop the experimental and theoretical potential for information processing and communications using the laws of quantum physics. Two fundamental questions motivate our work: (1) How can a large-scale, reliable quantum computer be realized? (2) What new algorithms, cryptographic primitives, and metrology techniques are enabled by quantum information?

The first question is primarily experimental. We intend to build a large-scale, reliable quantum computer over the next few decades. Based on our successes with realizing small quantum computers, and after years of testing, modeling, and planning, we have come to understand how this can be achieved by combining fault tolerance techniques developed by von Neumann, with methods from atomic physics. Our main approach is to develop highly integrated trapped ion systems, in which states of single atoms and ions are quantum bits, and logic gates are realized using Coulomb interactions controlled by surface electrode potentials and pulsed laser excitation.

The second question concerns the future of quantum information, which needs algorithms for more than just factoring, search, and key distribution. Protocols we have discovered in the last four years, for tasks such as distributed one-time computation and digital signatures, suggest new areas for useful algorithms, and motivate new approaches to experiments in electromagnetism and condensed matter systems.

Applications of the Schur Basis to Quantum Algorithms

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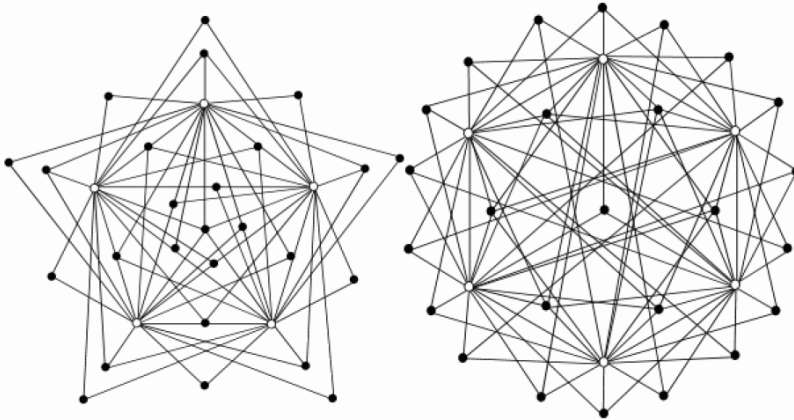
Army Research Office DAAD190310075

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The Schur basis is a generalization of the total angular momentum basis that is useful for exploiting symmetry under permutations or collective unitary rotations. It is useful for many tasks in quantum information theory, but so far its algorithmic applications have been largely unexplored. Related to such symmetries are the equivalences of graphs under permutations, and the search for new quantum algorithms based on hidden subgroups. As part of this search, we have recently identified a new set of equivalences between quantum states represented by graphs, those known as stabilizer states.

The equivalence of stabilizer states under local transformations is of fundamental interest in understanding properties and uses of entanglement. Two stabilizer states are equivalent under the usual stochastic local operations and classical communication criterion if and only if they are equivalent under local unitary (LU) operations. More surprisingly, under certain conditions, two LU equivalent stabilizer states are also equivalent under local Clifford (LC) operations, as was shown by Van den Nest et al. In our work, we broaden the class of stabilizer states for which LU equivalence implies LC equivalence to include all stabilizer states represented by graphs without cycles of length 3 and 4. We prove that LU is equivalent to LC for a very general class of stabilizer states with distance $d = 2$. We also explicitly construct the graphs representing $d > 2$ stabilizer states which arise from quantum error correcting codes with non-Clifford transversal gates.



These are two distance $d > 2$ graphs which do not fit into previously identified equivalence categories, and yet satisfy LU, LC equivalence. These graphs arise from a 31 qubit quantum Reed-Muller code with the non-Clifford transversal gate $\exp(-i\pi Z/16)$.

Research and Development of Integrated Ion Trap Quantum Computer Systems

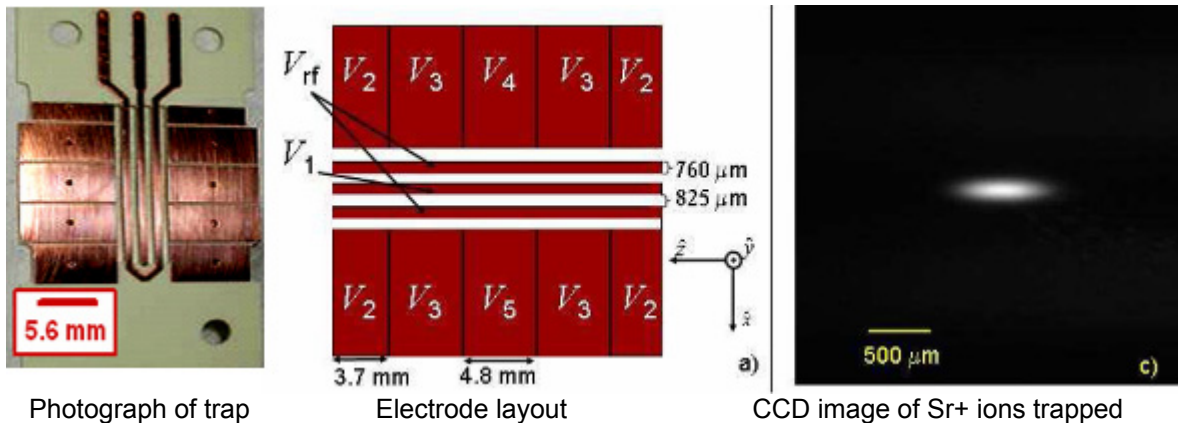
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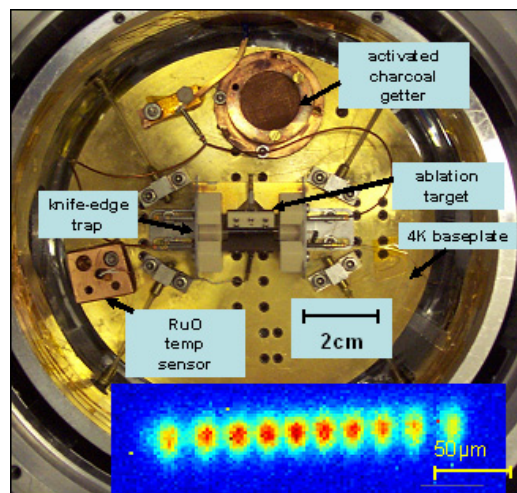
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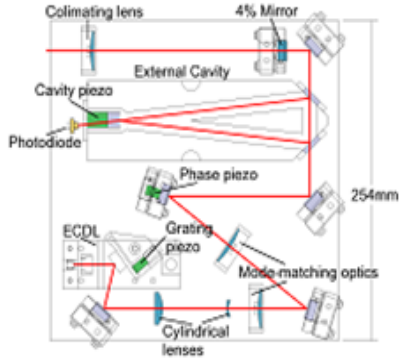
Traditional ion trap geometries, involving three dimensional structures, are unsuitable for large-scale quantum computation, because of the many ions which must be individually manipulated and tightly trapped. We have implemented a novel approach, which places all the electrodes in a single plane, and demonstrated trapping of strontium ions in this device.



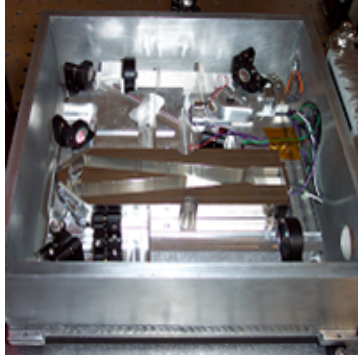
A significant problem facing ion traps is the excess noise which grows in power as $1/d^4$, for trap size d , due probably to fluctuations of surface charges. This noise significantly degrades the performance of two-qubit quantum logic gates such as the controlled-NOT gate. We have designed an experiment to reduce this noise by freezing out surface charge fluctuations using a cryogenic environment at liquid nitrogen and liquid helium temperatures. We have completed construction and initial testing of the cryogenic ion trap, trapping a linear chain ion crystal, at Doppler cooled temperatures. This is a photograph of the cryogenic ion trap base-plate showing an ion trap and a CCD image of a crystal of Sr⁺ ions:



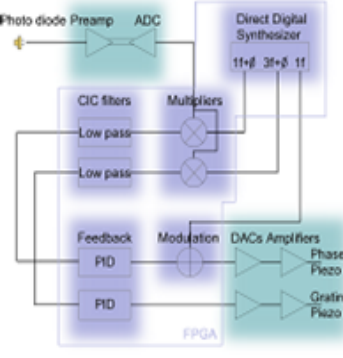
This ion trap system is driven by a monolithic optical-feedback stabilized 674nm laser system of novel design. Narrow linewidth laser excitation is necessary for measuring the temperature of a trapped ion such as Sr^+ . The 674nm light we use must be very carefully stabilized against short term and long term fluctuations, and our monolithic base-plate optical-feedback stabilized external cavity diode laser system is suitable for such trapped ion temperature measurements.



Optical design of laser



Photograph of laser implementation



Control system design

Planar Ion Trap Development

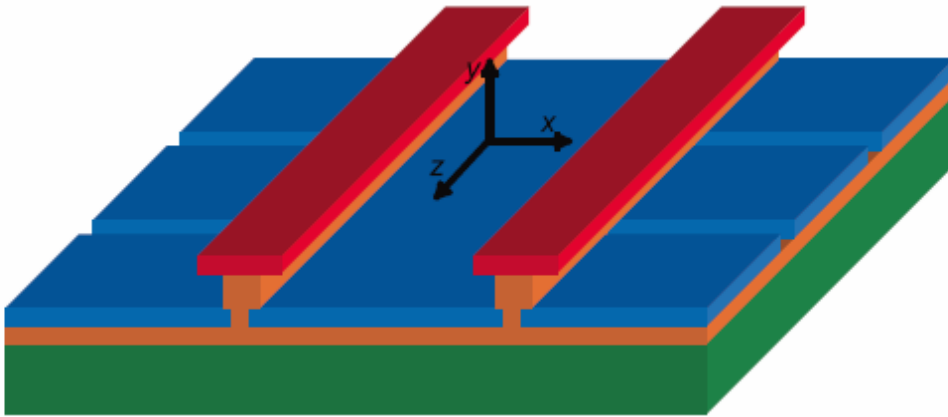
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In recent years, ion trap experiments have demonstrated the basic building blocks of a scalable ion trap quantum computer. The architecture uses the atomic states of ions trapped in an RF Paul trap as memory and accomplishes initialization, gates, and readout by laser-ion interactions. Ions are moved between zones in an array of many ion traps to perform two-qubit gates between arbitrary pairs of qubits. Recent experiments have accomplished state readout, one- and two-qubit gates, and ion movement. Scaling this architecture up to the thousands of ions necessary for a useful computation, however, will require careful application of very large scale integration (VLSI) techniques. This project on a scalable multiplexed ion trap seeks to build ion traps using standard silicon VLSI technology. The ion traps use a surface-electrode geometry shown below:



Green is highly doped silicon substrate, orange is oxide, blue is metal control electrodes, and red is metal RF electrodes. Ions are trapped at the origin of the coordinate system, and are confined along the x - and y -axes by RF potentials and along the z -axis by DC potentials. Because these traps are built using standard semiconductor fabrication processes it is possible to integrate them with CMOS electronics for driving the control electrodes, MEMS optics for laser delivery, and possibly even on chip ion state detection for scalable ion trap quantum computing.

While ion heating is not the dominant source of decoherence in current ion trap experiments, as traps get smaller and are made out of more resistive semiconductor materials ion heating will become more important. In collaboration Lucent, we formulated a new analytic framework for calculating resistive thermal fluctuation ion heating rates based on the fluctuation-dissipation theorem. We applied this framework to calculate the heating rates of ions in the original trap design. Using the intuition developed by our model, we designed a new control electrode layout which reduces the thermal fluctuation heating rates by a factor of 5. The resistive thermal fluctuation heating rates for the new control electrode layout are comparable to those in current ion trap experiments. The anomalous patch potential heating, however, is predicted to be 100 times worse. As patch potential heating is only poorly understood, experiments must be conducted to determine its origin and mitigate it before our integrated ion traps can be used for large scale quantum computation.

Publications

Journal Articles

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