Quantum computer hardware based on rare-earth-ion-doped inorganic crystals – a spectral hole-burning approach to quantum computing

Mattias Nilsson, Nicklas Ohlsson, Lars Rippe, Ingela Roos and Stefan Kröll
Dept. of Physics, Lund Institute of Technology (LTH), Box 118, S-221 00 Lund, Sweden
Klaus Mølmer
QUANTOP, Danish Research Foundation Center for Quantum Optics,
Department of Physics and Astronomy, University of Aarhus, DK-8000 Århus C, Denmark

A scheme has been designed for extracting quantum computer hardware from randomly located ions doped into a solid-state material [1]. In this scheme ensembles of rare-earth ions (e.g. Er^{3+}, Eu^{3+} or Tm^{3+}) in inorganic crystals (e.g. YAG, Y_2SiO_5 or $YAlO_3$) are used as qubits. Interaction between qubits is accomplished using the change in permanent electric dipole moment that is induced at the optical excitation of the ions. Initial experiments have demonstrated the two most important aspects of the scheme: the isolation of a single qubit in a pure state and the ion-ion interaction that will be used to entangle qubits [2].

When cooled to liquid helium temperatures, a rare-earth ion in an inorganic crystal can have a very narrow homogeneous absorption line (<1 kHz), corresponding to a long dephasing time, while the absorption frequencies of different ions can differ by many GHz, due to slightly different surroundings in the host. The inhomogeneously broadened optical transitions of the ions are utilised for creating qubits, consisting of sub-sets of ions, which are addressable because of their different absorption frequencies. Two of the long-lived hyperfine levels of the ion ground state are used as qubit states and optical pumping can be used for moving ions between these levels in the qubit preparation stage. Resonant Raman transitions via the excited state can be used to perform qubit operations. We have shown experimentally that it is possible to isolate ions in a selected frequency channel and the ions residing at a specific frequency have been pumped into one of the hyperfine levels and thereby one qubit has been prepared in a well defined state.

Quantum computing requires controlled interactions between different qubits. In the present scheme, this interaction is mediated by the change in permanent dipole moment experienced by the rare-earth ions when they are optically excited from the ground state to an excited state. The change in dipole moment changes the electric field experienced by ions situated close to the excited ion, thus their absorption frequencies are changed. Fig. 1 shows a spectral hole burnt in the inhomogeneous absorption profile. The left most curve shows the spectral hole when no other ions are excited and the middle (right) curve shows the hole after exciting ions within a 50 MHz (200 MHz) frequency region elsewhere in the inhomogeneous absorption profile. The figure clearly demonstrates that ions in the vicinity of the spectral hole are shifted into the hole when ions elsewhere are excited. The important aspect, in order to use such a frequency shift for controlled logic, is that the shift is sufficiently large that ions, originally resonant with a certain laser frequency, are shifted out of resonance with this laser field. The experimentally observed excitation-induced frequency shifts have been compared with theoretical calculations. Theoretical simulations (figure 2) predict that if the spectral width of the qubit is chosen to 1 MHz, close to 0.5 % of the ions in any other arbitrary frequency interval will experience a shift of sufficient magnitude for being used for implementing quantum gate operations. These simulations are supported by preliminary experimental results and this opens the way for the realisation of the first quantum gate in this type of solid state materials. Current experimental work is concentrated on distilling the qubits such that they contain only the strongly interacting ions [3].

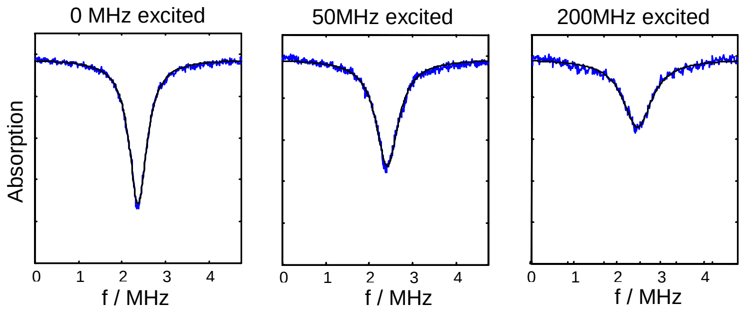

Figure 1. Broadening of a spectral hole. The absorption frequencies of the ions shift, when ions within a 50 or 200 MHz interval elsewhere in the absorption profile are excited.

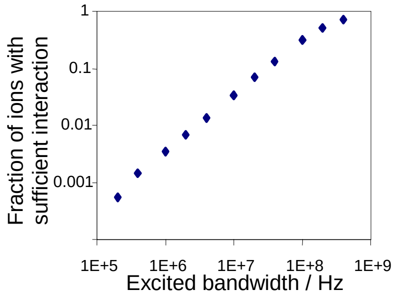

Figure 2. The simulations show the fraction of ions shifted enough to enable controlled logic.

In the scheme presented here each qubit consists of an ensemble of rare-earth-ions which ideally should respond identically to the laser pulses utilized for the gate operations. However, in reality the ions are non-identical. They have slightly different transition frequencies, they have different transition oscillator strengths for a given light polarization due to their orientation in the crystal, their Rabi frequencies may be different due to intensity variations across the laser beam profile, etc. To carry out reliable quantum gate operations it is necessary to compensate for the fact that the ions not are identical. Appropriately tailored excitation pulses and excitation pulse sequences have therefore been developed and simulations show that excellent quantum gate fidelities can be obtained also when the ions have slightly different properties [4].

The work on the rare-earth-ion quantum-computing scheme is presently carried out within the EU ESQUIRE (Experimental realisation of quantum gates and development of Scalable QUantum computer schemes In Rare-Earth-ion-doped inorganic crystals) project. In addition to the experimental demonstration of quantum gates the ESQUIRE project also includes growing new crystal materials specially designed for quantum gate operations and developing schemes and architectures for scalable rare earth crystal quantum computers. The rare earth quantum computing scheme and the experimental and theoretical results in the project will be discussed in this contribution.

References

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