A trapped-ion-based quantum byte with 10^{-5} cross-talk

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Application Note

Introduction

The manipulation of a selected quantum bit within a quantum register is a key prerequisite for scalable quantum computing. In recent experiments using the iXon Ultra 897 EMCCD camera (model DU897 UCS-EXF from Andor Technology) we demonstrate the addressing of individual qubits within a quantum byte (eight qubits) [1]. In general, and therefore also in our experimental setup, every manipulation of a single qubit is realized by the application of electromagnetic radiation that also affects the non-addressed qubits within the register. To characterize the addressability in our setup we precisely measure the error that is induced in the non-addressed qubits (cross-talk) associated with the application of single-qubit gates. As a result of our experimental study we can conclude this cross-talk to be on the order of 10^{-5}. These results are below the threshold that is commonly agreed sufficient to efficiently realize fault-tolerant quantum computing.

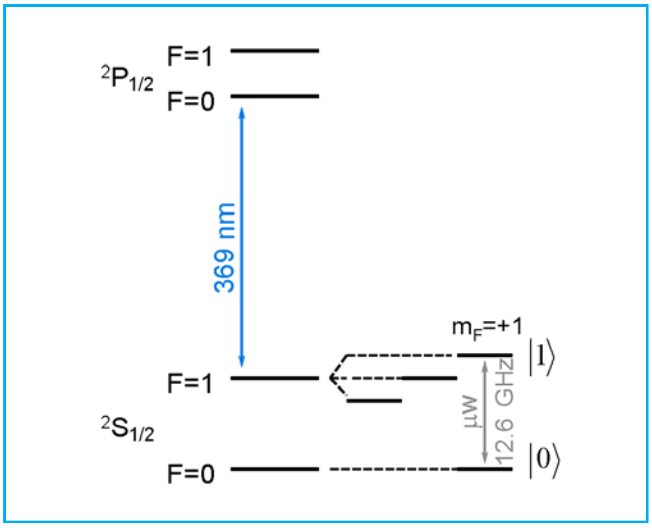

Figure 1: Relevant levels of $^{171}Yb^+$ ion. UV laser light near 369 nm is used for laser cooling and state selective read-out of the hyperfine qubit in the electronic $S_{1/2}$ ground state. The qubit is manipulated with microwave radiation near 12.6 GHz.

Experiment

The quantum byte is implemented using $^{171}Yb^+$ ions confined in a Paul trap. Hyperfine qubits are encoded in each ion's ground state ($|0\rangle \equiv |^2S_{1/2}, F = 0\rangle$ and $|1\rangle \equiv |^2S_{1/2}, F = 1, m_F = +1\rangle$).

As a speacial feature permanent magnets that apply a static magnetic gradient field are included in the trap design. Due to the Zeeman effect the magnetic gradient lifts the hyperfine qubits' degeneracy and allows to individually address them using microwave radiation. Doppler cooling of the ion chain and state selective detection of the ions' qubit state is achieved by driving the transition $|^2S_{1/2}, F = 1\rangle \leftrightarrow |^2P_{1/2}, F = 0\rangle$ with laser light near 369 nm (compare fig. 1). The UV fluorescence light is collected by an objective of NA 0.4 and magnification 25. Single-shot read-out of the quantum register is achieved by spatially resolved detection of the resonance fluorescence using an iXon Ultra 897 EMCCD camera during an exposure time of 2 ms. Dividing the read-out image into several sections (for each ion a single one) allows us to simultaneously detect the states of all qubits within the register.

In order to demonstrate the addressability within the quantum byte we make use of microwaveoptical double resonance spectroscopy. Therefore, the eight-qubit register is first initialized in the state $|00000000\rangle$ (all ions dark). In a next step microwave pulses of constant duration but with a variable frequency are applied to all ions. Then, all ions are illuminated with UV laser light near 369 nm. The spatially resolved resonance fluorescence that we can record with the EMCCD camera (compare fig. 2 (a)) allows us to identify each ion's qubit transition $|0\rangle \leftrightarrow |1\rangle$.

The coherent dynamics of a single-qubit manipulation are verified by the observation of Rabi oscillations. We therefore again initialize the quantum register in a state in which all ions are dark. Microwave pulses that are tuned to one of the qubit's addressing frequency but of variable length are then applied as a next step. From the UV resonance fluorescence recorded in the different image sections Rabi oscillations of the addressed ion only are observed while the others are virtually left unaffected (fig. 2 (b) and (c)).

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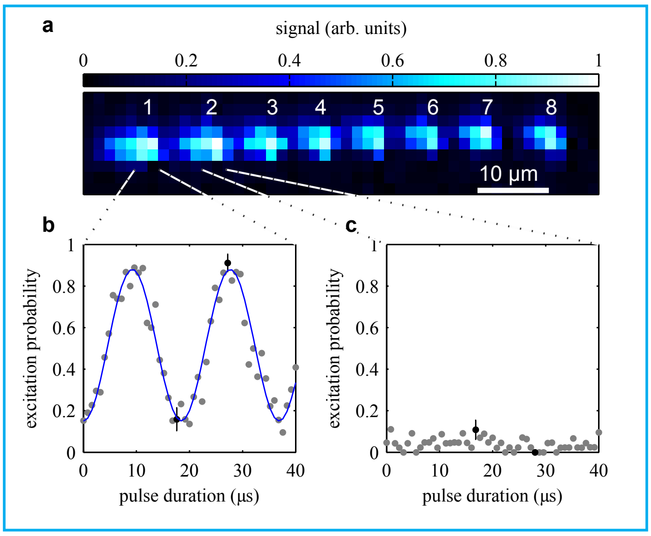

Figure 2: Coherent single-qubit manipulation of a single qubit within the quantum byte. (a) Spatially resolved resonance fluorescence (near 369 nm) of eight ions held in a linear Paul trap detected by the iXon Ultra 897 EMCCD camera. (b) Rabi oscillations (from dark |0⟩ to bright |1⟩) are only observed in the image section of ion 1 when irradiating all ions at the microwave addressing frequency of this ion. (c) The non-addressed ion 2 (and 3 through 8 as well) is left virtually unaffected.

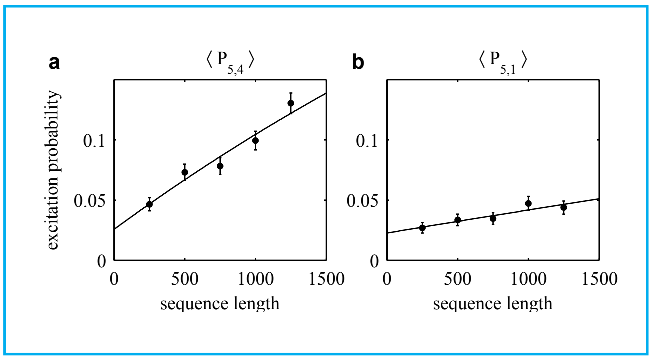

Figure 3: Exemplary error accumulation during benchmarking. A benchmarking sequence is addressed to ion 5 and the state selective resonance fluorescence signal in the image sections of individual ions is recorded. The larger next-neighbour cross-talk causes the excitation probabilities of the next-neighbour ion 4 (a) to accumulate faster than the ones of the non-next-neighbor ion 1 (b). From these data we deduce cross-talk errors per single gate of the order 10^{-5}.

The separation between the qubits' addressing frequencies (|0⟩ ↔ |1⟩) amounts to a few MHz, and is much larger than the Rabi frequency at which an individual qubit is manipulated (typically $2\pi \times 20$ kHz). The cross-talk error in our setup originates, therefore, from the effect of far off-resonance excitation. We can estimate this average excitation probability $\langle P_{i,j} \rangle$ of qubits j induced by a single π pulse (rotation from dark |0⟩ to bright |1⟩ addressed to a particular qubit i within the register to be off the order of 10^{-5}.

Such small changes in the state of qubit can efficiently be measured by making use of randomized benchmarking techniques [2]. The key idea is that instead of the application of a single π pulse a sequence of several rotations around different randomly chosen axes of rotation is applied before detecting the qubit state. In our experimental study we observe the spurious excitation probabilities to accumulate during sequences of up to 1250 randomized gates. The simultaneously detected results from the different ions' image sections recorded with the EMCCD allow us to efficiently characterize the cross-talk within the quantum byte (fig. 3). The deduced error per single gate is typically on the order of 10^{-5}.

References

[1] Piltz, Ch., Sriarunothai, Th., Varón, A. F. & Wunderlich, Ch. A trapped-ion-based quantum byte with 10^{-5} next-neighbour cross-talk. Nat. Commun. 5:4679 (2014).

[2] Knill, E. et al. Randomized benchmarking of quantum gates. Phys. Rev. A 77, 012307 (2008).

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