

Demonstration of conditional quantum phase shift between ions in a solid

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Due to their potential for long coherence times, dopant ions have long been considered promising candidates for scalable solid state quantum computing. However, the demonstration of two qubit operation has proven to be problematic, largely due to the difficulty of addressing closely spaced ions. Here we use optically active ions and optical frequency addressing to demonstrate a conditional phase shift between two qubits.

Solid state quantum computing is a field of active research spurred in part by the expectation that it will be easier to scale a solid state system to a large number of qubits. To date the only experimental demonstrations approaching that of a two qubit gate operation [1] have used qubits based on electron charge. While single electron charges are measurable, their strong interaction with the environment means that the coherence times are very short making necessary extreme experimental techniques.

In this work we demonstrate a conditional quantum phase shift in a two-qubit system, based on local interactions between optically active centers in a solid. The qubits were based on optical transitions of the dopant ions. The gate operations are performed with sequences of precise optical pulses in a manner analogous to techniques used in nuclear magnetic resonance.

The material chosen for the demonstration was Eu doped yttrium orthosilicate (YSO). This material was selected because of the narrow homogeneous linewidth of the ${}^7F_0 \leftrightarrow {}^5D_0$ transition of the Eu^{3+} ions at 579 nm, which can be as narrow as 100 Hz [2]. The long coherence time associated with this narrow line width simplifies the implementation of the optical pulse sequences as it allows the use of microsecond time scale pulses to control the gate operations. These pulses can be generated by simple modulation of the output of a narrowband continuous wave laser.

The dominant interaction between the europium ions is a non-resonant electric dipole-dipole interaction. The Eu^{3+} dopant ion possesses a permanent electric dipole moment that depends on the electronic state of the ion, therefore exciting one ion induces linear Stark shift in the optical frequencies of surrounding ions. For europium ions in adjoining Y sites, separated by 0.5 nm, the interaction is expected to be of the order of 10 GHz [3]. The interaction falls off as the inverse of the cube of the separation between the ions and therefore is larger than the ions' homogeneous linewidth out to distances of approximately 500 nm. A feature of the electric dipole-dipole interaction which will assist in scaling to a larger number of qubits, is that it can be effectively turned off by storing the quantum information in the dopants' optically

addressable hyperfine states, this has been demonstrated experimentally [4]. Another benefit is that the hyperfine have long coherence times, tens of seconds have recently been measured for these hyperfine transitions [5].

In a europium doped YSO crystal the europium ions substitute for the yttrium ions in the lattice and are distributed randomly throughout the available sites in the sample. In general, each of these ions has a unique optical transition frequency that is determined by the local crystal environment (i.e. inhomogeneous broadening). In principle it would be possible to implement two qubit gate operation on a single pair of closely spaced europium ions, addressing each ion by their different optical frequencies. In practice the optical detection of a single europium ion will be difficult due to the weak oscillator strength. Therefore, to increase signal strength, a high concentration of dopant ions is incorporated into the crystal, and from this starting ensemble of ions we select out a sub-ensemble with the desired characteristics.

The ability to select groups of ions that can be used as single qubits has been demonstrated previously [6, 7]. The general concept is to use optical pumping to an auxiliary hyperfine level to select a subgroup of ions with the desired characteristics. Here, a spectral hole is first burned into the broad inhomogeneous optical linewidth of the dopant ion transition. The hole width is usually chosen to be in the range of 1 MHz, so that it will be transparent to optical pulses having a smaller bandwidth. In the center of this broad spectral hole, a narrow anti-hole is then created. This is achieved using a narrow band laser to selectively excite a transition from one of the other ion ground-state sublevels to a convenient excited state, thereby optically pumping some of the ions back. This gives a narrow absorption feature (anti-hole) within the broad spectral hole. The width of this narrow anti-hole is determined by the inhomogeneous width of the spin transition, which is on the order of 100 kHz.

In principle, all the ions in this narrow anti-hole will respond in the same way to a sufficiently short laser pulse. However, in practice, non-uniformities in the laser intensity cause each ion to respond at a different rate (Rabi frequency) to an applied laser pulse. To overcome this limitation, a series of what are nominally 2π laser pulses are applied, these leave ions in a particular part of the laser beam in the ground state. Any ion that does not respond with the correct Rabi frequency is left partially

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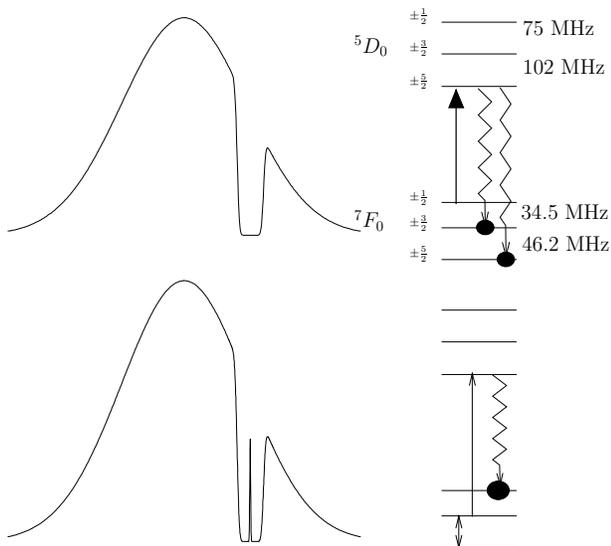
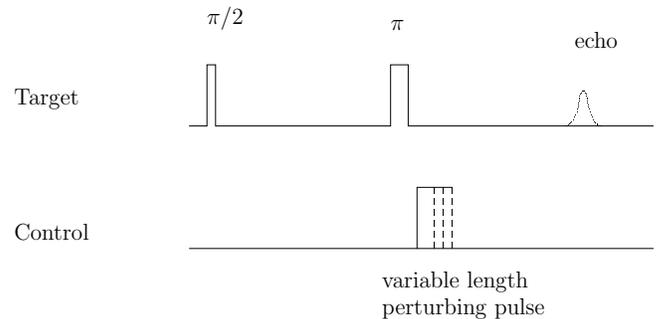


FIG. 1: Preparation sequence for distilling an ensemble of ions with well-defined properties out of an initially inhomogeneous distribution. First a broad hole is burned via spectral hole burning. (b) Next a narrow anti-hole is created in the center of the broad hole using optical pumping with a narrow band laser. Finally (not shown) ions in a particular part of the beam are selected using a series of 2π pulses. The absorption profiles shown are not to scale. The inhomogeneous linewidth was about 5 GHz, the broad spectral hole was 1 MHz wide and the narrow anti-hole was 100 kHz wide.

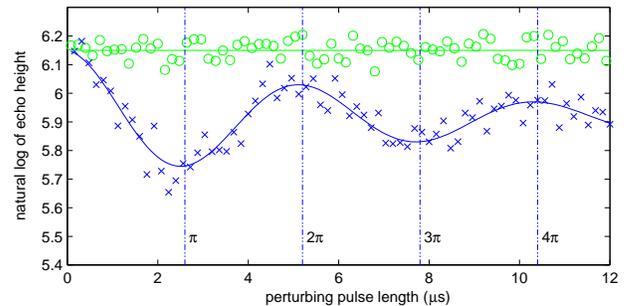
excited and is optically pumped to an auxiliary state after a few cycles. When driven with sufficiently short pulses (less than $10 \mu\text{s}$), the remaining ions can be viewed as an ensemble of identical single qubits. For long periods of evolution, π pulses are needed to rephase the ensemble, because the remaining 100 kHz inhomogeneous broadening means that the optical coherence will dephase over times of $1/(100 \text{ kHz})$. This rephased coherence, or optical echo, is also used for quantum state readout because it produces a measurable optical output beam whose properties are completely determined by the quantum state of the ensemble.

Here we extend the single qubit selection process to the selection of a group of ion pairs and then use this ensemble for a two-qubit demonstration. It should be noted that although we use ensembles, the ability to place every atom in an identical initial state enables this demonstration to be performed without the controversial pseudo-pure states that are used in liquid NMR quantum computers.

For two-qubit operation, two of the anti-holes described above were created, with one anti-hole used as the target qubit and the second used as a control. The interaction between the ions that is used here was first characterized by Huang et al. [8] and can be observed using a technique known as echo demolition. First, a two pulse photon echo sequence is applied to the target ensemble consisting of the usual $\pi/2$ pulse followed after



(a)



(b)

FIG. 2: (a) Pulse sequence for observation of control ion nutation on target ion echo. (b) Rabi flops of the control ion observed on the echo amplitude of the target ion ("x" symbols). For comparison, the "circle" symbols correspond to the control ion not being excited. To achieve such a clear Rabi nutation signal, the control ion was optically prepared by a sequence of 10 2π pulses, as described above.

a delay by the rephasing π pulse. For echo demolition, a perturbing pulse is applied to the control ensemble at the same time as the rephasing pulse is applied to the target. The effect of the perturbing pulse is to impart a frequency shift, and hence a phase shift, to each of the ions in the target ensemble such that the rephased coherence ends up phase shifted relative to the initial coherence. Since the perturbation is only applied during the rephasing part of the echo sequence, its effect is not canceled, as would be the case if it were applied immediately after the initial pulse.

FIG. 2 shows the effect of the interaction between two single qubit ensembles. Excitation of the control ions shifts the frequency of the target ions, and as this random frequency shift is only present for half of the photon echo sequence it stops the target ensemble rephasing to form an echo. In the figure Rabi flopping can be seen in the target ensemble's echo as the length of the pulse applied to the control ensemble is varied — driving the control to the excited state destroys the echo whereas cycling back to the ground state leaves the echo unchanged.

In order to perform two qubit logic operations, the echo demolition must be turned into a controlled phase shift that does not decrease the echo magnitude. This is accomplished by using spectral hole burning and the dipole coupling-induced frequency shift to further prepare the target ensemble. The target ions that do not shift in frequency by the correct amount are optically pumped to a passive level. Conceptually this technique has been previously proposed [3] using a CW approach. However it was found that pulsed techniques borrowed from NMR spectroscopy were needed to resolve the induced frequency shifts from the anti-hole's inhomogeneous broadening. Specifically, an echo pulse sequence is constructed that returns a target ion, with the correct control ion interaction, back to the ground state. However, target ions with no control ion or with a control ion coupling of the wrong strength are not returned completely to their ground state, and are therefore optically pumped away after several cycles. The pulse sequence used for selecting the ion pairs is illustrated in FIG. 3, the same pulse sequence can be used for CNOT gate in NMR quantum computing. As the control ions are not initially excited, the target ions with the correct interaction strength will be returned to the ground state.

Because of the rephasing pulses the spectral resolution of this technique is limited by the optical coherence time, which is orders of magnitude narrower than the width of the anti-holes used. It should be noted that in this initial experiment the selection process was only applied to the target ions. As a result there are ions left in the control anti-hole that don't interact with an ion in the target. An ensemble that is much closer to a true collection of pairs could be achieved using the same pulse sequence but with the roles of the two qubits reversed on alternate repetitions.

The operation of the conditional quantum phase shift is shown in FIG. 4, where the preparation pulse sequence described in FIG. 3 has been used. The in-phase and in-quadrature parts of the echo signal are plotted (superimposed) in FIG. 4(a) as a function of time. When the control ion is excited, the echo is phase shifted. Significantly, the echo magnitude is essentially the same in both cases, thus, the echo is no longer demolished by the perturbing pulse, but instead experiences a conditional phase shift (i.e. conditional quantum phase gate). The phase shift in this data is about 20 degrees, but in principle can be made larger by further refinement of the state preparation process.

Here we have started with a random ensemble of europium dopants in yttrium orthosilicate, and we used

spectral holeburning techniques to select out ions from one ensemble that have a particular interaction strength with ions in another. Using this prepared system we demonstrated a phase shift in one qubit conditional on the state of the other. The specific approach of selecting ensembles from randomly distributed ions is not scalable because the requirements for the ensemble get more and more stringent as the number of qubits increase. To

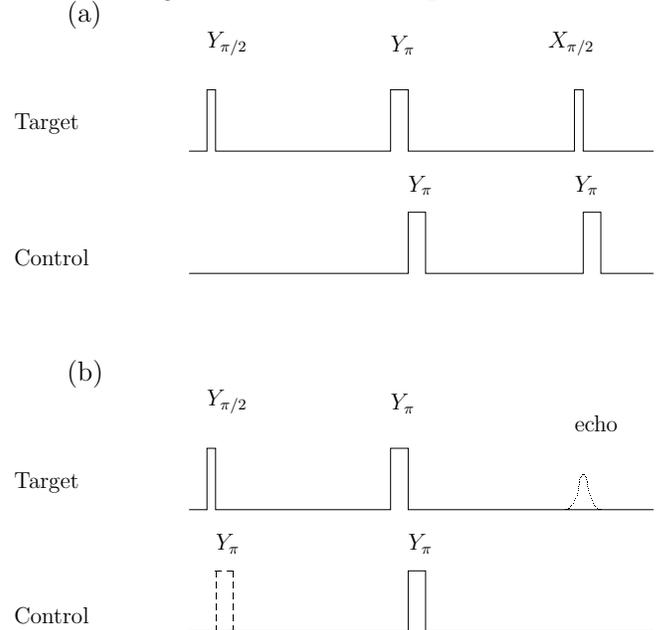


FIG. 3: Pulse sequence used to (a) select target ions based on their interaction with the control and (b) demonstrate the conditional phase shift.

achieve scalable quantum computing it will be necessary to either implement single site detection or develop a method of creating identical clusters of optically active ions. Single site detection will be difficult for rare-earth ions due to their weak oscillator strength, however the ion-ion interaction used here will be present in any solid state impurity site with a permanent electric dipole moment. This includes the NV-centre in diamond where single site detection is well advanced [9].

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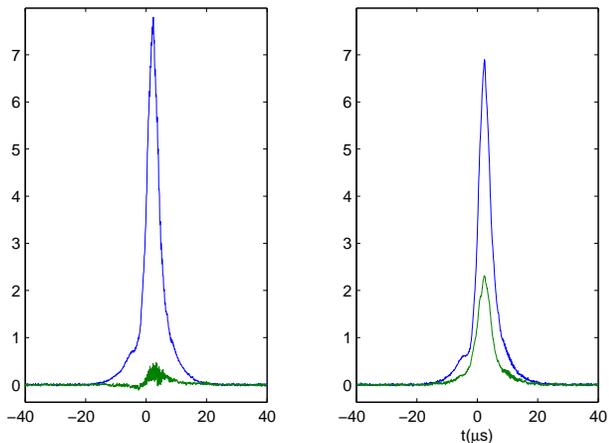


FIG. 4: Conditional quantum phase shift demonstration. The data for in-phase and in-quadrature echo signals are shown without (left) and with (right) the control ion initially excited. Significantly the phase shift is produced without noticeable decay in the echo magnitude, given by the RMS sum of in-phase and in-quadrature signals. In other words the conditional phase shift is achieved without increasing the affecting state purity. The phase shift in this very first experiment is about 20-degrees, but in principle can be made larger than π by upgrading the experiment.

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