Demonstration of Conditional Quantum Phase Shift Between Ions in a Solid

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Because of their long coherence times, dopant ions have been considered promising candidates for scalable solid state quantum computing. Here we demonstrate a conditional phase shift between two qubits based on an optical transition of europium ions. The demonstration uses ensembles that have been selected from a randomly doped sample using spectral hole burning techniques. The electron dipole-dipole interaction between the ions that usually causes instantaneous spectral diffusion is used to generate the conditional phase shift.

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Quantum computing based on solid state systems 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 a number of two-qubit demonstrations have using solid state systems been made including cases where the qubits are associated with electron charges [1], quantum dots [2], and nitrogen-vacancy center in diamond and a neighboring ^{13}C nuclear spin [3]. Rare-earth ions doped into solids provide alternative qubits. The rare-earth ions have a number of desirable properties for quantum computing, most particularly, long coherence times for both the optical [4] and hyperfine transitions [5]. Also there are optical transitions that exhibit large ratios of inhomogeneous to homogeneous optical line widths, and this is convenient as it enables separate qubits or group of qubits to be addressed using their optical frequencies. A further very important feature is that there is a strong direct electric dipole-dipole interaction over relatively long distances, (hundreds of nanometers), that provides an opportunity for gate operations. There have been proposals for the implementation of quantum computing using rare-earth ion dopants published previously [6–8]. The proposal most relevant to this work is that of Ohlsson *et al.* [8] which also uses direct dipole-dipole for the interaction between qubits.

In this Letter, we demonstrate a conditional quantum phase shift in a two-qubit system, based on local interactions between optically active rare-earth centers in a crystal. 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 europium doped yttrium orthosilicate. This material was selected because of the narrow homogeneous linewidth of the trivalent europium $^7F_0 \leftrightarrow {}^5D_0$ optical transition at 579 nm, which at liquid helium temperatures (2-4 K) has a linewidth of the order of 100 Hz [4]. The two levels of this transition are used to form the qubit. The long coherence time associated with this narrow linewidth 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 narrow-band continuous wave laser. The ions possess 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 yttrium sites, separated by 0.5 nm, the interaction is expected to be of the order of 10 GHz [8]. The interaction falls off as the inverse of the cube of the separation between the ions and at 500 nm the Stark shift is still larger than the homogeneous linewidth. These Stark shifts are used to implement the gate.

The europium ions in yttrium orthosilicate substitute for the yttrium ions and are distributed randomly throughout the crystal. 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 (0.02%), and from this starting ensemble of ions we select out a subensemble with the desired characteristics.

The ability to select groups of ions that can be used as single qubits has been demonstrated previously [9,10]. The general concept is to use optical excitation to select ions with desired characteristics pumping all others to an auxiliary hyperfine level. A spectral hole is first burned into the broad inhomogeneous optical linewidth of the dopant ion transition Fig. 1(a). The hole width is usually chosen to be in the range of 1 MHz, so that it will be transparent to optical pulses which have bandwidths less than 1 MHz bandwidth. The next step is to create a narrow antihole in the center of this broad spectral hole [Fig. 1(b)]. This is achieved using a narrow band laser to

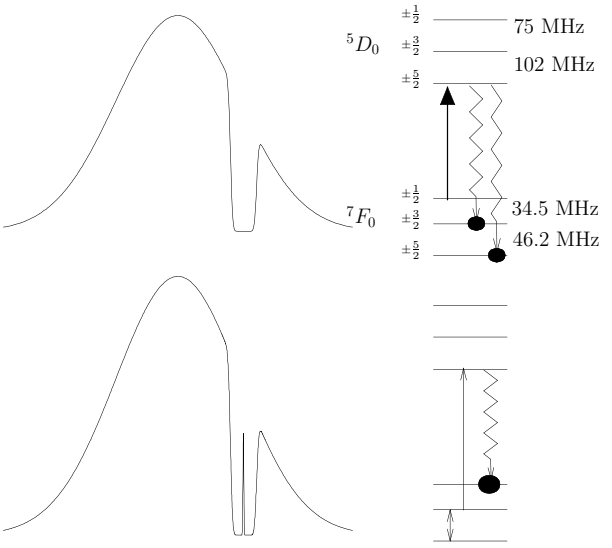

FIG. 1. Preparation sequence for distilling an ensemble of ions with well-defined properties out of an initially inhomogeneous distribution. (a) First a broad spectral hole is prepared using a laser beam swept in frequency. (b) Next a narrow antihole is created in the center of the broad hole using optical pumping with a narrow band laser. This leaves a spectrally narrow packet of ions resonant with the laser via their $\pm 1/2 \rightarrow \pm 1/2$ hyperfine transition. It is these ions and this transition that is used as the qubit. 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 antihole was 100 kHz wide. The straight arrows represents the effect of the laser driving and the wiggly arrows represents relaxation.

selectively excite a transition originating from one of the ground-state hyperfine levels to a selected excited state such that when the ion decays it gives an absorption (antihole) within the broad spectral hole. The width of this antihole 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 antihole will respond in the same way to a sufficiently short laser pulse. However, in practice, nonuniformities in the laser intensity cause ions across the laser beam to respond at different Rabi frequencies. To overcome this limitation, a series of what are nominally 2π laser pulses are applied. This leaves 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 excited and is optically pumped to an auxiliary state after a few cycles. When driven with sufficiently short pulses (less than 10 μs), 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 kHz). This rephased coherence 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. It should be noted that although the signals involve ensembles, the ability to place every atom in an identical initial state enables experiments to be performed without resorting to the pseudopure states that are used in liquid NMR quantum computers.

For two-qubit operation, two of the above antiholes were created, with one antihole to be used as the target qubit and the second used as a control. The experimental setup used was very similar to previous work [9,10] and used a ring dye laser with a line width of 200 Hz over timescales of 1 s. The sample was in one arm of a Mach-Zender interferometer and light on the sample was gated with two acousto-optic modulators. The modulators also introduce a net frequency shift of 10 MHz such that light transmitted through the sample and the coherent emission produced by the sample could be seen as a 10 MHz beat with the light from the other arm of the interferometer. Mixers enabled the beat to be down converted to an in phase and quadrature signal using a 10 MHz local oscillator.

With the two antiholes further selection, involving interaction between the two ensembles, is required. Studies of relevant ion-ion interaction was first performed by Huang *et al.* [11] using a technique known as echo demolition. For echo demolition a two pulse photon echo sequence is applied to the target ensemble consisting of the usual $\pi/2$ pulse followed after a delay by the rephasing π pulse. In addition a perturbing pulse is applied to the control ensemble. For this work the peturbing pulse is applied at the same time 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. As a result of the random separations between ions there is a distribution of phase shifts of the ions within the target ensemble. Because of this the rephasing of the target ions is not complete. Fig. 2 shows the result of such an experiment. 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 rather than a decrease in 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 give a chosen frequency shift are optically pumped to a passive level. Conceptually this technique has been previously proposed [8] using a continuous wave approach. The

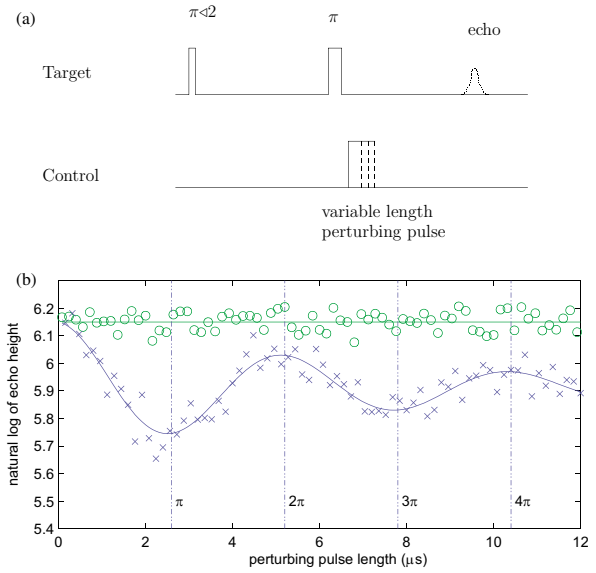

FIG. 2 (color online). (a) Pulse sequence for observation of control ion nutation on target ion echo. (b) Rabi flops of the control ion observed on the echo amplitude of the target ion ("x" symbols). For comparison, the "circle" symbols are shown, which correspond to the control ion not being excited. The control ion was optically prepared by a sequence of ten 2π pulses, as described in the text.

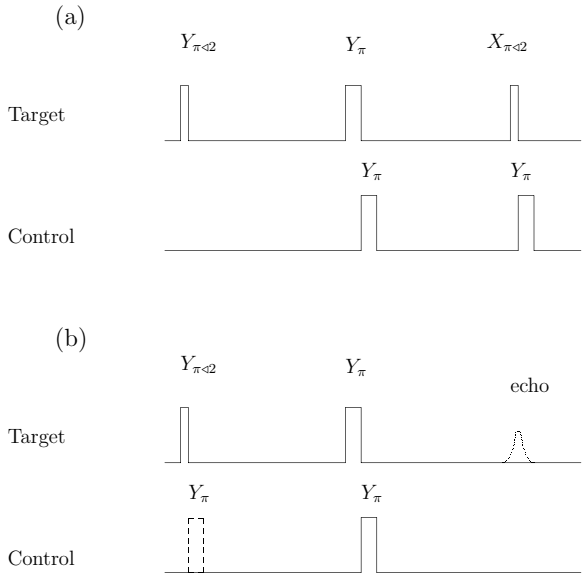

FIG. 3. Pulse sequence used to (a) select target ions based on their interaction with the control and (b) demonstrate the conditional phase shift.

limitation with the CW approach is the requirement that the excitation induced frequency shift be larger than the inhomogeneous width of the ensembles. In the approach taken here pulse techniques borrowed from NMR spectroscopy were used to resolve the induced frequency shifts from the antihole's inhomogeneous broadening. Specifically, an echo pulse sequence is constructed that returns a target ion, with the appropriate control ion interaction, back to the ground state. However, target ions with a control ion coupling strength not selected are not returned completely to their ground state and after several cycles are pumped to passive levels. The pulse sequence used for selecting the ion pairs is illustrated in Fig. 3. The first pulse puts the target ions on the equator of the Bloch sphere where it then precesses around the equator at a rate given by their detuning from resonance. The detuning is the combination of a static part (which causes inhomogeneous broadening) an nonstatic part dependent on the state of the control ions. The π pulse applied to the target halfway through the sequence refocuses the static detuning. However, because of the π pulse applied to the control at the same time, the π pulse applied to the target does not refocus the effect of the interaction with the control. Thus at the end of the sequence the target ions have a spread in-phase caused by their differing interaction with the control. This phase difference is converted to a population difference by the final $\pi/2$ pulse. The pulse sequence is described further in [12]. It is appreciated that the selection process has only been applied to the target ions and as a result there are ions left in the control antihole that do not 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. An echo from the target is shown for the control not excited (left) and excited (right). The in-phase and in-quadrature parts of the echo

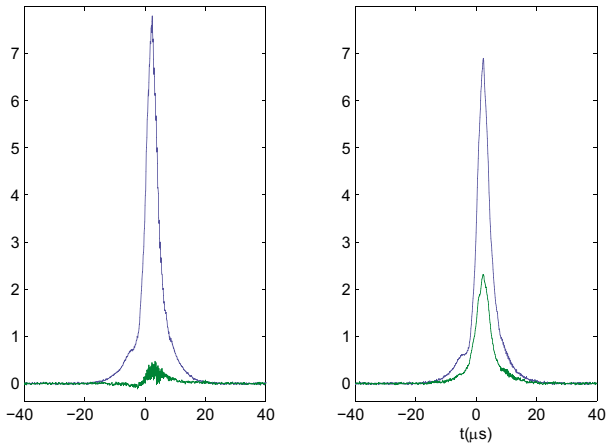

FIG. 4 (color online). Conditional quantum phase shift demonstration. The data for in-phase and in-quadrature echo signals are shown without (left) and with (right) the control ion initially excited. The magnitude of the echo given by the RMS sum of in-phase and in-quadrature signals is unchanged. The phase shift is $20 \pm 2°$.

signal are plotted as a function of time. The echo magnitude is the same in both cases and, hence, the perturbing pulse does not cause any demolition. However, with the control ion excited (right) the phase of the echo is shifted and thus experiences a conditional phase shift. The phase shift in this data is $20 \pm 2°$ (the phase of the signal is simply $\arctan(x_1/x_2)$ where x_i are the amplitudes of the quadratures), but in principle can be made larger by further refinement of the ensemble preparation process. At the time the experiments were performed the limiting factors were a combination of limited laser power and laser stability.

Here we have started with randomly doped europium ions in yttrium orthosilicate, and used spectral holeburning techniques to select an ensemble of ions that have a particular interaction strength with ions in a second ensemble. Using this prepared system we measure a phase shift for the selected ions conditional on the state of the other. The experiment therefore demonstrates a conditional quantum phase gate. The approach, in principle, is transferable to other optically active centers in crystals that have permanent electric dipole moments. It is also envisaged that optical gates of this type could be used where the quantum information is stored in the hyperfine levels (nuclear spin states). Qubits and gates can be addressed and controlled optically [13] and as the electric dipole-dipole interaction does not directly affect hyperfine transitions, operations on selected qubits and pairs of qubits can be made without affecting other nuclear qubits in the system. This facilitates scaling. Another clear benefit of using nuclear rather than optical qubits is the very long coherence times [5] with tens of seconds recently measured[14]. However, the current approach of selecting ensembles from randomly distributed ions is not scalable because the requirements for the ensemble become more and more stringent as the number of qubits increase. To 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 other types of optical centers. This includes the nitrogen vacancy center in diamond where single site detection is well advanced [15].

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[1] T. Yamamoto *et al.*, Nature (London) **425**, 941 (2003).
[2] X. Li *et al.*, Science **301**, 809 (2003).
[3] F. Jelezko *et al.*, quant-ph/0402087.
[4] R. W. Equall, Y. Sun, R. L. Cone, and R. M. Macfarlane, Phys. Rev. Lett. **72**, 2179 (1997).
[5] E. Fraval, M. J. Sellars, and J. J. Longdell, Phys. Rev. Lett. **92**, 0077601 (2004).
[6] K. Ichimura, Opt. Commun. **196**, 119 (2001).
[7] M. S. Shahriar *et al.*, Phys. Rev. A **66**, 032301 (2002).
[8] N. Ohlsson, R. K. Mohan, and S. Kröll, Opt. Commun. **201**, 71 (2002).
[9] G. J. Pryde, M. J. Sellars, and N. B. Manson, Phys. Rev. Lett. **84**, 1152 (2000).
[10] J. J. Longdell and M. J. Sellars, Phys. Rev. A **69**, 032307 (2004).
[11] J. Huang, J. M. Zhang, A. Lezama, and T. W. Mossberg, Phys. Rev. Lett. **63**, 78 (1989).
[12] J. J. Longdell and M. J. Sellars, quant-ph/0310105.
[13] A. L. Alexander, Honours thesis, Australian National University, http://eprints.anu.edu.au/archive/00000761/ (unpublished).
[14] E. Fraval (private communication).
[15] F. Jelezko, I. Popa, A. Gruber, and J. Wrachtrup, Appl. Phys. Lett. **81**, 2160 (2002).