Trapped Ion Qubit Operations with Ultrashort Pulses

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Abstract: We describe an experiment to achieve ultrafast qubit operations on trapped $^{171}\mathrm{Yb}^{+}$ ions. We plan to use a series of short optical pulses to perform bit rotations and multi-bit entangling gates independent of ion temperature.

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1. Introduction

Trapped ion quantum computing currently uses either Coulomb-coupled phonons [1] or scattered photons [2] to entangle qubits. For the motional coupling schemes, it has been necessary to be in the Lamb-Dicke regime where the spread of the ion's motional wavefunction is less than an optical wavelength. In order to reduce decoherence, cooling to the motional ground state is often used to prepare a pure motional state. This is a stringent requirement for which Doppler cooling is typically insufficient. Moreover, trap miniaturization is central in efforts to scale up the number of trapped ion qubits, and surface-induced heating increases as the trap size is reduced [4].

We report here on progress toward implementing temperature-insensitive gates [5, 6] using ultrashort laser pulses. Such fast gates circumvent the need for cooling to the Lamb-Dicke limit by performing operations much faster than the trap frequency. By using far-detuned optical pulses to make Raman transitions between qubit states, the Stark shift, differential Stark shift, spontaneous emission, and residual excited state population should be negligible. These gates may relax the requirements on electrode proximity and heating after ion shuttling and help to scale up trapped ion quantum computing.

2. Ultrafast Pulses

Our experimental work utilizes trapped $^{171}\mathrm{Yb}^{+}$, which possesses many of the desirable features of trapped ion qubits, such as diode laser accessible wavelengths and simple atomic energy level structure that allows using hyperfine-level clock states for the logical qubit states [see Fig. 1(a)]. The $m_F = 0$ states of the two hyperfine levels in the ground state of $^{171}\mathrm{Yb}^{+}$ are used as our logical qubit states $|0\rangle$ and $|1\rangle$. We are working toward performing bit rotations by applying ultrafast laser pulses that induce Raman transitions through couplings to excited electronic states.

Since the instantaneous intensity of an ultrashort pulse can be tremendously high, it is important to control the perturbing effect of the light on a trapped ion qubit. To avoid unwanted effects from the light field, we have chosen to work in the far-detuned regime, where most of these perturbations become negligible. Fig. 1 shows the differential Stark shift between the clock states of the ground state hyperfine levels (the logical qubit) as a function of laser wavelength.

The minimum in Fig. 1(b) occurs near 355 nm, where high-power tripled vanadate and YAG lasers are available. This large detuning ($>$10 nm) is in contrast to our previous work (see Ref. [3]) with near-resonant pulses that transfer significant population to the excited state. Our experimental efforts focus on the use of a picosecond ($\sim$10 ps) tripled vanadate laser to drive qubit rotations.

It should also be possible to use a series of multiple pulses to impart spin-dependent forces. By controlling the pulse timing and/or phase we could then entangle multiple ions [5, 6]. If successful, such fast gates may enable scalable quantum computation with large numbers of trapped atomic ions.

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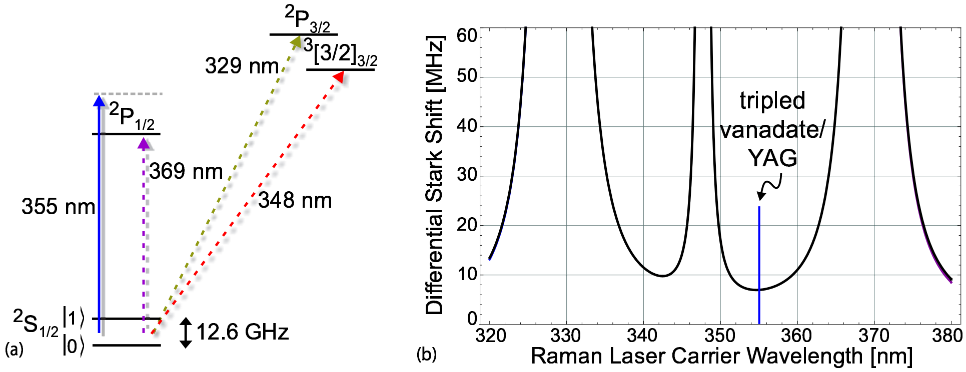

Fig. 1. (a) Relevant levels of $^{171}\mathrm{Yb}^+$ with the pulsed Raman laser at 355 nm. (b) Differential Stark shift between $|0\rangle$ and $|1\rangle$ vs pulsed laser wavelength. The three peaks are due to the transitions from the $^2S_{1/2}$ ground state to the $^2P_{3/2}$, $^3[3/2]_{3/2}$, and $^2P_{1/2}$ states at 329, 348, and 369 nm, respectively. This residual differential Stark shift is predicted to be much smaller than the Rabi frequency, which should be more than 10 GHz.

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