Toward Coherent Control of Single Yb^{3+} Ions in a Nanophotonic Cavity

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Abstract: We report on detection and coherent optical driving of single Yb^{3+} ions coupled to a nanophotonic resonator fabricated in the YVO_4 host crystal and outline a path toward control of single $^{171}Yb^{3+}$ spins. © 2019 The Author(s)

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Optically addressable solid-state spins are a promising platform for implementing quantum technologies [1]. Rare-earth ions (REIs) in solids are attractive for this purpose because long optical and spin coherence lifetimes have been demonstrated in these materials at cryogenic temperatures. While REIs typically have weak optical transitions that can make direct detection of single ions difficult, the ion emission rate and photon collection efficiency can be significantly increased by coupling to a nanophotonic cavity. Recently, this approach has been used to enable optical addressing of single neodymium [2] and erbium [3] ions. One future direction for this work is coherent manipulation and optical readout of the electron and nuclear spin transitions of single REIs. $^{171}Yb^{3+}$ is an interesting choice for pursuing such measurements because it has an effective electron spin and nuclear spin of 1/2. This gives rise to a simple level structure that allows efficient microwave manipulation of the electron spin and long term storage on the nuclear spin. Furthermore, recent spectroscopy of $^{171}Yb^{3+}$ doped in YVO_4 shows that the optical and spin properties of this material are promising for nanoscale quantum interfaces [4]. In this work, we report progress on detection and manipulation of single Yb^{3+} ions coupled to nanophotonic cavities fabricated in the YVO_4 crystal host.

To enable detection of single ions, a photonic crystal cavity was fabricated in YVO_4 using focused ion beam milling as described in [2] and measured on the mixing chamber of a dilution fridge held at 40 mK. The host crystal was nominally undoped, but had a residual Yb^{3+} concentration of < 20 ppm. This low concentration and natural inhomogeneous broadening in the crystal allows for the isolation of individual ions in the frequency domain. Cavity coupled ions were detected using pulsed resonant photoluminescence excitation (PLE) spectroscopy. Fig. 1a shows a typical PLE scan in the tail of the inhomogeneous distribution as function of laser detuning. In this scan, we identify three peaks that correspond to emission from single ions.

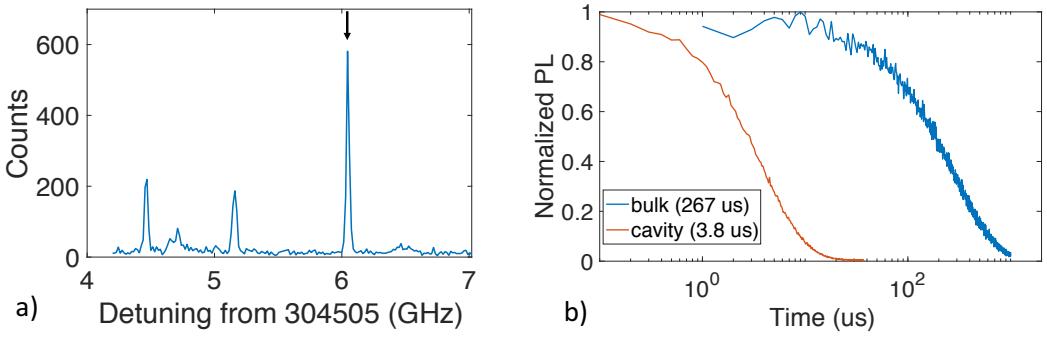

Fig. 1. a) Photoluminscence excitation (PLE) scan showing three isolated single ions. The arrow highlights the ion used for the measurements in this work. b) Optical lifetime measurement of the ion coupled to the cavity showing a Purcell-enhanced lifetime of 3.8 μs compared to the bulk lifetime of 267 μs.

The high Q ($\sim 10^4$) and low mode volume ($\sim 0.5(\lambda/n)^3$) of this cavity leads to a significant enhancement of the ion emission rate via the Purcell effect. Fig. 1b shows a PL lifetime measurement of the cavity coupled ion highlighted in Fig. 1a. We measure a cavity-enhanced lifetime of 3.8 μs, which is a reduction by a factor of ~ 70 from the bulk lifetime of 267 μs.

To verify that we are measuring single ions, we perform pulsed second-order autocorrelation measurements on the PL emission. Fig. 2a shows a typical measurement, which gives $g^2(0) = 0.09 \pm 0.01$ and confirms the single emitter nature of the observed emission.

By monitoring how the optical transitions of individual ions behave in an applied magnetic field, we can identify ions of different isotopes such as those with zero nuclear spin or those of the 171 isotope with nuclear spin 1/2. We show that the cavity-enhanced emission rate enables efficient spin initialization of the electron spin on a zero-nuclear spin isotope.

We demonstrate coherent driving of the optical transition through optical Rabi oscillations. Fig. 2b shows the emission from a single ion with zero-nuclear spin as a function of the excitation pulse length with a small magnetic field ($\sim$ 1 mT) applied to the sample. By fitting the decay of these oscillations, we extract an optical coherence time in this regime of $\sim$ 250 ns. Recent spectroscopy in $^{171}Yb^{3+}$:YVO_4 has shown optical coherence lifetimes greater than 100 us can be achieved by applying large magnetic fields ($>$ 500 mT) along the crystal symmetry axis. Working in this high field regime with these devices should thus enable single ion cooperativities up to ~ 50.

This work is a promising first step toward initialization and coherent manipulation of single $^{171}Yb^{3+}$ nuclear spins.

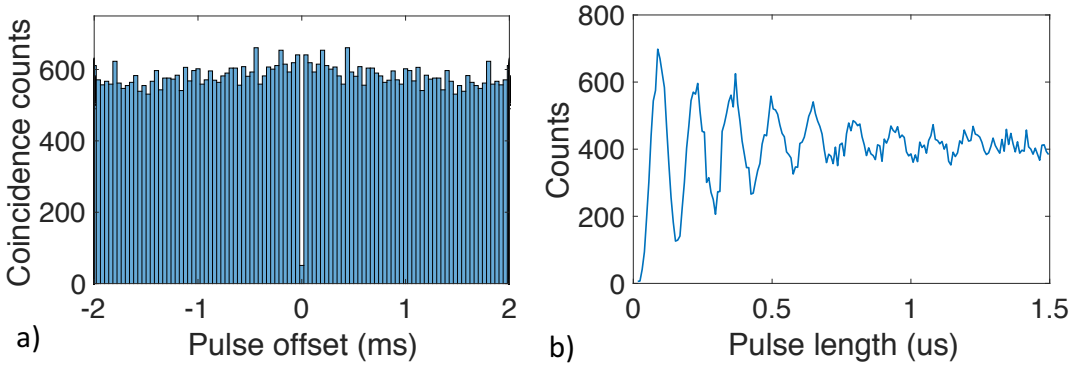

Fig. 2. Measurements on the ion highlighted in Fig. 1. a) Pulsed second-order autocorrelation of the photoluminescence giving $g^2(0) = 0.09 \pm 0.01$. b) Optical Rabi oscillations in the single ion emission as a function of excitation pulse length.

References

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