Single rare-earth ion spins in nanophotonic resonators

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Abstract: Rare-earth ions embedded in crystals are promising optically addressable spin qubits. We demonstrate this potential by measuring the optical and spin transition properties of single $^{171}\text{Yb}^{3+}$ ions coupled to nanophotonic resonators fabricated in YVO_4 . © 2020 The Authors

1. Introduction

An ongoing challenge in quantum science and technology is to distribute entanglement by combining ‘flying qubits’, like photons, with ‘stationary qubits’ based on matter. The leading platforms to realise protocols for such quantum networks are atomic systems, either individually trapped or as ensembles [1], and solid-state optical centers [2]. The aim in all these systems is to realize stable optical transitions coupled to cavities for efficient interfacing with photons, and spin coherence lifetimes that are long enough to store quantum states during photon transit through the network.

Rare-earth ions in crystals are one class of solid-state emitters that have shown appeal for quantum networking applications. Previous experiments with rare-earth ion ensembles in crystals have demonstrated that they can possess narrow (~ 1 kHz), stable optical transitions and spin coherence times longer than the time it takes light to travel global distances (~ 100 ms). However, repeating similar measurements with single ions is challenging because the long optical lifetimes ($100\ \mu\text{s} \sim 10$ ms) of the relevant $4f$ energy levels result in low emission rates compared to other quantum emitters [3,4].

In this work [5], we coupled the 984.5 nm transition of single $^{171}\text{Yb}^{3+}$ -ions in a commercially available yttrium orthovanadate (YVO_4) crystal to a one-dimensional nanophotonic resonator (shown in Figure 1(b)). The resulting Purcell enhancement of the transition increased the photon emission rate by over two orders of magnitude (optical T_1 in the cavity = $2.27\ \mu\text{s}$). We characterized the optical and spin transition properties of single ions at cryogenic temperatures between 40 mK and 1.2 K. In particular, we demonstrated optical coherence lifetimes (optical echo) $T_2 = 1.6T_1$, and spin coherence lifetimes up to 33 ms.

Fig. 1. (a) Zero-magnetic-field energy level structure for $^{171}\text{Yb}^{3+}$ -ions in YVO_4 . Transitions A and E (blue) are coupled to the cavity mode, whereas F (red) is orthogonally polarized. We targeted the spin clock-transition between states $|0\rangle$ and $|1\rangle$ at a frequency $\mu_g = 675$ MHz. (b) False-color scanning electron micrograph of the nanophotonic cavity located within a gold coplanar waveguide. (c) Schematic of the experiment. The device is maintained at a temperature below 1.2 K in a dilution refrigerator. We addressed the ion using optical excitation that is coupled to the device using a free space lens doublet, and microwave excitation that is coupled to a coplanar waveguide. Photon emission is collected back into a single mode fiber and detected by a superconducting nanowire single photon detector (SNSPD) in the same fridge.

2. Results and discussion

Fig. 2. (a) Single $^{171}\text{Yb}^{3+}$ ion optical coherence properties measured using Ramsey, post-selected Ramsey and echo pulse sequences. (b) Coherence lifetime measurements on the $\mu_g = 675$ MHz spin transition using a Carr-Purcell-Meiboom-Gill pulse sequence.

Using pulsed excitation from a gated Ti:Sapph laser we isolated single $^{171}\text{Yb}^{3+}$ -ions based on their frequency-resolvable optical transitions. Pulsed autocorrelation measurements yielded $g^2[0] < 0.15$ confirming that we were addressing a single ion. Figure 2(a) shows the data from optical coherence measurements. The $T_2^* = 390$ ns measured by a Ramsey sequence was limited by quasi-static fluctuations impacting the optical transition frequency, which were mitigated by using post-selection. We also applied an optical π pulse to rephase the quasi-static fluctuations and the resultant echo method yielded a significantly longer T_2 .

We also performed spin coherence lifetime measurements through pulsed microwave excitation at the ground-state spin transition frequency. We optically initialize the ion into state $|0\rangle$ or $|1\rangle$, apply microwave pulses at frequency μ_g , and then read out the population of state $|1\rangle$ on the highly cyclic ($>99\%$) transition A (see Figure 1). With a single rephasing π pulse we measure a $T_2 > 40$ μs, which can be extended to greater than 30 ms through dynamic decoupling sequences as shown in Figure 2(b). This coherence lifetime remained constant at temperatures up to 1.2 K. Factors limiting the coherence lifetime include contributions from the spin lifetime ($T_1 = 50$ ms) and residual magnetic dephasing arising from interactions with other spins in the host crystal.

In conclusion, we demonstrated single $^{171}\text{Yb}^{3+}$ -ions in YVO_4 nanophotonic cavities to be a promising optically addressable spin to realize light-matter interfaces for quantum networks. Future research will work to reduce spin impurities in the host crystal, and improve the cavity quality factor and light extraction efficiency to build toward multi-rare-earth ion networks.

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4. References

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