Coherent Optical Control of Single Ytterbium Ions in a GaAs Hybrid Photonic Crystal Cavity on Yb:YVO_4

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Abstract: We demonstrate coherent optical control of single Yb^{3+} ions in YVO_4 coupled evanescently to a GaAs photonic crystal cavity.

1. Introduction

Solid-state emitters have been explored as promising candidates for entanglement distribution and realizing quantum networks because of their scalability and integrability with nanophotonics [1]. Among different candidates, e.g. color centers in diamond and silicon carbide [2], rare-earth ions doped inside crystals have shown promising optical and spin coherence properties and the ability to address surrounding nuclear spins [3–5]. Previously, to improve the spin-photon interface efficiency, we have used ion-beam milling to fabricate an optical cavity in Yb:YVO_4 with quality factor Q=10,000 and mode volume $\sim 1(\lambda/n_{YVO})^3$, leading to a reduced lifetime of the 984 nm ^{171}Yb optical transition from 267 μs to 2.3 μs. This enabled high-fidelity single-shot readout of the ground state clock transition and measurement of a 1.4 MHz spectral diffusion limited linewidth [3]. In order to emit indistinguishable optical photons and create higher fidelity remote entanglement between ^{171}Yb ions, reducing the lifetime by improving the cavity Q factor is important. Here we develop a new hybrid platform using a GaAs photonic crystal cavity to evanescently couple to Yb:YVO_4. Harnessing the mature GaAs fabrication technology, people have demonstrated high Q factor (>100K) cavities with mode volume 1.5 $(\lambda/n_{GaAs})^3$ at 950 nm [6]. In this work, we fabricate a cavity at 984 nm and show the ability to detect and measure the properties of single Yb ions inside this hybrid platform.

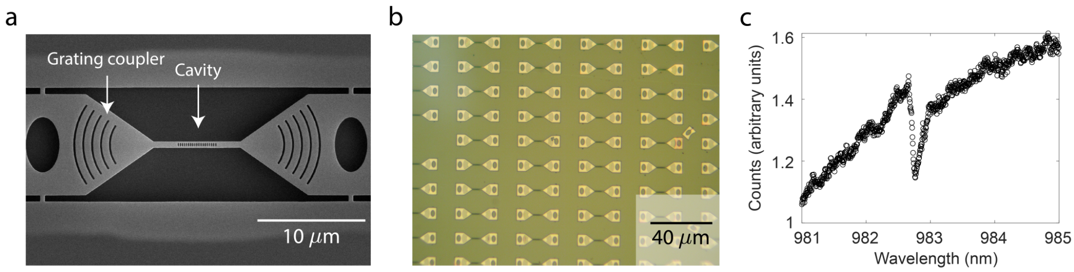

Fig. 1. Fabricated hybrid GaAs photonic crystal cavity devices. (a) Scanning electron microscope image of the suspended GaAs device. (b) Optical image of the GaAs devices after transferring onto YVO_4. (c) Cavity reflection spectrum of the hybrid device.

2. Results and Discussion

We fabricated a 1-D photonic crystal cavity from GaAs using standard ebeam lithography [7]. A scanning electron microscope image of the fabricated device is shown in Figure 1a. The suspended GaAs devices are transferred onto YVO_4 using a stamping technique [8], which is widely used in the 2D material community (Figure 1b). Light is coupled into and out of the device using the grating coupler. For the transferred device, we measured a typical Q factor of 5000 (Figure 1c) with a simulated effective mode volume $\sim 1.5\ (\lambda/n_{YVO})^3$.

Figure 2a shows the photoluminescence spectrum of the device measured in a ^{3}He cryostat at 0.5 K, which contains a bright Yb even isotope transition and resolvable narrow peaks. The narrow peaks are mostly single

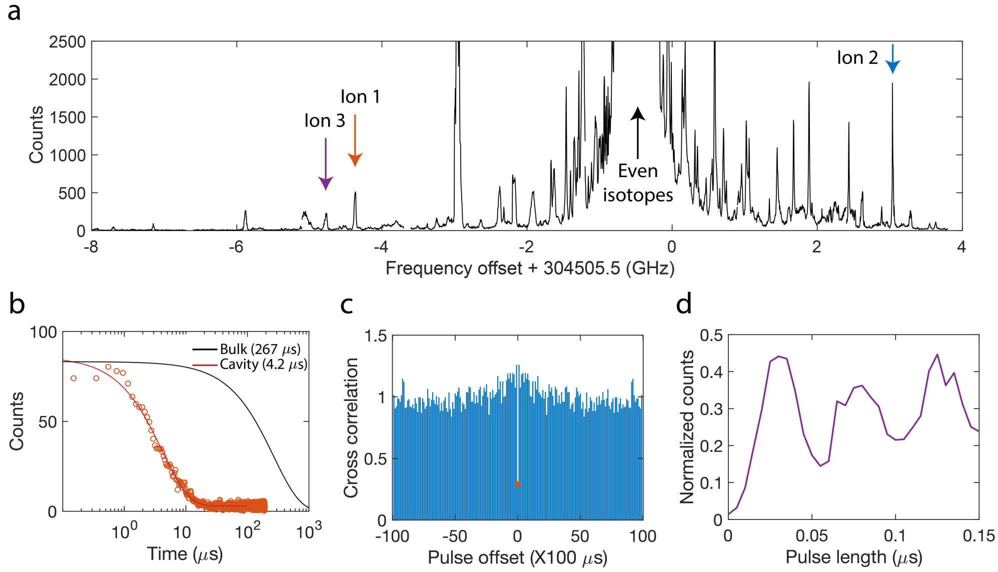

Fig. 2. Measurements of the GaAs hybrid device. (a) Photoluminescence spectrum of the device. Data was taken with a 50 kHz repetition rate and 10 second integration time. (b) Time-resolved photoluminescence measurement. Red circles are measured data for Ion 1 with a fitted lifetime of 4.2 μs. The black line is the reference lifetime of the bulk ions (267 μs). (c) Cross-correlation measurement of Ion 2 with $g^{(2)}(0)$=0.29. (d) Post-selected Rabi oscillation for Ion 3. The measurement was taken with alternating weak probes and optical Rabi pulses. Photons are accepted when the ion is resonant with the weak probe.

ions, their brightness depends on the Purcell enhancement and the number of ground state levels (related to the Yb isotope number). The shortest measured ion lifetime is 4.2 μs, which corresponds to a $\sim$64 times lifetime reduction (Figure 2b). We also performed a pulsed $g^{(2)}(t)$ auto-correlation measurement (Figure 2c), which shows $g^{(2)}(0) < 0.5$ indicating the presence of a single ion. Finally, in Figure 2d, we show post-selected optical Rabi oscillation measurements, which demonstrate the ability to coherently drive the ions inside the device.

In conclusion, we realize a new platform using a hybrid GaAs photonic crystal cavity, which has the ability to coherently optically address single Yb ions inside YVO_4. Future measurements will focus on studying surface effects on the optical coherence properties of the ions, and could pave the road for realizing quantum networks using Yb:YVO_4.

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