Correlated optical-spin coherence spectroscopy on telecom-wavelength epitaxial rare-earth qubits

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Abstract: We perform correlated optical-spin coherence spectroscopy on epitaxial rare-earth qubits in an oxide thin film. Single Er^{3+} ions are optically addressed and used to probe coupling to two-level-systems as a simultaneous optical-spin decoherence mechanism.

Rare-earth ions (REIs) in solids are promising candidates as spin-photon interfaces for quantum interconnects [1, 2]. Er^{3+} doped crystals are particularly attractive owing to their narrow telecom optical transition [3] and milliseconds long electron spin coherence times [4]. Rare-earth spin qubits have been demonstrated by coherently controlling the spin states with microwaves and performing optical single-shot readout [5, 6]. However, the optical homogeneous linewidth and the spin coherence times of these rare-earth qubits are so far considerably inferior compared with the ensembles of REIs in pristine bulk crystal hosts, likely due to proximity to defects at the interfaces. Recently we developed a wafer-scale rare-earth qubit platform using molecular beam epitaxy growth and atomic precise placement of rare-earth dopants in an oxide thin film. Performing in-situ noise spectroscopy on these epitaxial qubits will provide critical insights on the optical and spin decoherence mechanisms and inform noise mitigation strategies. Here we report correlated optical-spin coherence spectroscopy on epitaxial Er qubits at the telecom wavelength. Combining single-ion photoluminescence (PL) measurements and high sensitivity electron spin resonance (ESR) using superconducting microwave resonator at milliKelvin (mK) temperatures, we show a 1.9 MHz optical linewidth over 1.4 ms duration without noticeable spectral diffusion, and report evidence of Er qubits coupling to two-level-systems (TLS) as a mechanism for simultaneous optical and spin decoherence. With further material growth refinement and noise decoupling techniques, these results show a significant prospect of epitaxial rare-earth qubits as a scalable technology for quantum light-matter interfaces and interconnects.

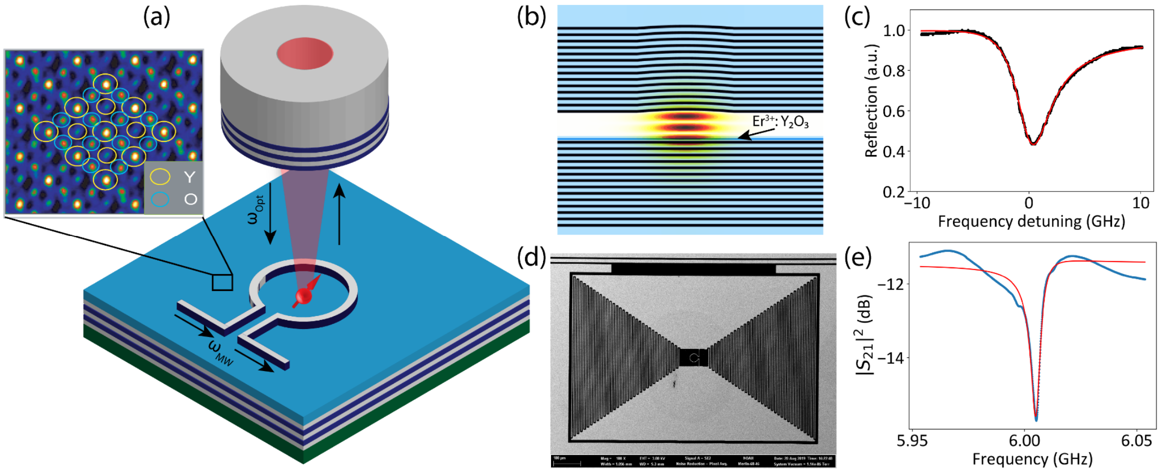

Fig. 1. (a) Schematic of an epitaxial rare-earth qubit simultaneously coupled to a fiber FP cavity (FFPC) and superconducting microwave resonator. Inset shows a TEM image of the epitaxial Er^{3+}: Y_2O_3 thin film. (b) Simulated optical cavity mode overlapping with the Er^{3+}: Y_2O_3 film. (c) FFPC reflection spectrum with bandwidth of 3.95 GHz. (d) SEM image of niobium superconducting resonator patterned on Er^{3+}: Y_2O_3 thin film. (e) Measured resonance at 7 mK.

Epitaxially grown single crystalline thin films offer an outstanding host for rare-earth qubits. Such an epitaxial platform enables wafer-scale fabrication of rare-earth quantum nanophotonic devices and hybrid rare-earth-superconducting circuits. We carried out correlated optical-spin spectroscopy using a cryogenic fiber Fabry-Perot cavity (FFPC) and superconducting microwave resonator that are coupled to an Er^{3+} dopant in an epitaxial Y_2O_3 thin film (Fig. 1(a)). The FFPC consists of two highly reflective DBR mirrors coated on the concaved fiber tip and on a Si substrate below the Y_2O_3 film. As shown in Fig. 1(b), a 100 nm Er^{3+}: Y_2O_3 film is transferred to a $3/2\lambda$-long FFPC and is situated at the cavity antinode for maximally enhanced atom-photon coupling. The cavity measured a $Q = 5.1\times10^4$ and a small mode volume of $16\ (\lambda/n)^3$ (Fig. 1(c)). The FFPC resonance frequency could be coarsely tuned in 40 nm range in telecom wavelengths and finely scanned over 80 GHz. The ultralow optical loss of the Y_2O_3 film is characterized to be <1.8 dB/m. Microwave spin spectroscopy was performed with low impedance niobium (Nb) superconducting resonator directly patterned on Y_2O_3 thin film, as shown in Fig. 1(d). The 6 GHz resonator has a coupling quality factor Q_e 4600 and an internal Qi 1100 measured at 7 mK (Fig. 1(e)).

Individual Er^{3+} ions were addressed via the PL measurement when the optical cavity is detuned ~200 GHz from the center of the inhomogeneously broadened Er $^4I_{13/2}$-$^4I_{15/2}$ transition in the C_2 symmetry site. As shown in Fig. 2(a), the Er^{3+} ion optical lifetime was shortened from 8.5 ms to 153 μs, giving a Purcell factor of 55 and the cavity-QED parameters of $(g, \kappa, \Gamma_0) = 2\pi \times (1\ \text{MHz}, 3.9\ \text{GHz}, 18.7\ \text{Hz})$. The autocorrelation measurement using a superconducting nanowire single photon detector (SNSPD) shows a clear antibunching with $g^2(0) = 0.06$. The optical homogeneous linewidth was measured using a transient hole burning technique [7] as the optical lifetime of the Er emitter is tuned by varying the cavity-ion detuning. This time-dependent linewidth measurement was used to reveal the sources of spectral diffusion. At 0 magnetic field, a linear growth of linewidth (black line in Fig. 2(c)) indicates a coupling to the TLS bath. At 350 mT applied field along Y_2O_3[111] direction, the linewidth is narrowed to 1.85 MHz, which remains constant up to 1.4 ms. This shows that the magnetic TLS could be frozen by the applied field.

We further investigated the decoherence mechanism in the shorter time scale by performing high sensitivity pulsed ESR with near-quantum noise limited travelling wave parametric amplifier (TWPA). Spin echo signal is observed for broad range of frequency (4-6 GHz) with varied external magnetic field amplitude and orientations. Moreover, the spin echo shows a magnetic-field independent coherence time of 1.8 μs which suggests a bath of TLS electrically coupled to the MW transmission line. The spectral diffusion linewidth was then measured through the three pulse echo method and the effective linewidth over 100 μs was estimated to be >1.6 MHz, in good agreement with the observed Er optical linewidths. We understand this correlated optical-spin decoherence as the excited-state Er^{3+} ions and ground-state spins are simultaneously coupled to the same TLS bath.

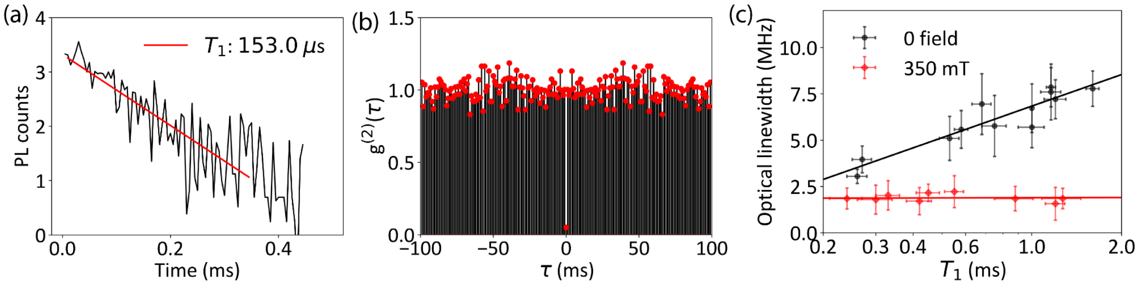

Fig. 2. (a) Photoluminescence decay of single Er^{3+} ion with a fitted T_1 of 153 μs. (b) Autocorrelation measurement on the single Er^{3+} showing antibunching [$g^2(0) = 0.06$]. (c) Time-evolution of Er^{3+} optical linewidths at 0 and 350 mT magnetic field.

In summary, we developed a scalable platform of epitaxial rare-earth spin qubits and performed correlated optical-spin coherent spectroscopy to reveal a common TLS noise source. With further material growth refinement and noise decoupling, rare-earth qubits can show significant potential for long-lived quantum memories and telecom spin-photon interfaces for quantum repeater and transduction applications.

References

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