QuEST: Quantum Erbium-qubit Sensor @ TTU

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Abstract

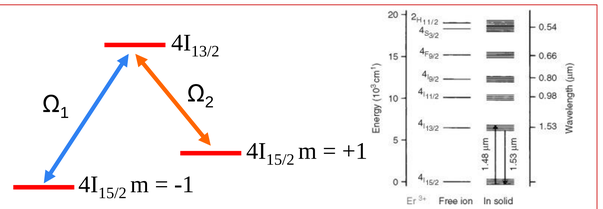
Quantum sensing focuses on utilizing quantum effects to gain non-classical metrological capabilities. Recently, solid-state qubits (quantum bits) are a promising alternative to superconducting or trapped-ion qubits because of easy integration and scalability. Rare-earth spin qubits have gained attention due to their narrow energy level transitions and long optical spin coherence lifetimes at visible and near-infrared. However, the lifetime of spin coherencies suffers from interactions between the rare-earth qubits and noisy environments. Here, we demonstrate a rare-earth spin qubit sensor embedded on an active resonant cavity on-chip. A single erbium ion is chosen as a spin qubit. By placing the device in the vicinity of a resonant cavity structure, Purcell enhancement occurs, increasing spin coherence lifetimes. Our cavity utilizes a thin film of VO2 deposited onto a gold back-mirror on a sapphire substrate. Vanadium Oxide is an active material whose index of refraction is controllable by a metal-insulator phase transition. We drop cast Er ions onto the VO2 surface and tune the cavity by adjusting its temperature. NMR information of the ensemble is obtained by placing the device in an optical cryostat, applying an external magnetic field, and observing fluorescence lifetime and spin relaxation rate using a pulsed laser and Raman-Ramsey interferometer. By observing that external factors can control the lifetime of coherencies and that the signal can be enhanced (or erased) by a reconfigurable cavity, we will demonstrate that our device can be used as a quantum sensor, whose output depends on the coherence of an ensemble of spin states.

QuEST Operating Principals

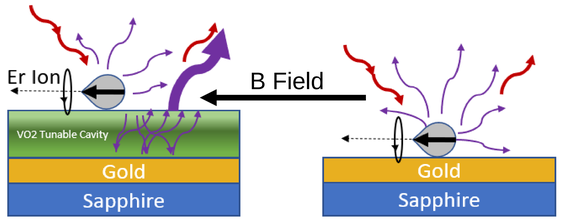
Quantum Optical Sensors take advantage of high quantum efficiency detectors to overcome the shot-noise limit, which allows for the observation of sub-Poissonian statistics in photon beams. By observing anti-bunching in the photoluminescent signal of an ensemble of Er ions, a single ion may be identified and selected as a qubit. The quality of this qubit depends on its local environment. While the sample is in an external magnetic field, a pulsed broadband telecom laser induces a resonant atomic level transition between the $I^{13/2}$ and $I^{15/2}$ states (1536 nm) of the ions. A percentage of the florescence re-enters the microscope and is then subjected to a Czerny-Turner monochromator. To obtain a spectrum the grating is rotated, an optical power related voltage is created by an InGaAs detector, measured using a lock-in amplifier, and then plotted vs grating angle. The lifetime of the fluorescence can be measured using a single photon detector, in the absence of an external B field. By modulating the phase of the laser beam, using an external magnetic field, and two single photon detectors, a spin echo measurement can be conducted to measure the T_2 coherence lifetime. Further, the signal may be enhanced by placing the qubits onto the surface of a controllable VO2 cavity, which when tuned, increases the probability of light-qubit interactions, as well as directs more fluorescence into the QuEST system.

Device

Our device will consist of erbium doped nanostructures placed onto a gold-backed VO2 thin film on a sapphire substrate. The Er ions are deposited using a drop cast technique. Single Er ions are identified by observing photon antibunching. The VO2 layer serves as a tunable thin film cavity, capable of enhancing the spontaneous emission rate of the Erbium.[1] Candidates for hosting nanostructures are Er:YSO and Er:OCl nanocrystals, and Graphene nano tubes/fullerenes. VO2 has a temperature dependent metal-insulator transition. By controlling the temperature of the device, the refractive index of the thin film can be adjusted to create the proper conditions for Purcell Enhancement. This metal-insulator transition can also be used to destroy the quantum state of the ensemble.

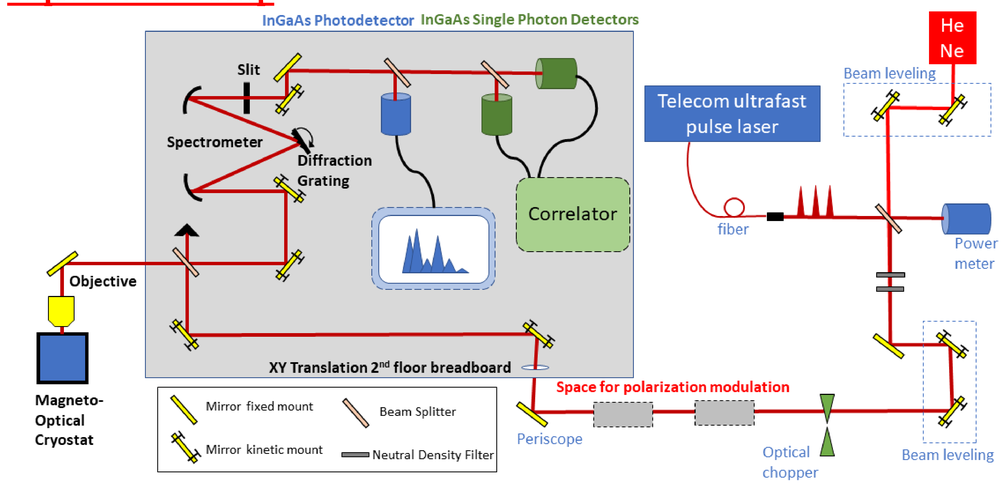


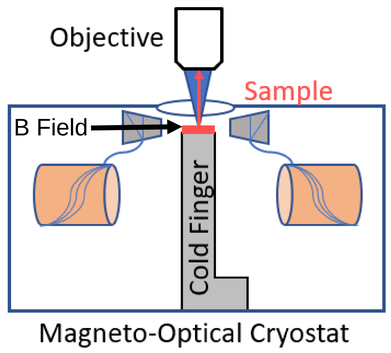
Pumping schematic of 3 level energy system. By using a pulsed broadband pumping laser, Raman transitions promote Er ions from $4I_{15/2}$ to $4I_{13/2}$ via transitions with state |3>.. On the right is a figure depicting the energy levels of Er^{3+}.[2]

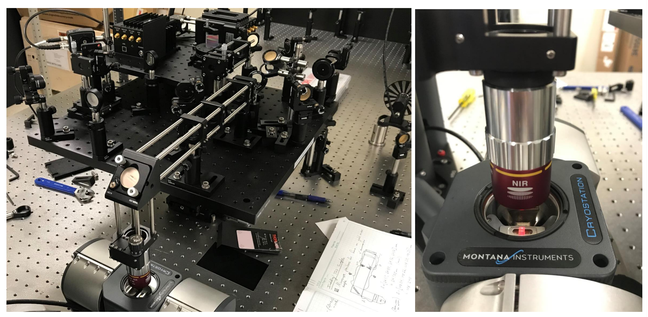


Schematic of a RE spin qubit situated on the surface of a VO2 tunable cavity, as well as a RE spin qubit situated on a gold mirror. As indicated by the large purple arrow, when the cavity is tuned an enhancement of the fluorescence occurs. Additionally, the cavity can be tuned to increase the probability of pump-Erbium interactions.

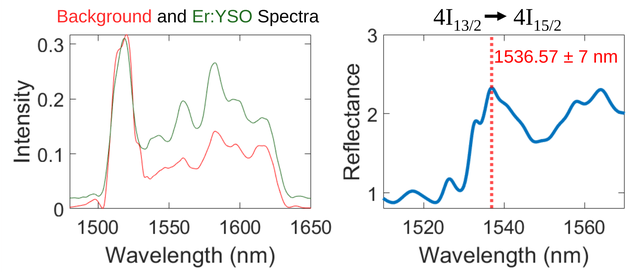
Experimental Setup







Preliminary Spectral Data



Left: In red, is a spectrum of the broadband femtosecond pulsed laser, collected directly. In Green, a spectrum collected by focusing broadband laser onto a gold-backed 0.02% Er:YSO crystal.

Right: In order to observe only the fluorescence of the Erbium and YSO, the sample spectrum is scaled, and then divided by the direct laser spectrum, producing the plot on the right. The figure is zoomed in to show fluorescence at 1536.57 nm.

Future Plans

Demonstrate Signal Enhanced Quantum Sensing:

- Communication with a single Er3+ ion by observing antibunching in the single photon signals.
- Demonstrate signal enhancement by varying temperature of VO2 cavity.
- Demonstration of state initialization and destruction via metal-insulator transition.

References

[1] Merkel, B., Ulanowski, A., & Reiserer, A. (2020). Coherent and Purcell-Enhanced Emission from Erbium Dopants in a Cryogenic High-Q Resonator. *Physical Review X*, *10*(4). https://doi.org/10.1103/physrevx.10.041025

[2] Daldosso, N., & Pavesi, L. (2008a). LOW-DIMENSIONAL SILICON AS A PHOTONIC MATERIAL. *Nanosilicon*, 314–334. https://doi.org/10.1016/b978-008044528-1.50010-5