Rare-Earth Spin Qubit Selection Using Conventional Spectroscopy Methods

Hira Farooq[1], Malsha Udayakantha[2], Rachel Davidson[2], Jacob Slocum[1], Zachary Brown[1], Olu Abraham[3], Sarbajit Banerjee[2] and Myoung-Hwan Kim[1]

[1]Department of Physics and Astronomy, Texas Tech University, Lubbock, TX 79409, USA, [2]Department of Chemistry, Texas A&M University, College Station, TX 77843, USA, [3]Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409, USA

Abstract

Rare-earth spin qubits are a promising quantum system because of narrow energy level transition, long optical and spin coherence lifetimes at visible and near infrared. Here, we present our efforts to develop a quantum sensing device based on a rare-earth spin qubit. We choose a single erbium ion as a spin qubit candidate because its atomic level transition is in telecom wavelength (1550 nm) which will benefit an integration into on-chip silicon photonic devices. We prepare for an erbium (Er) doped oxychlorides (OCl) of the lanthanides (Yb) nanocrystals on silicon (Si) and silicon carbide (SiC) substrates. We use two conventional spectroscopy methods for spin qubit selection on the substrate. First, we take infrared spectrum and look for absorption spectrum from the erbium ion or any cluster of ions with induce absorption spectrum broadening. Second, we take an infrared spectrum with a small magnetic field from a Helmholtz coil. Absorption band splitting due to the magnetic field, Zeeman splitting, creates the two-level systems that we will use for a single qubit operation. Resolution of two the absorption bands due to the two-level system depends on spectral band width and the strength of magnetic field. We take the infrared spectrum of small areas of the sample, using a Fourier Transform Infrared spectrometer with infrared microscope, to achieve the two-level system. Once the selection is done, we will use a home-built microscope imaging system for a single photon detection of telecommunication light at low temperature and immersed in external magnetic fields to communicate with a single erbium ion spin qubit.

Goal

A basic operational unit of a quantum computer is a quantum bit, called a qubit, which is a linear combination of two independent quantum mechanical states. Unlike a classical bit that expresses only two states, 0 and 1, a qubit can express and infinite number of states between 0 and 1. Having this combination opens new worlds of computational possibilities which may overcome classical computing limits.

Any two-energy-level system can be a qubit. A spin qubit is one of the most promising candidates because of a long quantum coherence time which indicates a long lifetime to hold quantum information. However, one challenge is that a single ion, two-level system is difficult to identify and construct. Our goal is to select a single rare-earth ion using conventional infrared spectroscopy methods without observing single photon trains from that particle, called antibunching, which is used to identify the single ion. Here, we will use erbium ions (Er^{3+}) which interact at a photon wavelength of 1550 nanometers. These ions are spread randomly within the silicon substrate and often form clusters. Our job is to find and interact with a single ion of Er^{3+} within the silicon using near-infrared light.

Project

We developed a home-built microscope imaging system for a single photon detection of telecommunication light (telecom: 1550 nm wavelength) at low temperature and immersed in external magnetic fields. We used this microscope system to investigate rare-earth spin qubit, an erbium (Er^{3+}) and an ytterbium (Yb^{3+}) ion, in various types of hosting materials like ErOCL and YbOCL.

We chose Er^{3+}ion as a spin qubit because of its atomic level transition in telecom, which will benefit a potential integration into on-chip photonic devices. A single Er^{3+} ion was prepared in nanoparticles/nanorods in oxychlorides and yttrium oxide (Y_2O_3) nano-crystals by collaborating with the Banerjee group at Texas A&M University.

We used the home-built microscope imaging system for probing the single telecom photon emission from the Er^{3+} spin qubit ion. We used an ultrafast (femtosecond, fs) telecom laser (Menlo Systems, Inc.) for the light source, two InGaAs single photon detectors (PicoQuant Photonics, Inc.), and a continuous flow optical cryostat system for microscopy. The single Er^{3+} ion doped sample will be in the optical cryostat to keep the sample in vacuum and low temperature. We illuminate the sample with the fs laser through the home-built microscope imaging system. We will evaluate the Er^{3+} ions by using an infrared camera attached near the microscope eyepiece.

Two InGaAs single photon detectors are located near the infrared camera to observe antibunching in the signal from the ions using a cross-correlation measurement technique. Two quantum levels, are produced by the applied magnetic field from a Helmholtz coil, are be used to observe a spin echo signal, which measures the coherence lifetime of the quantum state. We will observe the coherence lifetime while breaking parity-time symmetry using reconfigurable nanostructures nearby the spin qubit.

Experimental Setup

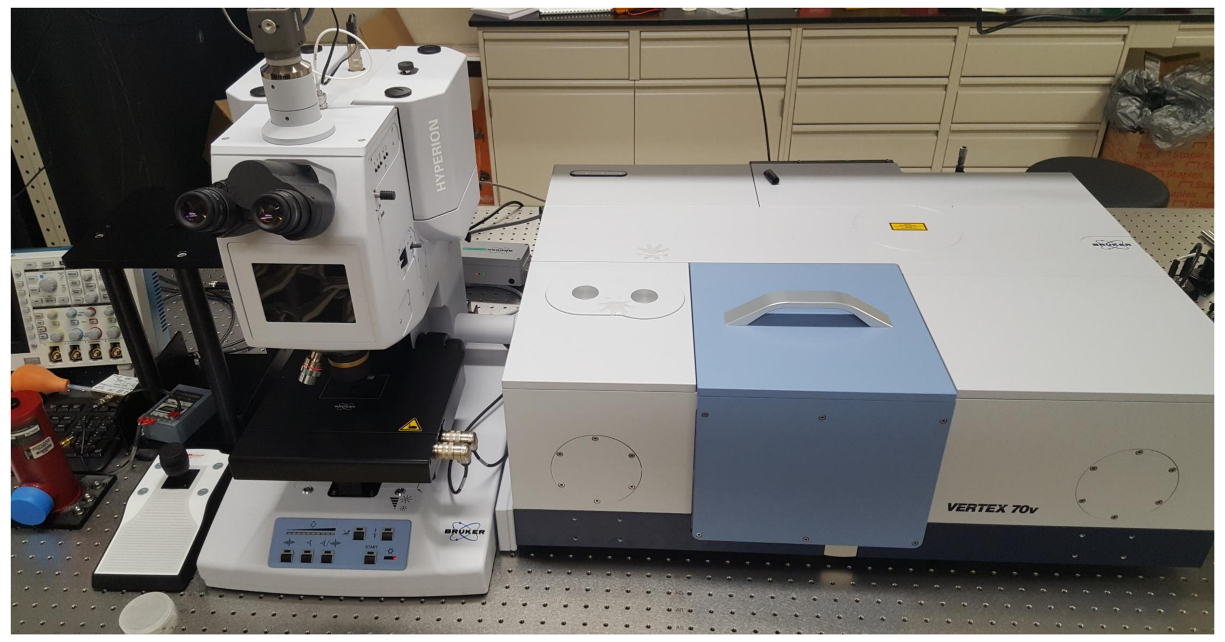


Fig.1.Picture of Fourier-transform infrared (FTIR) spectrometer

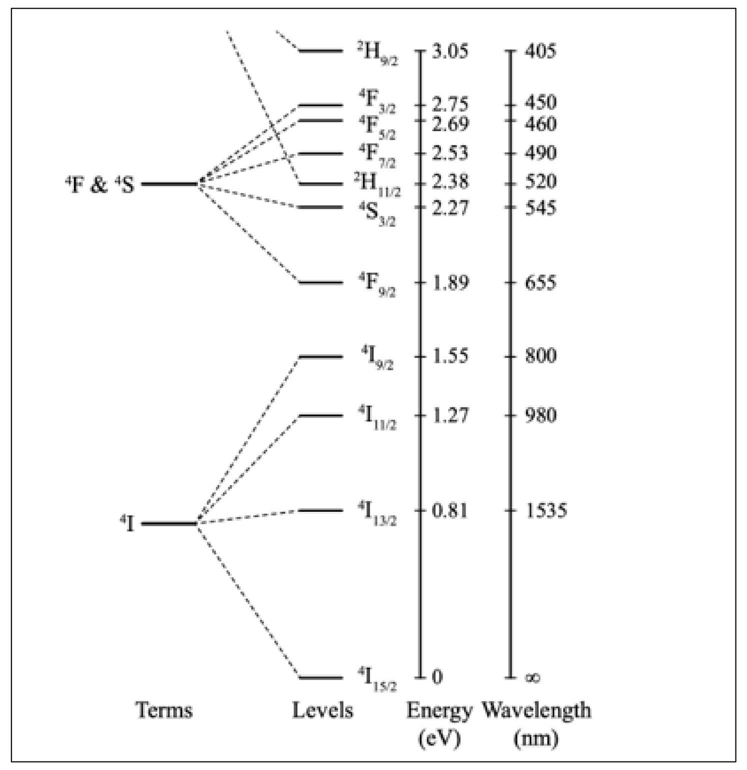


Fig.2. Energy level Diagrams for Er $^{3+}$.

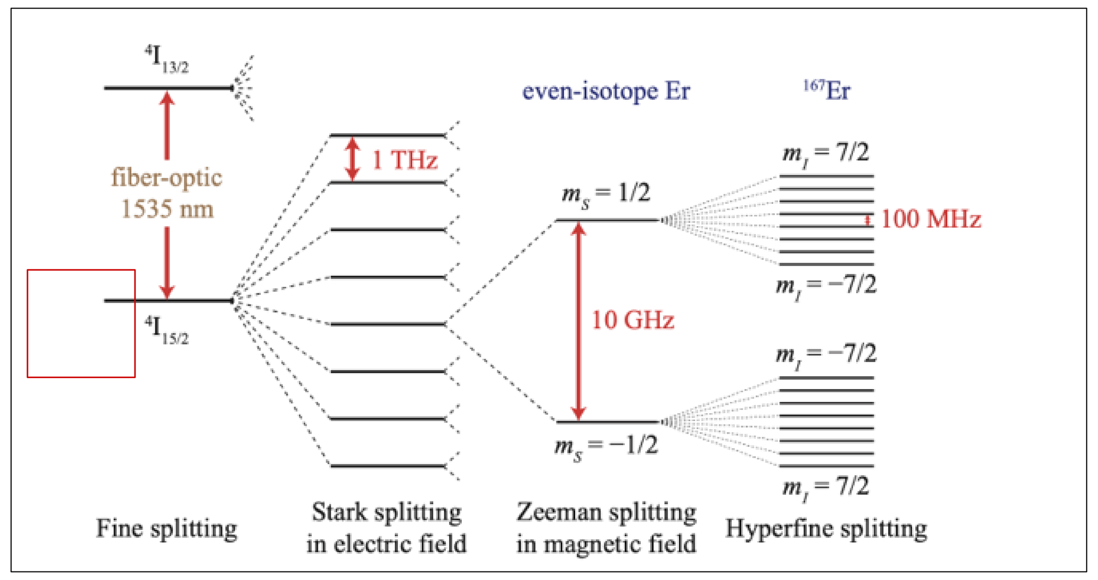
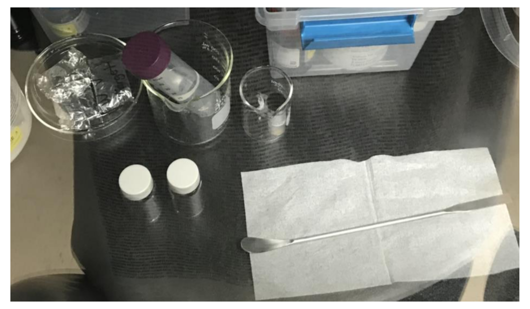


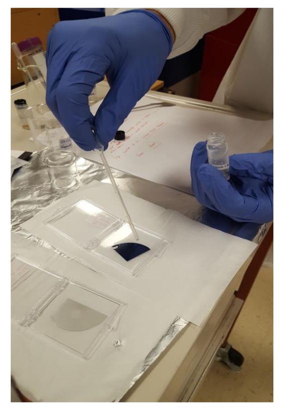
Fig.3. Illustration of energy-level splitting in Er $^{3+}$. Red text shows the approximate order of the energy levels

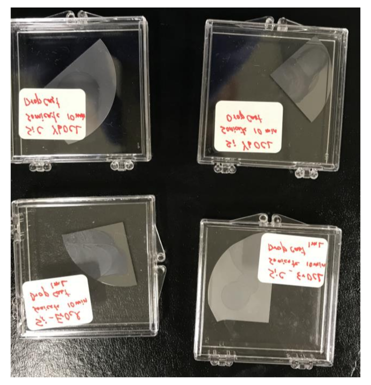
Preparation of Samples

We prepared a homogenous mixture of the YbOCL and ErOCL nano particles in Hexane in N_2 atmosphere in glovebox. The mixtures were sonicated for 5 minutes to attain homogeneous dispersion. Four samples were prepared by drop casting the mixtures on Si and SiC substrates.

Below are some of the pictures of the steps involved in sample preparation process.







Conclusions

Identifying a spin qubit system by:

- Communication with a single Er3+ ion by observing antibunching in the single photon signals.
- Construction of two-level systems in an external magnetic field and at low temperature.
- Observation of spin-echo signals to determine the coherence lifetime of the qubit systems

References

[1] S. Bogdanov, et al, Optical Materials Express, Vol. 7, pp 111-132 (2017). [2] D. Serrano, et al, Nature Communications, Vol. 9, 2127 (2018). [3] J. R. Weber, et al, PNAS, Vol. 107 (19) 8513-8518 (2010). [4] E. Saglamyurek, et al, Nature Photonics, Vol. 9, pages 83–87 (2015). [5] P. Siyushev, et al, Nature Communications, Vol. 5, 3895 (2014).