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Scalable quantum networks and devices using erbium ions integrated with silicon nanophotonics

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14. ABSTRACT This proposal aims to develop a new experimental platform for quantum science and technology: single Erbium (Er3+) ion impurities in a solid-state host that are optically initialized and measured via nanophotonic optical cavities. These are attractive because of their telecom-wavelength optical transition, compatibility with a wide range of host materials, as well as the possibility to scaleably address many ions in the same device using frequency domain addressing.			
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Final Report

Scalable quantum networks and devices using erbium ions integrated with silicon nanophotonics

AFOSR Grant No: FA9550-18-1-0081

Principal Investigator: Jeff Thompson

Institution: Princeton University

AFOSR Program Manager(s): Grace Metcalfe

Date: 3/31/2021

Program Objective: This proposal aims to develop a new experimental platform for quantum science and technology: single Erbium (Er^{3+}) ion impurities in a solid-state host that are optically initialized and measured via nanophotonic optical cavities. These are attractive because of their telecom-wavelength optical transition, compatibility with a wide range of host materials, as well as the possibility to scaleably address many ions in the same device using frequency-domain addressing.

Scientific Approach: Prior to this work, single photon emission from a single Er^{3+} ion has never been observed, because of the low photon emission rates of its (primarily magnetic dipole) optical transition. The central idea of our approach is to enhance this emission rate by many orders of magnitude by incorporating these ions into high-Q, small mode volume silicon nanophotonic cavities. Before beginning this project, we had demonstrated this concept, realizing 100-fold enhancement of the emission of an Er ensemble. In this work, we have extended this to 1000-fold enhancement of single ion emission, and used this result as a building block to demonstrate a number of important milestones discussed below.

Summary of major accomplishments during project (if final report):

With the support of this program, we have realized the following major objectives from our initial proposal:

1. Observation of single Er^{3+} ions. Using our strong Purcell enhancement from a silicon nanophotonic cavity, we have enhanced the emission rate of single Er^{3+} ions in yttrium orthosilicate (YSO) crystals from 100 Hz to 100 kHz. [**Dibos et al, Phys. Rev. Lett (2018)**]
2. We have additionally developed a novel technique to perform single-shot spin readout of the Er^{3+} spin through the optical cavity, and used this as a tool to study the coherence and dynamics of single Er^{3+} spins for the first time. Performing single-shot measurement of any qubit requires a quantum nondemolition measurement technique, where the state of the qubit is not perturbed by the measurement probe. In the case of fluorescence measurement of atomic spins, this requires a cycling transition. In the solid-state, cycling transitions are not very common because the low symmetry relaxes the strict angular momentum selection rules found in free space. However, we discovered that our large Purcell factor means that the selection rules are actually dominated by the density of states in the cavity, not in free space. Tuning the alignment of the dipole moment with respect to the cavity gives us the possibility to engineer a cycling transition, resulting in the ability to scatter more than a thousand photons before flipping the spin, and giving rise to a single-shot spin detection fidelity exceeding 95%, comparable to the state of the art for color centers in diamond (NV, etc.). Importantly, we have proven the generality of this technique to other atomic defects with a wide range of symmetry properties. We have also used this approach to characterize the spin dynamics of individual Er^{3+} ions. We find $T_1 > 50$ seconds at $T=0.5$ K, and infer that this is actually not limited by spin-lattice relaxation but by interactions with other neighboring Er spins. We find $T_2^* = 150$ ns, limited by

the abundant 89Y nuclear spin bath, and can extend the coherence to $T_2 > 100 \mu\text{s}$ using dynamical decoupling [Raha et al, *Nature Communications*, 2020].

3. Another key feature of Er^{3+} is the optical transitions are spectrally very narrow. This allows us to resolve the transitions of multiple ions within a sub-wavelength volume based on their different frequencies, which is effectively a form of super-resolution optical addressing. We have applied this to realize simultaneous initialization, measurement and control of up to six spins in the same device [Chen et al, *Science* 2020]. This is a unique capability for Er^{3+} in comparison to any other solid-state atomic defect platform, and is a key first step for realizing frequency-multiplexed quantum repeaters or studying ion-ion interactions at sub-wavelength scales.
4. The spin and optical coherence properties of the Er^{3+} host used in our initial experiments, YSO, are lackluster. In particular, the spin and optical coherence times are about a factor of 100 shorter than what would be required to implement useful quantum repeater networks. However, these problems are not intrinsic to Er^{3+} , but arise from the host, and one benefit of Er is that we can explore different host materials with better noise properties. Specifically, one would like a host with low abundance of nuclear spins, a high site symmetry for Er^{3+} (to eliminate static electric dipole moments), and a low concentration of other paramagnetic impurities. We have systematically explored incorporation of Er^{3+} into new materials via ion implantation, and have a number of promising candidates including TiO_2 , MgO , CaWO_4 (and related compounds) [Phenicie et al, *Nano. Lett.* (2019), Stevenson et al, *in preparation*]. In recent, unpublished work, we have observed single ion fluorescence from ion-implanted $\text{Er}:\text{MgO}$ in nanophotonic cavities, with record-high Purcell factors ($P > 1500$) and optical linewidths more than 20x narrower what we typically observed in YSO. Together with some modest improvements in our silicon photonics, this puts indistinguishable photon emission to demonstrate spin-photon entanglement within reach.
5. We have also recently demonstrated two-qubit gates between Er^{3+} and a neighboring nuclear spin. Nuclear spin ancilla qubits are very promising for quantum network applications because they can store quantum states while an electron is repeatedly cycled to generate single photons. So far, this technique has only been demonstrated with NV centers in diamond and divacancies in silicon carbide, which both have $S=1$ electronic spins. In this work, we have demonstrated a novel control technique for nuclear spins with an $S=1/2$ electron spin, that should be applicable to Er in other hosts as well as a wider range of atomic defects in the solid state. We are preparing a theory and experimental paper on this work.

Changes to originally proposed work (if applicable): None.

Next steps:

This work has demonstrated that Er^{3+} is a viable candidate for building scalable quantum networks. In a few years, we have built up this system to be competitive in many ways with more established color center technologies, by leveraging a high degree of control over the electromagnetic environment using nanophotonic cavities. Furthermore, we have established, in principle, that the coherence properties of this system can be engineered by exploring different host materials. In the coming years, we hope to use these works to reach the milestone of indistinguishable photon emission, which in turn will lead to demonstrations of spin-photon entanglement, entanglement swapping between remote spins, and so on.

Publications:

- [1] A. M. Dibos, M. Raha, C. M. Phenicie, and J. D. Thompson, *Atomic Source of Single Photons in the Telecom Band*, *Phys. Rev. Lett.* **120**, 243601 (2018).

- [2] M. Raha, S. Chen, C. M. Phenicie, S. Ourari, A. M. Dibos, and J. D. Thompson, *Optical Quantum Nondemolition Measurement of a Single Rare Earth Ion Qubit*, Nat. Commun. **11**, 1605 (2020).
- [3] C. M. Phenicie, P. Stevenson, S. Welinski, B. C. Rose, A. T. Asfaw, R. J. Cava, S. A. Lyon, N. P. de Leon, and J. D. Thompson, *Narrow Optical Linewidths in Erbium Implanted in TiO₂*, Nano Lett. **19**, 8928 (2019).
- [4] S. Chen, M. Raha, C. M. Phenicie, S. Ourari, and J. D. Thompson, *Parallel Single-Shot Measurement and Coherent Control of Solid-State Spins below the Diffraction Limit*, Science **370**, 592 (2020).
- [5] S. Chen, S. Ourari, M. Raha, C. M. Phenicie, M. T. Uysal, and J. D. Thompson, *Hybrid Microwave-Optical Scanning Probe for Addressing Solid-State Spins in Nanophotonic Cavities*, Opt. Express **29**, 4902 (2021).
- [6] D. Huang, D. Huang, A. Abulnaga, A. Abulnaga, S. Welinski, M. Raha, J. D. Thompson, and N. P. de Leon, *Hybrid III-V Diamond Photonic Platform for Quantum Nodes Based on Neutral Silicon Vacancy Centers in Diamond*, Opt. Express **29**, 9174 (2021).

Presentations:

1. University of Stuttgart, Virtual (December 2, 2020)
2. Duke ECE Colloquium, Virtual (November 16, 2020)
3. Rare earth ion quantum information workshop, Virtual (October 8, 2020)
4. FiO/LS, Virtual (September 14, 2020)
5. IEEE RAPID, Virtual (August 10, 2020)
6. APS DAMOP [declined--parental leave], Portland, OR (June 1, 2020)
7. Virtual AMO Seminar, Virtual (May 29, 2020)
8. CLEO [sent postdoc Songtao Chen--parental leave], San Jose, CA (May 3, 2020)
9. Yale Physics Colloquium, New Haven, CT (April 13, 2020)
10. APS March Meeting, Denver, CO (March 2, 2020)
11. UCSB Physics Colloquium, Santa Barbara, CA (February 21, 2020)
12. Max Planck Institute for the Science of Light, Erlangen, Germany (December 10, 2019)
13. PCTS Workshop on Quantum Supremacy, Princeton, NJ (November 13, 2019)
14. Rare earth ion quantum information workshop, Grenoble, France (October 8, 2019)
15. Texas A&M Condensed Matter Seminar, College Station, TX (September 27, 2019)
16. Dynamical Processes in Excited States (DPC), Christchurch, NZ (August 26, 2019)
17. SUNY Albany, Albany, NY (June 13, 2019)
18. Harvard-MIT Center for Ultracold Atoms Seminar, Cambridge, MA (May 7, 2019)
19. PQE, Snowbird, UT (January 6, 2019)
20. French National Quantum Information Conference (GDR IQFA) [declined -- parental leave], Montpellier, France (November 15, 2018)
21. Nature Photonics Conference on Nanophotonics and Integrated Photonics [declined -- parental leave], Nanjing, China (November 9, 2018)
22. Rare earth ion quantum information workshop [declined -- parental leave, sending student], Geneva, Switzerland (October 26, 2018)
23. Delaware Physics Seminar, Newark, DE (October 8, 2018)

24. Yale Quantum Institute Seminar, New Haven, CT (October 3, 2018)
25. SPIE Optics and Photonics, San Diego, CA (August 19, 2018)
26. MIT iQUISE Student-Invited Seminar, Cambridge, MA (March 22, 2018)
27. Nanoscale Quantum Optics Workshop, Prague, CZ (February 14, 2018)
28. Princeton Diamond Symposium, Princeton, NJ (January 15, 2018)

Awards:

- DOE Early Career Award, 2019
- Sloan Fellow in Physics, 2019
- Presidential Early Career Award for Scientists and Engineers (PECASE - ARO), 2019
- Lawrence Keyes Jr./Emerson Electric Co. Faculty Advancement Award, 2020

Patents: none

Thesis defenses:

Mouktik Raha (Forthcoming, April 2021)

Personnel supported by AFOSR project:

Mouktik Raha (-> postdoc in David Awschalom group)

Songtao Chen (-> faculty position at Rice University)