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(Quantum Accelerator) An entangled photon pair source for hybrid optical-microwave quantum networks

JOHN BARTHOLOMEW
UNIVERSITY OF SYDNEY
LEVEL 3, ADMINISTRATION BUILDING F23
THE UNIVERSITY OF SYDNEY, NSW, 2006
AUS

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John Bartholomew

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14. ABSTRACT

The vision of this research is to realize a quantum internet for distributed quantum information technology through efficient and robust distribution of quantum states over long distances. This project focuses on an essential component in such a network: a quantum interconnect between leading low temperature microwave-regime quantum computers and room temperature quantum optical fiber networks. Connecting leading quantum computing technology with optical quantum information networks leads to two major advances of importance to defense:

1. Forming networks of quantum computers will significantly increase computational power and accelerate solutions to materials design and advanced simulation problems that are beyond the capacity of classical computers to solve.
2. Incorporating future quantum computers as nodes in optical networks will provide the error correction and entanglement distillation required to enhance quantum encryption networks from simple point-to-point links to complex multi-node networks.

A key challenge is that optical networks cannot yet interface with leading quantum platforms like superconducting qubits. What is needed is a way to create quantum entanglement between microwave and optical photons.

Our aim is to engineer a hybrid source to generate a pair of entangled photons: an optical photon for fiber transmission at room temperature, and a microwave photon to couple to superconducting circuits. In this project we have made progress on the underlying theory of hybrid sources and characterized a candidate device to realize a new hybrid source protocol.

Our hybrid entangled source protocol is tailored to leverage the appealing properties of rare-earth atom ensembles in crystals. To build the best possible device it is essential to understand the theory of the atom-light interactions, and experimentally test the rare-earth atom properties in candidate architectures. Our theoretical work has focused on comparing our hybrid source and other proposals based on three-wave-mixing, and designing techniques to overcome limitations resulting from ensemble inhomogeneity. Our experimental work has focused on efficient coupling of the rare-earth ensemble to on-chip microwave and optical cavities, operating a hybrid system at low temperatures, and characterizing potential noise sources. We have also made progress on high performance optical filters that are essential to reduce noise in hybrid sources of entanglement and microwave-to-optical transducers.

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Section 2: Technical Report

Project Abstract

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Our next steps are to demonstrate the protocol, including the in-built atomic quantum memory that allows the second photon to be released on demand. If successful, this hybrid source will be a powerful building block for connecting superconducting qubit technology using optical networks.

Accomplishments

Summary of Objectives

The objectives for the project were to (1) demonstrate classical correlations between microwave and optical photons using existing on-chip, rare-earth atom devices, and (2) design the next generation device that will be optimized to produce entangled single photon pairs. The experimental demonstrations used integrated planar devices that simultaneously couple ensembles of rare-earth atoms, specifically erbium, in crystals to low loss optical and microwave cavities. The frequency of the microwave photons is approximately 5 GHz for compatibility with superconducting qubit devices and the optical photons will have a wavelength of approximately 1530 nm for compatibility with low loss distribution in optical fiber networks.

Objectives

1. Demonstrate classical correlations between optical and microwave modes.

Technical approach

The hybrid entangled photon source relies on quantum correlations between photons emitted in the optical and microwave regime. This correlation is created by controlling the energy states of an atomic ensemble through a specific series of optical and microwave pulses input into the system. As a preliminary step to realizing the full protocol, the pulse sequence can be tested in the classical regime to verify that the process is coherent.

Over the past five years our team has demonstrated the ability to convert between the optical and microwave domain using ytterbium-doped crystals both in a macroscopic bulk-crystal experiment [1] and an integrated, on-chip device [2]. Our most recent work opted to focus on conversion (also called transduction) between microwave and optical signals using erbium integrated on-chip devices [3]. Erbium has the advantage of optical transitions in the lowest loss frequency band for transmission through optical fibers (1530 nm compared to 980 nm for ytterbium) and, on-average, stronger coupling to the microwave circuit. Our approach is to use these on-chip devices, which have a geometry that is promising for generating hybrid entangled photons. Further details are provided in the Technical Updates section.

There are two avenues to verify that our approach for creating a hybrid source was feasible using these integrated devices. The first is to use phase sensitive measurements to show that the device could map an initial optical or microwave coherence to the other regime. The second is to use photon counting measurements to demonstrate that weak transduced signals in the optical regime can be separated from input excitation light. Since the last report, we have focused on the latter - photon counting measurements – because they have provided greater insights into regimes relevant for the hybrid entangled photon source protocol. These include noise processes in the atomic, optical and microwave system components and the benefits of pulsed schemes compared to continuous wave schemes.

Milestone completion progress

Milestone 1 specified in our application was to demonstrate classical phase correlations between optical and microwave modes using a rare-earth ion on-chip device. We have made substantial progress toward accomplishing this milestone and added results that were not anticipated when the proposal was written. The fully functioning erbium device and measurement infrastructure demonstrated conversion of input microwave coherences to output optical coherence with efficiencies 6 orders of magnitude greater than our previous work [2]. We prioritized implementing photon counting detection to characterize noise processes and pulsed operation, which has yielded important information for the hybrid source design. Classical phase correlation measurements will be straight forward to implement by changing the optical detection method from photon counting to coherent heterodyne detection and we expect that this should be possible in the coming months. Further details are provided in the Technical Updates section.

2. Theoretically optimize the operation of the hybrid entangled photon pair source protocol.

Technical approach

The theory of the new hybrid entangled photon pair source extends two previous protocols developed for rare-earth ion ensembles in solids. These demonstrated protocols are microwave-to-optical transduction [4] and all-optical entangled photon pair generation [5]. Combining concepts from both these protocols, we have focused the theoretical investigation on three aspects: protocol efficiency, low-noise performance, and comparisons with three-wave mixing hybrid entangled photon generation.

Two critical parameters have been identified that will impact the protocol's efficiency and noise characteristics. First, the relaxation rates of the optical and microwave transitions and how well these can be controlled by coupling the rare-earth ion ensemble to optical and microwave cavities. Second, the inhomogeneities of the relevant transitions, and in particular, the correlation between the inhomogeneities on different transitions.

Milestone completion progress

Milestone 2 specified in our application was to determine the device parameter regime for optimal hybrid source performance. We have expanded the scope of this milestone to include a comparative analysis between our new protocol and existing protocols based on three-wave mixing. An analytical theory of magneto-optical three-wave mixing hybrid entangled photon generation has been completed, and models developed for our new protocol to control the ensemble across both the microwave and optical domains. There are two remaining steps. First, we will analyze the entangled pair generation rate for realistic devices operated using the three-wave mixing and our new protocol. Second, we will complete our numerical analysis of our new protocol, which was delayed due to the failure of our high-performance computing workstation (see details under Changes). We expect to finalize both steps by the end of 2022. In strongly related work, we have also developed protocols to select suitable sub-ensembles from inhomogeneously broadened and inhomogeneously coupled ensembles. Further details are provided under Technical Updates.

Accomplishments

Major activities

Given the short time frame of the funded project period, the major activities since November 2020 have focused on research directly relevant to the grant objectives. These activities include the investigation of rare-earth ion properties (USYD and Caltech), device component modelling (USYD and Caltech), experimental demonstration of integrated hybrid microwave-optical devices (Caltech), and theoretical modelling of the hybrid system (USYD).

Specific objectives

Our work since November 2020 has focused on Objectives 1 and 2 as detailed in the previous section. Both objectives have taken on a broader scope than the initial grant proposal, which has greatly increased our knowledge of the performance and noise of rare-earth ion hybrid devices. The two main thrusts are: an experimental proof-of-principle demonstration of a device operating in a suitable regime for hybrid entanglement generation, and a theoretical analysis of the new protocol.

Significant results and key outcomes

i. Hybrid rare-earth ion device integrating planar photonic and superconducting resonators

Led by PI Faraon's group at Caltech, the collaboration has demonstrated an integrated hybrid microwave-optical device for transduction, which is also appealing for realizing hybrid entangled photon pairs. The device transduces photons from the microwave regime to the optical regime using an ensemble of erbium ions that is simultaneously coupled to a superconducting microwave resonator and a nanophotonic optical resonator. The device achieved an efficiency 6 orders of magnitude greater than our previous work [2] using pulsed operation at a low duty cycle. Although the overall efficiency is still low ($\sim 10^{-7}$), the measurement signal-to-noise ratio was sufficiently high to demonstrate that the spin temperature can be maintained below 100 mK and heating of the microwave resonator can be maintained below 0.15 quanta. The characterization of this device allowed important parameters for the hybrid entangled photon source to be confirmed experimentally. This work is the subject of Dr Jake Rochman's PhD thesis (*Microwave-to-Optical Transduction Using Rare-Earth Ions*, 2022) and is under consideration for publication [3].

ii. Analytic theory for hybrid entangled photon generation by three-wave mixing

Led by PI Bartholomew's group at USYD, the collaboration has developed and analyzed the theory of hybrid entangled photon generation using rare-earth ions simultaneously coupled to optical and microwave resonators. This theory was created to benchmark the new protocol, based on rephased amplified spontaneous emission (RASE), against three-wave mixing protocols, which have been studied in the all-microwave domain [6] and in electro-optic hybrid schemes [7]. Our new magneto-optic three-wave mixing theory provides an important framework to further analyze the advantages and disadvantages of the RASE-based scheme. It can also be combined with the experimentally measured parameters from the device described in (i) above to compare to other schemes for hybrid entanglement. We expect this research, along with the proposal of the RASE-based hybrid entangled photon pair source, will result in at least one publication in a journal such as npj Quantum Information.

iii. An appealing material candidate for the protocol
A candidate material for the protocol, erbium ions embedded in yttrium orthovanadate (Er^{3+}:YVO_4), was studied to determine its applicability to hybrid quantum technologies. This included characterizing the energy level structure with a particular focus on the properties of electron spin transition, the degree of freedom that couples to the microwave regime. Key results include: a relatively large magnetic dipole moments for the electron spin degree of freedom, the demonstration of multiple highly absorbing optical transitions with narrow inhomogeneous linewidths, and the demonstration of low-efficiency transduction of classical signals from the microwave regime to the optical regime. This work was published in Physical Review B as an Editors' Suggestion [8]. This material also formed the basis for the integrated hybrid device described in (i) above.

iv. Measurement of the electron spin relaxation rate for Er^{3+} ions coupled to a resonator
We have made two independent measurements of the electron spin relaxation rate for Er^{3+} ions coupled to microwave resonators. These measurements used different microwave resonator geometries and different host materials. Importantly, both measurements demonstrate that efficient collection of microwave photon emission into an on-chip superconducting resonator will be possible, which is crucial for the success of our protocol.

The first measurement was made in the device outlined in (i) above; a superconducting planar microwave resonator that couples to erbium spins in the Er^{3+}:YVO_4 substrate. The lifetime of the erbium electron spins was measured at the minimum device temperature (~35 mK) and found to be $T_1 = 1.61$ s. Subsequent measurements also show a shortening of the spin lifetime as laser light is coupled into the optical resonator, which increases the device temperature.

The second measurement was done in collaboration with the University of Otago, where we were able to infer the relaxation rate for erbium electron spins in yttrium orthosilicate (Er^{3+}:Y_2SiO_5) based on experiments made prior to the commencement of the current grant period. In this work the erbium ions were coupled to a copper loop-gap resonator, which has a much weaker coupling strength to the spins compared to the superconducting planar resonator mentioned above. The lifetime of the erbium electron spin was found to be $T_1 = 10 \pm 3$ s. This work was published in Physical Review B as an Editors' Suggestion [9].

Both measurements are significant because they demonstrate that the electron spin lifetime is sufficiently long (equivalently, the relaxation rate is sufficiently low) to allow planar microwave cavities to control the spin lifetime through Purcell enhancement (see further details under Technical Update). Such control will allow efficient collection of microwave photon emission into an on-chip superconducting cavity.

Other achievements
i. Technology for efficient, high-frequency resolution optical filtering
See Appendix 1.

ii. Other hybrid networking technology

The project participants have also made a significant breakthrough in a hybrid optical-nuclear spin system that shows significant appeal for establishing long-distance quantum communications. In work published in Nature [10], PI Faraon's team use a $^{171}\mathrm{Yb}^{3+}$ qubit to control and manipulate the surrounding $^{51}\mathrm{V}^{5+}$ ions in the lattice. This type of solid-state nuclear spin system coupled to an optically addressable qubit provides a crucial resource for quantum networks, computation and simulation. This approach provides a framework for leveraging the complexity in dense nuclear spin baths for long lived quantum memories and establishes a foundation for quantum networks using single rare-earth ion qubits.

Goals not met

Progress toward the goals of the experimental and theoretical programs (see Objectives above) has been successful despite ongoing delays (for example staff illness, delivery delays, and component shortages) relating to the COVID19 pandemic. Both project components have expanded in scope, which have allowed us to gain significantly deeper knowledge in the practical and theoretical aspects of creating the hybrid entangled photon source. We have made substantial progress towards accomplishing the milestones and have achieved other results that were not initially anticipated as part of the project (see the Change section for further details).

Dissemination to communities of interest

Our results thus far have been published in two peer reviewed journal articles: an Editors' suggestion in Physical Review B [8] and in Nature [10]. Our most recent work on the transduction device is also under consideration for publication.

PI Bartholomew has also presented the strategy, goals and preliminary results of this project in three presentations:

1. The Rare-earth Asia Pacific Network monthly meeting in December, 2020;
   A network of researchers working on harnessing rare-earth ion crystals for advanced classical and quantum technologies.
2. Australian National Fabrication Facility information session on the Advanced fibre Bragg writing suite at the University of Sydney in September, 2021 (available online: *Advanced fibre Bragg writing suite at the University of Sydney*).
   This broad audience was brought together by an interest in advanced fabrication and the capabilities of the newly established Fibre Bragg Grating Facility. Audience members came from diverse fields including astronomy, precision sensing, photonics, and optical fiber technology.
3. The Australian Research Council Centre of Excellence for Engineered Quantum Systems annual Workshop 2021.
   The audience consisted of approximately 20 PIs and their research teams from the five partner universities in the center (University of Sydney, University of Queensland, Macquarie University, Australian National University, and the University of Western Australia). All research teams focus on engineering quantum and supporting classical technologies.

Planning beyond the reporting period (Future plans)

Our current and future work will continue to extend the experimental architectures for hybrid quantum devices and develop the theoretical models to capitalize on rare-earth ion transitions to create strong nonlinearities capable of coupling the two domains.

From the experimental thrust there are three important aspects to measure in the short term. First, we aim to demonstrate phase correlations between the microwave and optical domain using hybrid photon echo sequences. We will investigate both 3-level and 4-level schemes in either ytterbium or erbium materials. In doing so, we will gain a greater understanding of the correlated and uncorrelated inhomogeneities that will ultimately govern the performance of the hybrid entangled photon source. Second, we will further explore the electron spin transition lifetimes and optimize the Purcell enhancement of the electron spin transition coupled to a superconducting microwave resonator. This is important to maximize the efficiency and fidelity of the hybrid entanglement. Third, we will fabricate and characterize integrated on-chip ytterbium devices to increase the magneto-optic nonlinearity relative to the current generation of devices. This harnesses the large light-matter interaction strength of ytterbium and ions incorporated directly within the optical resonator. The combination of these two aspects is expected to improve the nonlinearity by two orders of magnitude leading to more efficient and higher rate sources of hybrid entanglement and more efficient transducers. In the medium term, the aim is to leverage the best performing architecture to experimentally demonstrate the hybrid source.

From the theoretical thrust we will complete our numerical simulations and build on their complexity by reducing simplifying assumptions. We also intend to compare the theoretical predictions of our three-wave mixing and RASE protocol with four-wave mixing protocols to determine the optimum hybrid entangled source rate for a given physical device. In the medium term, our theoretical efforts will also analyze the most efficient measurements to generate remote entanglement between microwave regime quantum devices using hybrid sources of entangled photon pairs.

Impacts

Development of the principal discipline of the project

We anticipate the outcomes of this project to influence future developments in the field of rare-earth ion quantum devices. Rare-earth ion technology relies on leveraging the highly stable energy levels of the rare-earth atoms to store, preserve and manipulate fragile quantum information. There are three important regimes that these technologies operate in: the optical regime using light, the electron spin regime using microwave signals, and the nuclear spin regime using radio signals. There are very few proposals, however, that capitalize on the stability of the rare-earth atoms in all three of these regimes. The essence of our project is to harness all three regimes to create a quantum adaptor between the optical and microwave regimes with an inbuilt quantum memory based on the radio frequency regime.

In doing so, our project explores one limit of hybrid processing using rare-earth ion materials. This concept will likely influence directions in quantum information memory and control devices, where using all the stable regimes these atoms have to offer will open opportunities for new types of technology.

Impact on the development of human resources

Female researchers are significantly underrepresented in quantum technology research. For example, female Sydney Quantum Academy research experts represent only 15% of the total academic research expertise among the four leading quantum institutes in Sydney. This project provided opportunities for two female researchers to engage with quantum technology and applied quantum research. An engineering undergraduate student, Ms Sophia Kurianski (USYD) submitted her 4th year thesis on the entangled hybrid photon source protocol (*A Hybrid Entangled Photon-Pair Source to Connect Superconducting Quantum Computers*, November 2021). Without this project she would not have had the opportunity to apply her engineering and computer science skills to this type of research. This project also attracted Ms Gargi Tyagi, a talented Masters graduate in quantum theory, to join PI Bartholomew's group at USYD. She has been awarded a Sydney Quantum Academy PhD scholarship to focus on generating entanglement using rare-earth ion devices.

Impact on infrastructure

This project has provided a critical use case to support the fledgling Advanced Fibre Bragg Grating Facility at the University of Sydney. The Facility has unique capabilities in fabricating multiplexed and multifunctional fiber Bragg Grating filters and encompasses expertise developed over nearly two decades. With the success of the filter designed for rare-earth ion hybrid quantum networking, there is now significant external interest from researchers interested in making use of this Australian National Fabrication Facility infrastructure.

Changes

Changes in approach

Both the experimental and theoretical thrusts had small changes in approach that expanded the milestone objectives. In our experiments we chose to focus on photon counting measurements in the device characterization to gain greater insights into the noise processes relevant for rare-earth ion hybrid devices and also the benefits of pulsed, rather than continuous wave, protocols. In the theory program, it became clear that we needed a benchmark for the hybrid entangled photon source performance. Based on this, we expanded our scope to develop the theory of hybrid entangled photons generated by magneto-optic three-wave mixing. Details of this work are presented in the Technical Update.

Problems or delays

The most significant delay experienced in the full completion of the project milestones was the failure of the central processing unit and motherboard of the USYD workstation purchased for this project.

This meant that numerical modelling of the hybrid entangled photon source needed to be postponed for several months while the warrantee repair took place. In response, we concentrated our efforts on the analytical modelling of the three-wave mixing process.

Technical Updates

Experimental thrust

Figures 1 and 2 show on-chip rare-earth ion devices suitable for exploring hybrid protocols. These devices are not yet optimized for the hybrid entangled photon source protocol but do incorporate the required microwave and optical components to test key aspects of the protocol. Figure 1 shows a single device fabricated on an erbium-doped substrate for operation at an optical wavelength of approximately 1530 nm and Figure 2 shows a series of devices fabricated from an ytterbium-doped host for operation at 984 nm.

These integrated microwave-optical devices have both been studied in PI Faraon's labs. The devices are maintained at temperatures below 100 mK to minimize thermal noise and maximize the rare-earth coupling to the microwave devices. The characterization of the erbium device in Figure 1 has been particularly important for assessing the feasibility of using similar devices for hybrid sources of entangled photons. Below we highlight some of the key results.

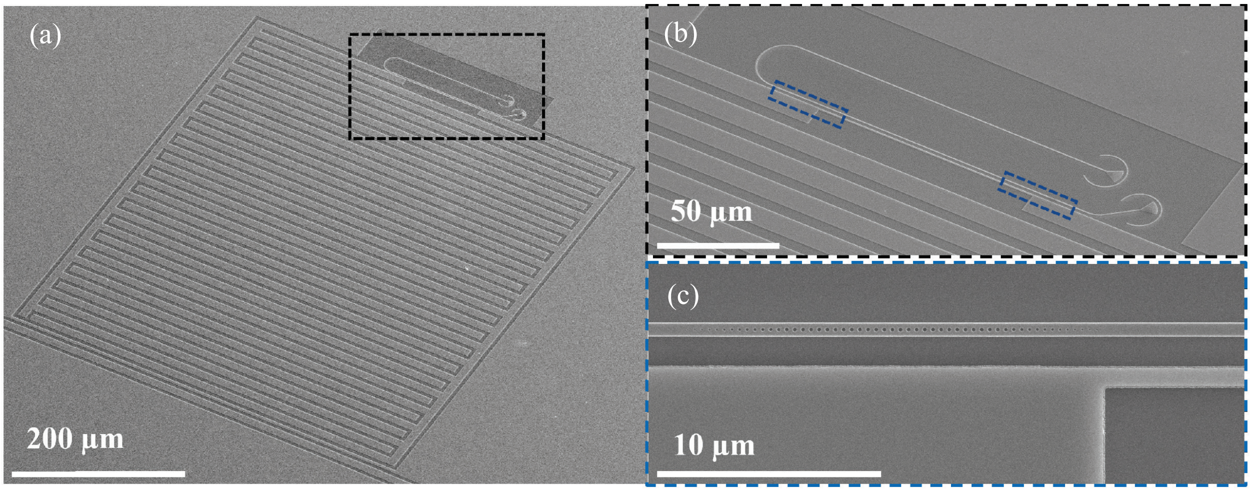

Figure 1. A scanning electron microscope image of an integrated microwave-to-optical transducer fabricated on an Er^{3+}:YVO_4 substrate. Panel (a) shows the full device with a microwave feedline coupled to the superconducting niobium microwave resonator, which consists of a large, interdigitated capacitor and a short, narrow inductor. Adjacent to the inductor is the optical resonator fabricated from amorphous silicon. Panel (b) shows a zoomed in section of the optical resonator and microwave inductor and Panel (c) shows the details of the photonic crystal mirrors.

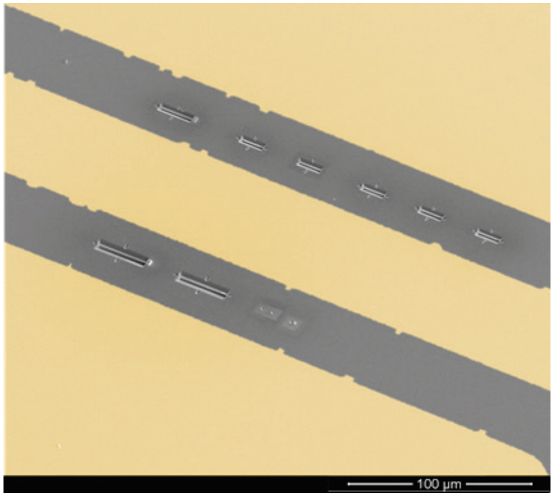

Figure 2. A false color scanning electron microscope image of a series of nanophotonic cavities (top row) and waveguides (bottom row) milled directly into a $Yb^{3+}:YVO_4$ substrate. The orange regime is a gold coplanar waveguide that allows broadband microwave waveguide that allows the control of electron and nuclear spins.

Maintaining low temperature operation

One challenge in operating these devices at dilution refrigerator temperatures while under excitation with optical beams is that they heat up considerably. Multiple iterations of the device have been tested to reach an experimental implementation where the chip can be kept cold at ~100 mK while undergoing optical and microwave excitation. This involved operating at low duty cycles where the optical and the microwave pulses are turned on for a short period of time (microseconds) followed by a wait time of hundreds of milliseconds to allow for the device to thermalize back to the base temperature as shown in Figure 3.

Further details are provided in Appendix 2.

Theoretical thrust

Our analysis has focused on extending the modelling of the all-optical entangled photon pair source known as Rephased Amplified Spontaneous Emission (RASE) to a hybrid protocol. Further details are provided in Appendix 3.

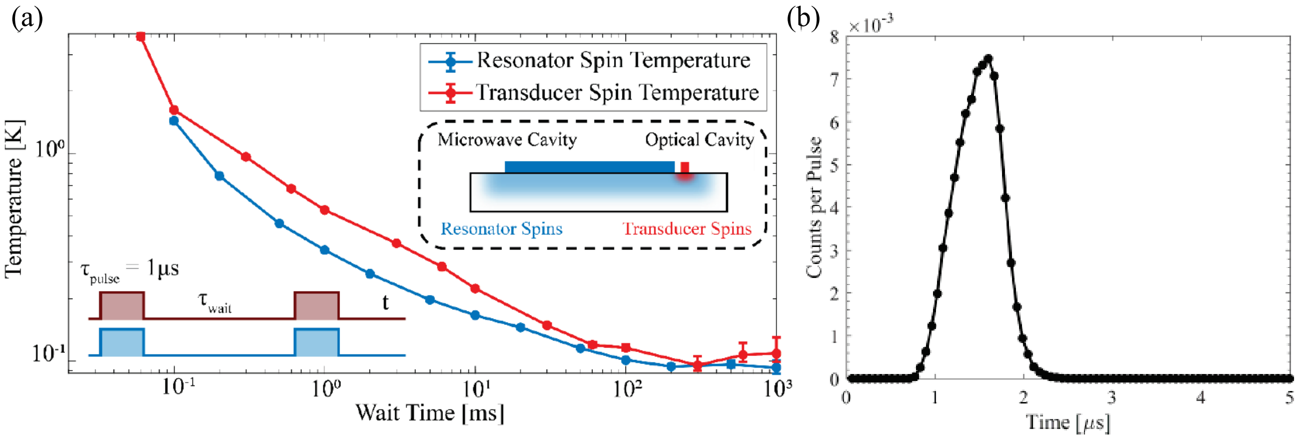

Figure 3. (a) The measured temperature of the erbium spins coupled to the microwave resonator (blue curve and light blue shaded region in the inset) and those spins coupled to both microwave and optical resonators (red curve and red shaded region in the inset) as a function of the waiting time between pulsed microwave and optical excitation. Wait times of 100 ms allow the spins to maintain temperatures of 100 mK for an optical excitation power of 550 μW. (b) Transduction occurs when the microwave and pump excitations coincide in time, which converts the microwave pulse to an optical pulse. Here we show the transduced optical pulse detected using photon counting. (Modified from [J. Rochman, Microwave-to-Optical Transduction Using Rare-Earth Ions, PhD thesis Caltech, 2022)

Erbium electron spin lifetimes at ~100 mK

Electron spin transitions with frequencies of the order of 5 GHz relax non-radiatively. Typically, the relaxation rate is governed by either spin-spin interactions or interactions with phonons in the host lattice. In this project we have made measurements of the erbium electron spin lifetime in two hosts with two different resonator geometries as shown in Figures 4 and 5.

We have measured the electron spin lifetime of $Er^{3+}:YVO_4$ coupled to the integrated hybrid device shown in Figure 1. At a temperature of approximately 35 mK, and magnetic field of approximately 62 mT (a transition frequency of 4.94 GHz), we infer a spin lifetime of $T_1 = 1.61$ s. More details on the measurement are provided in Figure 4.

In collaboration with the Longdell group at the University of Otago, we were able to measure the electron spin lifetime of $Er^{3+}:Y_2SiO_5$ at a field of approximately 200 mT (a transition frequency of 5.02 GHz) and temperature of order 100 mK. The measurements used a loop-gap resonator, which allowed the relaxation rate to be measured through the recovery of the ion-cavity polaritons following saturation (see Figure 5). The measured lifetime was 10 ± 3 s.

Further discussion is provided in Appendix 4.

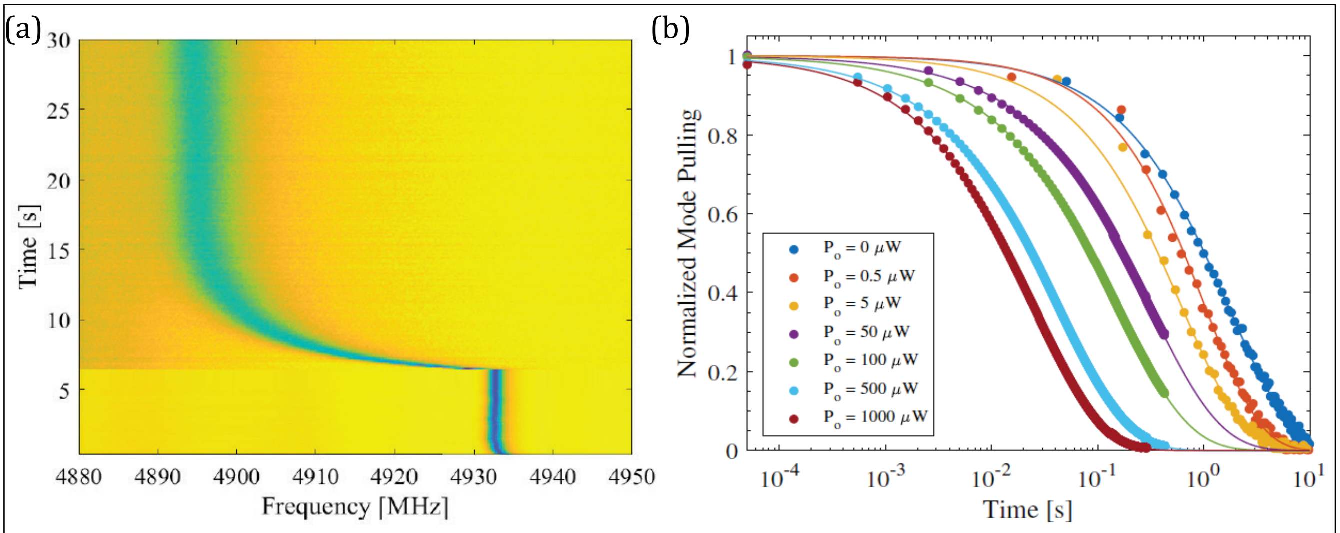

Figure 4. (a) Measurements of the electron spin lifetimes for Er^{3+} ions in a host YVO$_4$ crystal, inferred by monitoring the dispersive frequency shift of a superconducting microwave cavity (see Figure 1). A strong resonant microwave pulse is applied for 5 s, which saturates the spin transition. When there is no population difference between the two spin states, the dispersive shift g^2/Δ goes to zero and the spectrum shows the uncoupled cavity mode. As ions relax from the excited state, the population difference increases leading to an increased dispersive shift. (b) The normalized dispersive shift as a function of time for different optical powers P_o input into the optical resonator adjacent to the microwave cavity. The longest lifetime observed is T_1 = 1.61 s when the light is turned off. (Modified from [J. Rochman, *Microwave-to-Optical Transduction Using Rare-Earth Ions,* PhD thesis Caltech, 2022)

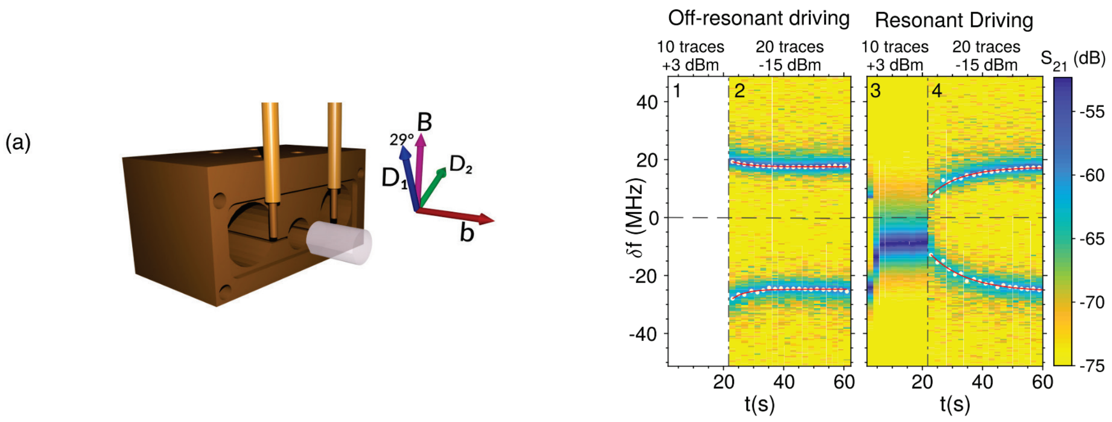

Figure 5. (a) An Er^{3+}:Y$_2$SiO$_5$ crystal is placed in a high Q copper loop-gap resonator in a static magnetic field. The field is applied in a specific direction to optimize the ensemble-cavity coupling.
(b) Measurements of the spin relaxation lifetime by monitoring the spin-cavity polaritons. A strong resonant microwave pulse in section (3) saturates the spin transition and the polaritons collapse to the uncoupled cavity mode. As ions relax from the excited state, the population difference increases leading to a recovery of the polaritons. (Modified from Ref. [9])

Fiber Bragg Grating Filter for hybrid quantum technologies

Hybrid quantum networks that bridge the microwave and optical domain will benefit from transducers and hybrid sources that create entanglement across these regimes. The challenge in realizing such technologies is that there is an energy gap of four orders of magnitude that needs to be overcome. To do so requires the input of a strong optical drive, either pulsed or continuous wave, that then needs to be separated from the single photon level signals within a few GHz in frequency. Hence, high performance optical filters are required to transmit the signals with high efficiency while heavily suppressing the optical drive (120 dB suppression).

Further details are provided in Appendix 5.

Note: all appendices extracted for public posting.

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