Rare-earth ions for quantum information

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A quantum light source compatible with telecommunication networks and a broadband $^{171}Yb^{3+}:Y_2SiO_5$ quantum memory

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Quantum repeaters would allow for the heralding of entanglement between remote nodes at a faster rate than via direct distribution of a photon pair state by exploiting multimode quantum memories. Such a scheme should be compatible with current telecommunication infrastructures, thus constraining one photon of the pair to be at a telecom wavelength, while the other photon should be compatible with the memory. A promising platform for single photon storage is an absorptive solid-state quantum memory based on a ytterbium-doped Y_2SiO_5 crystal, of which an inhomogeneously broadened optical transition is shaped into a broadband atomic frequency comb (AFC) [1,2], meaning the other photon should be at 979 nm.

We generate such photon pairs via spontaneous parametric down-conversion (SPDC), by converting a 600 nm pump into pairs of a 979 nm and a 1552 nm photon as mediated by a PPLN waveguide. Since the photons generated via sPDC are typically broad, it is necessary to select only the relevant frequency bands that will guarantee high energy correlations between the reemitted 979 nm photon and the telecom photon, as quantified by the second-order cross-correlation function. As the AFC selects a frequency band around the 979 nm transition, we filter the telecom photons using a Fabry-Pérot cavity whose linewidth is on the order of the AFC bandwidth. The energy correlation between the two photons is achieved by generating the 600 nm pump via sum-frequency generation of a 979 nm pump locked to the center of the AFC and a 1552 nm pump locked to the filtering Fabry-Pérot cavity.

We demonstrate single-photon storage with a storage time of 125 us and a 25 km fiber delay line for the telecom photon with normalized cross-correlation of 18, well above the classical limit of 2. Furthermore, we show the preservation of the time-energy entanglement between the telecom photon and the reemitted 979 nm photon, for a 25 us storage time, by observing two-photon quantum interference via a Franson-type setup with 94% visibility and violating the CHSH inequality with parameter S = 2.33(11).

[1] M. Afzelius et al., *Phys. Rev. A* ***79****, 052329* (2009)
[2] M. Businger et al, *Nat Commun 13, 6438* (2022)

Towards Novel Nanophotonic Interfaces with Rare-Earth Ion-Doped Nanomaterials

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Integrating quantum emitters into photonic circuits extends their functionalities and opens the way to realize on-demand single-photon and multiphoton entanglement sources, quantum memories, and photon-photon nonlinear quantum gates. Rare-earth (RE) ions, inserted into crystalline matrices are known for unique properties [1]: optical and spin transitions with long radiative and coherence times. Despite significant progress in integrating RE ions into nanophotonic structures [2], the need for a high-quality interface with rare-earth ion-doped nanomaterials prohibits using these materials for large-scale quantum information processing applications. In this regard, RE-doped thin films are especially promising [3].

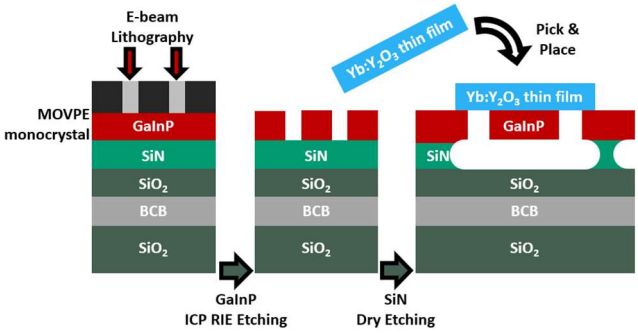

Figure 1: Schema of fabrication of GaInP suspended membranes coupled with RE ion-doped thin films.

For this, we are interested in hybrid platform consisting of a high-quality GaInP photonic crystal cavity interfaced with RE doped thin films chiplets (Figure 1). GaInP membranes provide broad transparency down to visible region (700 nm), large refractive index 3.2 and the wafer-scale epitaxial thin films. Their manufacturing is well established, with techniques such as MetalOrganic Vapor-Phase Epitaxy (MOVPE) to fabricate single crystal layers and Electron Beam Lithography (e-beam) and Inductive Coupled Plasma Reactive Ion Etching (ICP RIE) for nano structuring.

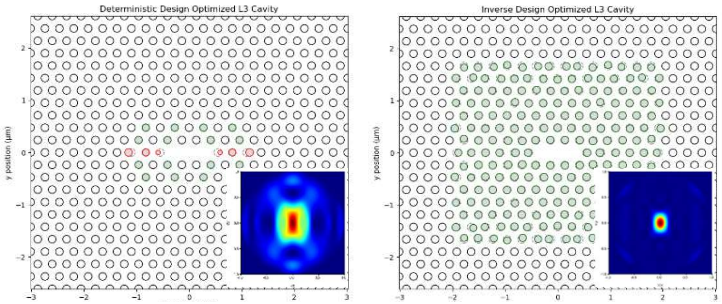

Figure 2: Optimized L3 cavities and its respective far-field, in the left by deterministic design using FDTD simulation and in the right by inverse design using GME simulation.

In this work, we present the optimization of a L3 photonic crystal cavity in a GaInP membrane using two design strategies – a deterministic design using FDTD simulation and an inverse design using GME simulation - as well as an approach to fabricate photonic cavities coupled with RE ion-doped nanomaterials (Figure 2). The best optimized L3 cavity has a simulated quality factor of the order of 10^5 and 40% of photon collection efficiency for a numerical aperture of 0.2 in the upward hemisphere. These results pave the way towards fabrication of nanophotonic interfaces with an easy and efficient addressability of RE ions by a free space fiber coupling.

[1] N. Harada et al., *Journal of Applied Physics*, **128**, 5 (2020)
[2] T. Zhong et al., *Nature communications*, **6**, 8206 (2015)
[3] S. Haddadi et al., *Optics Express*, **20.17**, 18876-18886 (2012)

Towards Nanophotonic Cavity-Enhanced Telecom-Compatible Quantum Memory on Thin-Film Lithium Niobate

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Quantum memory holds a pivotal role in advancing large-scale quantum networks and quantum computers. One promising candidate for this purpose is the use of rare earth ions doped in solid-state materials due to many factors including their exceptionally long coherence times and compatibility with nanophotonics [1]. A notable approach to achieving efficient broadband storage is through the atomic frequency comb protocol. However, many current implementations are constrained to bulk crystals, limiting their practicality for wafer-scale processes and integration with larger photonic devices. Transitioning from bulk crystals to thin films presents a challenge, as it reduces the optical depth, a critical factor for achieving high-efficiency storage. To address this issue, an impedance-matched cavity can be employed to enhance the effective optical depth [2]. Furthermore, utilizing a cavity offers the advantage of boosting the rate of spontaneous emission through the Purcell effect [3]. This is particularly valuable for Kramers rare-earth ions such as erbium (Er^{3+}), where the optical lifetime is comparable to the spin lifetime, resulting in a lower spectral hole burning efficiency [4]. To realize this, we utilize micro-ring resonator cavities fabricated on thin film lithium niobate on insulator (LNOI) platform doped with Er^{3+}: LNOI has emerged as one of the leading material platforms for large-scale quantum information processing due to its wide bandgap, large electro-optic coefficient, and low-loss waveguide fabrication. Moreover, it has shown to be a promising host for rare-earth atoms, making it an exciting prospect to implement quantum memory protocols [5]. Here we showcase our preliminary results in which we fabricated high-Q mircoring resonators (Q≈190k) on Er^{3+}:LNOI (Fig. 1(a)). We characterized the photoluminescence excitation spectrum of Er^{3+} and showcased a near 2.5-fold reduction in the optical lifetime of erbium due to the cavity resonance. We also further characterize the coherence properties of Er^{3+} ions by performing photon echo and measured a T_2 of 1.3 μs (Fig. 1(b)). Lastly, we showcase spectral hole burning in these nanophotonic devices with linewidths of under 12 MHz (Fig. 1(c)).

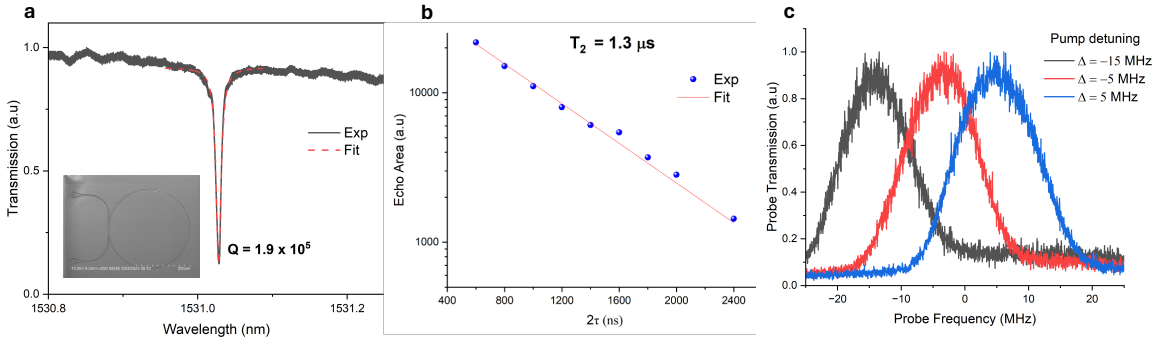

Figure 1: (a) Resonance spectrum and SEM image of a Er^{3+}:LNOI ring resonator (b) T_2 of Er^{3+} ions measured using photon echo (c) Spectral hole burned in Er^{3}:LNOI device measured by transmission of a weak probe at different pump detuning.

[1] T. Zhong et al., Science, **357**, 1392–1395 (2017)
[2] M. Afzelius et al., *Physical Review A*, **82,** 022310 (2010)
[3] S. Wang et al., *Applied Physics Letters*, **116,** 151103 (2020)
[4] E. Saglamyurek et al., *Nature Photonics*, **9**, 83–87 (2015)
[5] S. Dutta et al., *ACS Photonics*, **10**,1104–1109 (2023)

Spectroscopic investigations of multiple environments in Er:CaWO4 through charge imbalance

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The material Er:$CaWO_4$ has recently attracted significant attention as a platform for hardware for quantum networks due to its combination of optical transitions of Er in the telecommunication C-band and the favorable spin matrix of $CaWO_4$. [1, 2] While for laser application alkali metals were co-doped to avoid satellite lines from charge imbalance through potential vacancies [3-5], these are disadvantageous for quantum applications through their additional spin noise of owning a non-zero nuclear spin.

Here we present a detailed spectroscopic study of the $^4I_{13/2}$ and $^4I_{15/2}$ multiplet energy structure for not co-doped Er:$CaWO_4$ at 4 K. Using photoluminescence and photoluminescence excitation measurements, we find at least four different environments in which Erbium was incorporated and are able to assign the full $^4I_{13/2}$ and $^4I_{15/2}$ energy levels. Moreover, polarization-dependent absorption and emission spectroscopy reveal different transitions' irreducible representation and dipole nature. Further, we compare the different relaxation paths within $^4I_{13/2}$ and $^4I_{15/2}$ multiplets via line broadening and lifetime measurements. Finally, both lifetime and polarization investigations indicate an S4 symmetry of the studied environments.

[1] M. Le Dantec et. al, *Sci. Adv.*, **7**, 51 (2021)
[2] S. Ourari et. al., *Nature*, **620**, 977-981 (2023)
[3] F. Cornacchia et. al, *J. Appl. Phys.*, **101**, 123113 (2007)
[4] K. Nassau et. al, *J. Phys. Chem. Solids*, **24**, 1503-1510 (1963)
[5] K. Nassau et. Al, *J. Phys. Chem. Solids*, **24**, 1511 – 1517 (1963)

Efficiently Coupled Single Erbium Ions in Silicon Slow-Light Waveguides

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Erbium ions combine a telecom-wavelength optical transition with the long coherence times [1] they have in common with other rare-earth ions, which makes them particularly well-suited as memory qubits in fiber-based quantum networks. Doping thin-film crystalline silicon with erbium enables the fabrication of photonic nanostructures to interface the ions in a robust and scalable way. With the right implantation and annealing conditions, the dopants exhibit narrow inhomogeneous and homogeneous emission lines [2] and we found that the implantation can be performed even after the structures have been fabricated in a complex commercial process [3]. To create an on-chip quantum memory, single ions or ensembles of ions need to be efficiently coupled to an optical waveguide mode and ultimately to an optical fiber. Here we present the results of individually addressing efficiently coupled single erbium ions in weakly-doped photonic-crystal slow-light waveguides. We demonstrate the effect the photonic band gap of the waveguide has on the emission spectrum as well as the wavelength-dependent Purcell enhancement of the slow-light mode. We show that the lifetime of the optical excited state is reduced compared to the values encountered in silicon films of similar thickness and reaches that expected for bulk silicon measured in rib waveguides [2]. Featuring many spectrally resolved and efficiently coupled emitters, erbium-doped silicon slow-light waveguides might thus be a suitable platform for robust multiplexed quantum memories without the need for frequency tuning.

[1] Rančić, M. et al., Nature Physics 14, 50–54 (2018)
[2] Gritsch, A. et. al., Phys. Rev. X 12 (4), 041009 (2022)
[3] Rinner, S. et al. Nanophotonics 12 (17), 3455-3462 (2023)

Thulium ions in lithium niobate for quantum information applications

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We investigate trivalent thulium ions embedded in a lithium niobate crystal (Tm^{3+}:LN) as a platform for quantum information applications, including single and entangled photon sources, quantum memories, and quantum gates with and between spin qubits.

For this, we consider three infrared zero-phonon lines in Tm^{3+}:LN, corresponding to wavelengths of 795 nm, 1450 nm, and 1765 nm. In this poster, we first describe how to realize a quantum repeater (including source and memory) either using 795 nm photons or using energy-time entangled 1450 nm and 1765 nm photons. All photon sources rely on individual Tm ions and nanophotonic cavities that allow increasing the light-matter interaction by means of the Purcell effect, and the required quantum memories are based on large ensembles of Tm ions and mm-sized cavities. In addition, we also discuss the realization of qubits using Zeeman levels of a single Tm ion, and single and two-qubit gates that exploit the 795 and 1765 nm transitions.

For each of these quantum applications, we need to design, simulate, and fabricate nanophotonic cavities, details of which are presented in two other posters.

Crystalline waveguides for highly efficient integrated quantum memories

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Rare-earth (RE) doped crystals are a promising platform for quantum memories: at cryogenic temperatures they feature narrow optical transitions, long hyperfine coherence time [1], while maintaining very large inhomogeneous absorption lines, allowing for higher degrees of multiplexing. Current storage experiments in bulk RE doped crystal display limited efficiency for long storage time due to low absorption [2] and poor light-matter interaction strength due to free space beam divergence, especially when optically long samples are needed. Waveguides in RE doped crystals appear as a good solution to enhance memory performances: the optical Rabi frequency remains constant in the material, and the interaction length can be extended to match the desired absorption depth [3] to reach maximum efficiency, together with an improved scalability [4]. For this reason, many techniques for fabricating integrated quantum memories in RE ensemble have been investigated. Most of them either show poorer spectroscopic performances [5] or can't allow for complex functions [6] such as couplers, curvatures or cavities.

Here we present the fabrication of single-crystalline Y_2SiO_5 waveguides. Those structures are made from bulk crystals and should be able preserve the bulk properties. We describe our recent progresses on different steps of the fabrication process including recent results on crystal bonding, YSO layer thinning down to micrometric thicknesses and dry-etching of YSO. Simulations have been performed to determine the geometry and dimensions of the waveguide's structure. Cryogenic fiber coupling is verified and erbium spectroscopy at low temperature in crystalline waveguides is under progress. A preliminary quantitative study of the advantages of waveguides over bulk crystal for the Atomic Frequency Comb (AFC) protocol will also be presented.

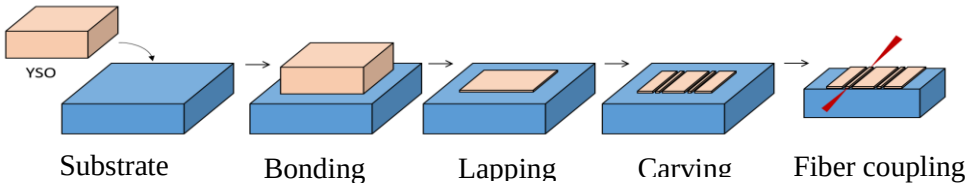

Figure 1: Fabrication process flow of crystalline waveguides

[1] M. Zhong et al., *Nature*, **517**, no 7533, p. 177-180, (2015).
[2] Y. Ma et al., *Nat. Commun.*, **12.**, 2381 (2021)
[3] M.Afzelius et al., *Phys.Rev.A*, **79.**, 052329 (2009)
[4] Jing et al., *Appl. Phys. Rev.* **11.**, 031304 (2024)
[5] Ourari et al., Nature, **620.,** 977-981 (2023)
[6] G. Corrielli et al., *Phys. Rev. Appl.*, **5.**, 054013 (2016)

Efficient and reversible optical-to-spin conversion for solid-state quantum memories

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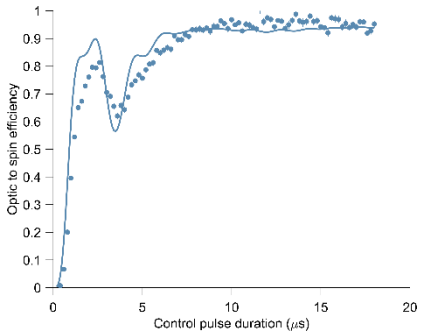
Quantum memories for optical photons are essential components in various quantum information schemes, particularly for quantum communication via quantum repeaters. Long duration storage is typically based on mapping the input state from the optical domain into the spin domain of an atomic system, using a pair of optical population inversion pulses. In addition, a minimum of two spin population inversion pulses are employed to reach spin storage times of the order of the spin coherence time. It has been a challenge, however, to design optical and spin population inversion pulse sequences for achieving a reversible optical-to-spin mapping with a total efficiency approaching unity.

In this talk, we demonstrate efficient and reversible mapping of light from the optical to the spin domain based on the AFC spin-wave memory, using a 151-europium doped crystal. We reach a total back-and-forth optical-to-spin efficiency of 95%, including all the optical and spin control pulses and the spin dephasing loss. We employ optical and spin inversion pulses with smooth amplitude envelopes and frequency chirping to achieve adiabatic conditions [1]. To address interferences between quantum paths caused by small Zeeman splits of the hyperfine levels [2], we apply a 230 mT magnetic field such that both the optical and spin pulses adress two-level systems at all times. Numerical Bloch-equation models have been developed to optimize the efficiency of the optical and spin sequences, accounting for experimental parameters such as AFC bandwidth, optical mode sizes, optical mode overlap and spin linewidth. These results are also of high relevance to spin-wave quantum memories in praseodymium-doped crystals and other systems relying on efficient optical and spin inversion pulses. These findings are critical for advancing quantum memory technologies and enhancing the feasibility of long-distance quantum repeaters.



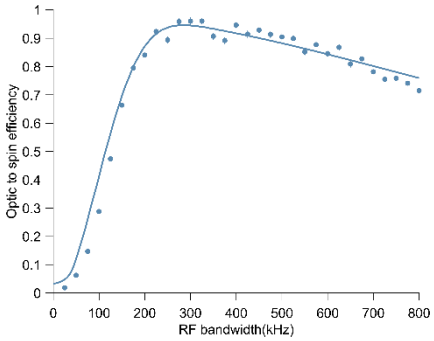


Figure 1: Optic to spin efficiency as a function of optic control pulse duration

Figure 2: Optic to spin efficiency as a function of RF bandwidth

[1] Ortu, Antonio, et al. "Multimode capacity of atomic-frequency comb quantum memories." Quantum Science and Technology (2022).

[2] Etesse, Jean, et al. "Optical and spin manipulation of non-Kramers rare-earth ions in a weak magnetic field for quantum memory applications." Physical Review A 103.2 (2021): 022618

Exploring Erbium Ions in Silicon Nanostructures

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Two of the most active and exciting areas of quantum science are cavity optomechanics [1] and spins in solid-state systems [2]. A hybrid spin-photon-phonon system is interesting both for enabling novel quantum applications and for gaining new insights into the very foundations of physics. As spin system, rare earth ions are particularly attractive, thanks to their long spin lifetime and coherence [3]. In our case, we work with erbium defects implanted in a silicon host. The choice of erbium is motivated by the optical transitions at telecom wavelength, suitable for quantum network purposes, and by the effective electron spin of ½.

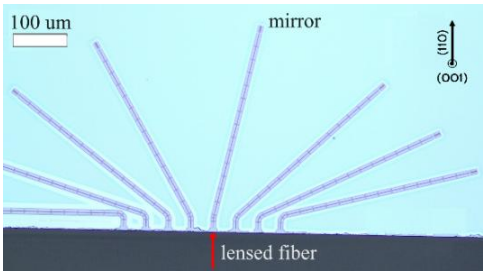

Figure 1: Optical microscope image of erbium doped silicon waveguides oriented in different crystal directions.

Silicon nanofabrication is well established, thus making the incorporation of erbium in silicon nanostructures appealing. We characterized the ensemble optical properties of erbium defects in silicon by fabricating 400 um-long silicon waveguides oriented in different crystal directions (see Figure 1).

We then implanted erbium ions in silicon nanobeams (see Figure 2). A nanobeam supports an optical cavity mode and a mechanical mode that couple to each other through the radiation pressure [4]. Therefore, our system enables the exploration of hybrid optomechanics. Promising orbital-strain coupling coefficients are reported for rare earth ions in various hosts [5]. Moreover, erbium defects in silicon feature large crystal field splitting [6], thus suggesting that the energy levels might be particularly sensitive to strain. Eventually, this study would open the way to the control of spins via phonons [7] and to the realization of nonlinear optomechanics.

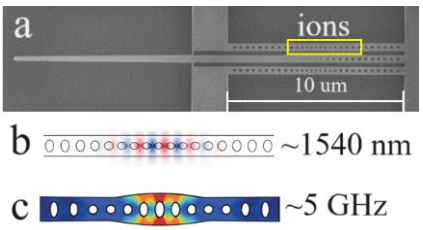

Figure 2: SEM picture of a silicon nanobeam (a). Simulations of optical mode at ~1540 nm (b) and mechanical breathing mode at ~5 GHz (c).

[1] M. Aspelmeyer et al., *Reviews of Modern Physics*, **86**, 1391 (2014)
[2] D. D. Awschalom et al., *Nature Photonics*, **12**, 516-527 (2018)
[3] M. Zhong et al., *Nature*, **517**, 177–180 (2015)
[4] S. Hong et al., *Science*, **358**, 203-206 (2017)
[5] A. Louchet-Chauver et al., *Review of Scientific Instruments*, **90**, 034901 (2019)
[6] A. Gritsch et al., *Physical Review X*, **12**, 041009 (2022)
[7] D. A. Golter et al., *Physical Review X*, **6**, 041060 (2016)

Er sites in Si for quantum information processing

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Rare-earth ions in a solid-state host exhibit low homogeneous broadening and long spin coherence at cryogenic temperatures, making them promising for a range of quantum applications, such as optical quantum memories and optical-microwave transductions. Emitters with long electron spin and optical coherence in Si, a leading material platform for electronic and photonic technologies, are especially attractive for quantum applications.

Here, we report on the extension of instrument-limited millisecond spin coherence of Er in Si to 40 ms using CPMG-like sequences, homogeneous linewidths below 100 kHz and inhomogeneous broadening approaching 100 MHz. This is achieved in a nuclear spin-free silicon crystal (<0.01% ^{29}Si) doped at 10^{16} cm^{-3} Er level. The Er homogeneous linewidth and spin coherence were addressed using optical comb-based spectral hole burning and optically detected magnetic resonance techniques. To enhance Er emission collection efficiency, samples were directly positioned atop specially fabricated superconducting single photon detectors and resonantly excited via fibre optics. Measurements with naturally abundant Si revealed that the Er electron spin coupling to ^{29}Si nuclear spins significantly shortens Er spin coherence times. The demonstration of a long spin coherence time and narrow optical linewidth show that Er in ^{28}Si is an exceptional candidate for future quantum information and communication applications [1,2].

[1] Ian R. Berkman et al., Phys. Rev. Applied **19**, 014037 (2023)
[2] Ian R. Berkman et al., arXiv:2307.10021(2023)

Light induced luminescence in Eu:YSO

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We report a novel luminescence phenomenon observed in Eu^{3+}:Y_2SiO_5 at cryogenic temperatures, induced by the presence of a monochromatic laser field. Whereas the underlying mechanism is not understood, we have carried out preliminary tests concerning its spectral and spatial behaviour as well as the decay dynamics. In the context of laser frequency stabilization, we have evaluated the impact of the observed luminescence, and implemented mitigating measures. By combining the knowledge obtained through our previous investigations [1,2], we demonstrate a fractional frequency stability of a laser locked on a multi-spectral hole pattern of $4(1).10^{-16}$ at 1 s. We will discuss possibilities for further improvements in order to benefit from the full potential of rare-earth ion reference ultra-stable lasers as a relevant tool in optical frequency metrology.

[1] X. Lin *et al*., Anomalous sub-kelvin thermal frequency shifts of ultra narrow-linewidth solid state emitters, submitted (2024)

[2] X. Lin *et al*., Multi-mode heterodyne laser interferometry realized via software defined radio, Optics Express, **31**, 38475 (2023)

Quantum Nano-Photonics with Rare-Earth Ions: quantum networking, transduction, many-body physics

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I will give an overview of our group's recent results in using rare-earth ions for demonstrations in quantum networking, microwave to optical transduction, and quantum many body physics. Namely, we demonstrated entanglement distribution between quantum network nodes with multiple optically addressable qubits per node. This has been shown in ytterbium 171 ions in yttrium vanadate at very dilute doping. Using the same material but at much larger concertation we demonstrate efficient microwave to optical transduction at single photon level and investigate quantum many body physics of interacting spins.

A cavity-enhanced solid-state spin wave quantum memory

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The realization of large-scale quantum networks requires the distribution of entanglement over large distances. In this long-range regime, direct transmission is prohibitive due to losses in optical fibers. Quantum repeaters are predicted to overcome direct transmission and allow entanglement distribution at continental scales. However, most quantum repeater schemes rely on the storage of quantum states into quantum memories. In order for memories to be useful in practical implementations, they must exhibit several features including a long storage time, a high storage efficiency and a large multiplexing capability. Solid-state quantum memories based on rare-earth doped solids promise excellent performances in terms of storage time and multiplexing capability.

With longer storage time, the efficiency of many memory protocols decays exponentially due to the coherence time of the material. This severely limits the applicability of the memory. Storage in a spin-state has the advantage, that spin-rephasing techniques can be applied to mitigate this efficiency decay.

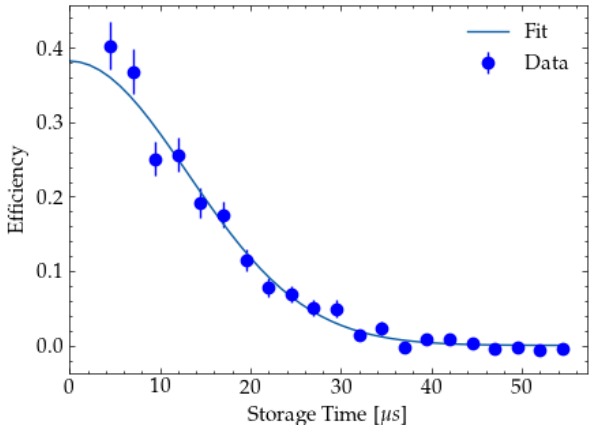

Figure 1: Scan of the device efficiency as a function of the on-demand storage time.

For rare-earth based memories, the efficiency for spin-wave storage at the single photon level was so far limited to around 31% using the spectral-hole memory protocol [1] which does not allow for qubit storage without sacrificing efficiency. The highest efficiency using spin-wave-storage with the atomic frequency comb protocol (AFC) was reported by Jobez et al [2] with 12% for coherent states at the classical level.

Using the AFC protocol, we present a quantum memory implemented in an impedance-matched cavity [3] built around the vacuum chamber of our cryostat [4]. We reached a device efficiency over 50% for storage of weak coherent states at the single photon level in the excited state for 8 μs and over 38% for storage in the spin-state for additional 5 μs. Maintaining a good signal-to-noise ratio (SNR) is more challenging for storage in the spin-state than in the excited state. We reached a SNR of about 16 with a mean input photon number of 0.44, making it feasible to store photons from SPDC sources. We characterized the efficiency and SNR with respect to photon bandwidth and storage time (see fig.1) and investigated the effect of the impedance-matched cavity on the noise level.

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Erbium dopants in silicon cavities

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Erbium dopants are promising candidates for the implementation of large-scale quantum networks since they can combine second-long ground state coherence [1] with coherent optical transitions at telecommunication wavelengths [2]. However, the long lifetime of the excited state makes it difficult to spectrally resolve and control individual ions. By embedding the dopants into optical resonators with a high quality factor, the light-matter interaction is enhanced and the optical lifetime can be reduced [3].

Thus, we integrate erbium dopants into nanophotonic silicon structures (Fig. 1a) [4,5] to control their coupling to light. This approach facilitates a strong Purcell enhancement, almost 200-fold by minimizing the mode volume down to the order of a cubic wavelength [4]. In magnetic fields, the electronic spins of individual dopants can be initialized and read-out with a fidelity ~0.9 and a spin-lifetime of several seconds. Adding coherent driving by microwaves, we find a Hahn-echo time of 40 µs [6]. Towards quantum networking, however, the spectral diffusion linewidth – on the order of 20 MHz – would need to be reduced.

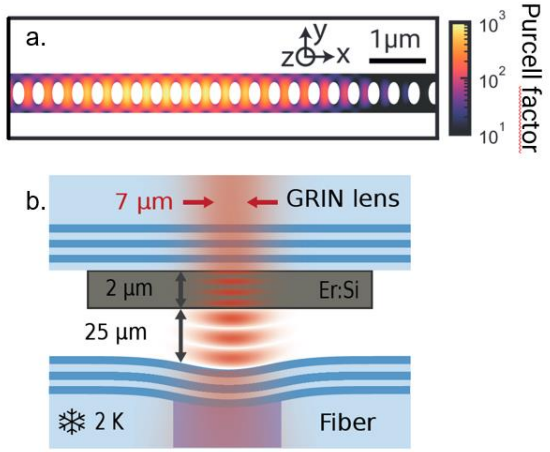

Figure 1: Two approaches explored for the spectrally-multiplexed control of individual erbium spins. a) The Erbium emitters are embedded in a photonic crystal resonator. b) Fabry Perot resonator: An Erbium doped membrane is transferred onto the flat mirror of the cavity.

To this end we use a micron-scale Fabry-Perot resonator (Fig. 1b). While currently this approach only allows for smaller Purcell enhancement due to the higher mode volume, because of the increased distance of the emitters to the next interfaces, the spectral diffusion is reduced below 3 MHz, while the optical coherence can approach the lifetime limit.

Thus, both approaches are promising towards the entanglement of remote emitters once the linewidth is further reduced to the lifetime limit. This might be achieved in isotopically purified host materials [7]. Furthermore, improved fabrication techniques have enabled us to reduce losses of undoped nano-waveguides to below 1.5 dB/cm, opening up new perspectives into both enhancing the quality factor of photonic crystal cavities for single-ion spectroscopy and using ring resonators for the coherent coupling to ensembles of dopants in order to implement on-chip quantum memories.

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[4] A. Gritsch et al., *Phys. Rev. X*, **12**, 041009 (2022).
[5] A. Gritsch et al., Optica **10**, 783 (2023).
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On-chip microwave-to-optical transduction with $^{171}Yb^{3+}$:YVO_4 at single photon levels

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*Equal contribution

Microwave-to-optical transduction of single photons will play an essential role in interconnecting future superconducting quantum devices and enable a hybrid quantum network connecting disparate physical platforms [1]. To perform efficient transduction that bridges five orders of magnitude in energy difference, materials with nonlinearity must be integrated into a system with that allows interfacing with both optical and microwave photons. A plethora of devices with various material platforms have demonstrated transduction, utilizing nonlinearities such as the Pockels effect, or some combination of electromechanics, piezoelectricity, and optomechanics [2-5]. However, the intrinsically weak nonlinearities of the materials used in these platforms require sophisticated fabrication of high-quality resonators, presenting difficulties in scaling and interconnection.

In this work, we use $^{171}Yb^{3+}$ ions doped in YVO_4, and demonstrate an on-chip microwave-to-optical transducer with device efficiency of about a percent, 1.2 added noise, 500 kHz bandwidth, and kHz-level repetition rate [6]. This is enabled by the large intrinsic nonlinearity of this material, which we show to be 3 to 4 orders of magnitude larger than $LiNbO_3$. The device consists of a planar superconducting microwave resonator which inductively couples to the ions, and a weak optical mode formed by the chip interfaces. Furthermore, due to the fixed nature of the atomic frequencies and lack of a high-finesse optical cavity, we demonstrate the interconnection of two nominally identical devices. Specifically, the transduced optical photons from two simultaneously operated transducers are interfered to mimic remote entanglement protocols, or one of the transducers is operated in the reverse optical-to-microwave transduction mode to mimic optical control and readout of superconducting qubits. These results establish rare-earth ions doped in solids as a suitable material platform for transduction and pave the way for efficient quantum transduction.

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[2] X. Han et al., *Optica* **8,** 1050-1064 (2021)
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[3] R. Sahu et al., *Nat. Comm.,* **13,** 1276 (2022)
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[5] W. Jiang et al., *Nat. Comm.,* **11**, 1166 (2020)

Towards a high efficiency integrated gradient echo memory

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Rare earth ion doped crystals (REICs) have interested the quantum information community for their applications in quantum communication networks [1] and photonic quantum computing [2]. Both their optical and spin transitions are ideal for quantum information storage and manipulation due to their long coherence times and narrow homogeneous linewidths. REICs can also be conveniently integrated into photonic circuits or waveguide-based systems [3]. One of the most common REIC QM protocols is the atomic frequency comb (AFC): with spin-wave storage it has been proved a good candidate for on-demand long-lived quantum memory for single photons [4,5]. In this protocol, strong control pulses are needed to make the storage readout on demand and extend the storage time, but these can easily submerge the photon detection. In bulk samples, the control pulses can be sent off axis, with respect to the single photons, leading to a large degree of noise suppression (up to 70 dB) [6]. In a waveguide device, this method of noise suppression is not available. With the use of polarization and spectral filtering (215 dB) [7], spin-wave AFC has been demonstrated at the few-photon level. However, for real single photons the required suppression is much higher. Our approach uses the gradient echo memory (GEM) protocol, based on controlled reversible inhomogeneous broadening, which does not require optical control pulses but electric field gradient to achieve on demand readout [8,9]. We have designed a photonic chip with spatially multiplexed QMs for implementing the GEM protocol in a Type I waveguide using femtosecond laser writing [10]. The waveguides are written into a Pr^{3+}:Y_2SiO_5 substrate and gold electrodes are deposited onto the chips surface. Using finite elements simulations, we have optimised the device architecture to obtain a uniform electric field gradient to maximise the efficiency and minimal cross-talk between QMs. Additionally, we have developed a python-based simulation tool of the GEM protocol based on the Maxwell Bloch equations to explore the dynamics of the protocol and find the optimal parameters for maximising the efficiency, storage time and bandwidth. To achieve high efficiency with the GEM protocol, a highly absorbing sample is needed. However, this increases the difficulty of spectral preparation. Laser written Type I waveguides have demonstrated a 1-order-of-magnitude increase in Rabi frequency due to spatial confinement [10], however the large parameter space makes the optimisation of the spectral hole burning process complex and time consuming. For this reason, we have developed a genetic algorithm that optimises the spectral features to maximize the efficiency.
Our work has the potential to demonstrate an integrated photonic quantum memory with unprecedented efficiency and spatial multiplexing capacity, which will also be readily compatible with fibre networks and employable in complex quantum photonic circuits.

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[2] A. Kinos et al., arXiv 103.15743 (2021)
[3] Z. Zong-Quan et al., Laser & Photon. Rev. 17, 2300257 (2023)
[4] J. Rakonjac et al., PRL 127, 21 (2021)
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[10] A. Seri et al., Optica 5, 8 (2018)

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Optical Spectroscopy of Main and Satellite Lines in Erbium Lithium Fluoride

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Crystals stoichiometric in a rare earth ion have been proposed for quantum information applications including quantum transduction [1] and optical quantum processors [2]. The transduction scheme utilises a three-wave-mixing process that is enhanced by the strong coupling of the ensemble of Er^{3+} ions to optical and microwave fields to achieve high efficiencies and large bandwidths. The computing scheme makes use of the cluster of rare earth ions around a defect, which give rise to satellite lines in the optical spectrum, as frequency-addressable qubits, allowing the creation of small qubit systems with strong ion-ion interactions for enacting gates. In both cases, the challenge lies in identifying suitable host crystals.

We study $ErLiF_4$ for both these applications because it has been demonstrated to have narrow main line optical linewidths (down to ~240 MHz) in the telecom transparency band [3]. This strong optical coupling with narrow linewidths is amenable to high-efficiency off-resonant three-wave-mixing, required in our transduction scheme. Additionally, $ErLiF_4$ has been demonstrated to spontaneously magnetically order as a bilayer anti-ferromagnet for temperatures below 380 mK [4], which enables the excitation of collective magnetostatic modes with resonances at microwave frequencies.

For computing it is crucial to achieve good coherence times on the satellite lines. The coherence properties of satellite lines due to substitution defects in crystals which are otherwise stoichiometric in Er (or any other Kramers ion) have never previously been measured. They could be expected to differ from those in dilute crystals due to the strong ion-ion interactions which lead to both the magnetic ordering and collective excitations. This effect combines with the normal interactions with the fluorine spin bath.
I will describe recent measurements of the coherence times of various satellite lines in $ErLiF_4$ over a range of different experimental conditions. We have observed coherence times on satellite structures in the paramagnetic phase of $ErLiF_4$ which exceed those reported in $Er:YLiF_4$. These comparatively long coherence times are surprising given the strong inter-ion coupling, and observation of collective excitations. The results indicate that the Er^{3+} ions surrounding substitution defects are sufficiently detuned from the bulk to regain single-ion properties (coherence) which are not seen in main line excitations (which are collective). The coherence times are strongly dependent on the magnetic phase the crystal occupies, which suggests some interaction with the collective modes remains.

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[4] C. Kraemer et al, *Science*, **336**, 1416-1419 (2012)

Demonstration of broadband, on-demand, and spectrally multiplexed optical memory

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Multiplexed and on-demand quantum memory plays a vital role in a wide range of quantum information processing applications. Here, we present an implementation of spectrally multimode on-demand optical memory using the revival of silenced echo scheme, employing two identical adiabatic chirped optical pulses colinear with the input pulse to rephase the input excitation (Fig. 1), similar to that explored in the microwave domain [1-4]. The main advantages of this method over spectrally multiplex atomic frequency comb QM are on-demand retrieval of stored excitations, long storage time, and simple implementation. We demonstrate over 25% efficiency of retrieving an input coherent pulse after 140 μs. For spectrally multiplexed input excitation, we can recall all spectral modes or individual modes on-demand for up to 700 μs. For our experiment we employed $^{171}Yb^{3+}$:Y_2SiO_5 at millikelvin temperatures at which 600 μs optical coherence time is determined. Work to reach single-photon level storage and improving performance with cavity enhancement and tuning of the bias magnetic field is ongoing.

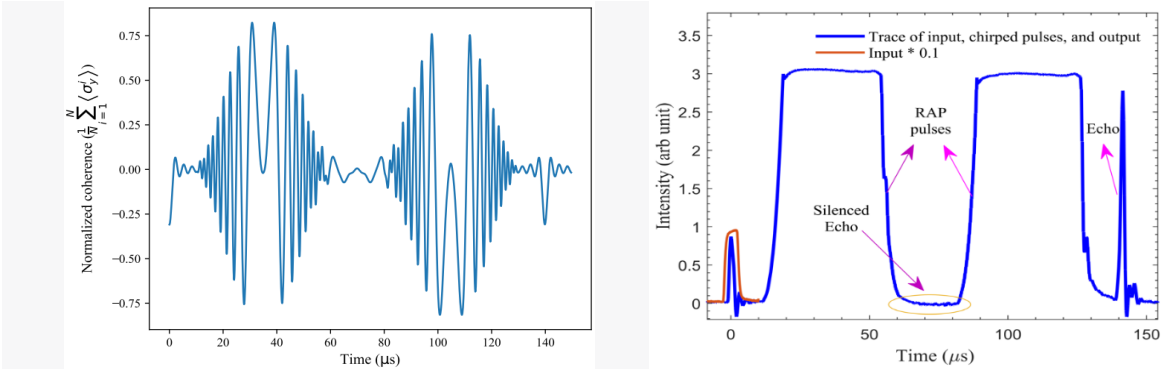

Figure 1: Rephasing an input excitation using adiabatic optical chirped pulses. (Left) Theoretical description of the protocol where evolution of σ_y operator is simulated. After absorption of the input excitation at t = 0, the first chirped pulse at time $t = \tau$ with a suitable amplitude envelope induces an additional phase to the spins, resulting in the silencing of the echo. Subsequently, after time T (where T is the time separation between the two chirped pulses) the application of the second chirped pulse leads to the rephasing of the input excitation, causing the emission of an echo at time $T - \tau$ after the second chirped pulse. (Right) Experimental realization of the phase imprint memory protocol. The orange peak, off-resonant input in which its intensity has been attenuated by 10 times. The corresponding blue line representing the non-interacted part of the input, two identical chirped pulses, and reemission after 140 μs. This setup demonstrates the successful implementation of the rephasing protocol using adiabatic optical chirped pulses.

[1] J. O'Sullivan et al., *Phys. Rev. X*, **12.**, 041014 (2022)

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Erbium dopants in optical resonators

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Optically addressable spin qubits are pristine candidates for large-scale quantum networks [1] and modular quantum computing architectures [2]. Among all investigated hardware platforms, erbium is the only emitter with a coherent optical transition in the minimal-loss-band of optical fibers. Furthermore, the narrow optical transitions allow for spectral multiplexing, such that coherent optical control of more than 100 qubits with lifetime-limited optical coherence could be demonstrated [3], and for the generation of indistinguishable photons [4] and spin-photon entanglement [5].

In silicon, erbium can be integrated at well-defined lattice sites [6], which are compatible with industrial-grade nanofabrication processes [7]. In nanophotonic resonators ($Q\approx10^5$, $V\approx\lambda^3$) (Fig. 1a), efficient spin-photon interfaces [8] can be realized, in which about ten single dopants (Fig. 1b) can be resolved with Purcell enhancement up to 177. Their spin state can be initialized and read out with a combined fidelity of 87%. This spin further exhibits a second-long lifetime and a Hahn-echo coherence time of 48(2) µs [9].

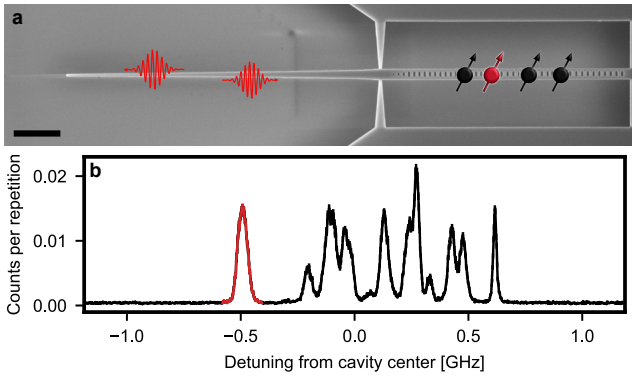

Figure 1: a. An efficient interface between a spin qubit encoded in a single erbium dopant embedded in a photonic crystal cavity and a telecom photon. b. Several individual qubits are addressed by spectral multiplexing.

In our current experiments, we further investigate the optical coherence and the spectral multiplexing capabilities in our silicon devices, which allows a detailed comparison to our experiments with YSO membranes integrated into Fabry-Perot resonators [10].

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[2] S. Simmons, PRX Quantum **5**, 010102 (2024).
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[8] A. Gritsch, et al., Optica 10, (2023).
[9] A. Gritsch, et al., arXiv:2405.05351 (2024).
[10] A. Ulanowski, et al., Advanced Optical Materials 12 (2024).

Design and simulation of nanophotonic cavities for quantum applications with Tm^{3+}:$LiNbO_3$

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We investigate trivalent thulium ions embedded in a lithium niobate crystal (Tm^{3+}:LN) as a platform to realize quantum information applications, including single and entangled photon sources, quantum memories, and quantum gates.

Towards this end, we need to engineer cavities either resonant at 795 nm, or bi-resonant at 1450 nm and 1765 nm and featuring a small mode volume and a large quality factor to achieve a high Purcell factor. We present in this poster the simulation results to optimally achieve this with two different approaches: standard photonic crystal structures, and topology optimized inverse designs.

The details of the nanofabrication and how these cavities are merged together with the Tm^{3+}:LN system for quantum information applications are presented in two other posters.

Thulium ions in lithium niobate for quantum information applications

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We investigate trivalent thulium ions embedded in a lithium niobate crystal (Tm^{3+}:$LiNbO_3$) as a platform to realize quantum information applications, including single and entangled photon sources, quantum memories, and quantum gates with and between qubits encoded into spin states of individual ions.

Towards this end, we consider three infrared zero-phonon lines (ZPLs) in Tm^{3+}:$LiNbO_3$, corresponding to wavelengths of 795 nm, 1450 nm, and 1765 nm. After an introduction of the different applications and how they benefit from, or require, the three ZPLs, we will briefly discuss how to create the nanocavities that underpin all photon sources and quantum gates. More precisely, we will introduce different ways to optimize such cavities to achieve large light-matter interactions (Purcell effect) using constrained and unconstrained (topologically-optimized) designs. In addition, we will also describe our approach to creating nano-cavities based on $LiNbO_3$-on-instulator chips and show recent results. More details of these three parts—applications, simulation and creation of nano-cavities—will be explained in complementary posters.

Fabrication of nanophotonic cavities for quantum applications with $Tm^{3+}:LiNbO_3$

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We investigate trivalent thulium ions embedded in a lithium niobate crystal (Tm^{3+}:LN) as a platform to realize quantum information applications, including single and entangled photon sources, quantum memories, and quantum gates.

To achieve this, we need to engineer cavities either resonant at 795 nm, or bi-resonant at 1450 nm and 1765 nm and allowing the transmission of 795 nm. We follow the approach of directly fabricating the cavities in lithium niobate on insulator (LNOI) chips. In this poster we present the procedure to perform the fabrication, together with our current results.

The details of the cavity design and simulations, and how these cavities are merged together with the Tm^{3+}:LN system for quantum information applications are presented in two other posters.

Single photon EIT light storage for one second in a doped solid

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Future quantum communication technology on a worldwide scale requires quantum repeaters to overcome signal loss. Realistic optical implementations of such quantum repeaters require an efficient, long term, high fidelity, and multimode photon memory. In our work we demonstrate light storage of weak coherent pulses at the **single photon level** based on **electromagnetically induced transparency (EIT)** in a Pr^{3+}:Y_2SiO_5 crystal. By employing **zero first order Zeeman shifts (ZEFOZ)** and simple two-π-pulse rephasing we reach a storage time of 1.8 s. Application of a robust error-correcting rephasing sequence [1] prolongs the storage time to 14 s (see Fig. 1).

We simultaneously prepare two ensembles to boost the storage efficiency and apply a specifically designed spectral filter implemented in an additional Pr^{3+}:Y_2SiO_5 crystal to separate the weak signal from the strong optical control field. We use now an ECDL-based laser system (replacing the previously applied OPO system) which helps to improve the spectral filter discrimination by almost 20 dB compared to our previous work [2]. This enables **storage of a single photon pulse for one second with SNR=1.3** (see Fig. 2).

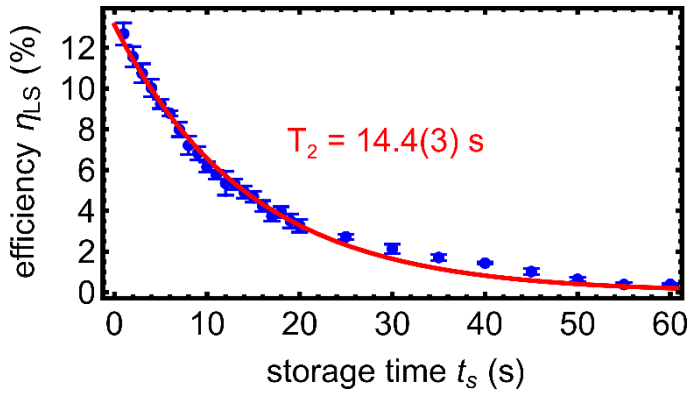

Figure 1: Light storage efficiency over storage time at ZEFOZ and with robust UR16 rephasing (blue) and exponential fit (red).

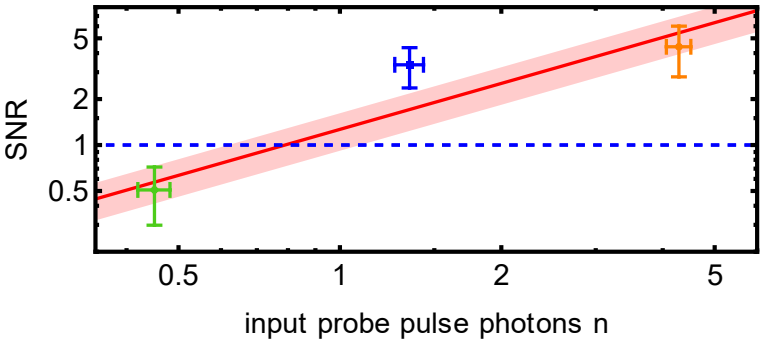

Figure 2: Signal-to-noise ratio (SNR) for different number of stored photons for a storage time of 1 s. The linear fit (red line) shows that we reach SNR = 1.3(3) for a single input photon.

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On the limits of Yb:YVO_4, a detailed study into qubit T_1 and T_2

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Future quantum networks will enable unprecedented applications, ranging from secure communication to quantum-sensor networks. Qubits based on single rare-earth ions (REIs) doped in crystals are promising candidates to act as nodes in such networks. Qubits can be encoded in the ions Zeeman or hyperfine levels, and optically connected excited states offer a qubit-photon interface at near-infrared wavelengths. Small computations can be run locally with the use of auxiliary qubits in the form of other spins in the host crystal. The complexity of the quantum circuits one can run on such networks is set by, among others, the qubit coherence (T_2), and ultimately the qubit lifetime (T_1). Hence, a good understanding of what is limiting the qubit T_2 and T_1 is crucial for the development of a suitable REI qubit platform.

Yb^{3+} in YVO_4 is an interesting platform. The vanadium nuclear spins in the host material provide a deterministic spin bath. And, at zero magnetic field, the ^{171}Yb isotope (I=1/2) forms electron-nuclear hybridized eigenstates, resulting in a qubit with long coherence time even in this dense nuclear spin bath due to first-order insensitivity to (local) magnetic fields. Previous work reported the spin coherence of ion to be $T_{s,\,echo}$ = 44 ± 2 us, $T_{2,\,CPMG}$ = 16.9±0.7 ms, and the spin lifetime to be T_1 = 54 ± 4 ms [1,2]. Given this performance, Yb:YVO_4 has been used for several proof-of-principle experiments, but towards more advanced networking experiments longer qubit coherence- and lifetimes are desired.

In our research, we investigate what limits the performance. We have eliminated several potential mechanisms to be the limiting factor of the qubit lifetime: 1) Yb-Yb spin flip-flops 2) Resonant interactions with other two-level systems 3) Phonon-mediated spins flips (as measured previously by J. Kindem, *unpublished*). Physically disconnecting the qubit from the control electronics, i.e. removing flat-band background noise using a switch, has improved the qubit lifetime up to a factor of 5. Ongoing work will focus on the effect of the nano-fabrication (FIB milling) and the proximity of the Yb ion to the surface of the crystal.

We have developed numerical simulations using a correlated-cluster expansion method to quantify the contribution of the dense vanadium nuclear spin bath on the spin coherence [3,4]. Concluding from this, the dense nuclear spin bath alone cannot explain the observed coherence times. Currently, we are extending the simulations to explore the effect of defects associated with an electron spin (V^{4+} defects). Again, the proximity of the Yb ion to the surface can result in interactions with surface charges and spins, and investigating this aspect is part of the ongoing work.

All in all, this work shines light on what could be the limiting factors for the spin lifetime and coherence of single Yb^{3+} ions in YVO_4. The methods used here are readily applicable to other platforms, and the insights obtained in this work may be generalized and help to improve other solid-state systems.

[1] J. M. Kindem, et. al., *Nature*, **580**, 7802, (2020)
[2] A. Ruskuc, et. al., *arXiv preprint* 2402.16224, (2024)
[3] W. Yang et. al., *Phys. Rev. B*, **78**, 8, (2008),
[4] M. Onizhuk et al., *Advanced Theory and Simulations*, **4**, 11, (2021)

Understanding optical and spin transitions of rare-earth antiferromagnets

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Rare-earth ions in solid-state crystals are a promising platform for quantum applications, owing to their long spin and optical coherence times. To date, a wide variety of quantum applications have been theoretically proposed and experimentally demonstrated such as quantum memories and transducers. Typically, such applications use low-spin host materials doped with rare-earth ions at about the 100 ppm level. Low concentrations reduce strain in the crystal, allowing the ions to retain low linewidths, and the low-spin host decreases magnetic field fluctuations in the ions' environment, which is a major cause of decoherence.

Stoichiometric rare-earth crystals intriguingly see many of the same benefits as doped systems. For example, sub-gigahertz linewidths have been observed [1]. A major reason is that the crystal is not distorted by dopants. Moreover, some of these fully concentrated rare-earth materials become magnetically ordered at low temperatures, which can further narrow linewidths; the ordering reduces magnetic fluctuations from neighboring spins. Unlike doped materials, stoichiometric rare-earth crystals gain much higher optical depths on their transitions. This can benefit processes such as quantum transduction, which can be limited by low optical depths. Despite such intriguing properties, their optical properties are not well understood. Hence, we explore fundamental spectroscopy on these materials to better understand their potential.

We will discuss the microwave and optical spectroscopy of some stoichiometric rare-earth crystals such as $NdGaO_3$, which is antiferromagnetically ordered below temperatures of about a kelvin. In Fig. 1, we can see absorption spectroscopy of Nd^{3+} ions next to an impurity. Selection rules allow us to identify the transitions of different sublattices of Nd^{3+} ions.

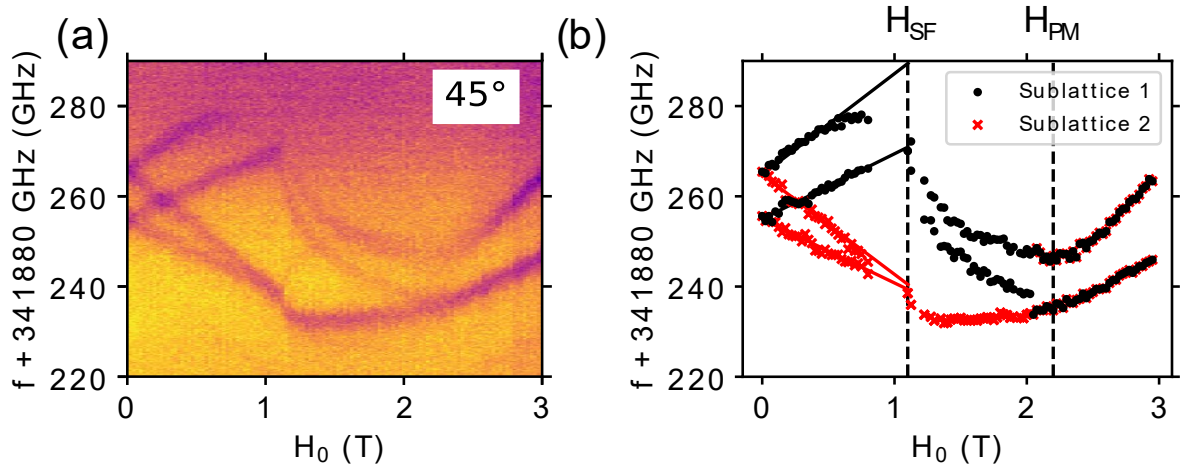

Figure 1: (a) Observed absorption strength of a satellite line of $NdGaO_3$, i.e. a Nd^{3+} ion next to an impurity, as we apply a magnetic field (H_0). (b) Identification of the absorption lines occurring due to two sublattices. The fields at which a phase transition to a spin-flop phase (H_{SF}) and paramagnetic phase (H_{PM}) occur are marked.

[1] M. C. Berrington et al., *Advanced Optical Materials*, **11**, 2301167 (2023)

Entanglement of spin-wave on-demand solid-state quantum memories for quantum repeater links

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Heralded entanglement of shared excitations between two remote matter nodes is a primitive for quantum repeater links. This type of architecture relies on quantum nodes consisting of sources of photon pairs and multimode quantum memories (QM). Entanglement is created by heralding at intermediate locations via the detection of a telecom photon, then stored in quantum memories and manipulated locally in real time. Some of the main requirements for practical quantum links are high heralding rates with photons at telecom wavelength and multiplexed operation. Most importantly, the ability to retrieve stored excitations on-demand is a crucial feature for synchronization of repeater links across a network.

In this talk, we report on recent progress towards remote entanglement of two on-demand solid-state quantum memories using cavity-enhanced non-degenerate spontaneous parametric down-conversion (cSPDC) sources and Pr^{3+} rare-earth doped QM. The sources emit entangled photon pairs with one idler photon in the telecom band and one signal photon at 606 nm, that is stored in a Pr^{3+} QM. Upon detection of an idler photon at one of the detectors of the central station, an entangled state is heralded at the memories. To verify entanglement, it is necessary to show that we operate in the single excitation regime and that the excitation is in a coherent superposition of the two memories.

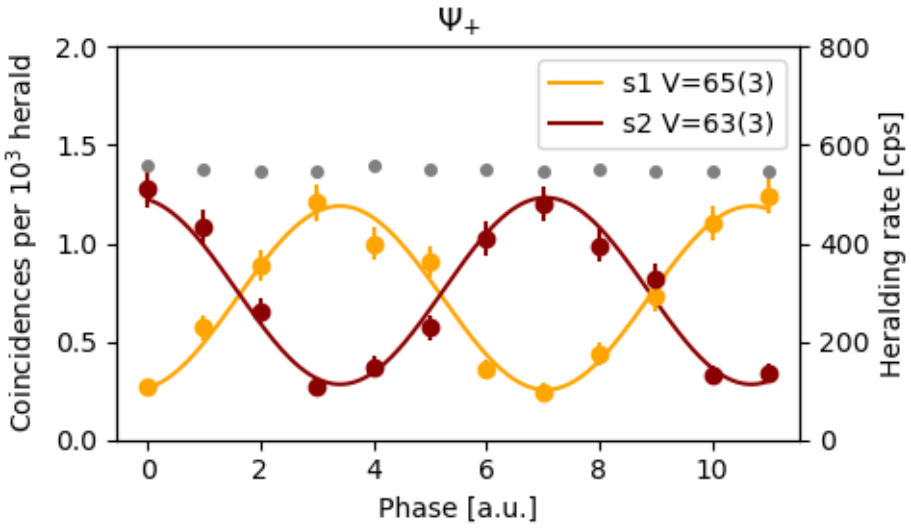

Figure 1: Fringes of interference produced by mixing the QM readout photonic modes. The visibilities of the fringes are V=65(3) for signal detector s1, and V=63(3) for signal detector s2. The heralding rate averages 550 cps.

By retrieving the excitations from the QMs and interfering the photons at a beam splitter, state tomography can be carried out. Figure 1 shows the conditional single-photon interference fringes measured at the signal detectors proving quantum coherence between the two spin-wave QM of Alice and Bob. The estimated concurrence of the detected heralded state is of $6(1)\cdot10^{-4}$

with single photon suppression $h_c = 0.24(2)$ and associated total heralding rate of around 550 cps indicating the successful heralding of a genuinely entangled state at high rate.

Together with the high multiplexing capability of Pr^{3+} QM, our system combines most requirements for efficient quantum repeater links thus paving the way towards real-world deployment of quantum networks.

Spectroscopy and coherent manipulation of REI-based organic molecular systems for quantum information applications

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Rare-earth-doped solid-state materials are attractive for the realisation of quantum registers given their long coherence together with electric dipole interactions that enable quantum gates. However, the low oscillator strengths present in such systems limits the ability to create efficient devices. Rare-earth-based organic molecular materials offer a solution to this problem through the ability to tailor the ligand-field in order to maximise the branching ratio of the transition of interest, whilst still maintaining the capability of forming high quality crystalline structures, which leads to long coherence times.

We report on the characterisation and manipulation of multiple europium-based molecular complexes. In particular, we further the work performed by [1] on $[Eu(Ba)_4(pip)]$ by achieving an optical coherence time of 2.5 µs at 4 K, in addition to measuring spin signatures and performing class preparation. Additionally, the binuclear organic complex $[Eu(btfa)_3]_2bpm$ [2] has shown a branching ratio (1.35%) e.g. double that of $Eu^{3+}:Y_2O_3$, a promising optical coherence time of 2.0 µs at 500 mK, and signatures of Eu-Eu interactions, which are required for the development of scalable, identical qubit gates. Furthermore, work has been performed on ytterbium-based molecular complexes to spectrally and temporally characterise such materials. These systems are of interest due to the high branching ratio of the transition of interest, in addition to the presence of zero-field ZEFOZ transitions, resulting in high spin coherence times.

Simultaneously, work is currently underway in order to integrate these molecular complexes into a fibre-based Fabry-Pérot microcavity, to increase the emission rate by the Purcell effect [3]. High quality single crystals grown from solution, in addition to the creation of homogenous thin films via sublimation, have been achieved on both DBR coated planar mirrors and fibres. Room temperature characterisation of these systems has been performed, showing the effects of dispersion and cavity-coupled emission.

[1] D. Serrano et al., Nature, **603**, 241 (2022)
[2] R. Ilmi et al., J. Mater. Chem. C, **8**, 9816 (2020)
[3] C. Deshmukh et al., Optica, **10**, 1339 (2023)

Spatial confinement of atomic excitation by composite pulses in a doped solid

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We experimentally demonstrate spatial confinement of atomic excitation by composite pulse sequences in Pr:YSO [1]. In particular, we implement several previously proposed sequences and compare their performance. We achieve population transfer that is spatially confined to an area significantly smaller than the diameter of the driving laser pulses. Our experimental data agree well with numerical simulations and confirm that the confinement improves with the number of pulses in the sequence. We find that inhomogeneous broadening in Pr:YSO reduces the performance of the sequences, i.e., leading to the formation of additional rings around the narrow centre. A theoretical treatment, confirmed by experiments, shows that the perturbing effect can be reduced by appropriate choice of experimental parameters. Our experiments prove that composite pulses are a versatile tool to localize atomic excitation, potentially also below the diffraction limit. Beyond media for quantum memories, the concepts are also of relevance to quantum computation, as further generalized composite sequences enable arbitrary quantum gate operations in precisely confined spatial regions.

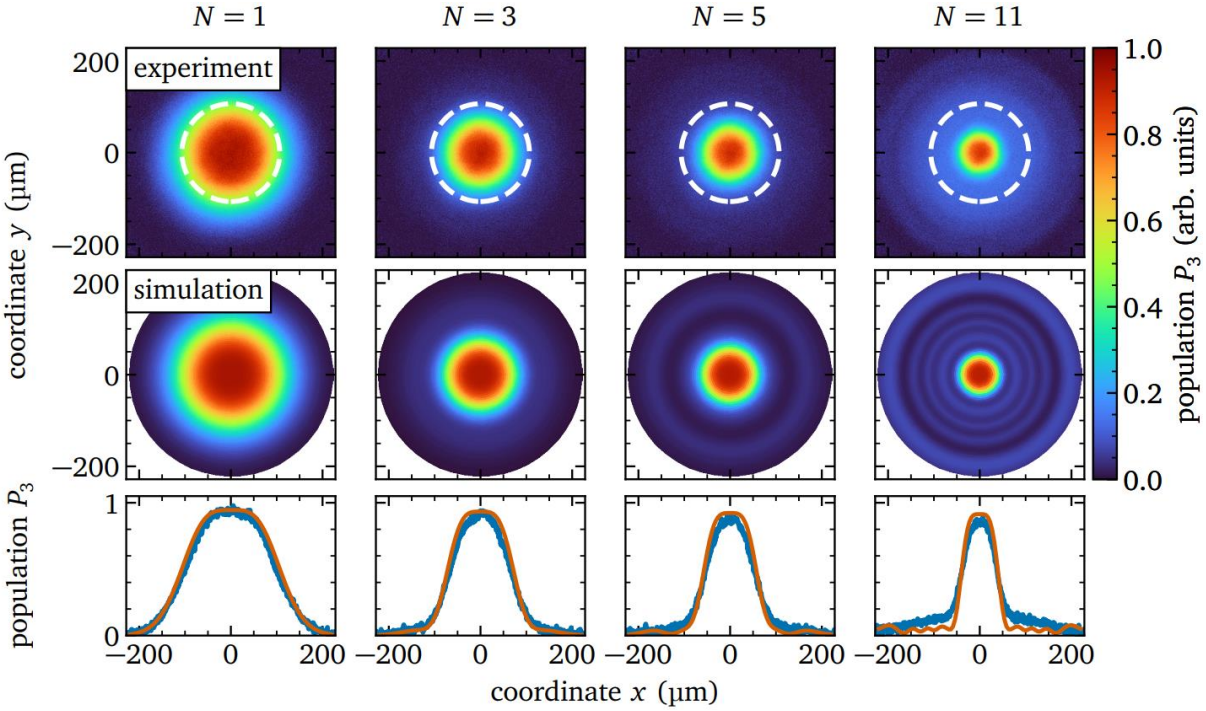

Figure 1: Narrowband composite pulse-driven localization in Pr:YSO using sequences optimized for inhomogeneously broadened media. Variation of the population $P_3(x, y)$ vs. coordinates x and y across the pump beam profile. (upper row) Experimental data for different numbers of pulses N. The white, dashed line indicates the diameter (FWHM) of the pump beam. (middle row) Numerical simulations. (lower row) Cuts through the experimental data (blue line) and simulation (orange line) at coordinate y = 0 [1].

[1] M. Stabel et al., Spatial confinement of atomic excitation by composite pulses in a doped solid, *Physical Review A*, submitted (2024)

Ridge architectures in Y_2SiO_5

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[2]*Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France*

We present here an integrated architecture designed to push the performances of quantum memories forward, particularly in REID Y_2SiO_5. To achieve this, we utilize ridge waveguide structures to effectively confine light and intensify the interaction between light and matter. We present the simulations that helped to determine the optimal waveguide dimensions, ensuring effective coupling to single-mode fibers. Additionally, a spectroscopic study has been performed to analyze the crystal properties when bonded to a silica substrate. This also provided an opportunity to evaluate the validity of the bonding, particularly at cryogenic temperatures.

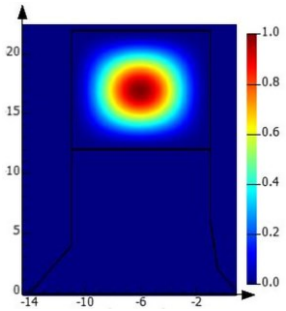

Figure 1: Simulated profile of the fundamental mode within the waveguide, demonstrating effective light confinement.

To manufacture the targeted architecture according to simulation outcomes, a ridge fabrication protocol has been developed utilizing readily available resources and ensuring reproducibility. This protocol, along with the resulting ridges, will be presented.

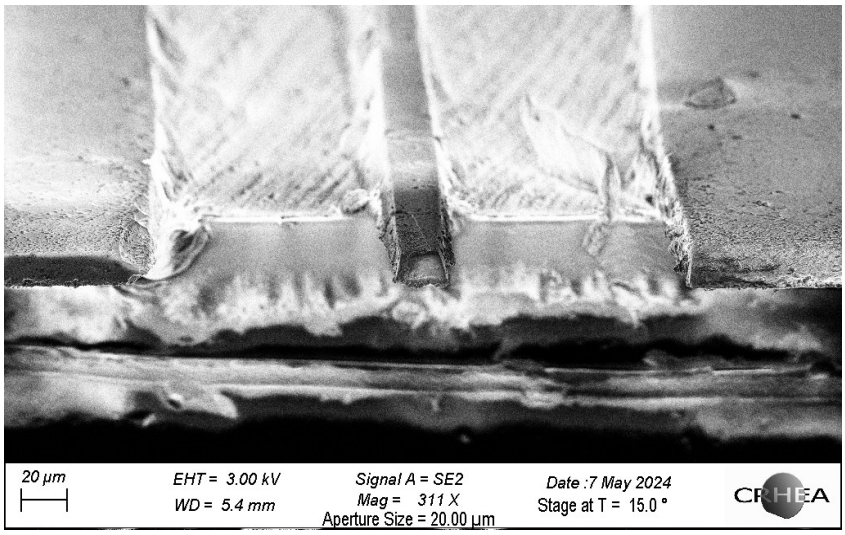

Figure 2: SEM image of the first fabricated ridge waveguides following the developed protocol.

From ground states to quantum gates: Phase control in rare-earth quantum systems

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[3]*Niels Bohr Institute, Copenhagen, Denmark*

The complex wave function, with its characteristic phase variation, fundamentally distinguishes quantum mechanics from classical mechanics. In the context of quantum computing, the ability to control the phase of a single-state component of a qubit is an elementary building block. This presentation explores the dynamics of phase control within qubits, particularly when using rare-earth crystals, which typically involve transitions between a ground state and an excited state.

I begin by discussing how to add a complex phase to the ground state of a two-level system [1]. I focus on the benefits and drawbacks of the Bloch sphere and how it can be complemented by examining the evolution of the complex ground state amplitude, as shown in figure 1. The added phase is often split into a geometric and a dynamic part, where there is an ongoing debate on an inherent robustness of the geometric part [2], and I will discuss why we believe such a robustness is unfounded [1].

Finally, I extend the analysis to three- and four-level systems and discuss how single- and multi-qubit gate operations can be implemented [1, 3]. I will also show how a rare-earth quantum computer can be run without any single-qubit operations, instead relying solely on two-qubit or multi-qubit operations [3].

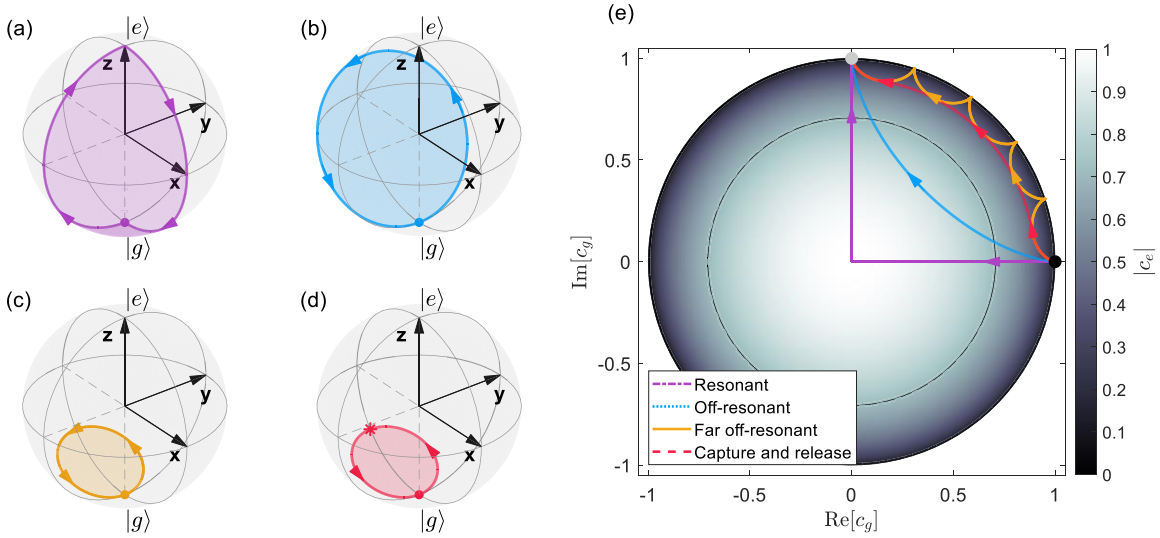

Figure 1: Shows the Bloch vector trajectory for four operations: (a) resonant drive, (b) off-resonant drive, (c) far off-resonant drive, and (d) capture and release of the energy eigenstate. All operations induce a phase $\theta = \pi/2$ on the ground state $|g\rangle$ (the trajectory in panel (c) is encircled 5 times). (e) Depicts the same operations in a complementary c_g-plot, which shows the real and the imaginary part of the complex amplitude c_g. The ground state population, $|c_g|^2$, is read from the figure as the square of the distance from the center of the disc (1 at the disc's edge, 1/2 at the dashed black circle, and 0 in the center). The color gradient indicates the amplitude of the excited state coefficient $|c_e|$. The phase θ is read as the angle between the initial (black dot) and the final (gray dot) state amplitudes.

[1] A. Kinos et al., *Physical Review A*, **105**, 062441 (2022)
[2] E. Sjöqvist, *International Journal of Quantum Chemistry*, **115**, 1311 (2015)
[3] A. Kinos et al., *Physical Review Research*, **5**, 013205 (2023)

In-situ Generation of High-Rate Photon-Memory Entanglement Using an Integrated Rare-Earth Photonic Device

Alexander Kolar[1], Ian Chin[1], Daniil Lukin[2], Mellisa Guidry[2], Milan Palei[1], Allen Zang[1], Yuzhou Chai[1], Jelena Vuckovic[2], Tian Zhong[1]
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[2]*E. L. Ginzton Laboratory, Stanford University, Stanford, CA, USA*

Generation and distribution of entanglement between quantum memory nodes is central for operating large-scale quantum networks. To enable generation of entanglement between information-transmitting photons and stationary quantum memories, two main methods are used. One method utilizes emissive quantum memories, based on individual photon-emitting atoms or ions. The other method utilizes **absorptive memories** paired with a **separate entanglement source**. While the emissive method generates deterministic entanglement with high efficiency, the absorptive method enables multi-mode, multiplexed operation that significantly enhances the generation rate. However, due to demanding impedance- and bandwidth-matching requirements between the photon source and memory, it remains an outstanding challenge to experimentally realize **high-rate photon-memory entanglement**. In this work, we develop a platform that enables **in-situ entanglement generation within an absorptive quantum memory**; this combines the advantages of both emissive and absorptive memories for photon-memory entanglement that is high-rate, high fidelity, and multi-mode.

Our platform is realized by **parametrically driving an optical cavity which simultaneously couples to an ensemble of rare-earth ions** in solids. The parametric drive produces pairs of non-degenerate cavity photons via spontaneous four-wave mixing, while one cavity mode spectrally overlaps with and transfers entanglement to an ensemble of rare-earth ions. This generation scheme leads to tripartite entanglement between the two photonic modes and the memory mode, effectively eliminating the loss and mismatch of coupling external photons to optical memories. Even after discarding one of the photonic modes, we find that resulting bi-partite photon-memory entanglement is still of **high fidelity** and is generated at a **high rate**.

Experimentally, we realize this in-situ generation using an **integrated SiC ring resonator** on **^{167}Er:Y_2SiO_5**. We first characterize the resonators, measuring high Q values up to **1.71 million** at C-band telecom wavelengths and a free spectral range of 167 GHz. We used this device to generate photon pairs with a pair generation rate of **8,700 pairs/s/mW** on-chip and a two-photon correlation time of 2 ns – corresponding to an entangled photon bandwidth of **171 MHz**. After observing the desired coupling between the resonator and the ion ensemble, we prepare an atomic frequency comb (AFC) within the inhomogeneously broadened linewidth of ^{167}Er:Y_2SiO_5 and show storage of an entangled photon with high efficiency. With expected AFC **storage of 1 µs and finesse of 3**, we estimate a memory heralding efficiency **greater than 50%** and a photon-memory entanglement rate in excess of **10 million** Ebits per second. For future experiments, we plan to deploy these systems over a long-distance fiber network, enabling remote memory-memory entanglement generation with extended storage times using long-lived hyperfine states of ^{167}Er. Additionally, we plan to explore potential multi-partite hybrid entanglement distribution for advanced distributed quantum information processing.

Seconds-Long Storage Times in an Erbium-Based Quantum Memory

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We are developing a telecom-wavelength quantum repeater with long range capabilities based on a memory using an $^{167}Er:Y_2SiO_5$ crystal. The memory protocol we are using is 4-level Rephased Amplified Spontaneous Emission (RASE) which serves as both an entanglement source and a quantum memory in the repeater. We operate on a 4-level system to generate telecom entangled pairs and utilise the long ground hyperfine coherence time for long-term storage [1].

In this talk, I will present the characterisation of spin-state storage in the inverted 4-level photon echo, which is identical to the RASE protocol with the addition of a weak coherent input pulse. By rephasing the ground hyperfine transition using radiofrequency π-pulses at ~800 MHz, we demonstrated a spin-state storage time of 3.7 s. The rephasing of the hyperfine transition was found to be 97% efficient with an overall photon echo efficiency of 15%.

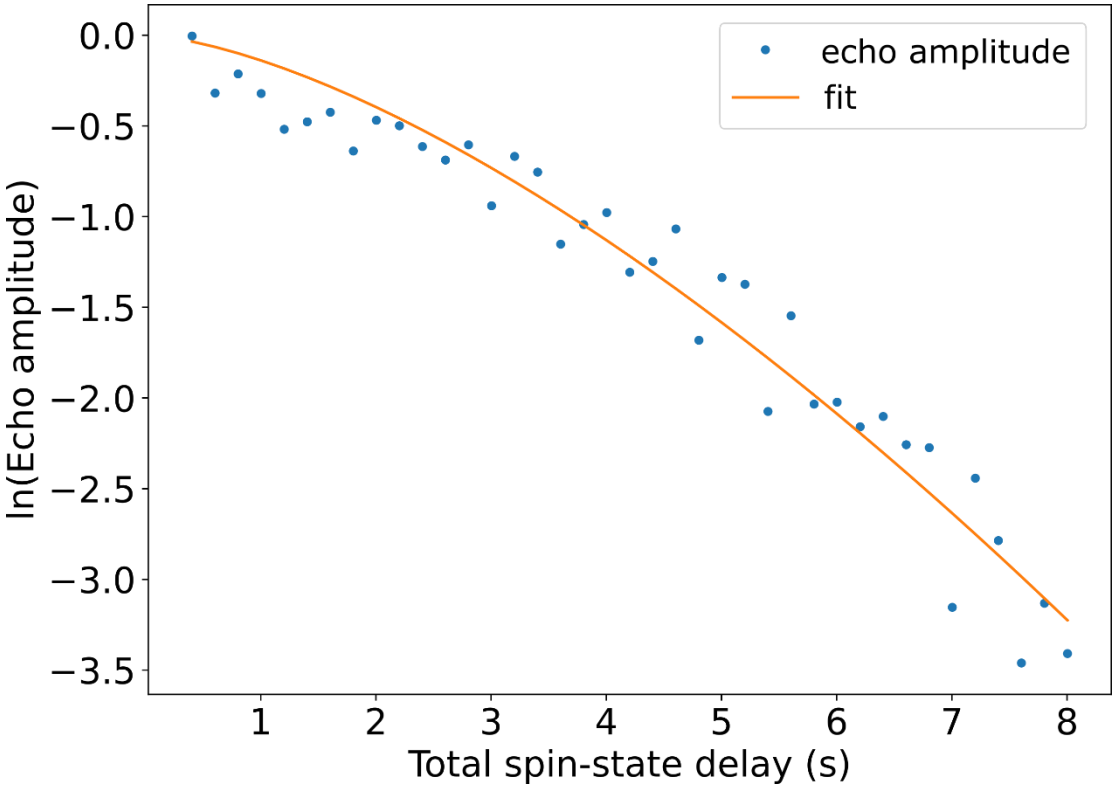

Figure 1: Amplitude of the hyperfine rephased inverted 4-level photon echo as the spin-state storage duration is extended.

[1] M. Rančić et al., *Nature Physics*, **14**., 50-54 (2018)

Reduction of Brownian Motion-Induced Frequency Noise through Slow Light Frequency Stabilization

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[3]*Princeton University, Princeton, USA*

Ultra-precise frequency-stabilized lasers are fundamental to modern metrology and are used as very precise oscillators in optical atomic clocks [1], space-based positioning [2], and tests of time variation of fundamental constants [3]. Frequency stabilization using Fabry Perot cavities relies on transforming the length stability of the cavity ($\Delta L/L$) into the frequency stability of the laser ($\Delta\nu/\nu$) by locking the lasers frequency to the cavity resonant frequency using a feedback system.

In 1999 a plateau in the attainable stability was reached [4], and in 2004 it was shown that the stability is consistent with the Brownian motion of atoms in the mirrors [5] resulting in cavity length fluctuations. By making the cavity longer it is possible to negate this effect as the relative frequency shift from any length fluctuation depends on the length of your cavity. However, it has proven difficult to increase the length *L* beyond a few tens of centimeters in current state of the art laser stabilization systems due to the difficulty of isolating vibrations.

Figure 1: Eu:YSO crystal with parallel flat mirrors on each end.

Using a highly dispersive Eu:YSO slow light crystal cavity (Fig. 1) the frequency stabilization of lasers could be significantly improved. This design leverages the unique optical properties of Eu:YSO to achieve a drastic reduction in the group velocity of light, effectively elongating the optical path length within the cavity [6]. This method inherently has the potential to lower the Brownian noise floor by a factor beyond 10^5, as group velocity reduction factors as large as 5×10^5 times has been achieved. The slow light effect is obtained by creating narrow spectral transmission windows in the absorption profile, causing strong dispersion.

Recent experiments have also demonstrated very narrow cavity modes at 3 kHz and Q-factors above 1×10^{11}, attributed to the large optical path length. Low mode drift is possible by locking to modes in the center of the transmission window. This results in symmetric window degradation, eliminating first-order frequency drift. The modes can be centered through an iterative process of burning transmission windows, measuring the mode offset to the center, and resetting the window using resonant magnetic fields targeting the hyperfine levels.

With a long cavity, narrow modes, and low drift, slow light frequency stabilization could offer a very low Brownian noise limited fractional frequency stability close to 10^{-17}, at an averaging time of 1 s.

[1] B. J. Bloom et al., *Nature*, **506.7486**, pp. 71–75 (2014).
[2] S. Schiller et al., *Nuclear Physics B - Proceedings Supplements*, **166**, pp. 300–302 (2007).
[3] T Rosenband et al., *Science (New York, N.Y.)*, **319.5871**, pp. 1808–1812 (2008).
[4] B. C. Young et al., *Physical Review Letters*, **82.19**, pp. 3799–3802 (1999).
[5] K. Numata et al., *Physical Review Letters*, **93.25**, pp. 1–4 (2004).
[6] S. Horvath et al., *New Journal of Physics*, **24.3**, pp. 1–13 (2022).

A millisecond integrated quantum memory for photonic qubits

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[2] *Anhui Province Key Laboratory of Quantum Network, University of Science and Technology of China, Hefei, China*
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[4] *Hefei National Laboratory, University of Science and Technology of China, Hefei, China*

Integrated quantum memories for photonics are essential for the construction of scalable quantum networks. However, the photonic storage lifetime of integrated quantum memories is currently limited to tens of microseconds, which falls short of the technical requirements for the practical implementation of quantum networks. In this study, we demonstrate an integrated quantum memory with a photon storage time of 1 ms, based on a laser-written optical waveguide fabricated in a $^{151}Eu^{3+}$:Y_2SiO_5 crystal. The spin decoherence of Eu^{3+} is overcome by applying a dynamic decoupling sequence with a coplanar waveguide electrode fabricated on the crystal surface. The storage fidelity of time-bin qubits encoded with single-photon-level inputs is 89.7 ± 1.5%.

Quantum storage of entangled photons at telecom wavelengths in a crystal

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The quantum internet -- in synergy with the internet that we use today -- promises an enabling platform for next-generation information processing, including exponentially speed-up distributed computation, secure communication, and high-precision metrology. The key ingredients for realizing such a global network are the distribution and storage of quantum entanglement. As ground-based quantum networks are likely to be based on existing fiber networks, telecom-wavelength entangled photons and corresponding quantum memories are of central interest.

Recently, $^{167}Er^{3+}$ ions have been identified as a promising candidate for an efficient, broadband quantum memory at telecom wavelength. However, to date, no storage of entangled photons, the crucial step of quantum memory using these promising ions, $^{167}Er^{3+}$, has been reported. Here, we demonstrate the storage and recall of the entangled state of two telecom photons generated from an integrated photonic chip based on a silicon nitride micro-ring resonator. Combining the natural narrow linewidth of the entangled photons and long storage time of $^{167}Er^{3+}$ ions, we achieve storage time of 1.936 μs, more than 387 times longer than in previous works. Successful storage of entanglement in the crystal is certified by a violation of an entanglement witness with more than 23 standard deviations (-0.234 ± 0.010) at 1.936 μs storage time.

Moreover, I will discuss our recent progress of nanophotonic integration using novel material platform, such as single-crystal erbium chloride silicate nanowire. These results pave the way for realizing quantum networks based on solid-state devices.

[1] Ming-Hao Jiang, Wenyi Xue, Qian He, Yu-Yang An, Xiaodong Zheng, Wen-Jie Xu, Yu-Bo Xie, Yanqing Lu, Shining Zhu, Xiao-song Ma, *Nat. Comm.* **14**, 6995 (2023)

Broadband electron spin resonance spectroscopy of Erbium ions in $CaWO_4$ with coplanar waveguides

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Hybrid systems comprising qubits and quantum memory units have been proposed to improve architecture in quantum processing units based on superconducting circuits [1]. In the microwave regime, rare-earth ions in single crystal host lattices, such as Er^{3+}:$CaWO_4$, are suitable quantum memory candidates. Due to the hyperfine coupling as well as quadrupolar interaction between the nuclear spin of the ^{167}Er isotope and its electronic spin, these systems exhibit a rich microwave spectrum in the frequency range between 0-4 GHz (Figure 1). The mixed-level structure exhibits ZEFOZ (Zero First Order Zeeman shift) transitions, where the longest coherence times are expected due to their first-order insensitivity to fluctuations of external magnetic fields [2]. Here, we present ESR measurements recorded at temperatures below 10 mK using a superconducting coplanar waveguide. The broadband microwave spectroscopy allows the reconstruction of the full Hamiltonian including the quantification of the coupling strengths. The saturation recovery measurements show spin state lifetimes (T_1 times) in the range of seconds to several minutes.

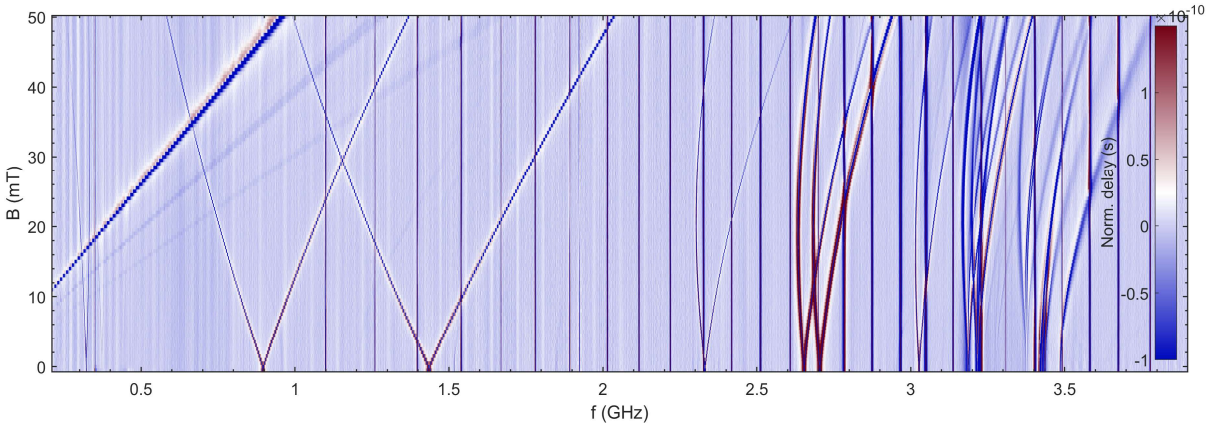

Figure 1: Broadband ESR spectroscopy in the low magnetic field regime reveals the hyperfine transitions of the ground state of Er^{3+}:$CaWO_4$.

[1] É. Gouzien et al., *Phys. Rev. Lett.* **127**, 140503 (2021)
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Microwave spectroscopy of the Ho^{3+} ground state hyperfine structure in Ho:YLF

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The strong hyperfine interaction in Ho^{3+} ions plays an important role in many quantum phenomena that draw interest in the $LiY_{1-x}Ho_xF_4$ dilution series [1-9].
In Fully concentrated $LiHoF_4$ the hybridization of electronic and nuclear spins alters the nature of its quantum phase transition [1]. In the dilute limit, the anticrossings between hyperfine levels allow thermally activated quantum tunneling leading to staircase-like magnetization curves [2]. We directly observed nuclear spin transitions between the ground state hyperfine levels in a longitudinal field using a broadband electron spin resonance (ESR) approach. The field dependence of the observed gaps can be ascribed to mixing with higher crystal field levels and nuclear Zeeman interaction. Using cavity-magnon-polariton technique [10] we also identified electronic spin flipping transitions within the electronic ground state doublet.

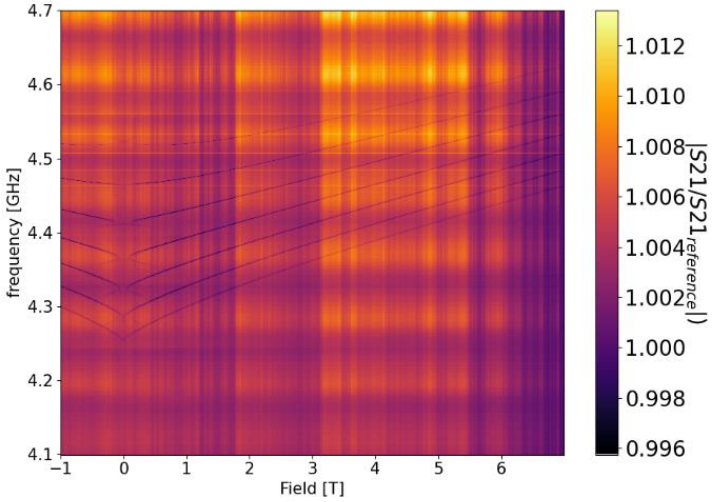

Figure 1: Nuclear spin transitions lines in a longitudinal field observed via broadband ESR-like measurement

[1] H. M. Rønnow et al., *Science*, **308**, 5720 (2005).
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[5] J. Brooke, et al., *Nature (London)*, **413**, 610 (2001).
[6] D. M. Silevitch, et al., *Nature (London)*, **448**, 567 (2007).
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[8] S. Ghosh, et al., *Science*, **296**, 2195 (2002).
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Microcavity-enhanced quantum memory with high efficiency and multiplexing

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Quantum memories (QMs) are fundamental building blocks for long-distance quantum communication and distributed quantum computing. The implementation of large-scale quantum network requires integrated QMs. Rare-earth-ion doped crystals (REICs) have shown ultra-long memory times, large bandwidth, and large multimode capacities. One-hour coherent optical memory [1] and a multiplexed quantum repeater [2] have been demonstrated in our laboratory. The inherently weak light absorption property of REICs poses a significant challenge in achieving high-efficiency quantum memory. Macroscopic cavities have been employed to enhance the light-matter interactions. However, this approach hinders the bandwidth and the integrated application of quantum memories.

Here we demonstrate a highly efficient and multiplexed quantum memory by utilizing a fiber-based microcavity and implementing the cavity-enhanced atomic frequency comb protocol. We stored time-bin qubits based on Eu:YSO with an average efficiency of 73.2% ± 0.5%, providing a new way for integrated quantum memories with both high efficiency and multiplexing.

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[3] M. Hedges, J. Longdell, Y. Li, et al. *Nature* **465**, 1052-1056 (2010).

Fluorescence detected photon echoes in Er^{3+}:Y_2SiO_5

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Measuring narrow homogeneous linewidths is key to understand quantum states dynamics and useful for various quantum applications. Photon echo is a robust and easy to implement technique that helps understanding the dephasing dynamics of emitters on different timescales [1].

Photon echo spectroscopy is typically implemented using ensembles of emitters in solids. It consists in a sequence of laser pulses that eliminates the dephasing due to inhomogeneous broadening and gives access to the other mechanisms affecting the optical phases such as magnetic noise. One limitation of this method is that the intensity of the echo becomes very weak for a low number of emitters. Indeed, in this case, the echo emission represents only a small fraction of the total excitation of the system. Such shortcomings can be addressed using optical resonators or waveguides, which are however complex to implement [2]. In this presentation, however, we will describe an easy way to implement a method to retrieve efficiently the information contained in the echo in systems with low numbers of emitters.

If, at the time of the photon echo rephasing, the optical coherence can be converted into the population of the excited state by adding a third optical pulse, it can lead to a much stronger fluorescence emission. The latter is expected to contain the photon echo information [3].

To devise the fluorescence detection of photon echoes, we envisage a confocal microscopy setup where the sample to study is held inside a cryogenic platform at 3K. For this proof of concept, we study a 500 µm thin slice of Er^{3+} in Y_2SiO_5 host matrix crystal with 10 ppm concentration.

Fluorescence detection of photon echoes could provide a viable tool to study materials with a low number of emitters and characterizing their coherent properties. This would be especially useful to study rare earth doped nano-materials, like nanoparticles, thin films, or implanted bulk crystals that are actively investigated for quantum communication and computing [4] [5] [6]

[1] P. Goldner et al., *Handbook on Physics and Chemistry of Rare Earths*, **46**, 1-78 (2015)
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[3] E. Billaud et al., *Phys. Rev. Lett.*, **131**, 100804 (2023)
[4] A. Ruskuc et al., *Nature*, **602**, 7897 (2022)
[5] S. Ourari et al., *Nature*, **620**, 7976 (2023)
[6] C. Deshmukh et al., *Optica*, **10**, 1339-1344 (2023)

Spectroscopic Investigations of Eu^{3+} ions in $EuCl_3 \cdot 6H_2O$ Doped with Er^{3+} ions

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Rare-earth ions(REI) in solids are promising candidates for a variety of quantum information processing technologies thanks to long coherence time [1-3]. By substituting host ions in a stoichiometric crystals, the rare-earth ions surrounding the dopant as an addressable ensemble spin cluster system also have been proposed to build small quantum processors [4]. However, few information about optical coherence of ions in satellite lines have shown so far. Here, we present the spectroscopic investigations Eu^{3+} ions in a Er^{3+} ions doped $EuCl_3 \cdot 6H_2O$ single crystals at different temperatures. At sub-Kelvin regime, doping does not influence the coherence of surrounding ions. But at temperature >2K, we observed obvious decoherence of Eu^{3+} ions caused by the doped Er^{3+} ions, including 1)a rapid increase of homogeneous linewidth due to a strong orbach spin relaxation of Er^{3+} ions, 2)an abnormal temperature dependence for some Eu^{3+} ions at 2~4K[5]. Following the results of stimulated photon echoes, obvious echo modulation suggest that there are strong ion-ion interactions between Er^{3+}-Eu^{3+} ions pairs. By directly exciting the Er^{3+} ion with cw laser and a laser pulse, we observed strong echo demolition and instantaneous spectral diffusion. It imply the possibility to use the double species REI system in quantum control. These results illustrate the utility of satellite lines in stoichiometric crystal as photonic quantum technologies platform.

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[2] C. Thiel et al., J. Lumin. 131, 353 (2011).
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[5]N. Kunkel, et al., Phys. Rev. B 94(18), 184301(2016)

Using single Er^{3+} ions to sense and manipulate the nuclear spin environment

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We study the interaction of single Er^{3+} ions in a $CaWO_4$ crystal with the nuclear spins of adjacent ^{183}W atoms. The Er^{3+} ions are detected via their electron spin transition, which occurs at a frequency of 7.5 GHz in a magnetic field of 0.46 T. This transition couples to the magnetic near-field around the sub-µm constriction of a superconducting microwave plasmonic resonator (Figure 1) [2], which shortens the excited-state lifetime to less than 1 ms. The emitted photons are detected by a microwave photon counter based on a superconducting qubit [2]. We have previously demonstrated the capability to spectrally resolve single Er^{3+} ions, revealing lifetime-limited coherence times [3].

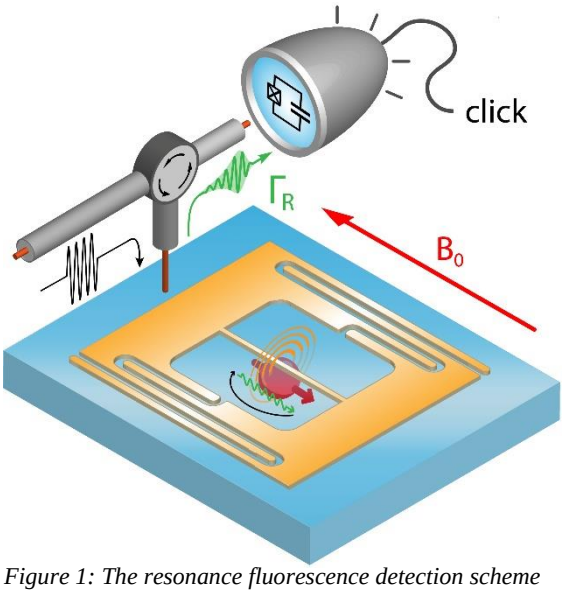

Figure 1: The resonance fluorescence detection scheme

More recently, we have detected discrete jumps in the resonance frequency of individual Er^{3+} ions due to spin-flips of nearby nuclear-spin-½ systems ^{183}W. This provides a single-shot non-demolition readout channel for the nuclear spin state. The electron-spin nuclear-spin interaction can be used to initialize the nuclear spin and apply quantum gates to it within a few milliseconds – much shorter than the nuclear spin coherence time of more than 1 s. Furthermore, we present Er^{3+}-mediated gates between two nuclear spins.

Having demonstrated state initialization as well as one- and two-qubit gates, this platform is highly promising for quantum information processing. In addition, since the methods of spin manipulation and readout are not limited to Er:$CaWO_4$, we are planning to employ them on various paramagnetic systems with the final goal of being able to reconstruct the structure of molecules by mapping the locations of all their nuclear spins.

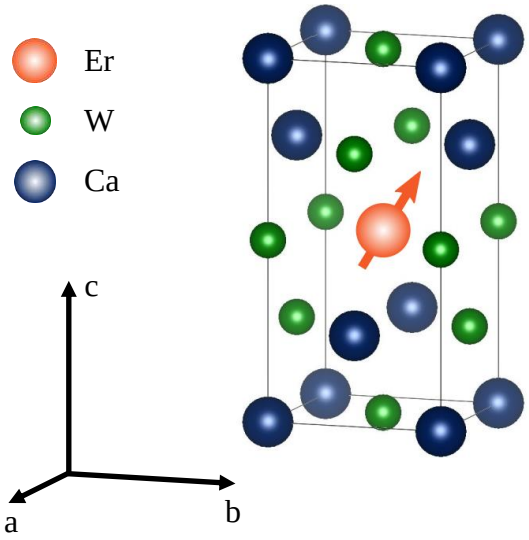

Figure 2: The unit cell of $CaWO_4$ with the central Ca ion replaced by an Er ion. O is omitted for clarity.

[1] A. Bienfait et al., *Nature*, **531**, 74-77 (2016)
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Sub-kHz optical homogenous linewidth in Eu^{3+}:Y_2O_3 ceramics

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Eu^{3+} doped Y_2O_3 transparent ceramics had been demonstrated the promising coherence properties[1], and also have the advantages of high transparency, easy and fast growth, stable chemical properties, which is of great potential for quantum information processing [2-4]. However, an in-depth study on quantum coherence properties of Eu^{3+}: Y_2O_3 ceramics will allow a possible of coherence time extension. Here, a comprehensive quantum coherence property characterization is carried out in Eu^{3+}: Y_2O_3 ceramics with three different concentrations (120 ppm, 200 ppm, 1000 ppm). A narrow optical homogenous linewidth ~ 750 Hz is measured in a 1000 ppm sample at 80 mK, and the ground-state energy level lifetime 30.4 h at 6.5 K is observed in a 120 ppm sample. Addtionanlly, a decrease in the optical homogenous linewidth in all of the samples with decreasing temperature (< 2 K). Thus the decoherence caused by charge defects [5] is also discussed. We also performed three-pulse photon echo measurements, the results of which show no obvious spectral diffusion at 80 mK. This work demonstrates the favourable quantum properties of Eu^{3+}: Y_2O_3 ceramics, providing an experimental basis for their application of quantum information processing.

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[2] A.F., et al., Physical Review B, **87(4)**, 041102, (2013).
[3] Nathalie, K., et al., J. Phys. Chem. C **120**, 13725–13731 (2016).
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Characterization of the spin and crystal field Hamiltonian for erbium in silicon

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[1] *Max-Planck-Institute of Quantum Optics, Quantum Networks Group, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany*
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The coupling of coherent emitter to low-loss photonic circuits is a key technology for scalable quantum networking. Direct integration of erbium dopants into a silicon matrix is a promising approach, combining the coherent emission of erbium in the telecom C-band with the highly advanced wafer-scale nanofabrication technology available for silicon. In recent studies, we have investigated two distinct sites in the silicon lattice in which erbium can be reproducibly integrated with particularly promising properties [1, 2]. In our most recent work, we now expand our understanding of these sites by an in-depth study of their magnetic interaction. Resonant fluorescence spectroscopy in a rotating magnetic field allows us to determine the point symmetry of both sites. For one of the sites, we are able to fit the spin Hamiltonians of two Kramers' doublets as well as a partial crystal field Hamiltonian, describing mixing within the 15/2 and 13/2 J-multiplets. The derived Hamiltonians and symmetries will not only help to predict physical quantities of the system, allowing for a more intentional design in future experiments, but also constitute a key step towards a better microscopic understanding of the doping sites. This, in turn, may pave the way for improved, high-yield implantation and annealing procedures and, thus, a high-performing nanophotonic quantum platform based on the Er:Si platform.

[1] A. Gritsch et al., *Physical Review X*, **12(4)**, (2022)
[2] S. Rinner et al., *Nanophotonics*, **12(17)**, (2023)

Towards microwave-to-telecom transduction based on Erbium crystals

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[2]*Max-Planck-Institute of Quantum Optics, 85748 Garching, Germany*

The development of a device capable of converting microwave photons to optical photons at telecommunication wavelengths would be a key enabler for the communication between remote quantum computers.

Erbium ensembles are promising materials in this context, as they exhibit both microwave and telecom transitions, making them effective as a nonlinear medium for an efficient Raman conversion process. We are exploring two distinct systems on different platforms: First, we explore stoichiometric crystals, in which erbium is integrated as part of the lattice and not as a defect. This results in a high concentration of erbium spins without compromising the inhomogeneous broadening. At temperatures below 0.1 - 4 K, these crystals exhibit long-range order, typically antiferromagnetic, and display magnon modes that can be used for transduction [1]. However, the spectroscopy of these materials is still at an early stage. Second, we investigate crystals with a low concentration of erbium dopants that are well-understood and can have well-suited optical and microwave properties for efficient transduction [2, 3]. To this end, we plan to integrate the crystals into resonators with high quality factor for both optical [4] and microwave [5] transitions. Compared to recent efforts that have achieved efficiencies of approximately 10^{-5}[5], we study which improvements can be expected from higher-Q resonators and different host crystals. The goal is to achieve transduction efficiencies approaching unity with a high bandwidth of several MHz, paving the way for the entanglement of remote superconducting qubits.

[1] Jonathan R. Everts et al., *Phys. Rev. A 99,* 063830 (2019)
[2] Christopher O'Brien et al., *Phys. Rev. Lett. 113, 063603* (2014)
[3] Lewis A. Williamson et al., *Phys. Rev. Lett. 113, 203601* (2014)
[4] Benjamin Merkel et al., *Phys. Rev. X 10, 041025* (2020)
[5] Xavier Fernandez-Gonzalvo et al., *Phys. Rev. A 100, 033807* (2017)

Long optical coherence in $LaPO_4:Eu^{3+}$ crystals

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Recent demonstrations of long optical and spin coherence times in oxide nanoparticles doped with rare earth ions [1,2] have opened the way to new functionalities for these nanomaterials, including single rare-earth ion addressing by coupling them to tunable fiber cavities [3,4].

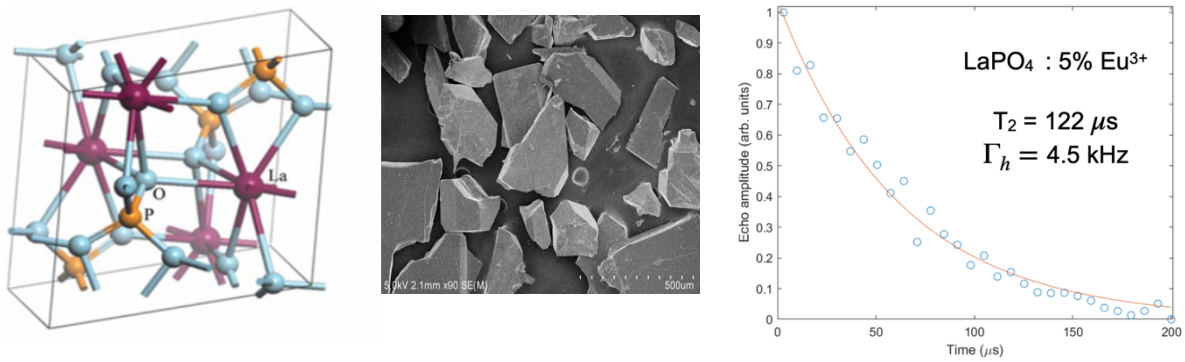

Figure 1: Left - $LaPO_4$ crystal lattice (monazite). Center – SEM image of $LaPO_4$:5%Eu^{3+} single crystals obtained by flux method. Right -Photon echo decay for the $^5D_0 \leftrightarrow {}^7F_0$ transition of Eu^{3+} at 578.63 nm in $LaPO_4$:5%Eu^{3+} microcrystals yielding an optical coherence time of 122 μs. T = 1.3 K

In the present work we introduce a new family of rare-earth crystals in view of their use for quantum technologies applications: the phosphates. We synthesized a series of $LaPO_4$: x%Eu^{3+} microcrystalline powders with x varying from 1 to 100 ($EuPO_4$) and characterized their structural (Figure 1 – left and center) and optical properties. Millimetric size bulk crystals of $LaPO_4$ doped with 5% Eu^{3+} (Figure 2 - center) were also fabricated and characterized. Optical coherence times (T_2) (Figure 1 right) were assessed for all Eu^{3+} concentrations, reaching a best value of 122 μs at 1.3 K. Similar temperature dependence for the optical coherence was observed for the bulk sample and the microcrystalline powder, as well as comparable spin population lifetimes (T_1). Strategies for obtaining these materials at the nanoscale with preserved optical coherence properties will be presented along with the first experimental results.

[1] J. Bartholomew et al., Nano Letters **17**, 778 (2017).
[2] D. Serrano et al., Nat. Commun. **9**, 2127 (2018).
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[4] C. Deshmukh et al. Optica **10,** 1339 (2023)

Entanglement Between a Telecom Photon and a Broadband and Multimode $^{171}Yb^{3+}:Y_2SiO_5$ Quantum Memory

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Quantum repeaters containing quantum memories are a required component of quantum networks aiming to communicate over long distances. These quantum memories are also required to be multi-mode to increase the speed of quantum communication [1]. We use ytterbium-doped Y_2SiO_5 crystals, which have clock transitions at zero magnetic field, and an atomic frequency comb (AFC) quantum memory to store a large number of temporal modes in the quantum regime. Previously, we showed storage of non-classical correlations of 1250 temporal modes over 100 MHz bandwidth with 25 us of programmed storage time [2]. With modifications to the optical pumping scheme in use for the preparation of the AFC, the bandwidth of the memory can be increased up to 288 MHz. We have also been able to significantly increase the storage time of the fixed-delay AFC echo memory, by stabilizing the AFC creation laser to a high-finesse ultra-low expansion (ULE) optical cavity, allowing us to increase the storage time to 125 us. We have also made changes to the AFC method, allowing more efficient spectral hole burning over a large bandwidth, a key requirement for creating AFCs with tens of thousands of teeth (AFC multimode capacity is $N_t = N_{teeth}/2.5$ [3]). Furthermore, the spontaneous parametric down-conversion (SPDC) source was also optimized with changes made to the filtering system, and superconducting nanowire single-photon detector (SNSPD) were installed at 980 nm. With this new setup, we store 10'000 time-bin modes and show non-classical correlations with telecom photons sent over 25 km of fiber. We also demonstrate the preservation of time-energy entanglement of 2000 modes after 25 us of storage time with an S parameter of 2.33(11).

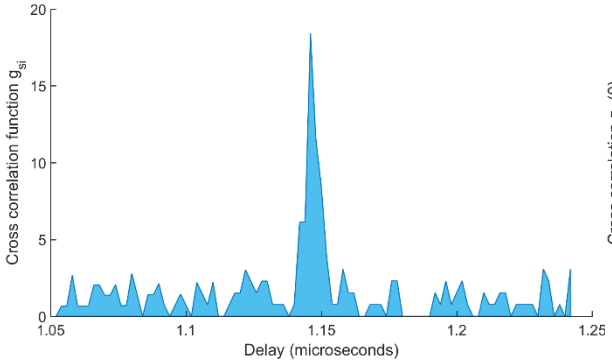

Figure 1: Cross correlation function g_{si} with a 12.5 ns mode size of a memory photon stored for 125 us and a telecom photon sent through 25 km of optical fiber.

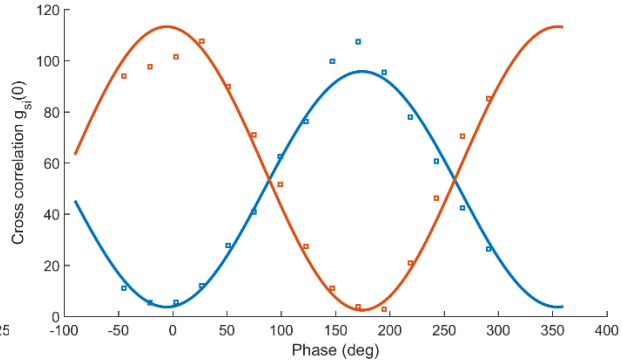

Figure 2: Visibility measurement done with at a storage time of 25 us and a mode size of 12.5 ns. Average visibility is 94.4 %. A fiber-based interferometer was used for the telecom photon and a double-AFC was used for the memory photon

[1] Simon et al. Quantum Repeaters with Photon Pair Sources and Multimode Memories. *PRL* **98**, 190503 (2007)

[2] Businger et al. Non-classical correlations over 1250 modes between telecom photons and 979-nm photons stored in $^{171}Yb^{3+}:Y_2SiO_5$. *Nat Commun* **13**, 6438 (2022)

[3] Ortu et al. Multimode capacity of atomic-frequency comb quantum memories. *Quantum Sci Technol* **7,** 035024 (2022)

Spectral hole burning for characterizing erbium ensembles in commercial silicon waveguides

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The integration of optically addressable coherent spins within silicon nanophotonic structures promises the acceleration of quantum technologies based on solid state spins via the advanced commercial nanofabrication possibilities for silicon. The reliable integration of coherent erbium emitters within commercial nanophotonic silicon waveguides demonstrated in our group [1] promises a scalable on-chip spin-photon interface in the telecommunication regime. While the erbium dopants show advantageous spectral properties such as narrow homogeneous and inhomogeneous linewidths [2] at cryogenic temperatures, we further characterize the properties of these new sites to estimate control possibilities as well as noise susceptibility to electric and magnetic fields.

We characterize the lifetime of the erbium electronic spin in an ensemble measurement using spectral hole burning at various temperatures and magnetic fields. We find a lower bound of 1~s for the spin lifetime at temperatures below 4.5 K and observe an Orbach-type decay at higher temperatures as shown in Fig. 1. At higher magnetic fields, we also find the signature of spin relaxation via direct phonon processes.

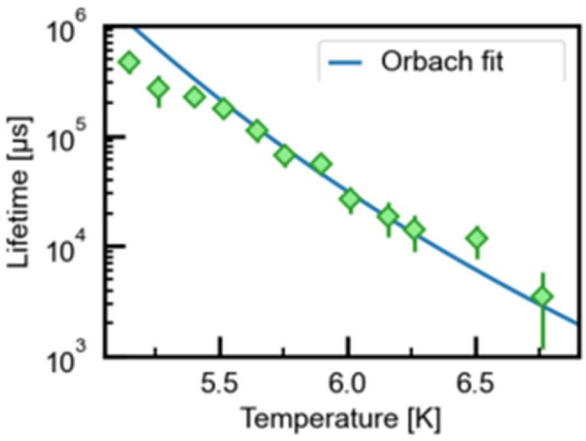

Figure 1: The lifetime of the electronic spin of erbium doped in commercial silicon nanophotonic waveguides is measured at various cryogenic temperatures. The values are extracted from spectral hole burning measurement of the erbium ensemble within the waveguide. The decrease of the lifetime fits well to a model considering phononic Orbach relaxation processes.

To understand the electric properties of the erbium sites, the waveguides are included in a p/n-diode structure that creates a transversal electric field across the waveguide. The differently doped zones of the diode are connected to an external voltage supply and we measure the emitter frequency shifts in reverse bias mode. In addition, the current-voltage curve of the diode is indirectly measured via photon emission into the waveguide in forward bias operation.

The demonstration of frequency shifts induced by electrical control fields applied on-chip next to the erbium ensembles promises the combination of advanced electrical control of silicon nanostructures with optically interfaced quantum emitters [3,4] for quantum network applications.

[1] S. Rinner et al., *Nanophotonics*, **12**., 3455 (2023)
[2] A. Gritsch et al., *Physical Review X*, **12**., 041009 (2022)
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Building blocks for rapid characterization of Erbium^{3+} ions

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Erbium (Er^{3+}) ion-doped yttrium orthosilicate (YSO) crystals, combined with silicon waveguides, have demonstrated significant potential for quantum memory applications [1]. Other host materials, such as yttrium vanadate (YVO) and calcium tungstate (CaWO), also show promise as efficient platforms for quantum memories [2] and microwave-to-optical transduction [3,4].

Here, we present innovative fabrication techniques designed to streamline the characterization of various on-chip coupling strategies for Er^{3+} ions across different host materials. A stamping transfer process [5] for silicon waveguides allows rapid prototyping on standard silicon wafers. Utilizing a PDMS stamp with a precision stacker, commonly used for 2D material transfer, we efficiently transfer silicon waveguide structures. Combined with inverse design grating couplers [6], this method enables fast characterization of different platforms. These grating couplers, designed for simultaneous transfer with waveguides, are arranged in arrays held together by a transfer structure.

Additionally, we introduce a macroscopic microwave split-ring resonator cavity, fabricated on a printed circuit board, for Er^{3+} spin control. This cavity, optimized for a second harmonic resonance frequency of 5.236 GHz with a full-width half-maximum of 24.08 MHz, achieves a measured quality factor of 217. The design allows for rapid modifications to accommodate different host materials and manage restricted cryostat space, as well as varying sample dimensions and orientations.

The integration of on-chip photonics enables the investigation of quantum memory applications using photonic crystal cavities. Combined with the microwave resonator, we can explore spin control and transduction [7], advancing the capabilities for quantum technologies.

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Anomalous sub-kelvin thermal frequency shifts of ultra narrow-linewidth solid state emitters

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We report our investigations of behavior of ultra-narrow spectral holes within a doped crystal structure (Eu:YSO). We have investigated how to artificially engineer a crystal environment at 4 Kelvin in which the spectral hole becomes insensitive (to first order) to temperature fluctuations [1]. However, due to their significant anticipated decrease in the frequency response to temperature fluctuations as the temperature drops, the operation of systems at sub-1 kelvin temperatures becomes particularly compelling for applications requiring high frequency stability. Our findings show that at these low temperatures, we can achieve spectral holes with discriminator phase slopes— the critical parameter for frequency locking — that are remarkably high for this type of system, setting a new standard. We also uncover a specific temperature regime where the response to temperature fluctuations deviates from the expected two-phonon Raman scattering theory. Specifically, around 290 mK, we observe a behavior indicating a temperature-induced frequency shift of zero to first order, surpassing expectations based on the current theory. Operating the crystal for the stabilization scheme at this temperature renders the spectral hole frequency highly immune to temperature fluctuations. Consequently, the fractional frequency instability of the laser, if solely influenced by temperature fluctuations, could be as low as 2.10^{-22} at 1s, and therefore ceases to be a limiting factor for any practical applications [2].

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Characterization of hyperfine transitions of rare earth spin ensembles via broadband ESR spectroscopy

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Rare earth spin ensembles possess hyperfine transitions at microwave frequencies making them attractive candidates for realizing microwave quantum memories [1]. They can further exhibit zero first-order Zeeman (ZEFOZ) transitions with a reduced sensitivity to magnetic field fluctuations yielding enhanced coherence times [2]. A precise knowledge of the spin Hamiltonian parameters allows for an accurate simulation of ZEFOZ transitions. In this work, we study the hyperfine transitions in ^{167}Er:^{7}LiYF$_4$ single crystals via broadband electron spin resonance (ESR) spectroscopy utilizing a superconducting coplanar waveguide in a magnetic field range from 0 mT to 50 mT.

The ESR spectra are obtained at 10 mK for different magnetic field ($\boldsymbol{B_0}$) orientations with regard to the crystalline *c*-axis, i.e. $\boldsymbol{B_0} \parallel c$ and $\boldsymbol{B_0} \perp c$. The utilized setup is schematically shown in Figure 1 [3, 4]. The recorded spectra allow for quantifying the parameters of the effective spin Hamiltonian, $\mathcal{H}_{eff} = \mathcal{H}_{EZ} + \mathcal{H}_{HF} + \mathcal{H}_{Q} - \mathcal{H}_{NZ}$ which includes the electron Zeeman ($\mathcal{H}_{EZ}$), hyperfine ($\mathcal{H}_{HF}$), quadrupole ($\mathcal{H}_{Q}$) and nuclear Zeeman ($\mathcal{H}_{NZ}$) interaction. We fit the measured spectra to the effective spin Hamiltonian yielding refined parameters and find good agreement between the measured and simulated transition frequencies. The true broadband nature of the measurement technique allows, furthermore, for characterizing the various hyperfine transitions in terms of their magnetic field dependence of the linewidth and power saturation behavior.

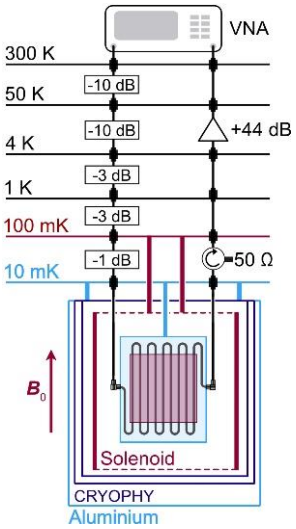

Figure 1: Broadband ESR spectroscopy setup.

In conclusion, we utilize a broadband ESR spectroscopy approach to probe the hyperfine transitions in ^{167}Er:^{7}LiYF$_4$ crystals and analyze the magnetic field dependence of the linewidth as well as the saturation behavior.

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Spatially-multiplexed solid-state quantum memory

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A long-distance quantum network requires quantum repeaters dispersed between the end-nodes and entanglement to be distributed across the network [1]. Successful entanglement events are heralded by detections at intermediate stations placed between the nodes. However, in a sequence of entangling attempts, the repeater nodes must wait for the heralding signal to return from the intermediate station before the next attempt [2]. At intercity distances, the entangling rate consequently may be limited by the time of the photon travel and the classical communication. Quantum repeaters based on rare-earth-doped crystals overcome this limitation, as the atomic frequency comb protocol [3] preparing these memories allows for temporal multiplexing, leading to a linear increase in the entanglement rate with the number of modes [3-4]. The entanglement rate is further increased by combining temporal multiplexing with spatial and frequency multiplexing.

In this poster, I will present experiments on quantum storage in a novel spatially-multiplexed solid-state memory array. We use acousto-optical deflectors to store and manipulate ten individual memory cells. We characterize the efficiency of the array, determine the cross-talk between the cells, and demonstrate on-demand storage at the single-photon level in 250 spatial-temporal modes. Furthermore, we encode qubits in the time and path degrees-of-freedom and store the qubits. The fidelities of the retrieved qubits are assessed via quantum tomography and violate the classical bound for all memory cells. In near future, we will entangle each cell with a telecom photon traveling 50km of fiber and demonstrate an increase of the entanglement rate due to the multiplexing.

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Lifetime-limited optical and sub-second spin coherences in $^{171}Yb^{3+}$:$CaWO_4$

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Rare-earth ions-doped crystals is an attractive solid-state platform for quantum technologies. $^{171}Yb^{3+}$ ions provide unique properties as the paramagnetic isotope with nuclear spin of ½ and inducing clock transitions for optical and spin transitions at zero magnetic field [1]. Here, we explore the novel material based on $CaWO_4$ crystal having one of the lowest nuclear spin densities doped with $^{171}Yb^{3+}$ ions. We find that it provides exceptional optical and spin properties, by demonstrating optical coherence times nearly limited by the radiative decay reaching 0.72 ms and realize all-optical spin control with spin coherence times up to 0.15 s.

In combination with large hyperfine splittings, narrow optical lines make it possible to initialize the whole spin ensemble in different ground state levels. Efficient optical pumping is allowed by the suppressed spin-phonon relaxation processes at temperatures below 2 K. Using broad optical pumping, we measured the spin ensemble recovery time up to above 3 hours at 50 mK cryogenic temperatures.

Moreover, coherence properties are achieved without strong external magnetic fields, and with temperatures up to a few K, making this material especially promising for optical quantum memories [2], coupling to superconducting circuits [3], nanophotonic structures for integrated spin-photon interfaces [4,5], and optical to microwave transducers.

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Spin coherence times of Eu ions doped in thin membranes of Y2SiO5 crystal

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Since the ground-state coherence time of Eu ions doped in a Y2SiO5 crystal under a specific magnetic field was extended to six hours [1], single Eu ion in Y2SiO5 have become a crucial candidate for quantum memory with ultra-long storage times. However, the samples used in cavity-enhanced emissions [2] and single-ion detections [3] need to be thin membranes to increase the Purcell enhancement factor. The spin properties of Eu ions doped in Y2SiO5 thin membranes, however, remain unclear. Here, we manufacture and polish Eu-doped Y2SiO5 membranes with thicknesses ranging from one hundred micrometers to several tens of micrometers, which can be further incorporated into microcavities. All membranes are cut from a whole bulk crystal, so that we can exactly observe how the spin coherence time varies with the thickness. By employing various methods to improve the signal-to-noise ratio, we measure the spin coherence times of Eu ions in these membranes using Raman heterodyne detection.

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Spin-photon entanglement of a single Er^{3+} ion in the telecom band

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Entanglement between photons and a quantum memory is a key component of quantum repeaters, which allow long-distance quantum entanglement distribution in the presence of fiber losses. Spin-photon entanglement has been implemented with a number of different atomic and solid-state qubits with long spin coherence times, but none directly emit photons into the 1.5 μm telecom band where losses in optical fibers are minimized. Here, we demonstrate spin-photon entanglement using a single rare earth ion in the solid state, Er^{3+}, coupled to a silicon nanophotonic cavity, which directly emits photons at 1532.6 nm. We observe an entanglement fidelity of 73(3)% after propagating through 15.6 km of optical fiber [1]. This work opens the door to large-scale quantum networks based Er^{3+} ions, leveraging scalable silicon device fabrication and spectral multiplexing. We will also briefly discuss rephasing approaches to mitigate spectral diffusion [2].

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[2] M. T. Uysal and J. D. Thompson, *Rephasing Spectral Diffusion in Time-Bin Spin-Spin Entanglement Protocols*, arXiv:2406.06497.

All-optical control and readout of individual ^{167}Er nuclear spin qubits

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Photon emission in the minimal-loss window of optical fibers, exceptional coherence properties and the potential for high scalability make erbium dopants in solids a promising platform for future quantum networks [1]. A key step towards the realization of a quantum network is the generation of spin-photon entanglement which requires spin coherence times that by far exceed the optical lifetime, coherent control over the spin state and a high-fidelity state readout.

To demonstrate this, we embed an erbium-doped YSO membrane into a cryogenic Fabry-Perot resonator [2,3,4] and investigate individual ^{167}Er dopants (I = 7/2) as potential nuclear spin qubits. Using a co-doping technique of the host crystal which we have shown in an earlier work [2] allows us to tailor the inhomogeneous broadening of the erbium ensemble and spectrally resolve all optical hyperfine transitions of several ^{167}Er dopants at a magnetic field > 4 T. We use a series of pump-probe measurements to unambiguously assign all eight optical spin-preserving and seven spin-flip ($\Delta m = \pm 1$) transitions belonging to an individual ^{167}Er dopant. Using optical pumping on the spin-flip transitions then enables deterministic initialization into any of the eight hyperfine states. The narrow linewidth of the optical resonator which is one order of magnitude smaller than the hyperfine splitting and a 50-fold Purcell enhancement allows us to perform a single-shot readout with 91(1)% fidelity.
Further, an all-optical Raman pulse scheme is used to coherently manipulate the qubit state encoded in the two lowest hyperfine ground states. We observe Rabi oscillations and in a Ramsey measurement we find a coherence time of 0.5 ms which can be extended with a dynamical decoupling sequence up to 200 ms.

This constitutes a crucial step towards spin-photon entanglement generation to be used in fiber-based large-scale quantum networks.

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Fourier-limited photons from frequency tunable, cavity enhanced Erbium ions

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REI embedded in crystals are promising candidates for quantum information processing and quantum network applications. Among them, Er3+ ions are appealing due to their telecom C band emission and long spin coherence times. However, multi-photon interference is challenging because of the distinct spectra of different emitters and low photon emission rates. Here, we demonstrate that coupling the ion to a silicon nanophotonic cavity enhances the emission rate by up to 143 times. Additionally, we achieve a Fourier-limited linewidth of photons emitted at millikelvin temperatures by applying a magnetic field. Furthermore, we show that the ion frequency can be tuned by up to 5MHz/100V through an electric field using external electrodes. These results highlight the potential of this platform for developing a rare-earth-ion-based quantum network.

The poster will explain in detail the experiments performed in *PhysRevLett.131.170801*

Measurements of thermal gradients in a Tm:YAG crystal: towards a better understanding of diffraction efficiency on large-band programmed gratings

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Spectral hole burning (SHB) properties of RE ions in solids allow to tailor the optical absorption, which can be used for some applications such as frequency multiplexed quantum memories [1] or large band RF processing [2]. We can achieve the latter using the "rainbow" analyzer architecture [3], in which the optically carried RF signal is diffracted and spatially dispersed from a spectro-spatial grating programmed over a large portion of the inhomogeneous bandwidth. However, we highlighted a strong dependence of the diffraction efficiency on the programmed RE ions doping concentration, which echoes directly on the analyzer dynamic range.

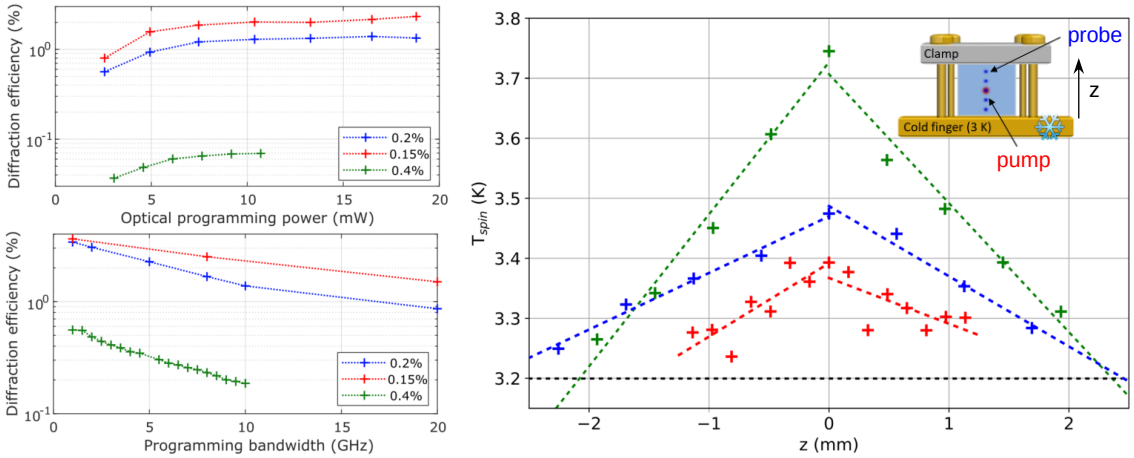

Fig. 1. Left: diffraction efficiency measured from echo experiments as a function of the optical programming power used to inscribe the spectral grating (top) and the programming bandwidth (bottom), for various doping concentrations. Right: temperature profile along the crystal height measured from spectral holes decay.

Here we first demonstrate that the diffraction efficiency is highly improved by decreasing the programmed ions concentration, by decreasing either the Tm concentration in the YAG lattice or the programming bandwidth, as presented on the left side of Fig. 1. In both cases, we reduce locally the number of programmed ions, decreasing accordingly the impact of instantaneous spectral diffusion (blurring of the optical resonance by the surrounding ions) and the heat load from the non-radiative decays. Then we study this local heating which is mainly induced by the decay from $^3H_4$ (excited state) to $^3F_4$ (metastable state) [4]. We highlight doping concentration dependent temperature gradients, as depicted on the right side of Fig. 1, with heating from 0.2 to 0.55 K at the pumping location. Under magnetic field, SHB lifetime is found to be very sensitive to temperature through spin-phonon processes, which corroborates our observations on diffraction efficiency.

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Characterization of hyperfine decoherence near a ZEFOZ transition in a Eu3+:Y2SiO5 crystal

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Rare earth doped crystals possess extremely long hyperfine and optical coherence times [1,2], thus they are considered as one of the most potential candidate systems for long-term quantum memories. In particular, hyperfine coherence time of 6 hours [2] has been achieved in Eu^{3+} ions doped in a Y_2SiO_5 crystal, and further extension in the coherence time is possible, but it requires more knowledge about the decoherence mechanism. Here, hyperfine decoherence process was conducted in this system within the temperature range of sub-Kelvin to 17 K and magnetic field tuned around a zero-first-order-Zeeman (ZEFOZ) transition at 1.35 T, which is the same ZEFOZ field as previous work [2]. Theoretical formulas were derived to describe this process which shows that different spectrum diffusion model is needed to describe the homogeneous broadening at magnetic fields far away and close to a ZEFOZ point. Furthermore, by applying dynamic decoupling (DD) sequences, we achieved a spin coherence time of 13 hours.

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ESA's Strategy for Satellite Quantum Communications and Quantum Memory Developments

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In the emerging domain of quantum communication, satellites can offer the solution for long-distance connections between short-range fibre based Metro Networks. In addition to secure communication applications, a Quantum Information Network (QIN), based on distribution of entanglement, is expected to enhance capabilities of quantum sensors, time and frequency sources, as well as enabling interconnections of quantum computers. These applications are not well defined yet, and neither are the specifications of the quantum satellite links, therefore it requires a long-term, coordinated strategy to understand the application and develop the space and ground segments and required technologies to unlock the full potential of a QIN.

To address this need, ESA has created a Strategy for Satellite Quantum Communication Networks. The strategy will be implemented under the QUAntum SpAce netwoRks (QUASAR) initiative which will support commercialisation and accreditation efforts for already initiated satellite QKD projects, as well as work towards preparation and future deployment of QIN in space and its future convergence with terrestrial quantum networks.

Quantum memories are fundamental building blocks for any scalable quantum communication network, and are not yet a mature technology even for terrestrial applications. When the network includes satellite links, the memory requirements become even more challenging. For instance, the coherence time has a threshold on the order of ~10ms, corresponding to the time-of-flight for light from a LEO satellite to ground. The long latency also necessitates having high-capacity memories for scalability. Therefore it is clear that there is a need to develop quantum memories considering the specificities of satellite communications. Moreover, these have to be initiated soon, as the space environment and market imposes additional challenges in terms of costs, development timelines and technology maturation.

In this talk I will present ESA's QUASAR initiative, as well as ongoing and future development plans addressing quantum memories for ground and space segment of a QIN.

Crystal growth and spectroscopy characterization of Eu^{3+} ions in a stoichiometric $EuCl_3.6D_2O$ crystal

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Owing to their long coherence time and large bandwidth, rare-earth ions (REI) doped in crystals have become one of the most promising physical platforms for quantum storage [1]. Since the main limitation of the REI comes from their relatively low optical depth (OD), we chose a stoichiometric $EuCl_3 \cdot 6D_2O$ single crystal to perform experiments of quantum storage. In this report, we first grew high-quality $EuCl_3 \cdot 6D_2O$ crystal from saturated solution with a deuteration process by isotopically replacing H atoms with D. By doing so the O-H bonds in the lattice were replaced by O-D bonds and non-radiative decay for the excited $^5D_0$ state was significantly depressed [2]. This resulted in Eu^{3+} optical coherence time of 389 us, which is about 4 times longer than in $EuCl_3 \cdot 6H_2O$. At a magnetic field of 0.11 T, the coherence time is further extended to 1.0 ms, comparable to the value observed in a low-concentration Eu^{3+}:Y_2SiO_5 crystal. These results imply the system's potential for developing quantum memories with high efficiency. We then implemented the atomic frequency comb (AFC) protocol [3] in this system and observed storage efficiency over 40% of coherent light signal.

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[2] Ahlefeldt R L, Hush M R, Sellars M J., *Physical review letters*, **117(25)**, 250504 (2016).
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An efficient and multimode quantum memory for light

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Rare-earth ions doped in solids are important candidates for quantum memories and quantum repeaters, due to their excellent performances in optical coherence and hyperfine coherence lifetimes. However, these 4f-4f optical transitions are parity forbidden and relatively weak which leads a weak absorption and low storage efficiency for light. Here, I will talk about our recent achievements of highly efficient quantum memories based on the Eu ions doped in a thin-film YSO crystal coupled to an impedance-matched fiber F-P cavity. We obtain a quantum storage efficiency of 73.2(5)% for time-bin encoded qubits, together with a fidelity of 99.4%. 20 temporal modes encoded with variable phases are stored simultaneously with an efficiency beyond 50%. We further demonstrate the efficient and multimode storage of true quantum light source, i.e. a telecom photon heralded 580-nm single photons. This demonstration of efficient and multimode quantum memories could play an essential role in the construction of multiplexed quantum repeaters and transportable quantum memories.

Erbium as an optical Boltzman thermometer for cryogenics

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Starting at room temperature, optical thermometry using luminescent local probes continues to gain popularity, now significantly amplified by its prospects in biology and healthcare.
The extension of these techniques at low temperatures is particularly appropriate at a time since developments in cryogenics are strongly stimulated by the perspectives in quantum technologies.

At cryogenic temperature, the question of the actual temperature of the sample arises systematically and can only be addressed by the use of a local probe whose optical interrogation avoids disturbance by electrical contacts.
The erbium ion is well suited for such a task, since the level splitting under a moderate magnetic field is generally of the order of 2 kelvins in units of k_B T.

In the range 2 – 7 K, I will show how we can deduce the temperature of the doped crystal by narrow-band spectroscopic techniques (Figure 1) and then calculate the conductance of the interface between the sample and the cold plate. Such a measurement, which is not so common, makes it possible to question the cooling of a typical dielectric substrate in the cryostat.

Despite the technological nature of our approach, it allows us to ask simple and fundamental questions about the physics of our systems, by requiring a good precision on the absorption measurements under magnetic field and by questioning the thermalization of the sample on the one hand and the spins themselves on the other.

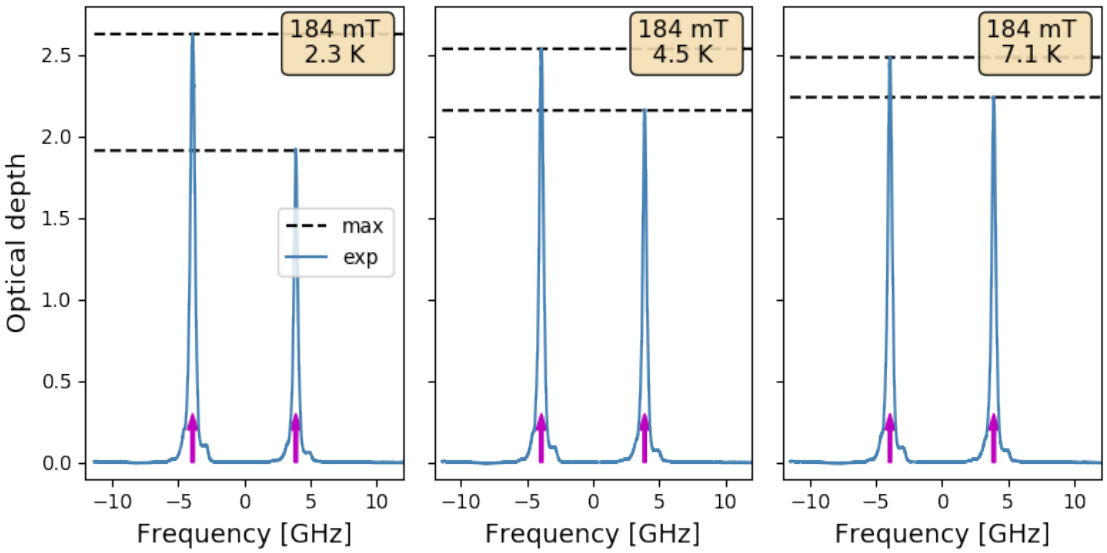

Figure 1: Optical measurement of the spin population using the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition of erbium in Y_2SiO_5 (184mT magnetic field). The relative amplitude of the absorption peaks reflects the temperature variation in the 2 – 7 K range.

Slow-Light Effect in Atomic Frequency Comb Quantum Memory Using a Stoichiometric Rare-Earth Crystal

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Rare-earth (RE) doped crystals have emerged as one of the most promising candidates for developing ensemble-based solid state quantum memories for long-distant quantum communication applications [1-3]. In this context, the atomic frequency comb (AFC) quantum memory protocol provides substantial temporal multimode capacity, grounded in the large ratio between the inhomogeneous and homogeneous linewidth of a RE crystal, while the system's low optical depth remains a main limitation for storage efficiency [4]. Here, instead of a doped RE system, we investigated the AFC storge using a stoichiometric RE system, the $EuCl_3 \cdot 6D_2O$ crystal [5], and achieved storage efficiency of 42% and 34% for bright pulse and weak coherence pulse respectively. We also observed slow-light effect on the AFC echoes arising from the system's high optical depth. Theoretical formulas were derived which allows quantitively analysis of the absorption and dispersion process contributing to these phenomena. These formulas can be applied to other memory protocols that are conducted in memory material systems with a high optical depth.

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[2] A. C. H.-P. J. B.-V. M. A.-J. N. Khabat Heshami et al., J. Mod. Opt.654 63 (2005),
[3] M. Guo et al., Front. Phys. 18, 21303 (2023).
[4] M. Afzelius et al., Phys. Rev. A 79(5), 052329 (2009)
[5] R. Ahlefeldt et al., Phys. Rev. Lett 117(25) 250504 (2016)

Decoherence mechanisms at low magnetic fields in rare-earth ion-doped Y_2SiO_5

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In this presentation, we show a numerical model that aims at describing spin decoherence mechanisms of rare-earth ion-doped yttrium orthosilicate (Y_2SiO_5) at low magnetic fields (sub-mT). To this extent, we rely on a full Hamiltonian approach of a system composed of the central ion and a few (up to 7) nearest neighbors non-zero nuclear spin ions (yttrium in our case) coupled via magnetic dipole interaction.

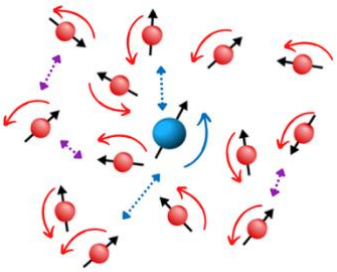

Figure 1: Spin dynamics.

Our model accounts for different relevant mechanisms responsible for the decoherence, illustrated in Fig.1, such as spin flips (blue and red arrows) and Y-Y flip flops (purple dashed arrows). We performed simulations on Eu-, Pr- and Yb-doped Y_2SiO_5, and confront simulations of simple free-induction decays with experimentally measured spin-wave atomic frequency comb and Hahn echo decays. We show a very good qualitative correspondence in the characteristic decay times, as illustrated for instance in Fig.2 for the Eu:YSO case.

Remarkably, we also show that the same approach allows to simulate very different behaviors: coherence time decreases with the field for Yb while it increases with the field for Eu and Pr, as witnessed experimentally. Moreover, 1/B scaling of the coherence time in Yb can be accurately reproduced [1].

Our approach allows us to identify the predominant decoherence mechanism in different magnetic field regimes, and spot favorable configurations for long duration and efficient storage.

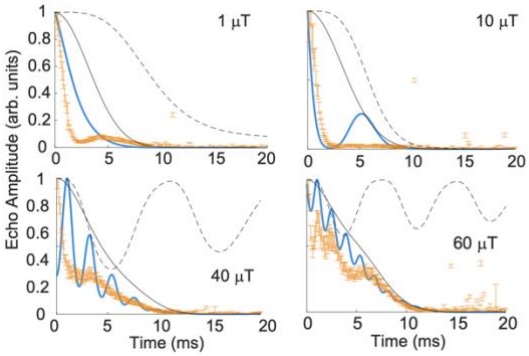

Figure 2: Spin-wave AFC decays in Eu:YSO (orange dots) vs numerical simulation of decoherence (blue lines).

[1] L. Nicolas et al., *NPJ Quant. Inf.* **9**, 1-7 (2023)
[2] C. Pignol et al, in preparation

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