# Towards a functional repeater link using Pr3+:YSO quantum memories

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Future quantum networks will rely on the distribution of entanglement between distant material quantum nodes [1]. Up to now, remote entanglement has already been demonstrated in several systems but none of these demonstrations satisfied all the requirements for a network architecture. Some of these requirements include heralding at telecom wavelengths, high heralding rate, resilience against optical losses, multimode operation, on-demand read-out of the stored entanglement and encoding in a functional basis. In this poster, we present ongoing progress towards functional entanglement between solid-state multimode quantum memories based on praseodymium-doped crystals heralded by cavity-enhanced SPDC photons at telecommunication wavelengths. Rare earth-doped crystals are prominent candidates for quantum network matter nodes thanks to their large multiplexing capacity in several degrees of freedom (time, frequency, space) [2] and spin/optical coherences allowing for long storage times (millisecond range) [3]. Together with the high heralding rates (1.4 kHz) of the SPDC sources [4], our architecture represents a promising route to the realization of practical quantum repeater links.

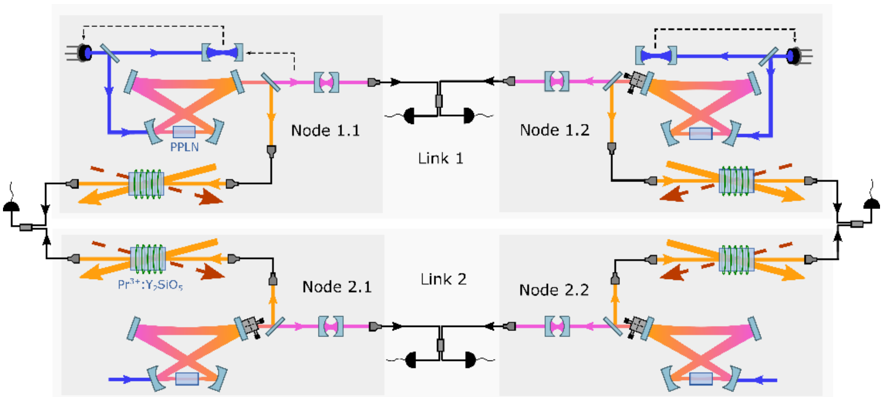


*Figure 1. Experimental setup for functional quantum repeater link architecture*

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# Proposal for a quantum repeater demonstration using $^{167}Er:Y_2SiO_5$

**James Stuart**, **Paul McMahon, Ellen Zheng, Rose Ahlefeldt, Matthew Sellars**

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Recent demonstrations in our lab have shown the creation, and storage, of non-classical states in a telecom-compatible quantum memory based on $^{167}Er:Y_2SiO_5$. Furthermore, we achieved efficient spin-state storage and high rephasing efficiency in the same crystal. We are now moving to demonstrate basic repeater operations on the Intra-government Communications Network (ICON), a government communications network in Canberra with over 2500 nodes connected by dark optical fibers.

In preparation for these demonstrations, we have begun experiments to distribute entanglement between two memories, using different frequency modes in a single spatial mode of the crystal. I will present preliminary results on these measurements, showing correlations between two frequency separated memories. To facilitate the network demonstration, we need to increase the coupling efficiency between the memory and an optical fibre channel. I will present a prototype fibre-coupled device with a coupling efficiency > 70%, with > 90% theoretically possible.

**Progress towards single photon EIT light storage at ZEFOZ conditions in Pr:YSO**

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Long storage time, large efficiency, and large signal-to-noise ratio (SNR) are crucial properties of optical quantum memories. We present single- and few-photon storage based on electromagnetically induced transparency (EIT) in Pr:YSO. By employing zero first-order Zeeman shifts (ZEFOZ) and dynamical decoupling with robust composite pulse sequences we reach storage times of several seconds. We implement a spectral filter in a Pr:YSO crystal to separate the weak signal from the strong control field. Previously, we reached a SNR=1 for stored weak coherent pulses with 11 photons at a storage time beyond one second [1].

We present recent progress towards single photon EIT storage in Pr:YSO. We simultaneously prepare two ensembles to increase the optical depth, thereby enabling higher efficiency. Furthermore, we use now an ECDL-based laser system, which improves the filter discrimination by almost two orders of magnitude. This pushes the SNR towards the requirement for single photon storage.

[1] M. Hain, M. Stabel, and T. Halfmann. New J. Phys. **24**, 023012 (2022)

**Spatial Confinement of Atomic Excitation by Composite Pulses in Pr:YSO**

Niels Joseph, Markus Stabel, Nikolay V. Vitanov and Thomas Halfmann

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We experimentally demonstrate spatial confinement of atomic excitation by narrowband composite pulse sequences in Pr:YSO. In particular, we implement a variety of 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 Gaussian-shaped laser pulses. Our experimental data agree well with a numerical simulation and confirm that the confinement improves with the number of pulses in the sequence. However, we find that inhomogeneous broadening in Pr:YSO reduces the performance, i.e., leading to the formation of additional rings around the localized centre. A theoretical treatment, confirmed by experiments, shows that the perturbing effect can be reduced by carefully choosing experimental parameters. Our experiments prove that narrowband composite pulses are a versatile tool to localize atomic excitation that will also be applicable for subwavelength localization.

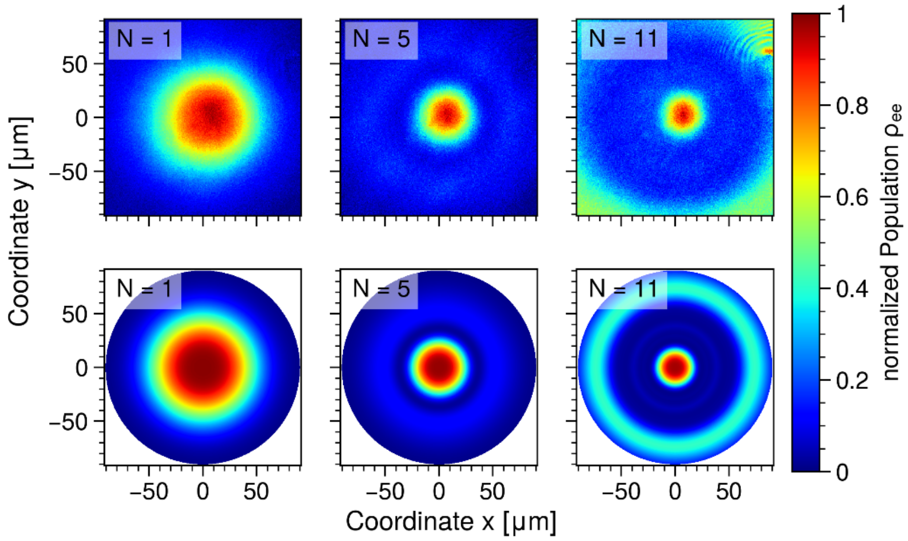


*Figure 1: NCP-driven localization in Pr:YSO. Variation of the population $\rho_{ee}(x, y)$ versus coordinates x and y across the laser beam profile with phases from [1]. (Upper row) Experimental data for different pulse counts. (Lower row) Numerical simulation, with the experimentally determined parameters.*

[1] Torosov et al., Phys. Rev. A **92,** 033406 (2015).

**Robust Dynamical Decoupling Driven by Pulses with Field Inhomogeneities in Pr:YSO**

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Institute of Applied Physics
Technical University of Darmstadt, Germany

We experimentally compare the robustness of state-of-the-art composite pulse (CP) sequences for dynamical decoupling with regard to typically unavoidable inhomogeneities in the driving radiofrequency (RF) pulses. To quantify their performance, we measure the coherence time of EIT light storage in a Pr:YSO crystal.

To systematically vary and characterize the field inhomogeneity, we modify the winding numbers of our driving RF coils and perform spatially resolved measurements of the Rabi frequency distribution in three dimensions.

We find that already for rather homogeneous driving fields, CP sequences and in particular the universal robust family of sequences [1] provide a large benefit over the standard CPMG sequence. This advantage further increases with the field inhomogeneity. However, at field inhomogeneities larger than about 5% standard deviation, pulse errors dominate and there is a loss in coherence even for the best CP sequences.

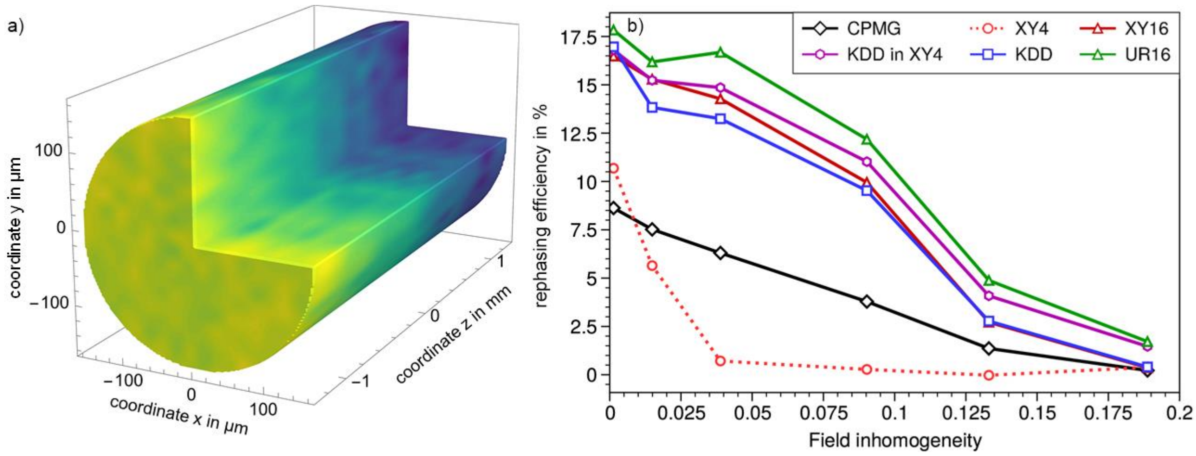


*Figure 1: a) Exemplary measured 3D Rabi frequency distribution (colour scale) vs. spatial coordinates. b) Rephasing efficiency of selected composite sequences after a storage time of 2ms and 160 RF pulses vs. the inhomogeneity of the driving pulses.*

[1] Genov et al., Phys. Rev. Lett. **118**, 133202

# Towards Nonlinear Optomechanics with Single Erbium Ions

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Two of the most active areas of quantum science are quantum optomechanics and individual spin systems, which are often used for quantum networking. Each of them has its own advantages and disadvantages. In optomechanics [1, 2], the optical field and mechanics are effectively linearly coupled to one another. Such systems have emerged as a leading candidate to investigate quantum physics at a macroscopic scale. However, they are limited by the linear interaction. Individual spins in solid-state systems [3], on the other hand, enable advanced quantum protocols thanks to their inherent strong non-linearity. However, high-quality optical cavities are needed to realize advanced quantum information processing [4]. Merging these two worlds together brings synergies that leverage their respective strengths and weaknesses, enabling novel quantum applications. I will show our most recent findings on the spectrum characterization of $Er^{3+}$ ions implanted in a silicon waveguide.

References

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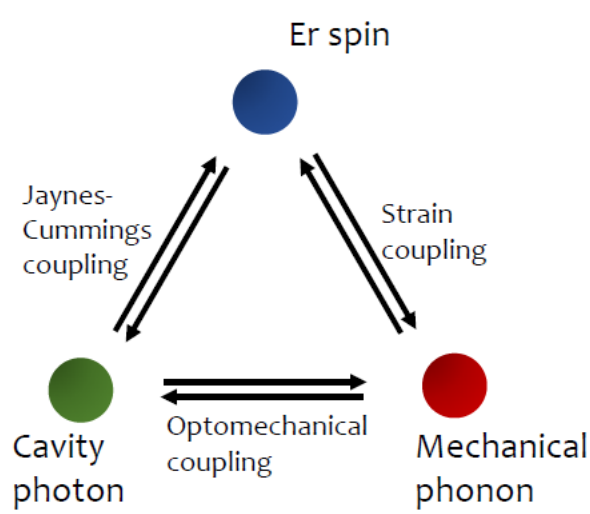

# Towards the realization of REI-based indistinguishable quantum emitters in the telecom band

Yong Yu,[1] Dorian Oser,[2] Gaia Da Prato,[1] Emanuele Urbinati,[1] Javier Carrasco Ávila,[3,4] Yu Zhang,[1] Patrick Remy,[5] Sara Marzban,[2] Simon Gröblacher [1,*] and WolfgangTittel[2,3,4,*]

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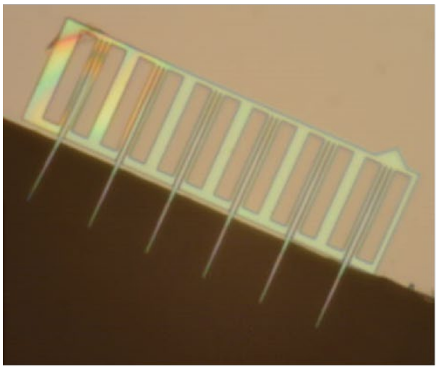
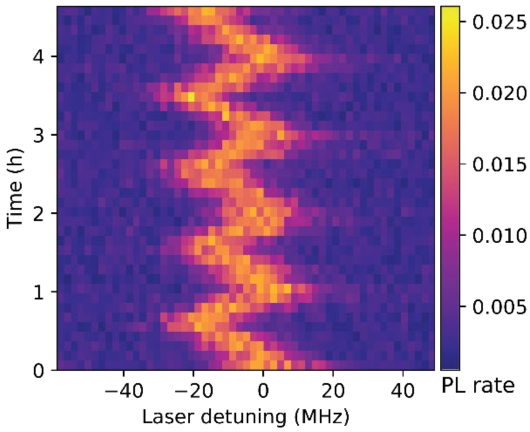
Single solid-state quantum emitters are attractive for quantum information processing and quantum networking. Among various candidates, $Er^{3+}$ ions are appealing due to their telecom C band emission and their long spin coherence times. However, the long lifetimes of their excited state and inhomogeneous broadening of the emission present challenges in networking. Achieving multi-photon interference is difficult due to low photon emission rates and distinct spectra of different emitters. Here we solve this challenge by demonstrating for the first time the linear Stark tuning of the emission frequency of a single $Er^{3+}$ ion. We enhance the ion embedded in a lithium niobate up to 143 increases in decay rate by evanescently coupling it to a silicon nano-photonic cavity. By applying an electric field, we achieve a Stark tuning greater than the ion's linewidth without altering its single-photon emission statistics. Our results are a key step towards rare earth ion-based quantum networks. The poster will explain in detail the experiments performed in *arXiv:2304.1468.*






(Left) Silicon nanocavities on the Er:LiNbO3. (Right) Stark tuning of a single Er ion.

# Modelling a Gradient Echo Memory (GEM) in a Laser-inscribed Waveguide in Praseodymium-doped Yttrium Orthosilicate Crystal

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Spin-wave atomic frequency comb (AFC) storage in $Y_2SiO_5:Pr^{3+}$ has been proved a good candidate for on-demand long-lived quantum memory. Though, it requires strong control pulses making the echo detection challenging. Noise suppression is achieved in bulk by steering the control pulses at an angle relative to the single photons, but this is impossible in waveguides. The GEM protocol, not requiring control pulses, enables on-demand waveguide quantum memories. We propose the use of a device configuration for implementing GEM protocol in a waveguide inscribed in $Y_2SiO_5:Pr^{3+}$ by fs laser micromachining. The crystal is carved using water-assisted laser ablation into an optimal geometry for depositing electrodes. We model the echo efficiency for a set of optimal key parameters to optimise the electrodes design and maximise the Stark shift, while ensuring a suppression of the electric fields in the mm range to enable spatial multiplexing.

# Investigations of Pr:$YVO_4$ for its application as a large bandwidth telecom quantum memory

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The atomic frequency comb (AFC) protocol is well used for rare-earth doped quantum memories (QMs). Yet, the bandwidth of the on-demand spin-wave AFC is limited by the ground-state hyperfine splitting. Recently, off-resonant cascaded absorption (ORCA) was used to store GHz-bandwidth telecom photons in a hot Rb gas. We propose an on-demand, large bandwidth QM protocol by combining the ORCA and AFC. While materials exist for either AFC or ORCA, there is yet no suitable host crystal/dopant combination for the combined protocol. Such a material should exhibit strong absorption in the telecom band, a long-lived excited state, and an allowed transition between the two. We investigate Pr:$YVO_4$ which has shown $^1D_2$ fluorescence lifetimes up to 23μs and telecom transitions between the $^3H_4$ and $^3F_3$ manifolds. Analysis of the crystal field structure and assignment of the level wavefunctions enabled us to determine whether Pr:$YVO_4$ fulfils the requirements to be employed as an AFC-ORCA QM.

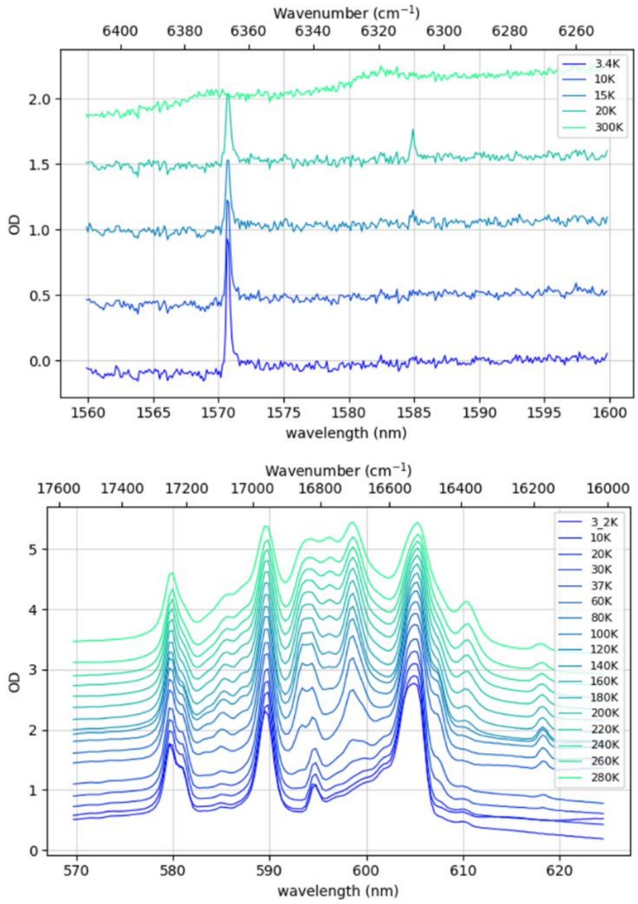


*Fig. 1. Top: Infrared absorption spectra for $Pr^{3+}$:$YVO_4$ with clear absorption at 1571nm and hot bands appearing at 15K. Bottom: Absorption spectra of 0.5% $Pr^{3+}$:$YVO_4$ for the $^3H_4$ to $^1D_2$ transition.*

# AFC spin-wave storage under 250 mT magnetic field in $^{151}Eu^{3+}:Y_2SiO_5$

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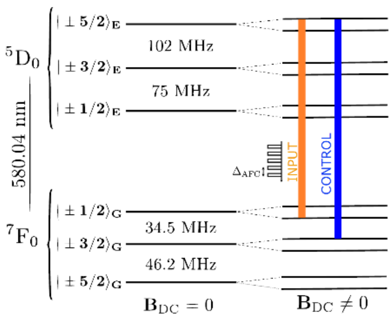
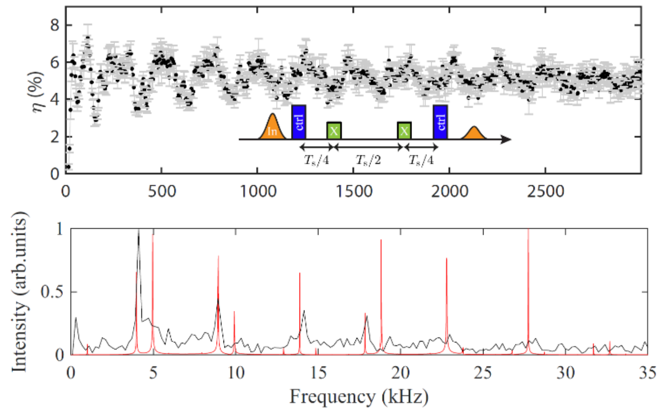
Rare-earth ion crystals have proven to be a promising platform for quantum memories. Our group has shown that in europium-doped yttrium orthosilicate one can achieve qubit storage for up to 20 ms[1] based on the atomic frequency comb (AFC) spin-wave memory, at a weak magnetic field of about 1 mT. However, when working at weak field, some mechanism lowers the spin-wave efficiency as compared to the optical AFC echo efficiency[2], which cannot be explained by the control-field transfer efficiency. Our working hypothesis is that the reduction is caused by interferences between different quantum paths due to small Zeeman splits of the hyperfine levels. Whereas under moderate field (250 mT) Zeeman split is larger than the memory bandwidth, thereby avoiding the multiple paths of excitations. We are able to demonstrate complete optical control of spin population in the six Zeeman-split hyperfine levels and realize full class cleaning on the Zeeman level under these conditions. In spinwave AFC scheme, we achieve 70% spin-wave memory efficiency with respect to the optical AFC echo signal. Current work is focused on optimizing beam overlap and geometries to further increase the relative memory efficiency.



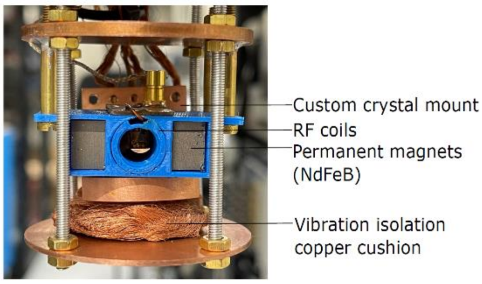




**Figure**: (upper left) Zeeman splitting of hyperfine levels under moderate magnetic field.

(upper right) Echo efficiency as a function of the spinwave storage time Ts under 1.4 mT magnetic field, small Zeeman splitting result in a interference between different quantum paths

(bottom) Photo of the crystal sandwich by permanent magnets (NdFeB) mounted on a L shape mount that is mechanical isolated inside the cryostat.

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# Towards large bandwidth spin-wave AFC storage in $^{171}Yb^{3+}:Y_2SiO_5$

T. Sanchez Mejia[1], M. Businger[1], L. Nicolas[1], E. Lafitte-Houssat[2], A. Ferrier[2], P. Goldner[2], and M. Afzelius[1]

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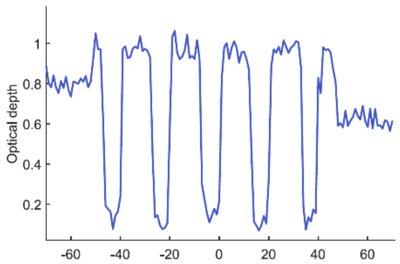
Rare-earth ion crystals have proven to be a promising platform for quantum memories. Using $Y_2SiO_5$ crystals doped with $^{171}Yb^{3+}$ ions, we have been able to show quantum storage of up to 1250 temporal modes over a 100 MHz bandwidth based on an optical AFC memory with up to 25 $\mu$s of programmed storage time [1]. We have also coupled a lumped-element microwave cavity to our $^{171}Yb^{3+}:Y_2SiO_5$ crystal for optical-microwave interfacing [2], which in principle would allow broadband AFC spin-wave storage at GHz spin frequencies. We here show first data of spin-wave storage slightly beyond 1 ms with an AFC bandwidth of 100 MHz [3], using the simplest sequence of two MW $\pi$ pulses for spin control. To achieve these results, we have exploited that efficient lambda-systems can be tailored in $^{171}Yb^{3+}:Y_2SiO_5$ thanks to the branching ratio table being dependent on the polarization of the laser light, an effect of the electronic nature of the hyperfine states. This allows optimizing the Rabi frequency of both the input/output and control fields, which is key to reaching the large bandwidth. Our goals for future experiments are to increase the memory lifetime by dynamical decoupling, to experiment with different optical preparations to increase our total bandwidth to up to 280 MHz, and to optimize our spin-wave storage over the full bandwidth of our memory.



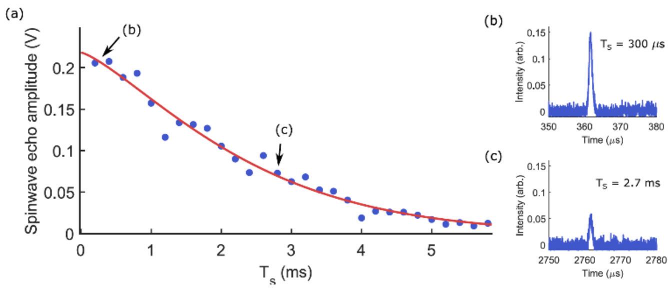
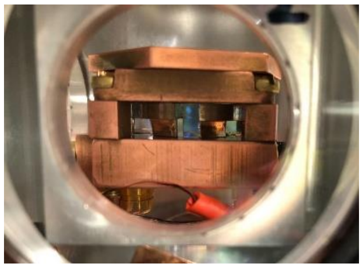




**Figure**: (upper left) AFC spectrum over 100 MHz, programmed for a short optical storage time of $1/\Delta$ = 50 ns. (upper right) Spin-wave AFC storage over 100 MHz bandwith as a function of spin-wave storage time. (right) Photo of the MW lumped-element resonator with optical access mounted in side the cryostat.



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# An optical spin-wave quantum memory with high efficiency

Ming Jin, Ruo-Ran Meng, Zhong-Yang Tang, Xiao Liu, Zong-Quan Zhou, Chuan-Feng Li, Guang-Can Guo

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In view of the ultralong nuclear spin coherence time of $Eu^{3+}$ in YSO crystals, pioneering works towards applications in quantum networks have been demonstrated, including coherent optical storage for 1 hour and single-photon level quantum memory for 20 milliseconds based on $Eu^{3+}$ ensembles. However, the inherently weak light absorption property of $Eu^{3+}$ ensembles poses a significant challenge in achieving high-efficiency quantum memory. To address this limitation, macroscopic cavities have been employed to enhance the light-matter interactions. However, this approach hinders the integrated application of the quantum memory system. Here, we propose a novel approach by utilizing a fiber Fabry-Perot cavity and implementing a noiseless photon-echo (NLPE) protocol. This approach allows us to construct a microcavity-enhanced quantum memory based on $Eu^{3+}$:YSO, paving the way for on-chip quantum memory with both high efficiency and long storage time.

**An integrated quantum memory in $^{151}Eu^{3+}:Y_2SiO_5$ using optical-lattice-like waveguides**

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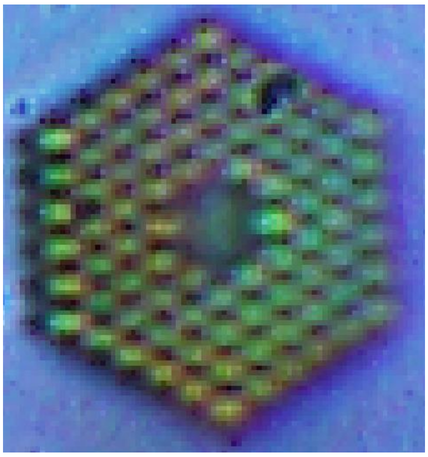
We report on an optical-lattice-like waveguide fabricated in a $^{151}Eu^{3+}:Y_2SiO_5$ crystal by femtosecond laser writing. Operating at 580nm, the waveguide has 40% efficiency, maintaining good properties like inhomogeneous broadening, absorption and coherence time of $^{151}Eu^{3+}$ optical transition. Furthermore, the waveguide has a small mode field diameter, which shows a great potential of butting with single mode fibers. Here we demonstrate an integrated quantum memory using optical-lattice-like waveguide connected with thermal diffusion fiber arrays, which can be directly integrated into fiber networks.



# Nonlocal quantum gate between nodes separated by 7 kilometers

Xiao Liu[1,2], Xiao-Min Hu[1,2], Tian-Xiang Zhu[1,2], Chao Zhang[1,2], Yi-Xin Xiao[1,2], Jia-Le Miao[1,2], Zhong-Wen Ou[1,2], Bi-Heng Liu[1,2,3], Zong-Quan Zhou[1,2,3], Chuan-Feng Li[1,2,3], Guang-Can Guo[1,2,3]

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Distributed quantum computing offers an excellent solution to the limitation of scaling up the number of qubits, by integrating multiple quantum devices via optical links of remote quantum nodes in large-scale quantum networks. The distributed modular architecture requires remote universal quantum gates to be implemented across network nodes using teleportation-based approaches. However, such remote quantum gates have only been realized within single quantum devices or between nodes separated by a few tens of meters. Here, we experimentally demonstrate the teleportation of a quantum logic gate over metropolitan distances, with two nodes separated by 7 kilometers. Moreover, we exploit this nonlocal quantum gate to illustrate the quantum parallelism by enacting nontrivial quantum algorithms between two remote nodes. Our results show the viability of distributed quantum computing in actual long-distance field-deployed fiber channels and pave the way towards large-scale quantum computing networks.

# Progress towards integrated long-duration quantum memory

Yuping Liu[1,2,3], Zhongwen Ou[1,2], Tianxiang Zhu[1,2], Chao Liu[1,2,3], Zongquan Zhou[1,2,3], Chuanfeng Li[1,2,3], Guangcan Guo[1,2,3]

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**Abstract:** Long-duration quantum memory plays essential role in long-distance quantum network. And integrated quantum memory is necessary for large scale quantum communication. In this work, we combined electrodes with a laser-written waveguide in a Eu151: Y2SO5 crystal to realize an integrated quantum memory for ~1ms. The electrodes are designed to provide decent RF field along the optical waveguide for dynamical decoupling, which is necessary in prolonging storage time. With both electrodes and waveguide integrated, this device shows a possible application in large scale quantum network.

**Poster title:**

On-demand multimode optical storage in a laser-written on-chip waveguide

**Name:**

Ming-Xu Su, Tian-Xiang Zhu, Chao Liu, Zong-Quan Zhou, Chuan-Feng Li, and Guang-Can Guo

**Abstract:**

Quantum memory is a fundamental building block for large-scale quantum networks. On-demand optical storage with a wide bandwidth, a large multimode capacity and an integrated structure is crucial for practical applications, but is not demonstrated yet. Here, we fabricate an on-chip waveguide in Eu:YSO crystal with an insertion loss of 0.2 dB, and propose a novel pumping scheme to enable spin-wave atomic frequency comb (AFC) storage with a bandwidth of 11 MHz inside the waveguide. Based on this, we demonstrate the storage of 200 modes using the AFC scheme and the on-demand storage of 100 modes using the spin-wave AFC scheme. The interference visibility between the readout light field and the reference light field is 99.0±0.6% and 97±3% for AFC and spin-wave AFC storage, respectively, indicating the coherent nature of this low-loss, multiplexed and integrated storage device.

# Multimode quantum storage of deterministic entanglement based on solid-state systems

Li Xue, Hu Jun, Liu Xiao, Zhou Zong-quan

University of Science and Technology of China

Solid-state quantum memories based on rare-earth-ion doped crystals have emerged as promising options for quantum networks and quantum repeaters. Among these materials, Yb:YSO crystals are particularly promising due to their unique advantages. Specifically, they possess the simplest energy level structure as Kramers ions, with hybridized electron-nuclear transitions enabling both long storage time and high bandwidth. Moreover, their transition wavelength aligns with deterministic entangled photon sources based on another promising solid-state system, that is, InGaAs quantum dots.

In this study, we investigate a multimode quantum memory utilizing a 38mm-long Yb:YSO crystal, specifically designed for coupling with photons emitted from InGaAs quantum dots. We employ fiber-based dual-channel laser-written waveguides to store arbitrary polarizations and achieve on-demand retrieval of stored photons through the use of the Stark-modulated AFC protocol. Finally, we demonstrate the multimode quantum storage of a deterministic polarization-entangled photon source generated by quantum dots. Our results show the great potential for the construction of high-speed quantum repeaters and quantum networks based on solid-state systems.

**Title:** Integrated Spin-wave Quantum Memory

**Name of authors:**
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**Abstract:**
Photonic integrated quantum memories are essential for the construction of scalable quantum networks. The spin-wave quantum storage, which can support on-demand retrieval with a long lifetime, is indispensable for practical applications but has never been demonstrated in an integrated solid-state device. Here, we demonstrate the spin-wave quantum storage based on a laser-written waveguide fabricated in a $^{151}Eu^{3+}$: $Y_2SiO_5$ crystal, using both the atomic frequency comb and the noiseless photon echo protocols. Qubits encoded with single-photon-level inputs are stored and retrieved with a fidelity up to 98.1±0.7%, which is far beyond the maximal fidelity that can be obtained with any classical device. Our results underline the potential of the laser-written integrated devices for practical applications in large-scale quantum networks, such as the construction of multiplexed quantum repeaters in an integrated configuration and high-density transportable quantum memories.

Towards Dynamic Atomic Mirrors

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We propose the use of spatially periodic spectral hole burning in Praseodymium ($Pr^{3+}$) doped in Yttrium Silicate ($Y_2SiO_5$) to create a narrowband reflective Bragg grating. The lifetime of the Bragg grating is determined by that of the hyperfine state of Praseodymium ions, which is about 100 seconds. Numerical simulations suggest the expected reflectance to be in excess of 90% over a narrow bandwidth of 100kHz. We shall then subject the Bragg mirror to a strong control field to effect electromagnetically induced transparency (EIT). This will optically turn the mirror transparent on microsecond timescale, thereby creating an all-optical switch. Such a narrowband switchable mirror has potential applications in creating dynamical cavities and reconfigurable quantum systems.s

# Towards coherent single praseodymium ion quantum memories in optical fiber microcavities

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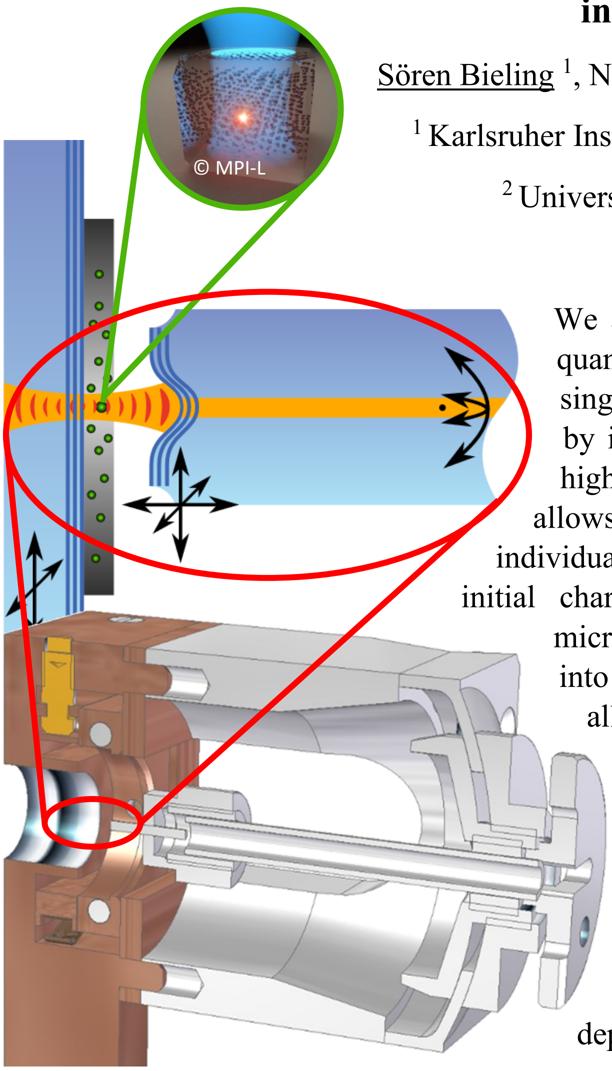


We aim to demonstrate both long and efficient single quantum storage in the ground-state hyperfine levels of single $Pr^{3+}$ ions doped into yttrium orthosilicate (YSO) by integrating them as bonded membrane into optical high-finesse fiber-based Fabry-Pérot microcavities. This allows for efficient addressing and detection of up to individual ions. We report on the design, commissioning and initial characterization of a next-gen cryogenic scanning microcavity as well as on its experimental integration into and design of a self-built vector magnet. It will allow for future coherence prolongation by operating under a zero first-order Zeeman (ZEFOZ) shift magnetic field alongside dynamical decoupling sequences. We will report on first cryogenic ensemble spectroscopy. Together with the Purcell-enhanced emission and ultrapure $Pr^{3+}$:YSO membranes this strives to realize efficient and coherent spin-photon interfaces suitable for deployment in scalable quantum networks.

**Novel $Yb^{3+}$-based materials for integration in open microcavities**

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Recently, there has been a growing interest in using rare-earth based molecular crystals for quantum information applications, in contrast to the conventional rare earth dopants in host crystals. These molecular materials showcase good optical coherence times and long spin lifetimes, in particular for $Eu^{3+}$-ions. Furthermore, these materials are extremely interesting for nanophotonic integration, since the molecular crystals can be produced in various sizes down to the nanoscale, and exhibit low surface roughness e.g. for microplatelets.

In this work, we extend this approach to other rare earth ion species. We investigate $Yb^{3+}$-based molecular crystals at cryogenics temperatures, characterizing their optical properties and working towards extracting their spin properties. We also report on progress of integrating $Yb^{3+}$-based nanomaterials into a fiber-based open access micro Fabry-Pérot cavity.

# A cryo-compatible, high-finesse all-fibre microcavity for REI spectroscopy

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Key obstacles encountered while developing an efficient light-matter interface for quantum technologies using rare-earth ion (REI) based solid-state systems are their long optical lifetimes ($T_{1,opt}$ ~ms) and low branching ratios (<1%). Both these obstacles can be remedied by the integration of such systems into high-finesse fibre-based Fabry-Pérot microcavities.

Here we present the development and testing of a cryo-compatible, high-finesse all-fibre microcavity designed for the purpose of REI spectroscopy. The cavity is mostly monolithic in design with a single controllable degree of freedom, which reduces the mechanical noise present in the system and therefore allows us to maximise the Purcell-factor. $Eu^{3+}$ based crystalline organic molecules were integrated into the cavity and the optical properties of this system were measured at both room and cryogenic temperatures.

# Micro-cavity length stabilization for fluorescence applications using higher order spatial modes

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**Abstract**

We experimentally investigated a potential high-performance cavity length stabilization using odd-indexed higher-order spatial modes. Our scheme could be particularly useful for micro-cavities that are used for enhanced fluorescence detection of few emitters, which needs to minimize stray photons from the stabilization beam. The experiment utilized a tilted locking beam coupled to the cavity mode from a flat mirror and a curved fiber as the other mirror for probing the nanocrystals and fluorescence collection.

The cavity with a finesse of 3000 is housed in a holder assembly with high passive damping capability using springs. We achieved a stability of about 30 fm rms while the error photons leaking from the continuous locking beam during the fluorescence collection remained below the detector dark counts. We investigated the performance for different mode orders.

# Slow light laser stabilization

David Gustavsson[1], Marcus Lindén[1,2], Kevin Shortiss[1], Sebastian P. Horvath[3], Andreas Walther[1], Adam Kinos[1,4], Martin Zelan[2], Stefan Kröll[1], and Lars Rippe[1]

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## Abstract

Ultra precise frequency stabilized lasers are core elements in modern metrology. They are used as oscillators in optical atomic clocks[1] and are integral to interferometer based tests of fundamental physics, such as gravity wave detectors[2]. The most common scheme for frequency stabilizing a laser involves locking the frequency of the laser to a stable cavity resonance frequency, using Pound-Drever-Hall locking. The cavity consists of two mirrors separated by a distance $L$ which determines the resonance frequency $\nu$. In this scheme, any variation in cavity length, $\Delta L$, will translate to a proportional variation in laser frequency, $\Delta\nu \propto \nu\frac{\Delta L}{L}$. This change in the cavity resonance frequency can be reduced by either minimizing $\Delta L$ or maximizing $L$. Current state of the art laser stabilization is limited by length variations due to Brownian motion in the atoms forming the mirrors – related to absolute temperature – and increasing $L$ beyond a few tens of centimeters has proven to be difficult[3]. The frequency stability of these references therefore approach the limits given by the Brownian length uncertainty.

By inserting a material with a low group velocity, a short cavity can be made to appear, to the light, as if it was orders of magnitude longer[4]. This has the effect of decreasing the frequency noise level by the same factor. In order to obtain slow light, a spectral hole can be made in a rare earth doped crystal by optically pumping all ions absorbing within a narrow interval of frequencies. Inside this spectral hole the index of refraction has a strong dependence on frequency and this has the effect of reducing the group velocity of light that passes through it.

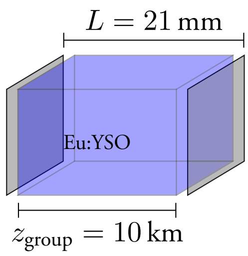


**Figure 1:** A spatially small but optically long cavity for laser frequency stabilization. Crystal real size.

We are implementing a locking scheme based on this effect in a highly polished and mirror coated yttrium orthosilicate crystal doped with europium, where a group velocity reduction of up to $5 \cdot 10^5$ can be achieved. This crystal displays the same cavity parameters as a ten kilometer long free space cavity (fig. 1).

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# A high-connectivity rare-earth quantum computer can be only tens of nanometers in size

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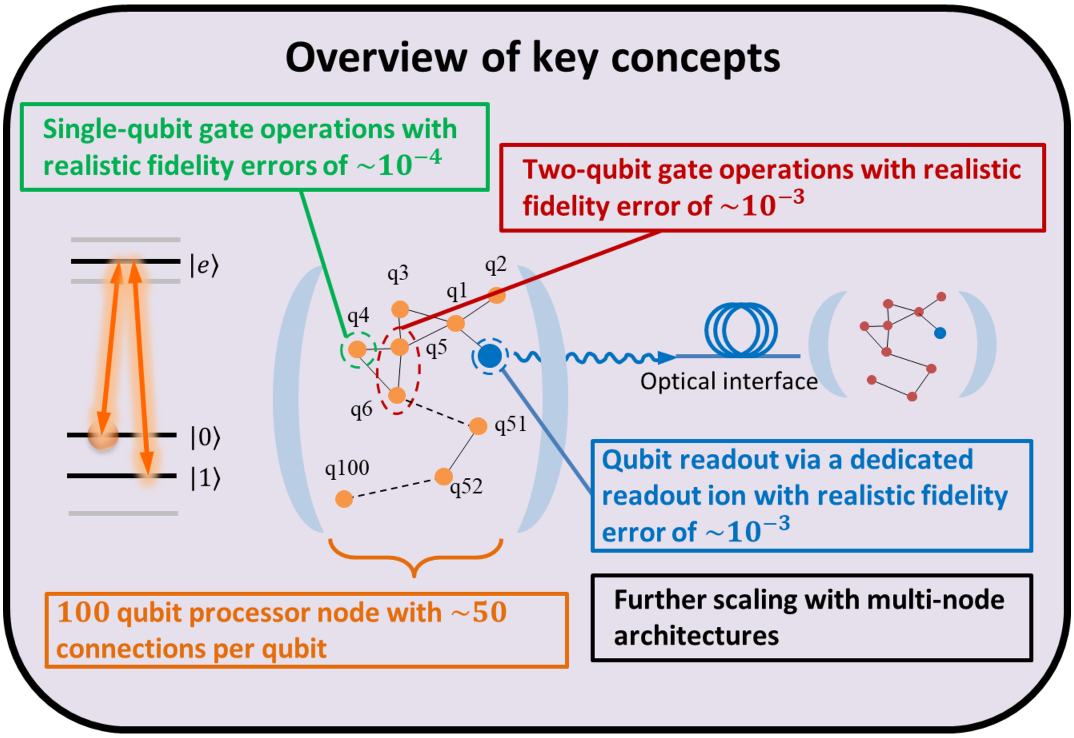
and the entire SQUARE Consortium (EU Flagship project)

Quantum computers are predicted to achieve significant speed-ups for certain applications when compared to classical computers. Here I give an overview of how quantum computing can be performed using rare-earth-ion-doped crystals [1]. These systems can potentially have very high qubit densities and connectivities as the doped ions sit only nanometer apart in three dimensions. The results of recent theoretical investigations show that high fidelity single- and two-qubit gate operations can be performed [2], [3]. Furthermore, the quantum processor nodes can contain roughly 100 qubits where the average number of qubits each qubit can interact with, denoted by the connectivity, can be partly tailored to lie between just a few and roughly 50 [4].





[1] **A. Kinos**, D. Hunger, R. Kolesov, K. Mølmer, H. de Riedmatten, P. Goldner, A. Tallaire, L. Morvan, P. Berger, S. Welinski, K. Karrai, L. Rippe, S. Kröll, and A. Walther, *Roadmap for rare-earth quantum computing*, arXiv:2103.15743 [quant-ph] (2021)

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# $Tm^{3+}$ doped $LiNbO_3$ and $LaF_3$ crystals for deep tissue optical imaging

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*E Damiano & M Tonelli, Dipartimento di Fisica, Universita' di Pisa*
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Early detection of breast cancer is extremely important for successful treatment and patient outcome. In both the screening and clinical situation, the most common technique for tumour detection is mammography, which in suspicious cases is followed by ultrasound and percutaneous biopsy for tissue characterisation and diagnosis. However, a method which does not require a physical intervention would be a more desirable solution, and specifically to avoid unnecessary invasive procedures in false positive mammographic findings.

Oxygenated and deoxygenated blood have different light absorption spectra making it possible to apply deep tissue imaging for the determination of blood oxygen level. Cancerous tissues can be oxygen deficient, this technique could therefore be interesting for differentiation between benign and malignant lesions and hence tumour characterization. However, its implementation is challenging since the light is strongly scattered inside the tissue. This problem can be alleviated by using a technique called ultrasound optical tomography (UOT) which combines light and ultrasound (US) to make deep tissue images [1]. The working principle of UOT is presented in Fig 1.

In this contribution we will describe our work on UOT. The probing wavelengths are around 690 and 790 nm and the chosen filters are $Tm^{3+}$ doped $LiNbO_3$ and $LaF_3$ crystals. This technique could provide us with information about the oxygenation of tissue and serve as a great tool for lesion characterization in breast, as a first clinical model.

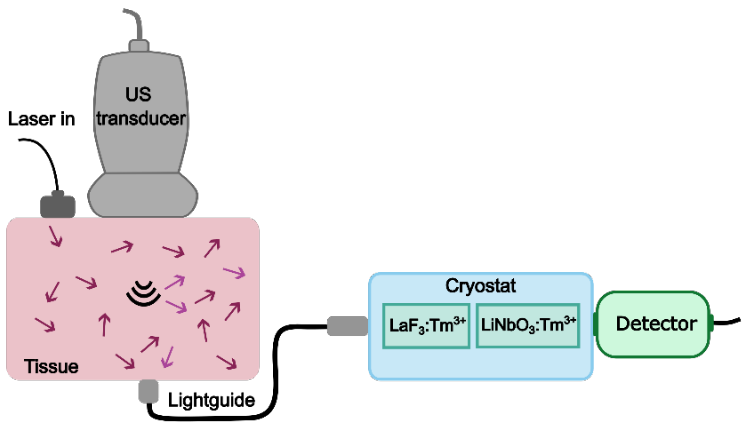


Fig. 1 Schematic drawing of two-wavelength ultrasound optical tomography set-up, US stands for ultrasound.

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## Fabrication of a superconducting transmission line in a planar design on a spin-doped crystalline membrane

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Scaling up the density of superconducting qubits on a chip is reaching its limits, and supplementing those with microwave quantum memory is a promising way to enhance the computing efficiency [1]. Rare-earth doped crystals are potential candidates to realize spin-based microwave quantum memories, due to the long coherence times of their spin states [2]. For efficient operation, one needs precise control of the spatial distribution of both the intensity and orientation of the oscillating magnetic field inside the sample. Here, we introduce a novel design of a planar superconducting transmission line based on a thin crystalline $CaWO_4$ membrane. The transmission line is designed to exhibit high transmission between 1 and 8 GHz, i.e. the frequency range of the hyperfine transitions of the rare-earth ions in near-zero external magnetic field. We discuss the fabrication techniques and present transmission spectra recorded at cryogenic temperatures.

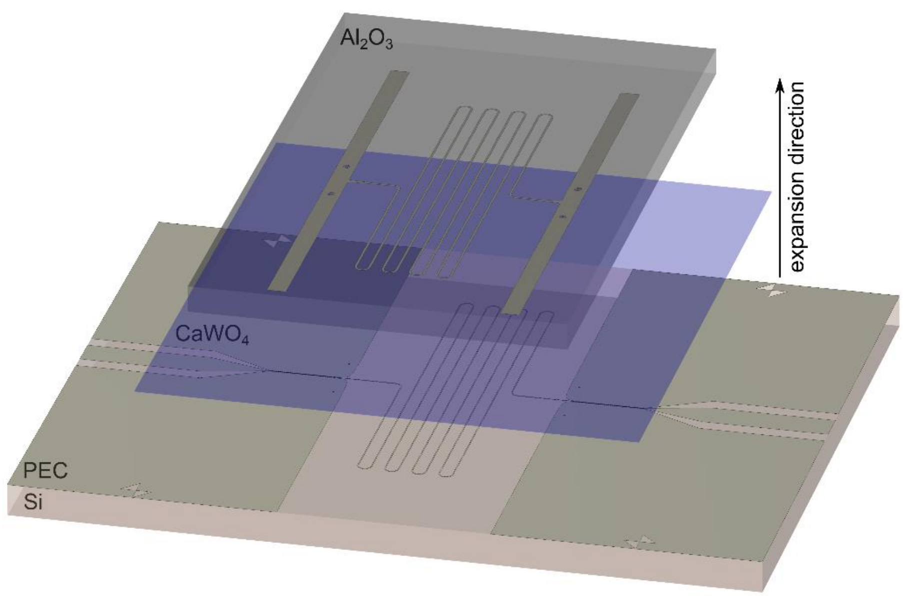


Figure 1. Transmission line using a planar waveguide based on a thin crystalline membrane.

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[2] N. Kukharchyk et al. New J. Phys. **20**, 023044 (2018).

**Broadband electron spin resonance spectroscopy of rare earth spin ensembles at mK temperatures**

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Rare earth spin ensembles are attractive candidates for realizing microwave quantum memories, which can be directly interfaced with superconducting quantum processors, due to their spin coherence times in the millisecond range and transitions at microwave frequencies [1]. One way of operating spin-based quantum memories is by interfacing them with a transmission line, which is considered for multi-mode concepts or atomic frequency comb protocols. In this work, we characterize the spin Hamiltonian of $^{167}Er{:}^{7}LiYF_4$ at mK temperatures using a broadband electron spin resonance (ESR) spectroscopy approach, which enables us to directly measure the hyperfine splitting. Hence, we can precisely identify the quadrupole and hyperfine parameters. This allows for the identification of ZEFOZ (zero first-order Zeeman) transitions, which are the key for implementing microwave quantum memory schemes at low magnetic fields.

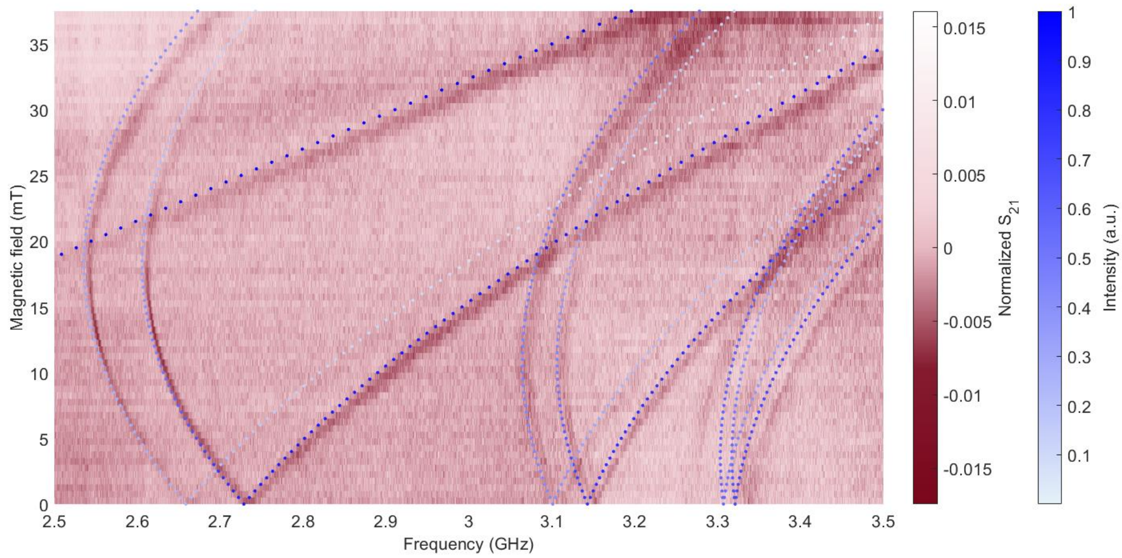


*Figure 1: Hyperfine splitting of $^{167}Er{:}^{7}LiYF_4$ for B ∥ c.*

[1] P.-Y. Li et al., Phys. Rev. Appl. 13, 024080 (2020)

**Erbium emitters in commercially fabricated nanophotonic silicon waveguides**

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Erbium dopants are ideal emitters for large fiber-based quantum networks as they combine long coherence with a telecom-wavelength optical transition. Using silicon as a host may then enable scalable manufacturing of photonic nanostructures, potentially in a nuclear-spin-free material [1]. Previous experiments used samples that were fabricated in an academic clean room, showing promising optical properties [2]. Now, we investigate if this can also be achieved in waveguides that were commercially fabricated as part of a multi-project wafer [3]. We observe a significantly larger, but still narrow inhomogeneous broadening (< 2 GHz). However, the optical transitions exhibit an additional decoherence mechanism that we attribute to paramagnetic impurities. In a 9 T magnetic field, these impurities are frozen, such that narrow homogeneous linewidths (< 30 kHz) are obtained. Our findings thus pave the way for wafer-scale fabrication of quantum network nodes.

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[3] Rinner, S. et al. *Submitted* (2023)

**Spectral and magnetic characterization of erbium sites in silicon nanophotonic waveguides**

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The 4f-electrons of erbium ions within silicon nanophotonic devices present a quantum system with good optical control possibilities on an industrially scalable platform. Our implantation procedure with subsequential annealing leads to an integration into two dominant sites [1] that show narrow inhomogeneous linewidths (around 1 GHz) and short radiative lifetimes (around 0.2 ms). However, a significant spectral diffusion To better understand the broadening mechanisms and Zeeman splitting of the crystal levels, we characterize the symmetry of the magnetic subclasses of the erbium sites using resonant fluorescence spectroscopy. Changing the relative alignment of the externally applied magnetic field vector with respect to the crystal axes provides information on the g-tensor. Furthermore, we use spectral hole-burning to measure the spectral diffusion linewidths and study the spin coherence. These studies define future optimization directions towards quantum networks with erbium in silicon nanostructures.

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# Efficiency trade-off for hybrid on-chip designs using the optical AFC protocol

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**Abstract:** We present a study about cavity designs limiting the overall optical AFC protocol efficiency for quantum memory application. The study is focusing on the hybrid silicon on Er:$Y_2SiO_5$ system. We highlight the importance of the cavity design to support the corresponding forced electric or magnetic dipole moment and discuss this in the context of different guided mode profiles. We identify $Q \cdot \beta$ as the bottleneck and critically reflect its importance on the maximum optical AFC efficiency for this hybrid approach. Finally, we show cavity designs weakening the $Q \cdot \beta$ limitation.

# Emergence of decoherence in rare-earth ion-doped crystals from coupling between ion species

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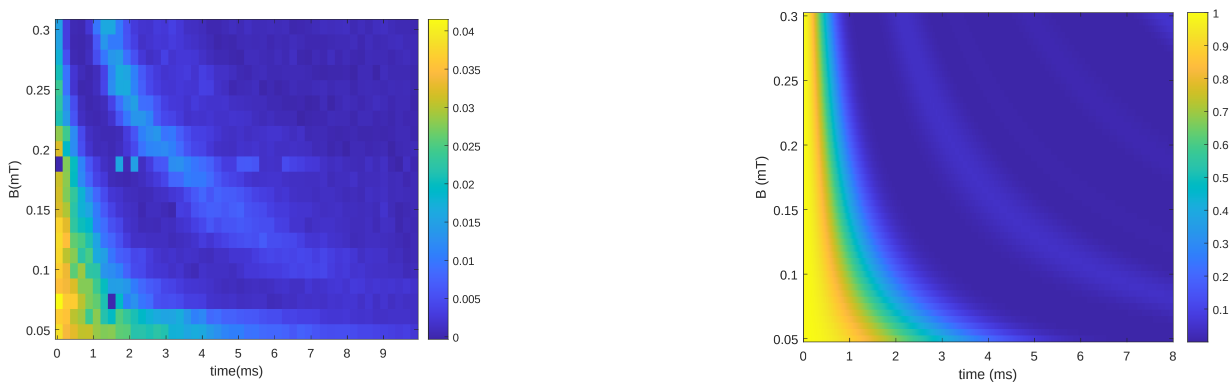
In rare-earth ion-doped crystals, experimental observations showed that the coherence time is heavily dependent on the amplitude and direction of the magnetic field applied on the system [1,2]. However no conclusion have been reached on the ideal working magnetic field regime of each rare-earth ion.

By simulating a system constituted of one rare-earth ion of our choice and the surrounding host matrix ions and their exact interactions and positions, we investigate for different magnetic field choices how the dipole-dipole interaction of the host matrix ions between each other and the rare-earth ion introduce frequencies in the spin echo. This leads to an echo decay and limits the coherence time, in the order of the millisecond for non-Kramers ions.

We then compare our simulations with experimental results in the case of Praseodymium and Ytterbium dopants and reach a satisfactory agreement between both.




(a) (b)

FIGURE 1 – Echo decay as a function of magnetic field amplitude along the $D1$ axis for Ytterbium, a) experimental data [1] and b) simulation.

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# Growth And Optical Spectroscopy Of Praseodymium Ethylsulfate Crystals For Quantum Transduction

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Quantum transducers are fundamental devices to connect quantum processors based on superconducting qubits utilizing the optical fiber network. Crystals doped with low concentrations of rare earth Kramers ions have been exploited to realize microwave-to-optical quantum transduction thanks to their narrow spin and optical inhomogeneous linewidth. Unfortunately, only low efficiency has been achieved so far.

It has been calculated that a great boost in efficiency can be accomplished with the use of stoichiometric rare earth crystals. This can be also achieved using non-Kramers ions in a highly symmetric environment since in this case, non-Kramers ions may possess electronic spin transitions with large dipole moment. In this regard, we have grown $Pr(C_2H_5SO_4)_3 \cdot 9H_2O$ and $Pr{:}La(C_2H_5SO_4)_3 \cdot 9H_2O$ crystals and characterized their optical properties at ultra cryogenic temperatures to assess their possible application for quantum transduction.

**Toward highly efficient integrated quantum memories in rare earth doped crystals**

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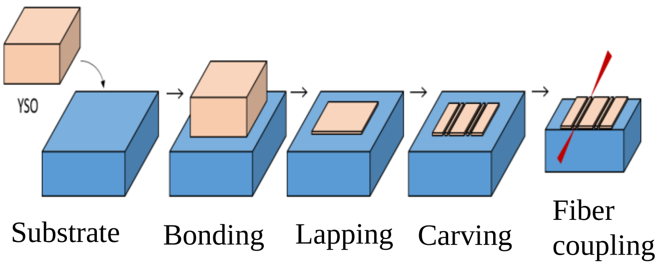
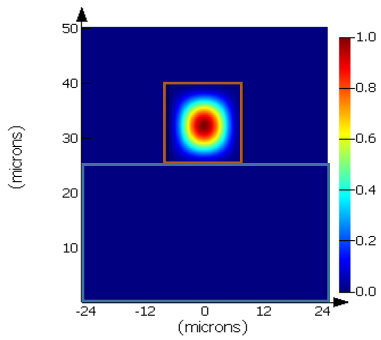
Rare-earth (RE) doped crystals are a promising platform for quantum memories: at cryogenic temperatures they feature narrow optical transitions and long hyperfine coherence time [1]. Current storage experiments in bulk RE doped $Y_2SiO_5$ display limited[2] efficiency for long storage time due to low absorption. Waveguides in RE doped crystals appear as a good solution to enhance light-matter interactions : the optical Rabi frequency can be much higher than the bulk[3]. Moreover, lithography technologies could allow for meander waveguides, thus increasing the optical depth.

For this purpose, we propose to associate YSO to a substrate by adhesive free bonding, then mechanically thin the YSO crystal layer and etch waveguides by dry-etching. Computer simulations will determine the geometry and dimensions of the waveguides' structure. Storage experiments set-up to be operated at 4K, based on end-fire coupling with polarization-controlled fibers is under progress.




Right: Simulation representation of TE00 mode in an Y2SiO5 waveguide on SiO2 substrate

Left: Waveguide fabrication strategy: from bulk YSO crystal to fiber coupled waveguides

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