# Optically Addressable Spin Qubits for Quantum Networks and Quantum Computing

718. WE-Heraeus-Seminar

03 – 07 August 2021 hybrid at the Physikzentrum Bad Honnef



## Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

#### Aims and scope of the 718. WE-Heraeus-Seminar:

Quantum technologies could revolutionize specific areas such as secure communication or computing. The basic building blocks required to realize quantum devices are qubits which can be controlled, interfaced and read out. Optically addressable spins represent a particularly promising choice since they have the proven potential to serve as long-lived qubits, while the optical interface enables efficient and scalable control and readout as well as interconnection of qubits over large distances. In recent years, several material platforms have been demonstrated that allow one to implement single or few spin qubits that serve as the elementary building blocks of quantum devices. Elementary demonstrations of coherent quantum control, spin-photon and spin-spin entanglement, quantum gates, and quantum network primitives could be successfully shown. Still, it remains a challenging task to develop this further towards devices and scalable systems with use for applications e.g. for quantum computation and quantum communication.

The aim of this workshop is to bring together the sub-fields of several promising platforms such as rare-earth-ion-doped solids, color centers in diamond and silicon carbide, quantum dots, and trapped ions, who all share the fundamental aspect of optically addressable spins. The goal is to provide an overview of the experimental and theoretical state-of-the-art with a focus on quantum computing and memory-based quantum communication, and to encourage interactions and exchange of ideas between the different fields..

#### **Scientific Organizers:**

Prof. David Hunger	Karlsruher Institut für Technologie, Germany E-mail: david.hunger@kit.edu
Dr. Andreas Walter	Lund University, Germany E-mail: andreas.walther@fysik.lth.se
Dr. Kangwei Xia	Universität Stuttgart, Germany E-mail: kangwei.xia@pi3.uni-stuttgart.de

## Introduction

## Administrative Organization:

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<u>Registration:</u>	Elisabeth Nowotka (WE Heraeus Foundation) at the Physikzentrum, reception office Tuesday (17:00 h – 21:00 h) and Wednesday morning	

## Tuesday, 03 August 2021

17:00 – 20:00 Registration

18:00 BUFFET SUPPER and get-together

## Wednesday, 04 August 2021

08:00	BREAKFAST	
08:45 – 09:00	Scientific organizers	Welcome words
	Stefan Jorda	About the WE-Heraeus-Foundation
09:00 – 09:45	Jörg Wrachtrup	Narrow photons and coherent spins in semiconducting materials
09:45 – 10:30	Hans Beukers	Realization of a multi-node quantum network of remote solid-state qubits
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:30	Hans Bartling	Entanglement of spin-pair qubits with intrinsic dephasing times exceeding a minute
11:30 – 12:00	Milos Nesladek	Readout of 14N nuclear spin using NV electron spin by photoelectric detection
12:00 – 12:30	Francesco Poggiali	Single-shot readout of NV centers in diamond via cryogenic spin-to-charge conversion
12:30 – 12:40	Conference Photo (in	the front of the lecture hall)

12:40 LUNCH

## Wednesday, 04 August 2021

13:45 – 14:30	Matt Sellars	Linear optics quantum computing with erbium doped crystals: concepts, developments and potential applications
14:30 – 15:15	Klaus Mølmer	Challenges and opportunities with optical networks
15:15 – 15:45	Nadezhda Kukharchyk	Decoherence processes in rare-earth spin ensembles at millikelvin temperatures
15:45 – 16:15	Poster I online	
16:15 – 16:45	COFFEE BREAK	
16:45 – 17:15	Poster I online	
17:15 – 18:00	Andrei Faraon	Towards optical quantum networks with rare earth ions
18:00 – 18:45	Jeff Thompson	Towards quantum networks with individual rare earth ions in nanophotonic structures
19:00	DINNER	
20:00 – 21:00	Poster on site	

## Thursday, 05 August 2021

08:00	BREAKFAST	
09:00 – 09:45	Mikael Afzelius	Optical spin-wave quantum memories based on rare-earth spins in crystals
09:45 – 10:30	Roman Kolesov	Scalable architecture of photonic circuits for fast control of Purcell enhanced quantum emitters
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:30	Chetan Deshmukh	Towards detection of single erbium ions in a tunable fiber micro-cavity
11:30 – 12:00	Andreas Reiserer	Erbium dopants – a novel platform for quantum networks
12:00 – 12:30	Mehmet Tuna Uysal	Coherent control of a single nuclear spin with an Er3+ ion
12:30	LUNCH	

## Thursday, 05 August 2021

13:45 – 14:30	Mikhail Lukin	Towards quantum networking with diamond nanophotonic systems
14:30 – 15:15	Nathalie de Leon	Engineering new solid state quantum defects for quantum networks
15:15 – 15:45	Diana Serrano	Rare-earth molecular crystals with ultra-narrow optical linewidth for photonic quantum technologies
15:45 – 16:15	COFFEE BREAK	
16:15 – 16:45	Zong-Quan Zhou	Quantum repeater and transportable quantum memory based rare-earth ions in solids
16:45 – 17:15	Jelena Rakonjac	Entanglement between a telecom photon and a spin-wave solid-state multimode quantum memory
17:15 – 18:00	Margherita Mazzera	Laser written platforms for integrated solid-state quantum memories for light
18:00 – 18:45	Christoph Simon	Photons and spins from quantum networks to quantum neuroscience
19:00	DINNER	
20:00 – 21:00	Poster II online	

## Friday, 06 August 2021

08:00	BREAKFAST	
09:00 – 09:45	Tracy Northup	Tutorial on trapped ions
09:45 – 10:30	David Lucas	Optical networking of trapped-ion spin qubits for quantum computing, communication and clocks
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:30	Gabriel Araneda	A two-node trapped-ion quantum network with photonics interconnects
11:30 – 12:00	Vadim Vorobyov	Programmable quantum register based on NV center in diamond and nuclear spins
12:00 – 12:30	Andreas Walter	Roadmap for rare-earth quantum computing
12:30	LUNCH	

## Friday, 06 August 2021

13:45 – 14:30	Claire Le Gall	Nuclear spins in quantum dots: Turning a noise source into a resource
14:30 – 15:15	Charles Babin	Nanofabricated and integrated colour centres in SiC with high-coherence spin-optical properties
15:15 – 15:45	Georgy Astakhov	Inverted excited-state structure of a SiC qubit enabling spin-photon interface
15:45 – 16:15	COFFEE BREAK	
16:15 – 16:45	Julian Bopp	Design of novel waveguide-coupled diamond nanostructures for efficient photonic integration
16:45 – 17:15	Matteo Pasini	Towards an efficient spin-photon interface based on tin-vacancy centres in diamond
17:15 – 18:00	Guido Burkard	Nuclear spin quantum memories in Silicon and SiC
18:00 – 18:45	David Awschalom	Scaling quantum systems with silicon carbide and molecules
	HERAEUS DINNER	

19:00 (social event with cold & warm buffet with complimentary drinks)

## Saturday, 07 August 2021

08:00	BREAKFAST	
09:00 – 09:45	Markus Hennrich	Sub-microsecond trapped ion quantum gates via Rydberg interaction
09:45 – 10:30	Tim Taminiau	Quantum processors based on spins in diamond
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:45	Wolfgang Wernsdorfer	Operating quantum states in individual magnetic molecules
11:45– 12:30	Scientific organizers	Panel discussion
		Poster prizes, conclusion

12:30 LUNCH

### End of the seminar and departure

**REI Workshop** (see separate schedule)

## Posters

## Posters Online I: Wednesday, 4 August, 15:45 h CET

Alexander Abulnaga	Heterogenous III-V on diamond nanophotonic platform for telecom quantum nodes based on neutral silicon vacancy centers in diamond
Georgy Astakhov	Inverted excited-state structure of a SiC qubit enabling spin-photon interface
Yoann Baron	Broad diversity of near-infrared single-photon emitters in silicon
Eduardo Beattie Chetan Deshmukh	Towards detection of single erbium ions in a tunable fiber micro-cavity
Yonder Berencén	Telecom single-photon emitters in silicon for scalable quantum photonics
Matthew Berrington	Optical spectroscopy of lithium erbium fluoride, an antiferromagnetic crystal
Sören Bieling Timon Eichhorn	Towards cavity-enhanced spectroscopy of single Europium ions in Yttria nanocrystals
Julia Brevoord Nina Codreanu	Photonic crystal cavities for spin-photon enhancement of color centers in diamond
Moritz Businger	Towards broadband quantum memory at the single photon level
Zihua Chai	Resonant quantum principal component analysis
Nathan Coste	Monitoring of Larmor precession of a single spin in a semiconductor quantum dot
Durga Dasari	Generation of multipartite entanglement using spin-photon interfaces

## Posters Online I: Wednesday, 4 August, 15:45 h CET

Nicolas Demetriou	Realisation of electron-spin-pair qubit in diamond
Jonas Foglszinger	Atomic scale sensor for magnetic fields using TR12 centers
Jianpei Geng	Ancilla assisted discrete quantum time crystal with nitrogen-vacancy center in diamond
Andreas Gritsch	Coupling erbium dopants to nanophotonic silicon structures
Jan F. Haase	Controllable non-markovianity for a spin qubit in diamond
Jannis Hessenauer Evgenij Vasilenko	Fully fiber coupled devices for efficient cryogenic spectroscopy of single and small ensembles of rare earth ions
Michael Hollenbach	Focused ion beam writing of color centers for quantum spin-photonic applications
Minsik Kwon	Toward on-demand control of charge state dynamics and spin polarization control of electron-nuclear spin system of NV center in diamond
Qiang Li	Room temperature coherent manipulation of single- spin qubits in SiC with a high readout contrast
Di Liu	Resonant excited-state spectroscopy and quantum efficiency of single silicon vacancies in silicon carbide
Xiao Liu	Heralded entanglement distribution between two absorptive quantum memories
Sjoerd Loenen	Entanglement of dark electron-nuclear spin defects in diamond

## Posters Online II: Thursday, 5 August, 20:00 h CET

Elham Mehdi	Measuring spin noise with a single spin and single detected photons
Naoya Morioka	Advanced approach to spin-selective intersystem- crossing rates and application to silicon vacancy center in silicon carbide
Robert Morsch	Indistinguishable single photons from negatively charged tin-vacancy centres in diamond
Louis Nicolas	Long coherence time electronic spin transitions at low magnetic field for large bandwidth quantum memories
Laura Orphal-Kobin	Spectral properties of single NV defect centers in diamond nanostructures
Maximilian Pallmann	Development of a coherent spin photon interface for quantum repeaters using NV centers in diamond
Maximilian Ruf	Enhancing the spin-photon interface of color centers in diamond for quantum networks
Fiammetta Sardi	High-speed tunable microcavities coupled to rare- earth quantum emitters
Markus Stabel	Solid-state few-photon storage on a second timescale using electromagnetically induced transparency
Philipp Stammer	Quantum information theory meets strong field physics via high harmonic generation
Timo Steidl	Shallow implantation of color centers in silicon carbide with high-coherence spin-optical properties

## Posters Online II: Thursday, 5 August, 20:00 h CET

Ana Strinic	Implementing frequency comb protocol into the purely microwave regime
Benedikt Tissot	Hyperfine structure of transition metal defects in SiC
Cem Güney Torun	Optimized diamond inverted nanocones for enhanced color center to fiber coupling
Alexander Ulanowski	Controlling single Erbium dopants in a Fabry-Perot resonator
Sacha Welinski	Stable and low-spurious laser source for fast addressing multiple optical qubits spread over a 100 GHz bandwidth
Sören Wengerowsky	Towards high-efficiency cavity enhanced atomic frequency comb quantum memories
Chun-Ju Wu	Single ion detection utilizing a gaas hybrid photonic crystal cavity on Yb <sup>3+</sup> :YVO4
Dayou Yang	Criticality enhanced quantum sensing via continuous measurement
Xin-Yue Zhang	AC susceptometry of 2D van der Waals magnets enabled by the coherent control of quantum sensors
Zihuai Zhang	Optically detected magnetic resonance in neutral silicon vacancy centers in diamond via bound exciton states

## **Abstracts of Talks**

(in alphabetical order)

## Optical spin-wave quantum memories based on rare-earth spins in crystals

#### **M. Afzelius**

University of Geneva, Geneva, Switzerland

Long-distance quantum communication via quantum repeaters requires quantum memories that are long-lived, efficient, and highly multimode. Long duration storage can be obtained by storing optical quantum states in so-called spin waves, that is collective excitations of spins. Solid-state spin-wave memories can be based on either nuclear or electronic spin excitations. These have different strengths and drawbacks, mainly in terms of coherence lifetime and bandwidth. In this talk I will describe our work on nuclear spin quantum memories in <sup>151</sup>Eu<sup>3+</sup>:Y<sub>2</sub>SiO5, where we have recently achieved storage of multimode quantum correlations for up to 20 ms using dynamical decoupling techniques on the nuclear spin states. I will also describe our work on a new promising rare-earth ion with an electronic spin, <sup>171</sup>Yb<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub>. We recently showed that the electronic hyperfine levels in <sup>171</sup>Yb<sup>3+</sup> behave like "clock" states, which results in optical and spin coherence times similar to nuclear states while having large energy spacings in the GHz regime that could be used for broadband quantum memories.

#### A two-node trapped-ion quantum network with photonics interconnects

<u>G. Araneda</u>,\* D. P. Nadlinger, B. C. Nichol, P. Drmota, D. Main, R. Srinivas, C. J. Ballance, and D. M. Lucas Clarendon Laboratory, University of Oxford, United Kingdom

Trapped ions are a leading platform for quantum computing due to the long coherence time, high-level of control of internal and external degrees of freedom, and the natural full connectivity between qubits. Single and multi-qubit operations have been performed with high fidelity (> 99.9%), which has enabled the demonstration of small universal quantum computers ( $\sim$ 10 atoms). However, scaling up to bigger sizes remains a challenge.

In our experiment we aim to demonstrate the first operational and fully controllable two-node quantum computer, where each node is small scale quantum processors ( $\sim$ 5 ions) connected via photonic entanglement. We use two ion traps systems separated by  $\sim$ 2 m, where we confine mixed chains of Strontium and Calcium ions [1]. Calcium-43 has excellent qubit coherence properties, while Strontium-88 has convenient internal structure for generating photonic entanglement. Single 422 nm photons emitted by the Strontium ion are used to generate remote entanglement. We recently have achieved a remote Strontium-Strontium entanglement fidelity of 96.0(2)% at a rate of 100 entangled events/s, and a average CHSH violation of 2.65.

In this talk I will present our current work on the implementation of high-fidelity local Calcium-Strontium entangling gates, to swap the remote Strontium-Strontium entanglement into Calcium-Calcium remote entanglement. Thereafter, creating a second pair of remotely entangled ions will allow us to perform entanglement distillation to create high-fidelity remote entanglement [2], at the same fidelity of local entangling operations (> 99%), which together with a a universal set of local gates will be use to demonstrate the first two-node quantum computer.

Furthermore, I will present our preliminary results on the demonstration of secure quantum communications between the nodes of our network certified by continuous violation of the CHSH inequality.



Figure 1: Two-node trapped-ion quantum network with photonic connections.a) Photons emitted spontaneously at 422 nm are entangled with the state of the ion after the emission ( $|0\rangle$  or  $|1\rangle$ ). b) Two identical ion trap systems, 'Alice' and 'Bob', are equipped with micro-fabricated segmented traps. Each system can trap both <sup>43</sup>Ca<sup>+</sup> and <sup>88</sup>Sr<sup>+</sup> ions in different potential wells. Individual ion control of the internal states of the ions is achieved using lasers (not shown in the figure). To create entanglement between Alice and Bob, creation of atom-photon entanglement is synchronized, and a Bell measurement of the photons' polarization using the 'entangler' apparatus is performed. Ions not to scale.

#### References.

[1] Stephenson, L. J., et al. "High-rate, high-fidelity entanglement of qubits across an elementary quantum network'." Physical Review Letters 124, 11 (2020). [2] Nigmatullin, R., et al. "Minimally complex ion traps as modules for quantum communication and computing." New Journal of Physics 18, 10 (2016).

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# Scaling quantum systems with silicon carbide and molecules

#### David D. Awschalom<sup>1</sup>

<sup>1</sup>Pritzker School of Molecular Engineering, University of Chicago, Chicago, IL, 60637 USA

Scaling spin-based quantum technologies requires new platforms for creating and controlling quantum states. We begin with the divacancy defect (VV0) in silicon carbide (SiC), which combines long lived spin states with a tunable optical interface. First, we leverage the semiconducting host material by integrating single spin qubits into wafer-scale, commercial optoelectronic devices, enabling near terahertz-scale tuning and a mitigation of spectral diffusion in the defect's optical structure [1].

We then discuss various strategies to extend the coherence of these spin qubits including isotopic purification, clock transitions, pulsed dynamical decoupling, and continuous driving to engineer a decoherence protected subspace [2,3]. These subspaces are decoupled from the major sources of noise, resulting in an over 10,000 times improvement in coherence [3]. Finally, we demonstrate the control and entanglement of a single nuclear spin with an electron spin in SiC. These nuclear memories can further extend coherence and enable multi-qubit quantum registers [2]. This protocol requires few key platform-independent components, suggesting that substantial coherence improvements can be achieved in a wide selection of quantum architectures.

Optically addressable spin qubits can also be created, engineered, and scaled through a purely synthetic chemical approach. Moreover, these structures offer new opportunities to construct hybrid systems. We demonstrate the optical initialization and readout, and coherent control, of ground-state spins in organometallic molecules [4]. This bottom-up approach offers avenues to create designer qubits and to deploy the diverse capabilities of chemical synthesis for scalable quantum and hybrid quantum systems.

- [1] C. P. Anderson\* and A. Bourassa\* et al., *Science* **366**, 6470, 1225 (2019)
- [2] A. Bourassa\* and C. P. Anderson\* et al., *Nature Materials* **19**, 1319 (2020)
- [3] K. Miao et al., Science 369, 1493 (2020)
- [4] S. L. Bayliss\*, D. W. Laorenza\*, et al., Science 370, 1309 (2020)

# Nanofabricated and integrated colour centres in SiC with high-coherence spin-optical properties

<u>C. Babin<sup>1</sup></u>, R. Stöhr<sup>1</sup>, N. Morioka<sup>1,2</sup>, T. Linkewitz<sup>1</sup>, T. Steidl<sup>1</sup>, R. Wörnle<sup>1</sup>, D. Liu<sup>1</sup>, V. Vorobyov<sup>1</sup>, A. Denisenko<sup>1</sup>, M. Hentschel<sup>3</sup>, C. Gobert<sup>4</sup>, P. Berwian<sup>4</sup>, G. Astakhov<sup>5</sup>, W. Knolle<sup>6</sup>, S. Majety<sup>7</sup>, P. Saha<sup>7</sup>, M. Radulaski<sup>7</sup>, N. Tien Son<sup>8</sup>, J. UI-Hassan<sup>8</sup>, F. Kaiser<sup>1</sup>, J. Wrachtrup<sup>1</sup>

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<sup>7</sup> Department of Electrical and Computer Engineering, University of California, USA
 <sup>8</sup> Department of Physics, Chemistry and Biology, Linköping University, Sweden

Optically active spins in the solid are an emerging platform for advanced quantum information processing [1]. To overcome the inherent low light collection efficiency from such systems, colour centre integration into nanophotonic resonators is mandatory [2]. In this regard, the major challenges remain protecting spin-optical coherences against surface charge fluctuations, fabrication-related crystal damage, and thermal heating issues during spin control. Here, we demonstrate that silicon vacancy (V<sub>Si</sub>) centres in semiconductor silicon carbide (SiC) [3-6] are prime candidates to overcome these issues. We show that ion-assisted implantation and integration into nonfabricated triangular cross-section waveguides do not degrade the spin-optical coherences, i.e., we observe nearly lifetime limited optical absorption lines and millisecond spin coherence times (Hahn echo). Our results represent the first successful integration of colour centres without inversion symmetry into nanophotonics structures. Further, capitalizing on the V<sub>Si</sub>'s exceptionally high operation temperature (T = 20 K) [7], we control multiple nuclear spin gubits with near unity fidelity without heating issues. Our work is a major step forward towards integrated multi-spin-multi-photon interfaces for distributed quantum computation and communication.

- [1] D.D. Awschalom et al., Nat. Photonics 12, 516 (2018)
- [2] E. Janitz et al., Optica 7, 1232 (2020)
- [3] R. Nagy et al., *Nat. Commun.* **10**, 1954 (2019)
- [4] N. Morioka et al., Nat. Commun. 11, 2516 (2020)
- [5] D. Lukin et al., npj Quant. Inf. 6, 80 (2020)
- [6] R. Nagy et al., Appl. Phys. Lett. 118, 144003 (2021)
- [7] P. Udvarhelyi et al., Phys. Rev. Appl. 13, 054017 (2020)

# Entanglement of spin-pair qubits with intrinsic dephasing times exceeding a minute

# <u>H.P. Bartling<sup>1,2</sup></u>, M.H. Abobeih<sup>1,2</sup>, B. Pingault<sup>1,2,3</sup>, M.J. Degen<sup>1,2</sup>, S.J.H. Loenen<sup>1,2</sup>, C.E. Bradley<sup>1,2</sup>, J. Randall<sup>1,2</sup>, M. Markham<sup>4</sup>, D.J. Twitchen<sup>4</sup> and T. H. Taminiau<sup>1,2</sup>

<sup>1</sup>QuTech, Delft University of Technology, Delft, The Netherlands <sup>2</sup>Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands <sup>3</sup>John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, USA <sup>4</sup>Element Six, Didcot, United Kingdom

Understanding and protecting the coherence of solid-state spin qubits is a central challenge for quantum technologies. Over the last decades, a rich variety of methods to extend coherence have been developed. A complementary approach is to look for naturally occurring systems that are inherently protected against decoherence. Here, we show that pairs of identical nuclear spins in solids form intrinsically long-lived qubits. We study three carbon-13 pairs in diamond and realize high-fidelity measurements of their quantum states using a single NV center in their vicinity. We then reveal that the spin pairs are robust to external perturbations due to a unique combination of three phenomena: a decoherence-free subspace, a clock transition, and a variant on motional narrowing. The resulting inhomogeneous dephasing time is  $T_2^* = 1.9(3)$  minutes, the longest reported for individually controlled qubits. Finally, we develop complete control and realize an entangled state between two spin-pair qubits through projective parity measurements. These long-lived qubits are abundantly present in diamond and other solids, and provide new opportunities for quantum sensing, quantum information processing, and quantum networks.

### References

See also arXiv:2103.07961.

## Realization of a multi-node quantum network of remote solid-state qubits

<u>H.K.C. Beukers</u><sup>1,2</sup>, M. Pompili<sup>1,2</sup>, S.L.N. Hermans<sup>1,2</sup>, S. Baier<sup>1,2</sup>, P.C. Humphreys<sup>1,2</sup>, R.N. Schouten<sup>1,2</sup>, R.F.L. Vermeulen<sup>1,2</sup>, M.J. Tiggelman<sup>1,2</sup>, L. dos Santos Martins<sup>1,2</sup>, B. Dirkse<sup>1,2</sup>, S. Wehner<sup>1,2</sup>, R. Hanson<sup>1,2</sup>

<sup>1</sup>QuTech, Delft University of Technology, Delft, Netherlands. <sup>2</sup>Kavli Institute of Nanoscience, Delft University of Technology, Delft, Netherlands.

Future quantum networks [1] may harness the unique features of entanglement in a range of exciting applications, such as quantum computation and simulation, secure communication, enhanced metrology for astronomy and time-keeping as well as fundamental investigations. To fulfill these promises, a strong worldwide effort is ongoing to gain precise control over the full quantum dynamics of multi-particle nodes and to wire them up using quantum-photonic channels. So far, the entanglement-based quantum networks have been limited to two network nodes.

Here we report on the experimental realization of a three-node entanglement-based quantum network [2]. We combine remote quantum nodes with communication qubits based on nitrogen-vacancy centers in diamond into a scalable phase-stabilized architecture. This is supplemented with a robust memory qubit, implemented with a

nuclear carbon-13 spin, and local quantum logic. In addition, we achieve real-time communication and feedforward gate operations across the network. We capitalize on the novel capabilities of this network to realize two canonical protocols without postselection: the distribution of genuine multipartite entangled states across the three nodes and entanglement swapping through an intermediary node. Our work establishes a key platform for exploring, testing and developing multinode quantum network protocols and a quantum network control stack.



[1] S. Wehner, D. Elkouss, R. Hanson, Science 362, eaam9288 (2018).
[2] M. Pompili, S.L.N. Hermans, S. Baier, H.K.C. Beukers et al., Science 372, 259-264 (2021).

## Design of Novel Waveguide-coupled Diamond Nanostructures for Efficient Photonic Integration

<u>J. M. Bopp<sup>1,2</sup>, M. Plock<sup>3</sup>, M. van der Hoeven<sup>1</sup>, T. Pregnolato<sup>2</sup>, S. Burger<sup>3,4</sup> and T. Schröder<sup>1,2</sup></u>

<sup>1</sup>Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany <sup>2</sup>Ferdinand-Braun-Institut, Berlin, Germany <sup>3</sup>Zuse Institute Berlin (ZIB), Berlin, Germany <sup>4</sup>JCMwave GmbH, Berlin, Germany

Defect centers in diamond have revealed outstanding properties that make them promising candidates for being used as quantum memories [1] and quantum emitters. Likewise, photonic integrated circuits (PICs) allow for scalable miniaturized and stable optical systems [2]. Bringing both approaches together is likely to lead in future to the possibility of assembling complex quantum information processing systems with high fabrication yield. Nowadays, it is still challenging to integrate pieces of diamond into on-chip optical waveguides in a scalable manner. However, efficient integration is essential for using them in complex PICs. Furthermore, it is challenging to provide high coupling efficiencies between light emitted from a single defect center located in a diamond cavity and a travelling light mode of a connected waveguide [3].

Here, we present our progress towards increasing the interaction strength between single defect centers in diamond and light fields by embedding the defect centers in new types of waveguide-integrated resonators with high quality factors and possibly low mode volumes. We carefully examine different design parameters of the waveguide-coupled resonator in order to ensure efficient adiabatic coupling and propose a way for deterministic high-yield fabrication of the developed nanostructures.

- [1] S. Mouradian *et al.*, Phys. Rev. X 5, 031009 (2015)
- [2] N. H. Wan et al., Nature 583, pp. 226-231 (2020)
- [3] S. Mouradian *et al.*, Appl. Phys. Lett. **111**, 021103 (2017)

## Nuclear spin quantum memories in Silicon and SiC <u>G. Burkard</u>

Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

Nuclear spins in solids show long coherence times and could therefore be employed as quantum memories in quantum processors or quantum networks. However, their good isolation from the environment also makes it challenging to prepare and measure (i.e., write and read) nuclear spins, or to coherently transfer information to and from electronic or photonic gubits. We have developed and modelled a method for the readout of a phosphorous donor nuclear spin by probing the transmission of a microwave resonator coupled to a silicon quantum dot-donor system subjected to a transverse magnetic field gradient. We have identified optimal readout points with strong signal contrast to facilitate the implementation of nuclear spin readout. Furthermore, we investigate the potential for achieving coherent excitation exchange between a nuclear spin qubit and microwave cavity photons. A different approach is possible for transition metal (TM) defects in silicon carbide (SiC) that represent another promising platform in quantum technology, especially because some TM defects emit in the optical spectrum into one of the telecom bands. We present a theory for the interaction of an active electron in the D-shell of a TM defect in SiC with the TM nuclear spin and derive the effective hyperfine tensor within the Kramers doublets formed by the spin-orbit coupling [2,3]. Based on our theory we discuss the possibility to exchange the nuclear and electron states with potential applications for nuclear spin manipulation and long-lived nuclear-spin based quantum memories.

- [1] J. Mielke, J. R. Petta, and G. Burkard, *Nuclear spin readout in a cavity-coupled silicon double quantum dot*, accepted for PRX Quantum [arxiv:2012.01322]
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## Engineering new solid state quantum defects for quantum networks

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Engineering coherent systems is a central goal of quantum science and quantum information processing. Point defects in diamond known as color centers are a promising physical platform. As atom-like systems, they can exhibit excellent spin coherence and can be manipulated with light. As solid-state defects, they can be produced at high densities and incorporated into scalable devices. Diamond is a uniquely excellent host: it has a large band gap, can be synthesized with sub-ppb impurity concentrations, and can be isotopically purified to eliminate magnetic noise from nuclear spins. Currently-known color centers either exhibit long spin coherence times or efficient, coherent optical transitions, but not both. We have developed new methods to control the diamond Fermi level in order to stabilize a new color center, the neutral charge state of the silicon vacancy (SiV) center [1,2]. This center exhibits both the excellent optical properties of the negatively charged SiV center and the long spin coherence times of the NV center, making it a promising candidate for applications as a single atom quantum memory for long distance quantum communication. We have recently discovered bound exciton transitions associated with SiV<sup>0</sup>, which enable efficient optical spin polarization and optically detected magnetic resonance [3]. Finally, I will describe our efforts to integrate SiV<sup>0</sup> centers in nanophotonic devices, specifically in heterogeneously integrated III-V/diamond nanophotonic platforms designed to enhance the atom-photon interaction and achieve quantum frequency conversion to the telecom band [4].

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# Towards detection of single erbium ions in a tunable fiber micro-cavity

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Rare-earth ion-doped crystals constitute a promising platform for quantum information processing and networking. They feature exceptional spin coherence times to store information, narrow optical transitions to act as an interface to optical photons, and possibilities to realize quantum gates between single ion qubits. Coupling quantum emitters to optical cavities enables channeling the emission from the emitters into the cavity mode while decreasing their emission lifetime. This allows the realization of an efficient and high-rate spin-photon interface, while also increasing the indistinguishability of the emitted photons in the presence of dephasing.

In this work, by utilizing erbium-doped nanoparticles that emit at telecom wavelengths coupled to a fully tunable high-finesse fiber-based microcavity in a cryostat, we demonstrate an average Purcell factor greater than 100 for a very small ensemble of erbium ions (Purcell enhanced lifetime of 90  $\mu$ s). Frequency selective excitation followed by fluorescence detection results in discrete features which indicate the sensitivity of the setup to few ions. Next steps involve isolating one such feature in a sparsely populated spectral region of the inhomogeneous line and measuring the auto-correlation function of the emitted photons. The presence of one or few ions can then be induced from the value of this function.

We have demonstrated with the previous version of our setup that we can control the Purcell factor and hence the emission rate of the ions on a timescale of hundreds of microseconds. Our current setup should enable us to reduce this time to a few tens of microseconds. If implemented at the single ion level, this ability will enable the generation of fully tunable narrowband single photons at telecom wavelengths, and quantum processing using single rare-earth-ions.

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## Towards Optical Quantum Networks with Rare Earth Ions

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Quantum optical networks will enable distribution of quantum entanglement at long distances, with applications including interconnects between future quantum computers and secure quantum communications. I will present our recent work on developing quantum networking components based on rare-earth ions, with a focus on devices based on single ytterbium 171 in yttrium orthovanadate which exhibits long spin coherence times, stable optical transitions and can access Vanadium nuclear spin local quantum memory registers.

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# Sub-microsecond trapped ion quantum gates via Rydberg interaction

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Trapped Rydberg ions are a novel approach for quantum information processing [1,2]. This idea joins the advanced quantum control of trapped ions with the strong dipolar interaction between Rydberg atoms. For trapped ions, this method promises to speed up entangling interactions and to enable such operations in larger ion crystals.

In this presentation, we report on the realization of fast Rydberg ion quantum operations. We have coherently excited trapped ions to Rydberg states [3], have investigated the effects of the trapping field on the Rydberg state, and recently we have realized a sub-microsecond entanglement gate between trapped ions via Rydberg interaction [4]. These are important results that enable fast quantum processors with trapped Rydberg ions.

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# Scalable architecture of photonic circuits for fast control of Purcell enhanced quantum emitters

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Electro-optical control of on-chip photonic devices is an essential tool for efficient integrated photonics. Lithium niobate on insulator (LNOI) is an emerging platform for on-chip photonics due to its large electro-optic coefficient and high nonlinearity. Integrating quantum emitters into LNOI would extend their versatile use in classic photonics to quantum computing and communication.

Here, we incorporate single rare-earth ions (REI) quantum emitters in electro-optical tunable lithium niobate (LN) thin films and demonstrate control of LN micro-cavities coupled to REI over a frequency range of 160 GHz with 5 µs switching speed. Dynamical control of the cavities enables the modulation of the Purcell enhancement of the REIs with short time constants. Using the Purcell enhancement, we show evidence of detecting single Yb<sup>3+</sup> ions in LNOI cavities. Coupling quantum emitters in fast tunable photonic devices is an efficient method to shape the waveform of the emitter. It also offers a platform to encode quantum information in the integration of a spectral-temporal-spatial domain to achieve high levels of channel multiplexing, as well as an approach to generate deterministic single-photon sources.

In addition, we discuss prospects of creating hybrid material systems combining the advantages of rapid tunability of LNOI and ultra-long coherence times of REIs in low-spin hosts, such as yttrium orthosilicate (YSO).

## Decoherence processes in rare-earth spin ensembles at millikelvin temperatures

#### <u>N. Kukharchyk<sup>1,2,3</sup></u>, D. Sholokhov<sup>3</sup>, O. Morozov<sup>4</sup>, S. L. Korableva<sup>4</sup>, A. A. Kalachev<sup>5</sup>, and P. A. Bushev<sup>3,6</sup>

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Rare-earth-doped crystals are promising candidates with a great variety of their potential applications in quantum information processing and quantum communications ranging from optical/microwave quantum memories to circuit QED and microwave-tooptics frequency converters. Some of the above listed applications require ultra-low temperature environment, i.e. temperatures below 0.1 K. Most of the experiments with erbium doped crystals have been so far carried out at temperatures above 1.5 K. Therefore, only little about erbium information is known coherence properties at millikelvin temperatures. We investigated optical decoherence processes of  $^{167}$ Er:Y<sub>2</sub>SiO<sub>5</sub>[1], <sup>166</sup>Er:<sup>7</sup>LiYF<sub>4</sub>[2] <sup>167</sup>Er:<sup>7</sup>LiYF<sub>4</sub>[3] and by crystals performing 2- and 3-pulse echo experiments and EIT at sub-Kelvin temperature range and at weak and moderate magnetic fields. We show that the deep freezing of the crystal results in an increase of optical coherence time by one order of magnitude compared to 1.5 Kelvin and of 0.2 T, taken as a reference point. We further describe the detailed investigation of the decoherence mechanisms in this regime including the detailed analysis of the phonon mediated processes.

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**Figure 1.** (a) Relaxation rate dependence on the magnetic field and temperature.

(b) Electromagnetically induced transparency at low magnetic field at the ZEFOR point.

# Nuclear spins in quantum dots: Turning a noise source into a resource.

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Interfaces between single photons and single spins underpin the promise of flexible quantum architectures and unconditional security for communication. Their versatility arises from our ability to measure the spin information deterministically and use photons to generate entanglement between spins over large distances. Using leading solid-state systems, semiconductor quantum dots (QDs) and Nitrogen Vacancies in diamond, important milestones have been reached [1]. In the case of QDs, their near-ideal optical properties have allowed to distribute entanglement at an unprecedented rate of 7.3 kHz. Thus far, fewer praises can be sung about their spin coherence. The electron couples to a mesoscopic ensemble of N~100,000 nuclei and gaining control over this many-body system to the point where nuclei are a resource is a frontier challenge in the field.

In this talk, I will present our latest advances in gaining control and understanding of this mesoscopic ensemble [2, 3]. Semiconductor quantum dots are a physical realization of a central-spin system, where the electron spin can be operated both as a control and a probe over the dense ensemble of nuclear spins within the QD. This talk will introduce how we can engineer all-optically a "flip-flop" interaction term between the electron and the nuclei and control the interaction strength. Further, I will present our latest experimental progress on manipulating and characterizing the nuclear spin state, specifically the manifestation of subradiance in optically tailored polarised nuclear states [4]. At last, I will report on our latest experiments with lattice-matched GaAs/AlGaAs QDs which feature a highly coherent nuclear spin ensemble. Nuclear spins in GaAs/AlGaAs QDs have recently been exploited for NMR quantum computing [5], and we believe they could also serve as a collective quantum memory [6], opening pathways to scalability for QD-based quantum networks.

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# Optical networking of trapped-ion spin qubits for quantum computing, communication and clocks

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We have recently constructed a two-node quantum network, allowing optical interfacing of trapped-ion spin qubits. Remote entangled states of the qubits can be prepared with both high fidelity (94%) and rate (180/sec), as described in [1].

For applications such as entanglement distillation, different ion species can be used as "optical interface" qubits and "memory" qubits; we have demonstrated local entangling operations between these different ion species with fidelities of up to 99.8% [2]. Distillation should allow the fidelity of the optical link to approach that of the local operations.

Applications of a simple two-node network include quantum key distribution, and entanglement-enhanced spectroscopy for comparing optical atomic clocks. Preliminary results on this work will be presented [see also the separate talk by G.Araneda].

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## Towards quantum networking with diamond nanophotonic systems

### M. Lukin<sup>1</sup>

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We will report on our progress towards realization of quantum networking systems based on color centers in diamond. Specifically, we will describe experimental realization of memory-enhanced quantum communication, which utilizes a solid-state spin memory integrated in a nanophotonic diamond resonator to implement asynchronous Bell-state measurements. This enables a four-fold increase in the secret key rate of measurement device independent quantum key distribution over the loss-equivalent direct-transmission method while operating at megahertz clock rates. In addition, recent advances demonstrating optical entanglement of distinguishable quantum emitters and realization of high quality single photon sources will be described. Prospects for scaling up these techniques, including realization of larger quantum processors and quantum networks will be discussed.

## Laser written platforms for integrated solid-state quantum memories for light

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The coherent interaction between photons and atoms lays the bases of quantum information science, whose purpose is to open new possibilities for the transmission and the processing of information. It is crucial, e.g., for the realisation of quantum networks. Solid-state systems have emerged as promising platforms; more specifically rare earth ion doped crystals are one of the most interesting candidates. The implementation of quantum memory protocols in waveguide has the potential of opening further avenues towards scalable quantum information protocols using complex quantum photonic circuits on chip. In this contribution, I will review a successful strategy to develop integrated quantum devices using Pr<sup>3+</sup>: YSO, a material that has proved promising for quantum light generation [1] and storage [2]. I will report on the demonstration of a platform for quantum light storage based on laser written waveguides in a writing regime that enables improved confining capabilities [3] compared to other laser written demonstrations [4]. I will show how it opens the way for spatial and frequency multiplexing in guantum storage protocol [5], besides the remarkable advantages that this platform offers with respect to other integrated designs, such as the compatibility with fibre cords and the 3D capability. I will also report on the recent advances towards the on-demand storage of single photon level light. Finally, I will show that this type of laser written waveguides (type I) can be machined to guide light in a wide range of wavelengths and at different polarization, thanks to a substantial improvement of the fabrication process. This, on the one hand, opens the possibility of realising integrated quantum memories with other crystals, e.g. Yb or Er doped YSO, thus making our technology ion agnostic. On the other, it allows using the crossed light field polarisation as an additional tool to filter the noise excess in on-demand storage protocols [6].

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#### Challenges and opportunities with optical networks

#### Klaus Mølmer

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I shall review some recent ideas to mitigate the challenges for quantum computers and quantum networks that are based on optically addressable spins. Some strategies for improvement of matter-light interfaces imply proposals for entirely new schemes in complex networks that integrate communication and multi-qubit gates on quantum states. Finally, I shall share my "favorite concern for many years" about the casual way that we often deal with the interaction of stationary matter qubits and light pulses. I shall highlight some important complications and their resolution by new quantum optical methods, and some surprising new possibilities.
#### Readout of <sup>14</sup>N Nuclear Spin Using NV Electron Spin by Photoelectric Detection

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Nuclear spins in diamond represent an interesting spin system for exploring quantum information science applications due to their attractive long coherence times and the possibility to control and read them via near-by electron spin of the nitrogen- vacancy (NV) centre. Here we accomplished a photoelectrical readout of a unit composed of a single <sup>14</sup>N nuclear spin, coupled to the NV electron spin employing two-qubit gates. The electron spins are polarised at the NV Excited State Level Anticrossing (ESLAC). Both the MW assisted, and the MW-free readout are used. The demonstration of a basic spin processor unit is a step towards larger-scale integrable diamond quantum devices using electrical spin-state readout in solid-state [1,2]. The advantage of the presented method is its compactness and integrability with microelectronic platforms, as well as working below the confocal resolution of optical microscopes, allowing thus potentially to scale-up the unit by electron spin dipole-dipole interactions.



Figure 1: Schema of PDMR detection at ESLAC. a) Un- der the application of the magnetic field (510 G for ESLAC), the NV- centre-ground state (GS) energy lev- els are well separated, whereas the excited state (ES) at ESLAC becomes nearly degenerate, resulting in spin mixing between the states with the equivalent total spin projection quantum number. The spin mixing combined with the electron spin polarisation to Ms(0) through the metastable state (MS) [grey arrows] results in the spin polarisation to the Ms(0) electron and Ms(1) nuclear spin state. The yellow arrows depict optical transitions in- duced by the application of the yellow-green laser. The Ms(0) spin sublevel in the ES is more likely to be excited by the second photon and contribute to the photocurrent by promoting the NV electron to the diamond conduction band (CB)

P Siyushev, M Nesladek, E Bourgeois, et al., Science 363 (728), 2019
M Gulka, et al., Nat. Commun. (12), 4221, 2021

## Tutorial on trapped ions <u>T. E. Northup</u><sup>1</sup>

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This tutorial on trapped ions will focus on the optically addressable transitions that enable a light-matter interface for quantum networks and distributed quantum computing. We will review trapped ions as single-photon sources, and we will consider which spin qubit encodings are best suited for quantum communication and computing applications. Finally, we will examine state-of-the-art demonstrations of quantum network primitives and the challenges that the community faces in scaling up these efforts in the coming years.

## Towards an efficient spin-photon interface based on tin-vacancy centres in diamond

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Colour centres in diamond are promising candidates for the realisation of quantum network nodes, thanks to their good optical and spin coherence properties. High-precision quantum control over the NV centre has enabled milestone experiments in quantum science, but the NV's susceptibility to charge noise hinders large-scale onchip integration. The tin-vacancy (SnV) centre recently emerged as a resourceful alternative platform thanks to its improved optical properties, the second-long relaxation times expected around 1K and compatibility with nanophotonic integrated devices, thanks to the first-order insensitivity to electric field fluctuations arising from its symmetry properties. Together with the recent developments in all-diamond nanofabrication and hybrid integrated photonics, this makes the SnV interesting for realising scalable platforms and on-chip devices.

We are working towards realising an efficient spin-photon interface based on the SnV centre in diamond, with the goal of embedding it in nanophotonic structures and using it as building block for quantum network applications. Here we report on the fabrication and spectroscopy of single SnV centers. Also, we present all-optical measurements to measure dephasing mechanisms, working towards the control of a qubit defined within the electronic structure of the SnV.

## Single-Shot Readout of NV Centers in Diamond via Cryogenic Spin-to-Charge Conversion

## D.M. Irber<sup>1</sup>, <u>F. Poggiali<sup>2</sup></u>, F. Kong<sup>3</sup>, M. Kieschnick<sup>4</sup>, T. Lühmann<sup>4</sup>, D. Kwiatkowski<sup>5</sup>, J. Meijer<sup>4</sup>, J. Du<sup>3</sup>, F. Shi<sup>3</sup> and F. Reinhard<sup>2</sup>

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Nitrogen-Vacancy (NV) centers in diamond are a front-runner platform for quantum sensing and quantum computing. Disruptive applications, such as long-range (> 50nm) entanglement with spin impurities in the lattice, require a speedup of measurements by 2 to 3 orders of magnitude (OM) over the state of the art. This is achievable by improved techniques for spin readout [1], which however need efficient collection optics not always available, as immersion optics or all-diamond micro-optics.

We present a readout scheme for the NV spin-state that achieves single-shot fidelity by combining resonant excitation with spin-to-charge conversion (SCC). Cryogenic temperatures reduce the optical transition linewidth to a level where resonant laser excitation can selectively address the spin-sublevels [2]. In combination with a second laser pulse, a SCC protocol [3] is implemented, where the NV center is spin-selectively excited and converted to different charge-states.

These are more stable than the initial spin-state and their photoluminescence contrast approaches 1. Therefore, by counting the number of acquired photons, the qubit state is read-out with single-shot fidelity (96.4 $\pm$ 2.2%, signal-to-noise ratio 3.5 $\pm$ 1.2), even using poor collection optics [4,5]. The technique is also applicable to shallow (< 100nm close to the diamond surface) NV centers.

Our method accelerates measurements by 3 OM over standard fluorescence readout. Therefore, this technique enables weak-interactions experiments, requiring long (ms) protocols, so far precluded by acquisition speed. A sensing time >1 ms pushes the detection range for single electron spins to several tens of nanometers. As important consequence, it will become a pivotal ingredient for two-qubit gates in scalable NV-based quantum registers.

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## Entanglement Between a Telecom Photon and a Spin-Wave Solid-State Multimode Quantum Memory

<u>J. V. Rakonjac<sup>1</sup></u>, D. Lago-Rivera<sup>1</sup>, A. Seri<sup>1</sup>, M. Mazzera<sup>2</sup>, S. Grandi<sup>1</sup>, and H. de Riedmatten<sup>1,3</sup>

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<sup>3</sup> *ICREA-Institució Catalana de Recerca i Estudis Avançats*, *08015 Barcelona*, *Spain* Quantum repeaters offer the possibility to perform quantum communication over a long distance. One possible repeater node can be made with a photon-pair source and an absorptive quantum memory. To this end, we are developing a system which combines a solid-state quantum memory with a source of photon pairs. The memory is based on a rare-earth doped crystal (Pr<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub>), where quantum information can be stored in Pr<sup>3+</sup> ions as a collective optical excitation using the Atomic Frequency Comb (AFC) protocol. On-demand retrieval is realised by transferring the excitation to a long-lived spin state [1]. Entangled pairs of single photons are generated by parametric down conversion in a periodically poled crystal placed inside an optical cavity. This generates narrow band photons pairs, where the signal is spectrally matched to the memory (606 nm) for storage, while the idler is in the telecom band to allow for higher optical transmission through fibre [2].

We will present our results demonstrating energy-time entanglement between the telecom idler photon and the signal photon stored as a spin-wave excitation [3]. The entanglement of the original pair is maintained by the memory's temporal multimodality. The entanglement analysis is performed using time-bin qubit analysers made of a fibre-based Mach-Zehnder interferometer for the idler photon, and a solid-state equivalent based on the AFC for the signal photon [4]. With this setup, we have measured entanglement between the telecom photon and the excitation in an optically excited state, with a fidelity high enough to violate a Bell inequality. The storage time in the memory was 10  $\mu$ s, 100 times longer than previous demonstrations in similar systems [4]. We also demonstrated entanglement with the signal photon in a spin-wave excitation, which is necessary to achieve the longer storage times required for long-distance entanglement between individual nodes in a quantum network, as well as on demand read-out of the stored quantum state.

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# Erbium dopants – a novel platform for quantum networks

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In spite of decade-long research into different physical systems, the demonstration of a scalable platform for quantum networks and distributed quantum information processing remains an outstanding challenge. In this context, our group investigates the use of erbium dopants in silicon [1] and silicate crystals [2–4]. This platform offers unique potential to overcome the main bottlenecks of other quantum hardware: First, erbium dopants can exhibit second-long coherence in a temperature range that is accessible with 4He cryocoolers [5]. Second, the optical transition of erbium is the narrowest spectral feature ever measured in a solid. Thus, frequency-multiplexed addressing of individual dopants [6] gives access to an unprecedented qubit density as long as spin-spin interactions can be suppressed by dynamical decoupling [4]. Finally, by embedding the dopants into a Fabry-Perot resonator with a quality factor of 107, we could demonstrate up to 59-fold Purcell enhancement with lifetime-limited optical coherence in the telecommunications frequency window [2].

In recent experiments, we could observe and coherently control ~100 individual dopants with ultra-low spectral diffusion, <100 kHz, determined by the nuclear spin bath. Using nuclear spin initialization or silicon [1] instead of silicate host crystals may further reduce this value to the homogeneous linewidth and thus enable the realization of remote entanglement with high fidelity. Thus, our novel hardware platform may facilitate the implementation of scalable quantum networks and repeaters based on single dopants at telecom wavelength.

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- [4] B. Merkel, P. C. Fariña, and A. Reiserer, arXiv:2005.08822v2 (2021)
- [5] M. Rančić, M. P. Hedges, R. L. Ahlefeldt, and M. J. Sellars, Nat. Phys. 14, 50 (2018).
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## Linear optics quantum computing with erbium doped crystals: concepts, developments and potential applications

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The storage of optical quantum states is a key enabling technology for optical quantum computing and long-range quantum communications. The primary role of quantum memories is to synchronise quantum states arising from stochastic events, an operation critical for scaling of linear optical quantum computers to a large size and for the operation of quantum repeater communication protocols. Further, through the creation and manipulation of quantum states within memory there exists the potential to construct sophisticated a linear optics quantum processor platform based on the memory itself.

We are developing a platform based on large ensembles of erbium optical centres in doped crystals. This platform has characteristics that make it uniquely suited to implementing repeaters for long range quantum communications. This platform offers long memory storage times (> 1 second), wavelength compatible with optical fibre and satellite optical communications, the potential for high data storage capacity and the ability to be integrated into complex quantum optical circuits [1,2].

This talk will describe the key concepts of the processor design and recent work demonstrating rephased amplified spontaneous emission in  $Er^{3+}$ :Y<sub>2</sub>SiO<sub>5</sub>, a method for generating non-classical states within the memory.

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- [2] J. Stuart et al., arXiv:2103.04581v1 [quant-ph], (2021)

## Rare-Earth Molecular Crystals with Ultra-Narrow Optical Linewidth for Photonic Quantum Technologies

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A promising perspective of using rare-earth ions (REIs) to build quantum light-matter interfaces relies on nano-fabricating crystalline host materials preserving the REIs quantum properties while enabling integration into nanophotonic devices. Molecular chemistry is very attractive in this respect, offering unmatched flexibility in terms of material composition, fine structural tuning, together with integration capabilities.



Figure 1: A – Two pulse photon echo decay from the molecular europium crystal yielding  $\Gamma_h$  = 30.2 kHz. B – Spectral diffusion measured by three-pulse photon echoes.

Here, we report here europium molecular crystals exhibiting linewidths in the 10s of kHz range (Figure 1), several orders of magnitude narrower than other molecular centers [1]. We harness this property to demonstrate efficient optical spin initialization, coherent storage of light using an atomic frequency comb, and optical control of ion-ion interactions towards implementation of quantum gates [2]. These results open the way to using rare-earth molecular crystals as a new platform for photonic quantum technologies.

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- [2] D. Serrano et al., "Rare-Earth Molecular Crystals with Ultra-Narrow Linewidth for Photonic Quantum Technologies": *arXiv:2105:07081v1 (2021)*

## Photons and spins from quantum networks to quantum neuroscience

#### **Christoph Simon**

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Photons and spins are at the heart of my research on both quantum networks and quantum neuroscience. On the quantum networks side, I will describe recent work on quantum memories, transducers, and repeaters with rare-earth ions, and towards quantum network architectures that can operate at room temperature, among other topics. On the quantum neuroscience side, I will discuss the potential existence of photonic communication channels in the brain, as well as a potential role for radical pairs with entangled spins in anesthesia.

## Quantum processors based on spins in diamond

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Electron-nuclear spin systems based on optically active defects in diamond provide a promising platform for quantum networks, quantum simulations and quantum computation. We have recently shown that it is possible to detect and image large numbers of nuclear spins around a single NV center [1]. In this talk, I will review our recent progress in leveraging these systems for quantum simulations of many-body physics [2] and for the development of quantum computations [3].

- [1] M. H. Abobeih et al., <u>Nature 576, 411 (</u>2019)
- [2] J. Randall et al., <u>arXiv:2107.00736</u> (2021)
- [3] C. E. Bradley et al., Phys. Rev. X. 9, 031045 (2019)

# Towards quantum networks with individual rare earth ions in nanophotonic structures

#### Jeff Thompson<sup>1</sup>

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I will discuss our work with rare earth atom defects in solid crystalline hosts, in particular erbium ( $Er^{3+}$ ). By incorporating these ions into nanophotonic cavities, we have demonstrated the first atomic source of single photons in the telecom band [1], and high-fidelity single-shot readout of the  $Er^{3+}$  electron spin using cavity-induced cycling transitions [2]. Furthermore, we have realized optical manipulation and single-shot readout of multiple atoms with spacings far below the diffraction limit of light, using a novel frequency-domain super-resolution technique [3]. I will conclude by discussing prospects for long-distance quantum repeater networks based on  $Er^{3+}$  ions, as well as fundamental studies of strongly interacting spin systems in the solid-state.

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[3] S. Chen, M. Raha, C. M. Phenicie, S. Ourari, and J. D. Thompson, *Parallel Single-Shot Measurement and Coherent Control of Solid-State Spins below the Diffraction Limit*, Science **370**, 592 (2020).

## Coherent control of a single nuclear spin with an Er<sup>3+</sup> ion

## <u>Mehmet T. Uysal</u><sup>1</sup>, Mouktik Raha<sup>1</sup>, Songtao Chen<sup>1</sup>, Christopher M. Phenicie<sup>1</sup>, Salim Ourari<sup>1</sup>, V. Dobrovitski<sup>2</sup>, Jeff D. Thompson<sup>1</sup>

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Single Er ions in solid-state hosts are excellent candidates for quantum network applications due to their emission in the telecom band and compatibility with silicon photonics, while nuclear spins provide coherent resources for quantum information processing. In this work, we observe coherent coupling of an Er electronic spin (S=1/2) and a nearby nuclear spin (I=1/2), with a measured gyromagnetic ratio equivalent to proton. We utilize this interaction to construct a SWAP operation, measure the coherence properties of the nuclear spin, identify its location with respect to the Er ion and probe its environment. In particular, by performing spectroscopy on the nuclear spin, we find that it is coupled to a system consistent with two spin-1/2 nuclear spins. These results provide a pathway towards combining multiple long-lived quantum registers to a telecom-compatible quantum memory for future quantum repeater-based quantum network applications.

- [1] Raha, et al. Nat.Commun. 11, 1605 (2020)
- [2] Chen, et al. Science **370**, 592–595 (2020)

## Programmable quantum register based on NV center in diamond and nuclear spins

#### V. Vorobyov

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To track and control a quantum system, it is necessary to understand the underlying properties of the hardware it is based on. In case of Nuclear magnetic resonance in diamond, we rely on well studied NV centre spin optical properties to harness quantum resources of the quantum bath around it.

Typically the state readout of this system is based on the macroscopic data of the observable associated with the system. Compared to the classical problem of filtering and control, the main difficulty in the quantum case is that the probabilistic properties of the classical readout signal and quantum process of the target system differ significantly. We consider this problem in the context of weak measurements of a single nuclear spin in a diamond with an electron spin as a meter, which is a well-controlled and understandable multipartite quantum system.

Furthermore, we advance this result with studies towards an ideal quantum measurements and combine it with a feedback mechanism, to steer the target system to desired state. Additionally, applications of our multiqubit quantum register would be discussed for efficient quantum simulation of the quantum heat engine, and time crystalline phase. Finally the applications of robust nuclear spin control in quantum sensing such as NMR of proximate and nuclear spins and gyroscopes will be presented.

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## **Roadmap for Rare-earth Quantum Computing**

#### Adam Kinos<sup>1</sup>, David Hunger, Roman Kolesov, Klaus Mølmer, Hugues de Riedmatten, Philippe Goldner, Alexandre Tallaire, Loic Morvan, Perrine Berger, Sacha Welinski, Khaled Karrai, Lars Rippe<sup>1</sup>, Stefan Kröll<sup>1</sup>, and <u>Andreas Walther<sup>1</sup></u>

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Several platforms are being considered as hardware for quantum technologies. For quantum computing (QC), superconducting qubits and artificially trapped ions are among the leading platforms, but many others also show promise, e.g. photons, cold atoms, defect centers including Rare-Earth (RE) ions. So far, results are limited to the regime of noisy intermediate scale qubits (NISQ), with a small number of qubits and a limited connectivity, and it is likely that future QC hardware will utilize several existing platforms in different ways. Thus, it currently makes sense to invest resources broadly and explore the full range of promising routes to quantum technology.

Rare-earth ions in solids constitute one of the most versatile platforms for future quantum technology. One advantage is good coherence properties even when confined in strong natural traps inside a solid-state matrix. This confinement allows very high qubit densities and correspondingly strong ion-ion couplings. In addition, although their fluorescence is generally weak, cavity integration can enhance the emission greatly and enable very good connections to photonic circuits, including at the telecom wavelengths, making them promising systems for long-term scalability.

The primary aim of this roadmap [1], and this talk, is to provide a complete picture of what components a RE quantum computer would consist of, to describe the details of all parts required to achieve a scalable system, and to discuss the most promising paths to reach it. In brief, we find that clusters of 50-100 single RE ions can act as high fidelity qubits in small processors, occupying only about (10 nm)^3. Due to the high capacity for integration of the RE systems, they be optically read out and connected to other such clusters for larger scalability. We make suggestions for future improvements, which could allow the REQC platform to be a leading one.

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## Operating quantum states in a magnetic molecule W. Wernsdorfer<sup>1</sup>

#### <sup>1</sup>PHI & IQMT, Karlsruher Institut für Technologie (KIT), Germany

The endeavour of quantum electronics is driven by one of the most ambitious technological goals of today's scientists: the realization of an operational quantum computer. We start to address this goal by the new research field of molecular quantum spintronics, which combines the concepts of spintronics, molecular electronics and quantum computing. The building blocks are magnetic molecules, i.e. well-defined spin qubits. Various research groups are currently developing low-temperature scanning tunnelling microscopes to manipulate spins in single molecules, while others are working on molecular devices (such as molecular spin-transistors and carbon-nanotubebased devices) to read and manipulate the spin state and perform basic quantum operations [1]. We will present our recent measurements of geometric phases, the iSWAP quantum gate. the coherence time of a multi-state superposition, and the application to Grover's algorithm [2-3].



Fig. 1: Pictorial representation of an optoelectronic device with a triple- decker molecule containing two coupled rare- earth ions in the centre. Two independent fluorophores are attached to the molecule [1].

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- [2] C. Godfrin, A. Ferhat, R. Ballou, S. Klyatskaya, M. Ruben, W. Wernsdorfer, F. Balestro, Phys. Rev. Lett. 119, 187702 (2017).
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# Narrow photons and coherent spins in semiconducting materials

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There is a decade-long effort to identify proper spin-photon hardware for quantum technology. Individual systems satisfy selective criteria, i.e. small spin-orbit or spin-phonon coupling, charge stability and low abundancy of paramagnetic constituents. However, attempts to combine all properties so far have been futile. Reducing the dimensionality of host systems, i.e. reducing 3D hosts to 2D materials, helps to achieve some of the aims [1], while they e.g. enhance spin-orbit coupling. Other systems, like e.g. silicon carbide (SiC), although being non-centrosymmetric, show excellent figures of merit in terms of photon emission and spin properties [2,3]. In my talk, I will summarize recent developments on spin-photon systems in general and on the two systems in particular.

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## Quantum repeater and transportable quantum memory based rare-earth ions in solids

#### Zong-Quan Zhou<sup>1</sup>

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The inevitable channel loss prevents long-distance quantum communication. Protocols involving quantum memories can overcome this problem and enable the construction of a large-scale quantum internet. I will introduce the basic concept of the quantum repeater and the transportable quantum memory. Based on rare-earth-ion doped crystals, we recently demonstrate an elementary link of a quantum repeater based on absorptive quantum memories [1] and extend the optical storage time to 1 hour [2]. Future developments along these directions will be discussed.

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## **Abstracts of Posters**

(in alphabetical order)

**Title:** Heterogenous III-V on diamond nanophotonic platform for telecom quantum nodes based on neutral silicon vacancy centers in diamond

Authors: <u>Alex Abulnaga</u>,1 Ding Huang,1 Sacha Welinski,1 Mouktik Raha,1 Zi-Huai Zhang,1 Paul Stevenson,1 Jeff D. Thompson,1 and Nathalie P. de Leon1 <sup>1</sup> Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA

#### **Abstract Body:**

Integrating quantum memories based on color centers in diamond with on-chip photonic devices may enable entanglement distribution over long distances, but efforts towards integration have been challenging as color centers are sensitive to their environment and their properties degrade in nanofabricated structures [2]. We present a heterogeneously integrated, on-chip, III-V diamond platform designed for neutral silicon vacancy (SiV0) centers [4]. The combination of stable optical transitions and long spin coherence times makes the SiV0 center an attractive candidate for nodes in quantum networks [1,3]. Our design does not require etching the diamond substrate, thus avoiding material damage and spectral diffusion arising from nanofabrication. Through evanescent coupling to SiV0 centers near the diamond surface, the platform can enable Purcell enhancement of SiV0 emission and quantum frequency conversion to the telecommunication C-band. The proposed structures can be realized with readily available fabrication techniques, and fabrication results towards realizing these structures in three different III-V material platforms are discussed.

This work was primarily supported by DARPA under Young Faculty Award (award number D18AP00047) and work on the neutral silicon vacancy center was supported by the NSF under the EFRI ACQUIRE program (grant 1640959).

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## Inverted excited-state structure of a SiC qubit enabling spin-photon interface

#### I. D. Breev<sup>1</sup>, Z. Shang<sup>2,3</sup>, A. V. Poshakinskiy<sup>1</sup>, H. Singh<sup>4</sup>, Y. Berencén<sup>2</sup>, M. Hollenbach<sup>2,3</sup>, S. S. Nagalyuk<sup>1</sup>, E. N. Mokhov<sup>1</sup>, R. A. Babunts<sup>1</sup>, P. G. Baranov<sup>1</sup>, D. Suter<sup>4</sup>, S. A. Tarasenko<sup>1</sup>, <u>G. V. Astakhov<sup>2</sup></u> and A. N. Anisimov<sup>1</sup>

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Optically controllable solid-state spin gubits are one of the basic building blocks for the applied quantum technology. The efficient extraction of emitted photons and a robust spin-photon interface are crucial for the realization of quantum sensing protocols and essential for the implementation of guantum repeaters. Though silicon carbide (SiC) is a very promising material platform hosting highly-coherent silicon vacancy spin qubits [1,2], a drawback for their practical application is the unfavorable ordering of the electronic levels in the optically excited state. Here, we demonstrate that due to polytypism of SiC, a particular type of the silicon vacancy qubits possesses an unusual, inverted fine structure. It results in the directional emission of light along the hexagonal crystallographic axis, making photon extraction more efficient and integration into photonic structures technologically strait forward. From the angular polarization dependencies of the emission, we reconstruct the spatial symmetry and determine the optical selection rules depending on local deformation and spin-orbit interaction, allowing direct implementation of robust spin-photon entanglement schemes. Furthermore, the inverted fine structure leads to the unexpected behavior of the optical spin pumping. It vanishes and recovers with lattice cooling due to two competing mechanisms. Our experiments and theoretical analyses demonstrate a promising approach to select over a broad variety of spin centers the most suitable ones for quantum communication and distributed quantum information processing.

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#### Broad diversity of near-infrared single-photon emitters in silicon

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The boom of silicon in semiconductor technologies was closely tied to the ability to control its density of lattice defects [1]. After being regarded as detrimental to the crystal quality in the first half of the 20<sup>th</sup> century [2], point defects have become an essential tool to tune the electrical properties of this semiconductor, leading to the development of a flourishing silicon industry [1]. At the turn of the 21<sup>st</sup> century, progress in Si-fabrication and implantation processes has triggered a radical change by enabling the control of these defects at the single level [3]. This paradigm shift has brought silicon into the quantum age, where individual dopants are nowadays used as robust quantum bits to encode and process quantum information [4]. These individual qubits can be efficiently controlled and detected by all-electrical means [4], but have the drawback of either being weakly coupled to light [5] or emitting in the mid-infrared range [6] unsuitable for optical fiber propagation. In order to isolate matter qubits that feature an optical interface enabling long-distance exchange of quantum information while benefiting from well-advanced silicon integrated photonics [7], one strategy is to investigate defects in silicon that are optically-active in the near-infrared telecom bands [8–10].

During this workshop, we will present our lastest results on the isolation of single optically-active defects in silicon [10, 11]. Despite its small gap, this semiconductor hosts a large variety of emitters that can be optically detected at single scale at 10 K. We have identified individual emitters in silicon belonging to different families of fluorescent defects, including the common carbon-complex called G-center [12]. These artificial atoms have been created by carbon implantation or are natively present in a silicon-on-insulator (SOI) wafer usually employed for integrated photonics. Single-photon emission is demonstrated over the 1.1-1.5  $\mu$ m range, spanning the O and C telecom bands. We have further observed that some single defects exhibit additional appealing properties, such as a small spread of the ZPL energies or a strong PL intensity well above the liquid nitrogen temperature. Given the advanced control over nanofabrication and integration in silicon, these individual artificial atoms are promising systems to investigate for Si-based quantum technologies [7], including integrated quantum photonics and quantum communications.

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# Towards detection of single erbium ions in a tunable fiber micro-cavity

#### <u>Chetan Deshmukh<sup>1</sup></u>, <u>Eduardo Beattie<sup>1</sup></u>, Bernardo Casabone<sup>1</sup>, Samuele Grandi<sup>1</sup>, Diana Serrano<sup>2</sup>, Alban Ferrier<sup>2,3</sup>, Philippe Goldner<sup>2</sup>, David Hunger<sup>4</sup>, and Hugues de Riedmatten<sup>1,5</sup>

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Rare-earth ion-doped crystals constitute a promising platform for quantum information processing and networking. They feature exceptional spin coherence times to store information, narrow optical transitions to act as an interface to optical photons, and possibilities to realize quantum gates between single ion qubits. Coupling quantum emitters to optical cavities enables channeling the emission from the emitters into the cavity mode while decreasing their emission lifetime. This allows the realization of an efficient and high-rate spin-photon interface, while also increasing the indistinguishability of the emitted photons in the presence of dephasing.

In this work, by utilizing erbium-doped nanoparticles that emit at telecom wavelengths coupled to a fully tunable high-finesse fiber-based microcavity in a cryostat, we demonstrate an average Purcell factor greater than 100 for a very small ensemble of erbium ions (Purcell enhanced lifetime of 90  $\mu$ s). Frequency selective excitation followed by fluorescence detection results in discrete features which indicate the sensitivity of the setup to few ions. Next steps involve isolating one such feature in a sparsely populated spectral region of the inhomogeneous line and measuring the auto-correlation function of the emitted photons. The presence of one or few ions can then be induced from the value of this function.

We have demonstrated with the previous version of our setup that we can control the Purcell factor and hence the emission rate of the ions on a timescale of hundreds of microseconds. Our current setup should enable us to reduce this time to a few tens of microseconds. If implemented at the single ion level, this ability will enable the generation of fully tunable narrowband single photons at telecom wavelengths, and quantum processing using single rare-earth-ions.

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# Telecom single-photon emitters in silicon for scalable quantum photonics

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Single-photon sources emitting indistinguishable photons in the optical telecom O and C bands are key building blocks for long-haul fiber-optic quantum communication and quantum photonic integrated circuits. Single-point defects in diamond, silicon carbide and hexagonal boron nitride are demonstrated to be instrumental for single-photon sources [1]. Yet, isolated single-vanadium dopants in silicon carbide have only been reported to exhibit single-photon emission in the telecom O band [2]. In contrast to this, the SiC applications in quantum photonics are limited due to the lack of commercial availability of SiC on insulator wafers of adequate quality, currently obtained using the smart cut process. In this context, silicon with its stable oxide (SiO<sub>2</sub>) and its mature computer-chip manufacturing process would provide a crucial advantage in building large-scale quantum networks, which can enable a link between quantum computing and quantum communication in the same framework. The first experimental demonstration of single-photon emitters in silicon emitting in the telecom O band has only been accomplished recently [3, 4].

In this work, we report the creation of single-photon emitters with a high brightness approaching 10<sup>5</sup> counts per second in commercial silicon-on-insulator (SOI) wafers [3]. The emission occurs in the infrared spectral range with a spectrally narrow zero-phonon line in the telecom O-band and shows a high photostability even after days of continuous operation. The origin of the emitters is attributed to one of the carbon-related color centers in silicon, the so-called G center, allowing purification with the <sup>12</sup>C and <sup>28</sup>Si isotopes. Furthermore, we envision a concept of a highly-coherent scalable quantum photonic platform, where single-photon sources, waveguides and detectors are integrated on an SOI chip. These results provide a route toward the implementation of quantum processors, repeaters and sensors compatible with present-day silicon technology.

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## Optical spectroscopy of lithium erbium fluoride, an antiferromagnetic crystal

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Lithium erbium fluoride is a concentrated rare earth crystal that orders antiferromagnetically below 370mK [1], and will have magnon resonances of order 10 GHz. The 1530 nm optical transition of erbium makes this material an excellent candidate for realising highly efficient microwave-to-optical transduction [2]. Here we present the optical spectroscopy of lithium erbium fluoride below its magnetic ordering temperature and in an applied magnetic field. Correlated spin behaviour is evident in the data, and a model of this is presented. The optical inhomogeneous linewidths of some transitions are below 30 MHz, which is very narrow. The smallest optical inhomogeneous linewidth measured in any solid state is 16 MHz, and in contrast to this material, was measured for a low erbium concentration of 50 ppm [3].

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# Towards broadband quantum memory at the single photon level

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To ensure reliable highspeed entanglement distribution between nodes in a largescale quantum network one needs highly multiplexed quantum memories. In an atomic frequency comb (AFC) scheme this means increasing either the memory time or the bandwidth to allow for the storage of multiple photons at the same time. Here we present our efforts of producing high quality AFC structures over a bandwidth of 100 MHz in a Yb:YSO crystal where we previously demonstrated AFC spin-wave storage of up to 1.2 ms using a 20 MHz AFC [1]. This system has the advantage of strong ground-state splittings due to the electronic nature of the spin states which potentially lets us store very broad photons even in the much longer lived ground states. Together with a SPDC single photon source which we filter down to the memory bandwidth we aim to create entanglement between our quantum memory and a photon at telecom wavelength ideal for long distance communication.

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## **Resonant Quantum Principal Component Analysis**

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Principal component analysis has been widely adopted to reduce the dimension of data while preserving the information. The quantum version of PCA (qPCA) can be used to analyze an unknown low-rank density matrix by rapidly revealing the principal components of it, i.e. the eigenvectors of the density matrix with the largest eigenvalues. However, due to the substantial resource requirement, its experimental implementation remains challenging. Here, we develop a resonant analysis algorithm with minimal resource for ancillary qubits, in which only one frequency scanning probe qubit is required to extract the principal components. In the experiment, we demonstrate the distillation of the first principal component of a 4×4 density matrix, with an efficiency of 86.0% and fidelity of 0.90. This work shows the speed-up ability of quantum algorithm in dimension reduction of data and thus could be used as part of quantum artificial intelligence algorithms in the future.

## Photonic Crystal Cavities for spin-photon enhancement of color centers in diamond

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Future quantum networks promise to enable new applications, such as secure communication, distributed quantum computing, and quantum enhanced sensing. Optically active spins in diamond represent a promising building block for the realization of future quantum networks [1]. NV centers are currently amongst the leading platforms, recently enabling the first demonstration of the heralded generation of a multipartite entangled state across a 3 node quantum network [2]. However, further scaling of the network is hindered by a low rate of spin-photon entanglement generation, resulting from a low number of coherent collected photons.

The entanglement generation rate can be increased by embedding the NV centers in an optical cavity, making use of the Purcell effect. However, the optical transitions of the NV center degrade when placed in the vicinity of surfaces due to their sensitivity to charge noise as a result of a large permanent electric dipole moment. Group IV color centers represent a promising alternative: the inversion symmetry of these systems makes them first order insensitive to electric fields, re-opening the path towards integration in nanophotonic cavities [3, 4].

The fabrication of such nanophotonic cavities in diamond itself is challenging, as there is no known wet-processing technique that would allow to fabricate free-hanging structures starting from bulk diamond material. Here, we present our recent developments in the realization of all-diamond nanophotonic photonic crystal cavities [5]. We introduce our fabrication process flow, present measurements of the quality factor of the resulting structures, and outline a path towards the realization of extended quantum networks, making use of the highly efficient spin-photon interface provided by nanophotonic structures.

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# Monitoring of Larmor precession of a single spin in a semiconductor quantum dot

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In semiconductor quantum dots, the spin of a confined charge carrier, whether electron or hole, has attracted a lot of interest since spin-polarized optical transitions enable the generation of spin-photon and photon-photon entanglement. Most importantly, this can be extended to generate multi-photon entangled states such as photonic GHZ or linear cluster states [1], which are building blocks for the realisation of quantum technologies such as measurement-based quantum computing and large scale quantum networks.

In addition, semiconductor quantum dots have shown excellent properties as singlephoton sources, including record levels of brightness, purity and indistinguishability [2]. However, the combination of such high quantum purity single-photon emission whilst maintaining access to the light polarization properties – linked to the spin degree of freedom – remains challenging.

In this work, we exploit a phonon-assisted, off-resonant excitation scheme [3] which enables access to the polarization degree of freedom to probe the spin dynamics, whilst maintaining efficient single-photon generation and high quantum purity. We demonstrate that we can address the spin-selective transitions, and we observe the Larmor precession of a single hole spin around an in-plane magnetic field. This is done either on the ground or excited state of the transition, giving access to a lower bound of the hole spin coherence time. This opens the route towards efficient generation of polarization-encoded multi-photon entangled states.

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## Generation of Multipartite Entanglement using Spin-Photon Interfaces

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All-optical quantum communication and computation protocols suffer a major drawback from the ultra-weak coupling of photons, and the constraints imposed by their dissimilarities. Solid-state systems offer a robust solution to this problem by interfacing these photons with the spin degrees of freedom of their intrinsic optically-active, atom-like defect centers. We will show here how solid-state quantum emitters with overlapping emission profiles within diffraction limited excitation spots, can lead to the generation of multipartite entangled states such as Greenberger-Horne-Zeilinger (GHZ) and Cluster states. Further, we will discuss their role in establishing Quantum Error-correctable nodes in a Quantum Repeater network.

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## Realisation of electron-spin-pair qubit in diamond <u>N. Demetriou<sup>1</sup></u>, H. P. Bartling<sup>1</sup>, N, Zutt<sup>1</sup>, M. J. Degen<sup>1</sup>, S.J.H. Loenen<sup>1</sup>, T. H. Taminiau<sup>1</sup>

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Realizing quantum networks requires quantum registers with robust optically addressable qubits. A variety of approaches have been reported, including our recent work on nuclear-spin pairs and single electron spins surrounding nitrogen-vacancy centers[1][2]. In this work, we investigate a qubit encoded in a pair of electron spins formed by two P1 centers. We find long inhomogeneous dephasing times of tens of milliseconds, due to the spin pair forming a decoherence-free subspace and a clock transition, making the qubit robust to magnetic field fluctuations. By observing the spin pairs' temporal evolution and utilizing RF pulse sequences to address various transitions, we characterize the internal interactions and resolve the characteristic degrees of freedom of the P1 centers; the Jahn-Teller distortion and nitrogen state. This work provides a robust qubit with potential application in quantum networks and sensing, whilst enriching the understanding of electronic spin-pair dynamics.

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## Towards Cavity-Enhanced Spectroscopy of Single Europium Ions in Yttria Nanocrystals

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A promising approach for realizing scalable quantum registers lies in the efficient optical addressing of rare-earth ion spin qubits in a solid state host. Within the EU Quantum Flagship project SQUARE we study  $Eu^{3+}$  ions doped into  $Y_2O_3$  nanoparticles (NPs) as a coherent qubit material and work towards efficient single ion detection by coupling their emission to a high-finesse fiber-based Fabry-Pérot microcavity. A beneficial ratio of the narrow homogeneous line to the inhomogeneous broadening of the ion ensemble at temperatures below 10K makes it possible to spectrally address and readout single ions. The coherent control of the single ion  ${}^{5}D_{0}{}^{-7}F_{0}$  transition then permits optically driven single qubit operations on the Europium nuclear spin states. A Rydberg-blockade mechanism between ions within the same nanocrystal permits the implementation of a two-qubit CNOT gate to entangle spin qubits and perform quantum logic operations. Theoretical simulations of the single and two-qubit gate operations predict fidelities of up to 99.5% and 96.5%, respectively, with current material properties. We report on our progress to experimentally implement this scheme.

#### Atomic scale sensor for magnetic fields using TR12 centers

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Nitrogen-vacancy (NV) centers in diamond are excellent sensors of magnetic and electric fields as well as temperature. However, they are insensitive to strong magnetic field except for orientations along NV symmetry axis. Here we present optically detected magnetic resonance (ODMR) studies of TR12 centers in diamond in their excited triplet state under ambient conditions. The results suggest that TR12 centers can sense arbitrarily strong magnetic fields in a wide angular range. Beyond the field of quantum applications, TR12 is most interesting for showing a static Jahn-Teller effect which was detected through fluorescence switching between two levels at low optical excitation power, directly observable in the real-time fluorescence signal.

## Ancilla assisted discrete quantum time crystal with nitrogen-vacancy center in diamond

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Time crystal [1] is a phase of matter of which the time-translation symmetry is spontaneously broken. Though continuous quantum time crystal is controversial [2], discrete quantum time crystal has been experimentally demonstrated in various systems [3-6]. The observation of the discrete quantum time crystal signature relies on the interplay between periodic driving, disorder, and interaction. Here we consider the possibility of preparing a non-interacting quantum system into the time-crystal phase by coupling it with an ancillary system. We show that the coupling between the system and the ancilla, even if just an ancilla qubit, could introduce an effective interaction in the system, and thus enables the emergence of the time-crystal phase. We demonstrate the time-crystal signature of non-interacting nuclear spins by simulation and experiment on nitrogen-vacancy center in diamond [7].

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## Coupling Erbium Dopants to Nanophotonic Silicon Structures

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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 telecom- munication wavelength [2]. Among potential host crystals for erbium, silicon stands out because of its compatibility with CMOS technology which allows scalable fabrication of nanophotonic devices based on established processes of the semiconductor industry. In contrast to observations of previous studies [3], we have recently shown that erbium ions implanted into silicon nanostructures are located on a few well-defined lattice sites with narrow inhomogeneous (~1 GHz) and homogeneous (<0.1 GHz) linewidths (Fig 1) [4].

By optimizing the sample preparation, we have further improved the homogeneous linewidth down to 20 kHz for some sites. In order to determine the symmetry of these, we measure the crystal field splitting in the ground and excited states as well as magnetic field splittings. Furthermore, we have studied the power and temperature dependencies of the homogeneous linewidths.

To harness our novel material platform for quantum networks, we proceed towards the control of individual erbium dopants. As the long lifetime of the optically excited state, around 0.25 ms, would limit the achievable rates, we designed and fabricated photonic crystal cavities which may reduce the lifetime by more than three orders of magnitude. This will allow us to resolve and control individual dopants, making our system a promising candidate for the implementation of distributed quantum information processing over large distances.

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## Controllable Non-Markovianity for a Spin Qubit in Diamond

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We present a flexible scheme to realize non-Markovian dynamics of an electronic spin qubit, using a nitrogen-vacancy center in diamond where the inherent nitrogen spin serves as a regulator of the dynamics<sup>1</sup>. By changing the population of the nitrogen spin, we show that we can smoothly tune the non-Markovianity of the electron spin's dynamics. Furthermore, we examine the decoherence dynamics induced by the spin bath to exclude other sources of non-Markovianity. The amount of collected measurement data is kept at a minimum by employing Bayesian data analysis. This allows for a precise quantification of the parameters involved in the description of the dynamics and a prediction of so far unobserved data points.

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# Fully fiber coupled devices for efficient cryogenic spectroscopy of single and small ensembles of rare earth ions

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Rare earth ions in solid state hosts are a prime candidate for optically addressable spin qubits, owing to their excellent optical and spin coherence times. Due to the long optical lifetime of the optical transitions, an efficient spin-photon interface for quantum information processing requires the coupling of single ions to a microcavity. This serves to enhance the transitions via the Purcell effect and to increase the emission into a single, well-collectible cavity mode.

Fiber based Fabry-Pérot cavities have been demonstrated to achieve high quality factors and low mode volumes, while also offering large tunability and efficient collection of the cavity mode. In order to minimize scattering losses, we integrate rare earth ion doped nanocrystals into the cavity, which retain very good optical and spin coherence. Operation of these cavities at cryogenic temperatures has however proven difficult, due to the high demands on mechanical stability of the cavity length. To tackle these challenges, we report on the development of two different, monolithic cavity assemblies, both sacrificing some lateral scanning ability in order to significantly increase the passive stability.

Our first approach uses two fiber mirrors, that are mounted on shear piezos and guided inside a glass ferrule, demonstrating a high passive stability of below 2 pm at room temperature. In order to place the nanocrystals inside the cavity mode volume, we developed a sophisticated picking method that allows us to pick up single nanocrystals well centered on the core of a single mode fiber with a precision of below 2  $\mu$ m.

The second approach relies on mounting the fiber mirror on a monolithic three axis movable tube piezo, that is mounted in a rigid titanium cage opposite of a macroscopic mirror, eliminating vibrational modes and compensating for possible drifts upon cooldown. This device features both a high passive stability as well as a lateral scanning ability.

Recently, new nanomaterial platforms for rare earth ions emerged. Most notably, rare earth ion based molecular complexes have shown excellent optical coherence properties. Investigating and characterizing the optical and spin properties of these novel materials requires spectroscopic measurements of ensembles, such as spectral hole burning and photon echo spectroscopy. We report on the development of a miniaturized, fiber coupled scheme to perform these types of experiments inside a homebuilt dipstick cryostat. Our design requires only microscopic amounts of sample and comparatively low laser power in order to see well resolved spectral hole spectra.

# Focused ion beam writing of color centers for quantum spin-photonic applications

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Color centers and their optically interfaced spin read-out are one of the key building blocks for quantum information, quantum computing and quantum sensing [1,2]. The creation of atomic-scale spin centers as well as their integration into photonic structures such as micro-resonators, nanopillars and photonic crystals with submicrometer precision is of great importance for practical spin-photonic applications [3,4]. This work presents the controlled creation of quantum defect centers in silicon carbide with spin-photon interface using focused ion beam technologies. We also show the local writing of a novel color center in silicon, which has recently been demonstrated to exhibit single-photon emission in the optical telecom O-band [5,6], making it a promising candidate for quantum photonic applications.

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# Toward on-demand control of charge state dynamics and spin polarization control of electron-nuclear spin system of NV center in diamond

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A Nitrogen-Vacancy (NV) color center in solid state originates from a vacancy of a missing carbon atom combined with substitutional nitrogen impurity in diamond crystal lattice. As atomic scale defect, NV color center can have different charge states, for example, negatively, neutrally, or positively charged NV center, depending on the configuration of spins in NV color center [1,2,3,4]. In this research, first, we investigated optically induced interconversion (ionization and recombination) between charge states. Additionally, the post-selection analysis of emission photons counts from projective observation on electron or nuclear spin state was executed to contribute to the high fidelity measurement of spin by understanding charge state dynamics in NV color center. On top of that, aligning with current emergent researches for quantum information processor and quantum simulator [5,6], we explored the control of spin polarization in electron-nuclear spin system in single NV center at room temperature. We designed effective flip-flop interaction of spins as unitary operation in quantum circuit. Electron spin in single NV center is flipped periodically by combinatory array of rotations in Bloch sphere, and drive flipping of nuclear spin due to hyperfine coupling. We also selectively manipulate the various neighbor nuclear spins by central NV electron spin to build quantum simulator. The experiment significantly contributes to understand energy conversion and polarization transfer between electron and nuclear spins. The study provides important awareness about fundamental charge state dynamics, quantum information processing, high resolution microscopy and nanoscale sensing.

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### Room temperature coherent manipulation of singlespin qubits in SiC with a high readout contrast

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Spin defects in silicon carbide (SiC) with mature wafer-scale fabrication and micro/nano-processing technologies have recently drawn considerable attention. Although room temperature single-spin manipulation of colour centres in SiC has been demonstrated, the typically detected contrast is less than 2%, and the photon count rate is also low. Here, we present the coherent manipulation of single divacancy spins in 4H-SiC with a high readout contrast (-30%) and a high photon count rate (150 kilo counts per second) under ambient conditions, which are competitive with the nitrogen-vacancy (NV) centres in diamond. Coupling between a single defect spin and a nearby nuclear spin is also observed. We further provide a theoretical explanation for the high readout contrast by analysing the defect levels and decay paths. Since the high readout contrast is of utmost importance in many applications of quantum technologies, this work might open a new territory for SiC-based quantum devices with many advanced properties of the host material.



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# Resonant excited-state spectroscopy and quantum efficiency of single silicon vacancies in silicon carbide

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In quantum communication and distributed quantum computation networks, information is exchanged via flying photons, and subsequently stored and processed in local nodes. Defect centers in solids are promising platforms for such applications. One key challenge for large-scale quantum networks lies in highly-efficient spinphoton interfaces enhancing the collection efficiency and cyclicity of spin-preserving transitions.

To identify the optimum parameters for predictive tailoring of such resonanceenhancement structures, we performed spin-selective excited-state spectroscopy on single silicon vacancy centers (V1) in silicon carbide due to their excellent spin and optical properties [1,2]. In particular, the excited-state lifetimes were measured in a spin-selective manner using resonant pulses. With our resonant depletion scheme, the spin-dependent initialization fidelity is near deterministic (99.2±0.3%). We also realize optical coherent control of the system employing pulsed optical Rabi measurements, which also show that the two spin-dependent transitions have the same transition dipole moment and it is comparable to that of NV centers in diamond [3]. Furthermore, the quantum efficiency of V1 reaches at least 20% which was inferred from field calibration and simulation at the defect location. Based on these, we estimated the minimum required Purcell enhancement for cavities in the case of V1.

Our study provides a guideline for the optical nanoscopic cavity design which plays a crucial role in quantum information applications.

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# Heralded entanglement distribution between two absorptive quantum memories

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Owing to the inevitable loss in communication channels, the distance of entanglement distribution is limited to approximately 100 kilometres on the ground. Quantum repeaters can circumvent this problem by using quantum memory and entanglement swapping. As the elementary link of a quantum repeater, the heralded distribution of two-party entanglement between two remote nodes has only been realized with built-in-type quantum memories. These schemes suffer from the tradeoff between multiplexing capacity and deterministic properties and hence hinder the development of efficient quantum repeaters. Quantum repeaters based on absorptive guantum memories can overcome such limitations because they separate the guantum memories and the guantum light sources. Here we present an experimental demonstration of heralded entanglement between absorptive quantum memories. We build two nodes separated by 3.5 metres, each containing a polarizationentangled photon-pair source and a solid-state quantum memory with bandwidth up to 1 gigahertz. A joint Bell-state measurement in the middle station heralds the successful distribution of maximally entangled states between the two quantum memories with a fidelity of 80.4%. The quantum nodes and channels demonstrated here can serve as an elementary link of a quantum repeater. Moreover, the wideband absorptive quantum memories used in the nodes are compatible with deterministic entanglement sources and can simultaneously support multiplexing, which paves the way for the construction of practical solid-state quantum repeaters and high-speed quantum networks.

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# Entanglement of dark electron-nuclear spin defects in diamond

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A promising approach for scalable multi-qubit quantum network nodes is to use optically addressable spins to control multiple dark electron-spin defects in the environment. While recent experiments have observed signatures of coherent interactions with such dark spins, it is an open challenge to realize the individual control desired for quantum networks and applications. Here we demonstrate the heralded initialization, control and entanglement of individual dark spins associated to multiple P1 centers, which are part of a spin bath surrounding a nitrogen-vacancy center in diamond. We realize projective measurements to prepare the multiple degrees of freedom of P1 centers – their Jahn-Teller axis, nuclear spin and charge state – and exploit these to selectively access multiple P1s in the bath. We develop control and single-shot readout of the nuclear and electron spin, and use this to demonstrate an entangled state of two P1 centers. These results provide a proof-of-principle towards using dark electron-nuclear spin defects as qubits and quantum memories for optically connected quantum networks based on solid state spins.

#### Measuring spin noise with a single spin and single detected photons

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A future quantum network requires the development of an interface between a flying qubit and a stationary qubit. Here we want to use the polarisation of a single photon as the flying qubit and the spin of a single charge (trapped in a semiconductor quantum dot) as the stationary one. A spin-photon interface can be built using a pillar microcavity embedding a charged InAs/GaAs quantum dot (QD). This QD-cavity system is excited with a linearly polarized continuous wave laser. The reflected photons are, after their interaction with the spin qubit, rotated clockwise or counterclockwise depending on the QD spin state [1].

The spin-dependent polarisation rotation angle fluctuates as a function of time depending on the spin state at a given moment. This was used for instance by Dahbashi et al. [2] to characterize this "spin noise" for a single hole spin in a QD. However, in absence of a cavity, it requires a very large number of photons to start measuring the small polarisation rotation angle induced by the single spin.

Here, we make use of the giant polarisation rotation induced by a single QD-hole spin in an electrically-contacted and deterministically-coupled pillar cavity [3]. This allows measuring spin noise spectroscopy with single detected photons, using photon counters. At a given moment, t=0, a first click in a detector, for example in diagonal polarisation (D), partially measures the spin in state up. This decreases the probability to detect a second photon in the opposite, antidiagonal polarisation (A). The observed correlation between the detection events in the two detectors is similar to a spin noise signal obtained with giant polarisation rotation angles.

Interfacing a single spin with a single photon will provide a platform to study solid-state spin physics and the physics of fundamental quantum measurements. The perspectives of using spin-photon interfaces to demonstrate new forms of spin-photon and photon-photon entanglement to carry out quantum communication experiments will also be discussed.

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# Advanced approach to spin-selective intersystemcrossing rates and application to silicon vacancy center in silicon carbide

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Solid-state spin-active color centers are an attractive platform for realizing on-chip integration of efficient spin-photon interfaces such as resonators to boost performance and connect multiple quantum network nodes.

Silicon carbide (SiC) hosts several color centers and is one of the candidate materials for the quantum networking application thanks to the material's scalability and advanced fabrication techniques. Negatively charged silicon vacancy centers in 4H-SiC at hexagonal sites (V1 center) have recently been identified as a promising system demonstrating excellent spin-optical properties such as long-coherence ground-state spin coupled to nearby nuclear spins [1] and indistinguishable photon generation and its deterministic spin control [2]. Towards predictable engineering of radiative lifetime shortening and Purcell enhancement of resonators, the critical challenge is the precise determination of the involved spin-optical dynamics, including radiative, non-radiative, and intersystem crossing rates. However, the relevant rates are not well understood for the V1 center in SiC. To address this, we develop a novel method to infer the radiative and non-radiative spin-selective intersystem crossing rates and apply this to V1 center. Our approach utilizes sublifetime laser pulses to prepare the spin population and probe the dynamics from the fluorescence with the analysis based on a generalized five-level rate model that is applicable to most spin-active color centers. The method works at strong excitation conditions, which leads to fast data acquisition and excellent data quality. Also, our technique is insensitive to the optical deshelving processes, which were proposed to explain conventional  $g^{(2)}$  function measurement results of V2 center in 4H-SiC [3]. Our work pushes forward the implementation of the silicon vacancy center into cavities for realization of spin-photon interface.

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# Indistinguishable single photons from negatively charged tin-vacancy centres in diamond

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For various applications in the field of quantum information processing (QIP) long-lived, stationary qubits are required that can be controlled coherently and read out optically. Quantum computing with linear optics (LOQC) moreover inherently relies on bright light-matter interfaces that provide single indistinguishable photons.

Colour centres in diamond, more specifically the group-IV-vacancy centres, have emerged as a promising candidate among solid state qubits. They exhibit favourable features such as individually addressable spins with long coherence times and bright emission of single, close-to-transform limited photons. While for silicon-vacancy centres (SiV) long spin coherence times are only achieved at milliKelvin temperatures, recent experiments have shown that the negatively charged tin-vacancy centre (SnV) [1] overcomes this drawback. Its large ground state orbital splitting results in the suppression of phonon induced dephasing processes of the spin states, allowing long spin coherence times at significantly higher temperatures (>1K) [2].

Among its good spectral qualities such as bright single photon emission and transform limited linewidths [3,4] the indistinguishability of the emitted single photons remains a missing cornerstone to be demonstrated for tin-vacancy centres.

By means of Hong-Ou-Mandel interferometry we here investigate the indistinguishability of single photons emitted by an off-resonantly excited single SnV-centre. We find high Hong-Ou-Mandel visibilities, being a direct measure for high indistinguishability of the single photons. We compare the experimental results with the predictions of a theoretical model [5] and extract the magnitude of spectral diffusion potentially affecting single photon indistinguishability in the present system.

Furthermore, we estimate the timescale of spectral diffusion by repeating the experiment with various delays between emission of the interfering photons.

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# Long coherence time electronic spin transitions at low magnetic field for large bandwidth quantum memories

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Long coherence time electronic spin transitions at low magnetic field for large bandwidth quantum memories Solid-state optical quantum memories relying on nuclear spins of rare earth ions allows for very long storage time. However, low spin splitting prevents their use for storing large bandwidth photons. Recently, a hybrid system has shown to be promising: Ytterbium ions in YSO held a nuclear and an electronic spins which are hybridized which leads in a four state non-degenerate spin manifold. Clock transitions have been observed for both optical and spin transitions [1] and long coherence times have been measured on the 655 MHz transition for different magnetic field configurations. Spinwave storage has been realized [2] but the achieved bandwidth remains low because of the poor optical strength of one optical transition of the used lambda system. That can be overcome in using higher energy spin transitions which cannot be driven by a regular coil. Such transitions are also expected to have longer coherence time.

To do so, we have developed a loop-gap resonator similar to those used for NV centers in diamond [3]. We also used low doping concentration (2 ppm) to reduce spin flip-flops and so to enhance the T2. We have extensively studied the coherence properties of the 2.5 GHz spin transition of Yb in YSO using Raman heterodyne scattering spin echo. The spin echo has been recorded while monitoring the static magnetic field along the three directions. Thus, Zero First Order Zeeman (ZEFOZ) transition is observed at zero magnetic field as well as a near-ZEFOZ regime when the field is aligned along a given axis of the D1-D2 plane. Out of this direction, superhyperfine interaction with Yttrium ions is evidenced by a periodic revival of the echo. We measure coherence time up to 10 ms at the ZEFOZ point.

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### Spectral Properties of single NV Defect Centers in Diamond Nanostructures

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Lifetime-limited photons form an important resource for a variety of quantum applications, e.g. in long-distant quantum networks stationary qubits can be entangled by photon-mediated protocols. In solid-state systems, noise in the environment of a quantum emitter, e.g. fluctuations in the local charge density, leads to a change of the optical transition frequency over time and therefore to inhomogeneous broadening, which is referred to as spectral diffusion. Overcoming spectral diffusion is still a major challenge for solid-state quantum emitters and limits the generation of indistinguishable single photons.

In our work, we investigate the spectral properties of NV defect centers in diamond nanostructures by performing photoluminescence excitation experiments. In particular in nanostructures, surface defects formed during the fabrication process, but also native bulk defects could cause a strong broadening of the NV emission linewidth. We analyze the impact of different excitation parameters on the optical linewidth and spectral dynamics of the NV zero-phonon-line. We performed a large number of experiments to allow for statistical analysis methods. Understanding the process of spectral diffusion in more detail, will help to implement measures to reduce the inhomogeneous broadening mechanism – an important step towards quantum applications and photonic integration.

# Development of a coherent spin photon interface for quantum repeaters using NV centers in diamond

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Building a long distance quantum network is one of the big challenges in the field of quantum communication, which requires the development of a quantum repeater. A crucial component of this is an efficient, coherent spin photon interface, and coupling single color centers in diamond to a microcavity is a promising approach therefor. In our experiment, we integrate a diamond membrane to an open access fiber-based Fabry-Perot microcavity to attain emission enhancement into a single well-collectable mode as well as spectral filtering. Simulations predict the feasibility of a strong enhancement of the ZPL emission efficiency, reaching values of up to 80%. We present a spatially resolved characterization of a coupled cavity-membrane device and present a cryogenic cavity platform featuring sub pm mechanical noise during quiet periods.



# Enhancing the spin-photon interface of nitrogenvacancy centers in diamond for quantum networks

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Future quantum networks will allow for secure communication, networked quantum computing and tests of quantum theory at a large scale. The Nitrogen-Vacancy (NV) center in diamond is an excellent node candidate, because of its long spin coherence and controllable local qubit registers [1]. While coherent photon collection is inherently limited, integration into a cavity can drastically boost this value via the Purcell effect. However, poor optical coherence of near-surface NV centers has so far prevented their resonant optical control, as would be required for entanglement generation [2,3].

To overcome this challenge, we embed a thin diamond membrane containing NV centers into an open, tunable Fabry-Perot cavity and show that this can preserve the optical coherence of near-surface NV centers in cavities [4]. This allows us to demonstrate resonant addressing of individual, fiber-cavity-coupled NV centers, and collection of their Purcell enhanced coherent photon emission. We extract Purcell factors of up to 4, consistent with a detailed theoretical model including collection efficiencies and cavity length fluctuations.

Based on our results and model, we project that with near-term improvements present-day network links may be sped up by a factor of 100. This could allow entanglement generation which outpaces decoherence even for distant NV centers, a crucial ingredient for large scale quantum networks. Furthermore, the open and tunable nature of Fabry-Perot microcavities makes them a promising platform for quantum applications with many different qubit host materials and defect centers beyond those that can easily be integrated into photonic nanostructures.

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# High-Speed Tunable Microcavities Coupled to Rare-Earth Quantum Emitters

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Electro-optical control of on-chip photonic devices is an essential tool for efficient integrated photonics. Lithium niobate on insulator (LNOI) is an emerging platform for on-chip photonics due to its large electro-optic coefficient and high nonlinearity [1]. Integrating quantum emitters into LNOI would extend their versatility in classic photonics to quantum computing and communication [2, 3]. Here, we incorporate single rare-earth ions (REI) quantum emitters in electro-optical tunable lithium niobite (LN) thin films and demonstrate control of LN microcavities coupled to REIs over a frequency range of 160 GHz with 5 µs switching speed. Dynamical control of the cavities enables the modulation of the Purcell enhancement of the REIs with short time constants. Using the Purcell enhancement, we show evidence of detecting single Yb3+ ions in LN cavities. Coupling quantum emitters in fast tunable photonic devices is an efficient method to shape the waveform of the emitter [4]. It also offers a platform to encode quantum information in the integration of a spectral-temporal-spatial domain to achieve high levels of channel multiplexing, as well as an approach to generate deterministic single-photon sources [5, 6].

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# Solid-State Few-Photon Storage on a Second Timescale Using Electromagnetically Induced Transparency

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We present the experimental demonstration of light storage towards the single photon level at long storage time by electromagnetically induced transparency in a rare-earth ion-doped Pr<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub> crystal. We combine decoherence control by static magnetic fields and appropriately designed radio-frequency composite pulse sequences to prolong the storage time in the memory, a rare-earth ion-doped filter crystal prepared by optical pumping to efficiently separate the signal at the single photon level from optical noise, and a multipass setup around the memory and the filter crystals to improve the storage efficiency and filter selectivity. Already without decoherence control, the setup permits storage of single photons in the µs regime and at a storage efficiency of 42%. With decoherence control we demonstrate storage of weak coherent pulses containing some 10 photons for up to 10s, at a signal-to-noise ratio of 3 and a storage efficiency of several percent. We still get a well detectable signal for EIT light storage of a few photon pulse with an average photon number n=7 for a long storage time above 1s. The experimental data clearly demonstrates the applicability of EIT light storage to implement a true quantum memory in Pr<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub> at long storage times. The scientific findings and technical developments are of relevance also to other protocols and media for quantum information storage.

#### Quantum information theory meets strong field physics via high harmonic generation

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In the following we connect two mainly unrelated fields: quantum information science and strong field physics. This is done by investigation of single- and two-color high order harmonic generation. We demonstrate that all involved field modes in the high harmonic generation process are naturally entangled and how this can be used to generate a whole class of non-classical field states. Performing a quantum operation on the driving field modes leads to coherent state superpositions and entangled coherent states, both with large amplitude. These states can be used for high photon number quantum information processing with the novel property that the underlying dynamics are fundamentally within the attosecond time regime.

### Shallow implantation of color centers in silicon carbide with high-coherence spin-optical properties C. Babin<sup>1</sup>, <u>T. Steidl<sup>1</sup></u>, F. Kaiser<sup>1</sup> and J. Wrachtrup<sup>1</sup>

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Solid-state color centers offer fascinating opportunities by linking atom-like optical transitions and long-lived electron and nuclear spin qubit clusters [1] in nanofabrication-friendly host materials. Scaling up solid-state platforms requires boosting the efficiency of the associated spin-photon interfaces, e.g. by precisely creating color centers in the center of optical cavities. Most efforts have been carried out using diamond color centers for which a major challenge remains to grant spectral and spin stability at the same time [2].

Silicon carbide (SiC), a well-established industrial semiconductor, host multiple promising color centers, in particular the silicon vacancy (V<sub>Si</sub>) center, which provides ultra-robust spectral [3,4] and spin properties [4] at exceptionally high operation temperatures (T = 20 K) [5]. V<sub>Si</sub> can also be straightforwardly Stark shift tuned [6] across >10 times their inhomogeneous distribution [7] without degradation of coherences.

Here, we report the creation of shallow  $V_{Si}$  centers with high spatial resolution using implantation of protons, Helium ions and Silicon ions. For the former two, we observe remarkably robust spin-optical properties. In particular, we show nearly lifetime limited absorption lines and the highest reported Hahn echo spin-coherence times of the system. We attribute these findings to the much lower ion energy used in our experiments (few keV), which minimizes collateral crystal damage.

Our results highlight the tremendous potential of the SiC platform, and provide a decisive forward toward the integration of  $V_{Si}$  in nanophotonic resonators.

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# Implementing frequency comb protocol into the purely microwave regime

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The necessity to develop robust quantum memory systems is motivated not only by their application in quantum communication as a crucial element of quantum repeaters, but also in quantum computing [1]. Recent advances in building and expanding quantum processor units demonstrate outstanding potential of superconducting qubits for the realization of quantum processors, and microwave quantum memory is an underestimated goal.

Most successful realizations of quantum memory imply optical manipulation of trapped cold ions, color centers in diamond, quantum dots, or rare-earth ions with re-pumping of the coherent optical states into the spin states, in particular into the hyperfine states, due to their long lifetime [2]. Such memories, however, require an additional quantum transducer element in order to match the optical frequency of the stored photons into the microwave range. In order to avoid losses on transduction, it is particularly interesting to store the microwave photons directly into resonant long-living microwave states.

In our work, we aim to directly access the long-living hyperfine spin states of the rare earth ions with microwave signals and to store and recall the microwave quantum signals by exploiting well-developed optical techniques such as spectral hole burning and frequency comb. In our presentation, we shall demonstrate preliminary results of our study.



Figure 1:

(a) Transmitted S<sub>21</sub> amplitude measured on <sup>167</sup>Er:Y<sub>2</sub>SiO<sub>5</sub>.
(b) Sample crystal on top of a copper transmission line.

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# Hyperfine Structure of Transition Metal Defects in SiC

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Transition metal (TM) defects in silicon carbide (SiC) are a promising platform in quantum technology, especially because some TM defects emit in one of the telecom bands. We develop a theory for the interaction of an active electron in the *D*-shell of a TM defect in SiC with the TM nuclear spin and derive the effective hyperfine tensor within the Kramers doublets formed by the spin-orbit coupling. Based on our theory we discuss the possibility to exchange the nuclear and electron states with potential applications for nuclear spin manipulation and long-lived nunclear-spin based quantum memories.



The figure shows a sketch of the energy level structure given by group theory (a) including the hyperfine levels (b). An illustration of the defect orbital with the crystal structure indicated by balls (only nearest neighbours) with electron spin and nuclear spin as well as the *z*-direction (crystal axis) indicated by arrows.

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# Optimized diamond inverted nanocones for enhanced color center to fiber coupling

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Color centers in diamond have been shown to be promising candidates for spin gubits that allow coherent control. However, fiber coupling of the emission from these centers is challenging due to the mode mismatch to dipole radiation and the reduced light outcoupling caused by the total internal reflection resulting from the refractive index contrast between air and diamond. Nanostructures fabricated into diamond are popular tools utilized to boost the light outcoupling and to engineer the outgoing mode. Nevertheless, while the fiber coupling properties are crucial for a single mode of indistinguishable photons, this performance of nanostructures is rarely investigated. Here, we simulate the emission of color centers and the overlap of this emission with the propagation mode in a single-mode fiber for a novel nanostructure called inverted nanocone. Using different figures of merit, the parameters are optimized to maximize fiber coupling efficiency, free-space collection efficiency or emission rate enhancement. The optimized inverted nanocones show promising results, with 66% fiber coupling or 83% free-space coupling efficiency at the tin-vacancy center zerophonon line wavelength of 619 nm. Moreover, when evaluated for broadband performance, the optimized designs show 55% and 76% for fiber coupling and freespace efficiencies respectively, for collecting the full tin-vacancy emission spectrum at room temperature. An analysis of fabrication insensitivity indicates that these nanostructures are robust against imperfections. For maximum emission rate into a fiber mode, a design with a Purcell factor of 2.34 is identified. Possible improvements offered by a hybrid inverted nanocone, formed by patterning into two different materials, are also investigated and an increase of the achievable fiber coupling efficiency 71% is found. Finally, we present our progress on fabrication and analysis of these promising nanostructures with SnV color centers for enhanced fiber coupling.

# Controlling single Erbium dopants in a Fabry-Perot resonator

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Erbium dopants exhibit unique optical and spin coherence lifetimes and show great promise for long-distance quantum networks, as their emission lies in the minimalloss window of optical fibers. To achieve an efficient spin-photon interface for single dopants we integrate thin host crystals into cryogenic Fabry-Perot resonators. With a Finesse of  $1.2 \cdot 10^5$  we can demonstrate up to 58(6)-fold Purcell enhancement of the emission rate, corresponding to a two-level cooperativity of 530(50). Our approach avoids interfaces in the proximity of the dopants and therefore preserves the optical coherence up to the lifetime limit [1].

Using this system, we resolve individual erbium dopants which feature an ultra-low spectral diffusion of less than 100 kHz, being limited by the nuclear spin bath. This should allow us to realize frequency-multiplexed spin-qubit readout, control and entanglement, opening unique perspectives for the implementation of quantum repeater nodes.

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# Stable and low-spurious laser source for fast addressing multiple optical qubits spread over a 100 GHz bandwidth

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Optical manipulation of photonic solid-state qubits such as rare-earth ions in single crystals need stable laser sources able to perform complex and high bandwidth excitation waveforms (adiabatic pulses, STIRAP, HSH pulses) [1,2]. Such waveforms can be generated using an acoustic-optical modulators (AOM) connected to an Arbitrary Waveform Generator (AWG) [4]. However, the limited bandwidth of AOMs sets a severe limitation in the bandwidth and frequency agility, typically a few MHz. Using an electro-optical modulator (EOM) such as a phase or an intensity modulator made of LiNbO<sub>3</sub> make it possible to access to higher bandwidth, but it generates unwanted harmonics that can perturb the experiment, reducing the fidelity and/or the efficiency of the protocol [4]. There is currently no architecture able to give enough versatility and stability to perform parallel multiple qubit gates operations over a few GHz range.

Here we develop a laser source that is able to deliver high-bandwidth optical signals at multiple frequencies over a span of 10 GHz (scalable to 100 GHz), with low optical and RF phase and intensity noise. The central wavelengths can be tuned to match the resonance of the different species of optical qubit (in our case  $Eu^{3+}$ , or  $Er^{3+}$  ions in solid-state matrices). The architecture is based on the combination of multiple fixed-frequency laser sources at 1.5 µm. Each laser is externally modulated with a LiNbO<sub>3</sub> IQ optical modulator and goes through a narrow optical filters to obtain the required performances in terms of arbitrary pulse shaping, signal-to-noise ratio and spurious suppression. After the optical signal combination, a non-linear up-conversion can be performed with high efficiency in order to get, for example, a central emission at 580 nm, typical for  $Eu^{3+}$  resonance wavelength.

In this poster, we show the preliminary results in term of modulation bandwidth, spurious suppression and wavelength tuning.

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# Towards high-efficiency cavity enhanced atomic frequency comb quantum memories

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We implement a cavity-enhanced quantum memory using the atomic frequency comb (AFC) protocol in a  $Pr^{3+}$ : Y<sub>2</sub>SiO<sub>5</sub> crystal [1].

The AFC protocol employs spectral tailoring of the inhomogeneous broadening of the  ${}^{3}H_{4} \leftrightarrow {}^{1}D_{2}$  transition (606 nm) of the  $Pr^{3+}$  ions into the shape of a comb with 4 MHz bandwidth. The periodic structure of the comb with a frequency spacing of  $\Delta$  can absorb a photon and will collectively re-phase and re-emit it after 1/ $\Delta$  seconds. In our case, the storage time was 2 µs.

The retrieval efficiency of this protocol is theoretically limited by the process of reabsorption to 54%. We overcame this limit by embedding the crystal in an impedancematched cavity to enhance the interaction with the material [2]. The cavity is 21 cm long and has a finesse of 6.

It is built outside the cryostat that keeps the  $Pr^{3+}$ : Y<sub>2</sub>SiO<sub>5</sub> crystal at 3K.

With this setup, we reached 63% efficiency for storing classical pulses. To the best of our knowledge, this is the highest AFC efficiency reported up-todate. We also reached 39% using weak coherent states with a mean photon



number of 0.2 photons/pulse (see figure). At the single photon level, this is the highest efficiency reported so far with a cavity-enhanced quantum memory. Currently the performance is limited by the cavity stability.

In future experiments plan to increase these efficiencies and to store heralded single photons produced by cavity enhanced spontaneous parametric down-conversion and to store time-bin qubits.

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# Single Ion Detection Utilizing a GaAs Hybrid Photonic Crystal Cavity on Yb<sup>3+</sup>:YVO<sub>4</sub>

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Solid state defects are promising quantum network node candidates due to their scalability and capability to integrate with microwave controls and nanophotonics. To construct a quantum network, it is important to distribute entanglement between different nodes. This requires high-fidelity initialisation and control followed by indistinguishable photon emission. Previously, we worked on a single <sup>171</sup>Yb<sup>3+</sup> ion coupled to a YVO<sub>4</sub> photonic crystal cavity made by focused ion beam milling, and demonstrated high-fidelity initialisation, coherent control, and readout of the ZEFOZ spin transition with over 30 ms coherence time [1]. Despite the high-fidelity operations on the spin transition, the optical  $T_2^*$  of the ion is still limited to 370 ns (1 us using post-selection), which is several times shorter than the 4.4 us lifetime limit. To increase the indistinguishability of photons, it is necessary to increase the Purcell enhancement to lower the lifetime with larger cavity Q/V. Motivated by the possibility of making high quality factor nano-cavities in GaAs, we develop a new hybrid platform with GaAs photonic crystal cavities evanescently coupled to Yb<sup>3+</sup>:YVO<sub>4</sub>. In our experiment, a 1D photonic crystal cavity is fabricated using ebeam lithography in GaAs, and transferred onto YVO<sub>4</sub> using a stamping technique, adopted from the 2D material community. The highest measured Q factor of the transferred devices is around 5000. In the current device, we are able to detect a single ion with a lifetime 30 times shorter than bulk ions, and do a pulsed  $g^{(2)}$  measurement at 4K. Further optimization of the fabrication to increase the Q factor of the GaAs photonic crystal cavities is required to show higher Purcell enhancement and lifetime limited  $T_2^*$ .

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# Criticality Enhanced Quantum Sensing via Continuous Measurement

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#### Abstract

We analyze the theoretical problem of criticality enhanced quantum sensing with open systems at dissipative critical points. For these systems, the precision limit is represented by the global quantum Fisher information of the joint system and bath. Under general assumptions such as Markovianity, we show that the global quantum Fisher information obeys universal scaling laws featuring transient and long-time behavior at dissipative criticality, governed by the underlying critical exponents. Such scaling laws well exceed the standard quantum limit, and can be very close to the Heisenberg limit, therefore allowing for criticality enhanced quantum sensing. As a practical approach for accessing such criticalityenhanced precision, we propose a sensing protocol based on continuous detection of the radiation guanta emitted by the critical open system. In such a protocol a single sensing interrogation corresponds to a (stochastic) guantum trajectory of the open system evolving under the non-unitary dynamics dependent on the parameter to be sensed and the backaction of the continuous measurement. We illustrate the protocol via counting the photons emitted by the open Rabi model, a paradigmatic model for the study of dissipative phase transition with finite components. For this model, we show that our protocol achieves a criticality-enhanced precision scaling, which is more favorable than that provided by measurement of the critical steady state.

# AC susceptometry of 2D van der Waals magnets enabled by the coherent control of quantum sensors

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The nitrogen-vacancy (NV) center in diamond has emerged as a probe with nanoscale spatial resolution for static magnetism in 2D van der Waals materials. Here we expand NV magnetometry on 2D magnets to the dynamic regime. By coherently controlling the NV center's spin precession, quantitative ac susceptometry is realized with varying temperature, field, and frequency. We demonstrate this technique with few-layer CrBr3 and illuminate the formation, mobility, and consolidation of magnetic domain walls.



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### Optically Detected Magnetic Resonance in Neutral Silicon Vacancy Centers in Diamond via Bound Exciton States

#### <u>Zi-Huai Zhang</u><sup>1</sup>, Paul Stevenson<sup>1</sup>, Gergő Thiering<sup>2,3</sup>, Brendon C. Rose<sup>1</sup>, Ding Huang<sup>1</sup>, Andrew M. Edmonds<sup>4</sup>, Matthew L. Markham<sup>4</sup>, Stephen A. Lyon<sup>1</sup>, Adam Gali<sup>2,3</sup>, and Nathalie P. de Leon <sup>1</sup>

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Neutral silicon vacancy (SiV<sup>0</sup>) centers in diamond are promising candidates for quantum networks because of their excellent optical properties and long spin coherence times<sup>1</sup>. In this work, we present the observation of previously unreported optical transitions in SiV<sup>0</sup> that are capable of efficiently polarizing the ground state spin<sup>2</sup>. We assign groups of transitions from 825 to 890 nm to higher-lying excited states of SiV<sup>0</sup> through a combination of optical and spin measurements. We interpret these spectroscopic lines as transitions to bound exciton states of the defect. Optical spin polarization via these bound exciton states enables the observation of optically detected magnetic resonance of SiV<sup>0</sup>.

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