Photonic Links for Quantum Technology Platforms

749. WE-Heraeus-Seminar

31 May - 03 June 2021
online via MeetAnyway

WILHELM UND ELSE
HERAEUS-STIFTUNG

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 749. WE-Heraeus-Seminar:

Quantum information technology based on solid state qubits has created much interest in converting quantum states from the microwave to the optical domain. Optical photons, unlike microwave photons, can be transmitted by fiber, making them suitable for long distance quantum communication. Moreover, the optical domain offers access to a large set of very well developed quantum optical tools, such as highly efficient single-photon detectors and long-lived quantum memories. For a high fidelity microwave to optical transducer, efficient conversion at single photon level and with low added noise is needed. A variety of physical implementations are able to provide the non-linearities essential for transduction. Researchers working on systems such as electro-optic crystals, magneto-optic materials, nano-mechanical devices and ensembles of cold atoms have all demonstrated prototype devices. Furthermore, a wide range of devices and platforms may benefit from quantum microwave - optical interconnects. With work in this area being carried out by researchers from disparate communities, there is a danger that the field becomes somewhat fragmented.

This seminar will therefore bring together investigators from the many and varied areas that are interested in photonic links between different quantum systems. With particular focus on students and newcomers to the field, the seminar will cover the diverse physical systems used to demonstrate photonic conversion between quantum systems, and also cover the quantum information principles underlying the need for efficient transduction.

Scientific Organizers:

Prof. Dr. Harald Schwefel	University of Otago, New Zealand E-mail: harald.schwefel@otago.ac.nz
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Introduction

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Venue: online via MeetAnyway

Program *(CET time)*

Monday, 31 May 2021

Berlin 6:45 PM	**Otago NZ** +1 day 4:45 AM	**Singapore** + 1 day 12:45 AM	**Boston** 12:45 PM	**San Francisco** 9:45 AM

https://www.timeanddate.de/uhrzeit/

06:45 – 06:50 PM	Harald Schwefel Nicholas Lambert Johannes Fink	**Welcome words**
06:50 – 07:00 PM	Stefan Jorda	**About the WE-Heraeus-Foundation**
07:00 – 07:55 PM	Amir Safavi-Naeini	**Approaches and limits to networking quantum machines**
08:00 – 08:55 PM	Oliver Benson	**Delaying and synchronizing single photons for quantum processors using alkali vapor cells**
09:00 – 09:15 PM	**Flash poster session A**	
09:15 – 10:00 PM	**Poster session A**	
10:00 – 10:55 PM	James Haigh	**Microwave-optical conversion using ferromagnetic magnons**
11:00 – 11:55 PM	Cindy Regal	**Towards mechanically-mediated electro-optic quantum transduction**

Program *(CET time)*

Tuesday, 1 June 2021

Berlin 7:00 PM	**Otago NZ** +1 day 5:00 AM	**Singapore** + 1 day 1:00 AM	**Boston** 1:00 PM	**San Francisco** 10:00 AM

https://www.timeanddate.de/uhrzeit/

07:00 – 07:55 PM	Andreas Wallraff	**Operating microwave quantum links between superconducting circuits over meter-scale distances**
08:00 – 08:55 PM	Christoph Becher	**Telecom links between nodes in quantum networks**
09:00 – 09:15 PM	**Flash poster session B**	
09:15 – 10:00 PM	**Poster session B**	
10:00 – 10:55 PM	Jevon Longdell	**Microwave optical conversion using rare earth spins in solids**
11:00 – 11:55 PM	Marko Lončar	**Quantum interconnects with lithium niobate**

Program *(CET time)*

Wednesday, 2 June 2021

Berlin 7:00 PM	Otago NZ +1 day 5:00 AM	Singapore + 1 day 1:00 AM	Boston 1:00 PM	San Francisco 10:00 AM

https://www.timeanddate.de/uhrzeit/

07:00 – 07:55 PM	Andrew Cleland	**Remote quantum communication between superconducting qubit nodes: Challenges and solutions**
08:00 – 08:55 PM	Benjamin Brecht	**Nonlinear integrated quantum devices**
09:00 – 09:15 PM	**Flash poster session C**	
09:15 – 10:00 PM	**Poster session C**	
10:00 – 10:55 PM	Liang Jiang	**Protocols of quantum transduction**
11:00 – 11:55 PM	Wenhui Li	**Microwave-to-optical conversion via wave mixing in an atomic Rydberg ensemble**

Program *(CET time)*

Thursday, 3 June 2021

Berlin 7:00 PM	**Otago NZ** +1 day 5:00 AM	**Singapore** + 1 day 1:00 AM	**Boston** 1:00 PM	**San Francisco** 10:00 AM

https://www.timeanddate.de/uhrzeit/

07:00 – 07:55 PM	Oskar Painter	**An integrated superconducting qubit to optical transducer**
08:00 – 08:55 PM	Birgit Stiller	**Waveguide optomechanics – coherent control of traveling acoustic waves**
09:00 – 09:15 PM	**Flash poster session D**	
09:15 – 10:00 PM	**Poster session D**	
10:00 – 10:55 PM	Paul Seidler	**Microwave-optical transduction with integrated gallium phosphide devices**
11:00 – 11:55 PM	Hong Tang	**AlN cavity electro-optic circuit for microwave-to-optics conversion in the quantum ground state**
12:00 – 12:15	Harald Schwefel Nicholas Lambert Johannes Fink	**Poster prize awards and closing words**

Posters

Posters Monday, 31 May 2021

1	Kazemi Adachi	**Suppression of substrate mechanical mode noise in an electro-opto-mechanical transducer**
2	Scott Agnew	**3D cavity microwave-to-telecom transduction**
3	Gabriel Araneda Machuca	**A two-node trapped-ion quantum computer with photonics interconnects**
4	Sissel Bay Nielsen	**Cavity optomechanics with bulk acoustic waves**
5	Maxime Bergamin	**Optical investigation of GeV center in diamond observation of energy level fluctuations and blinking**
6	Terence Blésin	**Quantum coherent microwave-optical transduction using high overtone bulk acoustic resonances**
7	Antariksha Das	**A spectrally-multiplexed long-lived quantum memory in a thulium-doped crystal**
8	Hugo Doeleman Tom Schatteburg	**An aligned optical cavity at mK temperatures for microwave-to-optical transduction**
9	Brandon Grinkemeyer	**A quantum network node based on a nanophotonic interface for atoms in optical tweezers**

Posters Tuesday, 1 June 2021

10	Burak Gurlek	**Organic molecules with long-lived quantum coherence**
11	Jeffrey Holzgrafe	**Cavity electro-optics in thin-film lithium niobate for microwave-to-optical transduction**
12	Wentao Jiang	**Microwave-to-optical quantum frequency conversion with piezo-optomechanics in lithium niobate on silicon-on-insulator**
13	Gavin King	**Rare-earth ions for the upconversion of microwave photons**
14	Akira Kyle	**Intrinsic entanglement thresholds of a single doubly-parametric quantum transducer**
15	Dante Loi Paul Falthansl-Scheinecker William Hease Liu Qiu	**Fabrication of ultra high quality factor WGM resonator for two-mode squeezing of microwave and optical fields**
16	Li Ma	**$^{170}\mathrm{Er{:}Y_2SiO_5}$ whispering gallery mode resonator electro-optic conversion**
17	Felix Mayor	**Gigahertz phononic integrated circuits on thin-film lithium niobate on sapphire**
18	Sonia Mobassem	**Measuring thermal noise in electro-optic devices at cryogenic temperatures**

Posters Wednesday, 2 June 2021

19	Kevin Multani	**Development of a microwave-to-millimeter-wave quantum frequency converter**
20	Krzysztof Pomorski Łukasz Pluszyński	**Holonomic quantum computation and quantum communication in semiconductor Wannier qubits**
21	Alexandra Popp	**Localized stimulated Brillouin scattering in hot CS -filled liquid-core optical fibers**
22	Maximilian Protte	**Superconducting microwire single-photon detectors fabricated with laser lithography**
23	Curtis Rau	**Thresholds for establishing remote microwave entanglement over an optical link using two doubly-parametric quantum transducers**
24	Daniel Riedel	**A quantum photonic interface for tin-vacancy centers in diamond**
25	Fabian Ruf	**Low-loss all-optical ns-switching for scalable quantum photonic links**
26	Maximilian Ruf	**Enhancing the spin-photon interface of color centers in diamond for quantum networks**
27	Rishabh Sahu	**Quantum-enabled microwave optical interface with unity internal efficiency**

Posters Thursday, 3 June 2021

28	Yannick Seis	**Ultra-coherent electro-mechanics in the quantum regime**
29	Prasoon Kumar Shandilya	**Optomechanical interface between telecom photons and spin quantum memory**
30	Linbo Shao	**Electrical control of gigahertz surface acoustic wave on lithium niobate**
31	Luca Talamo	**Narrow-band and efficient Fabry-Perot cavities for electro-opto-mechanical transducers**
32	Chiao-Hsuan Wang	**Generalized matching condition for efficient N-stage quantum transduction**
33	Lorenz Weiss	**Towards quantum networks with erbium dopants in silicon**
34	Tian Xie Jake Rochmann	**On-chip microwave to optical transduction using erbium in YVO_4**
35	Xinglin Zeng	**Stimulated Brillouin scattering of helical Bloch modes in 3-fold rotationally symmetric chiral 4-core photonic crystal fibre**

Abstracts of Talks

(in alphabetical order)

Telecom links between nodes in quantum networks

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Photons are prime carriers of information and can bridge large distances in fiber-based networks provided their wavelength is within one of the low-loss telecommunication windows. This established technology is the basis of today’s optical communication networks. On the other hand, physicists have the vision of a “quantum internet” where local quantum bits and memories are interconnected by flying quantum bits, e.g. single photons, to provide secure communication, distributed quantum computing or networks of quantum sensors. The majority of atomic or solid-state systems serving as qubits or quantum memories, however, do not offer optical transitions at telecom wavelengths but commonly emit in the visible to near-infrared range.

Surprisingly, simple nonlinear optics, i.e. frequency conversion in nonlinear crystals, provides an efficient and low-noise interface between qubit and telecom wavelengths, even at the single photon level [1]. This technique has reached a level of maturity to be employed in demonstrations of remote entanglement in quantum network settings. I will report on application of quantum frequency conversion in such demonstrations with neutral atoms [2], trapped ions [3] and semiconductor quantum dots [4].

References

[1] S. Zaske et al., Phys. Rev. Lett. **109**, 147404 (2012).
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Delaying and synchronizing single photons for quantum processors using alkali vapor cells

Esteban Gomez Lopez[1], Chris Müller[1], Tim Kroh[1], Janik Wolters[2], Oliver Benson[1]

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Single photon sources, reconfigurable integrated photonic circuits, and conditional detection are key ingredients for photonic quantum processors [1]. Such processors have performed quantum computational tasks [2], showed supremacy in Boson sampling [3] or acted as memories in quantum communication devices [4]. For many of these devices photon synchronization via controlled delays is required or would improve performance. Additionally, in measurement based or ‘one-way’ computing [5] delays are mandatory to make fast enough feed-forward possible.

In this presentation we report on our work to realize quantum delays and storage devices using alkali vapor cells. By coherent manipulation of atomic transitions matching the wavelength of on-demand photon sources controllable delays can be realized [6]. Vapor cells are also compatible with integration into micro-optical platforms [7] or with in-cell photonic structures [8] to improve photon-atom interaction. We introduce recent experiments and discuss future directions.

References

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[2] Quantum circuits with many photons on a programmable nanophotonic chip, J. M. Arrazola et al., Nature **591**, 54 (2021).

[3] Quantum computational advantage using photons, H.-S. Zhong et al., Science **370**, 1460 (2020).

[4] Experimental demonstration of memory-enhanced quantum communication, M. K. Bhaskar, R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Lončar, D. D. Sukachev, M. D. Lukin, Nature **580**, 60 (2020).

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[8] Coherent interaction of atoms with a beam of light confined in a light cage, T. Kroh, F. Davidson-Marquis, J. Gargiulo, E. Gómez-López, B. Jang, C. Müller, M. Ziegler, S. A. Maier, H. Kübler, M. Schmidt, and O. Benson, Light: Science & Applications, accepted.

Nonlinear integrated quantum devices

Benjamin Brecht

Universität Paderborn, Department of Physics, Germany

Remote quantum communication between superconducting qubit nodes: Challenges and solutions

Andrew N Cleland[1]

[1]*Pritzker School of ME, University of Chicago, Chicago IL USA*

Superconducting qubits, through their easy engineering and facile fabrication, provide a useful means for developing concepts in quantum information, as well as candidates for quantum computation and communication in their own right [1,2]. I will give a brief introduction to how these devices operate in the quantum regime, then demonstrate two developments from my group's research: First, an approach we have been developing to use superconducting qubits to test theoretical concepts in quantum communication [3,4], including the recent demonstration of small communication networks based on microwave photons that enable the transfer of high-fidelity, multi-qubit entangled states between remote nodes [5], as well as the purification and preservation of inter-nodal entangled states [6]. Second, I will provide a description of our parallel initial steps towards building a microwave phonon-based quantum communication capability, which may lead to interesting and new methods for linking hybrid quantum systems [7,8,9].

References

[1] R. Barends et al., "Coherent Josephson qubit suitable for scalable quantum integrated circuits," *Phys. Rev. Lett.* **111**, 080502 (2013)

[2] R. Barends et al., "Superconducting quantum circuits at the surface code threshold for fault tolerance," *Nature* **508** 500-503 (2014)

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Microwave-optical conversion using ferromagnetic magnons

J. A. Haigh[1] **and A. J. Ramsay**[1]

[1]*Hitachi Cambridge Laboratory, Cambridge, UK*

We review the use of magnons in a ferromagnetic material as the intermediary excitation in the conversion between microwave and optical photons. Whilst so-far rather limited in the conversion efficiency, progress has been made in raising the magneto-optical coupling rate. This has involved moving from large scale whispering gallery mode resonators [1] to smaller mode volume optical cavities [2,3]. In addition, the time-reversal symmetry breaking introduced by the magnetization may embed directional functionality in the system.

References

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Protocols of Quantum Transduction

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Quantum transducers can convert quantum signals from one bosonic mode to another. In practice, the signal attenuation and added noise still prevent us from achieving quantum transduction between microwave and optical modes. To overcome these practical imperfections, we investigate and compare different quantum transduction protocols, including direct quantum transduction [1], adaptive quantum transduction [2], and teleported quantum transduction [3]. Besides loss and added noise, the bandwidth of quantum transducer is also important for future applications. We propose a metric of *quantum transduction channel capacity* to characterize the maximum transduction rate of quantum transducers.

References

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Microwave-to-optical conversion via wave mixing in an atomic Rydberg ensemble

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We demonstrated coherent and broadband microwave-to-optical conversion in free-space via frequency mixing in Rydberg atoms, where the phase information of the microwave field is coherently transferred to the optical field [1]. We achieved a photon conversion efficiency of ~ 5% and a broad conversion bandwidth of more than 4 MHz [2]. Our results are in good agreement with a numerical simulation based on Maxwell-Bloch equations. With theoretical analysis and simulation, we have identified a range of experimental conditions, under which the conversion efficiency could be further improved by an order of magnitude [2].

References

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Quantum Interconnects with Lithium Niobate

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Lithium niobate (LN) is an “old” material with many applications in optical and microwave technologies, owing to its strong electro-optic (EO) coefficient, second order nonlinearity, and piezoelectricity. Conventional - discrete - LN components, the workhorse of the optoelectronic industry for many decades, are reaching their limits, however. I will discuss our efforts aimed at the development of integrated LN photonic platform aimed at applications for quantum optical interconnects. Examples include, fast and low loss electro-optic switches, frequency converters, quantum transducers, and components for frequency domain quantum computing.

Microwave optical conversion using rare earth spins in solids

Gavin King[1], Johnathan Everts[1], Peter Barnett[1], Li Ma[1], Matthew Berrington[2], Rose Ahlefeldt[2] and Jevon J. Longdell[1]

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Rare earths in solids provide offer narrow linewidths for both their spin and optical transitions and the possibility for large ion densities. Efficiencies of order 10^{-5} have been achieved [1] at 4K temperatures using Erbium dopants. Theoretical work suggests that improvements toward efficiencies closer to unity [2] are possible with a number of achievable improvements. We will discuss progress towards implementing these improvements.

These include

- Lower temperatures, which will increase the effective number of atoms by a factor of roughly 30 by freezing spins into the ground state.
- The use of isotopically pure dopants, to avoid unwanted optical absorption lines.
- The use of high quality factor whispering gallery mode resonators.

We are also investigating a new class of materials for quantum information processing with rare earths. To date such work has involved crystals doped with rare earth ions. *Fully concentrated* crystals, those were the rare earth ions are part of the host crystal, offer an alternative. They have the obvious benefit of large concentrations. Previously it has been shown that narrow linewidths optical transitions are possible [3]. Here we will present results [4] showing that the same is true for spin transitions. We will discuss the implications for microwave to optical conversion [5].

References

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An integrated superconducting qubit to optical transducer

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The transduction of quantum microwave signals to optical photons would enable a new form of long range entanglement distribution between superconducting quantum circuit nodes. Mechanical transducers of various forms are currently being explored for quantum microwave-to-optical transduction, with key figures of merit being transducer efficiency and added noise. In this presentation I will describe recent work at Caltech [1] to realize an integrated piezo-acoustic-based transducer for direct coupling of a transmon qubit with an optomechanical cavity. While added noise of approximately 0.5 quanta was obtained in this transducer design, significant improvements in the internal and external efficiency, as well as the repetition rate are required to perform remote entanglement between superconducting nodes over an optical channel. I will discuss our current work to address these limitations.

References

[1] M. Mirhosseini, et al., Nature **588,** 599-603 (2020)

Towards mechanically-mediated electro-optic quantum transduction

B. M. Brubaker, R. D. Delaney, M. D. Urmey, J. M. Kindem, S. Mittal, L. Talamo, K. J. Adachi, C. A. Regal, K. W. Lehnert

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Superconducting qubits have become a powerful resource for the creation of arbitrary quantum states. Yet optical links are the best way to preserve a quantum state over long distances. I will present our work on an efficient and low added noise link between the microwave and optical domains via the motion of a micromechanical SiN membrane. With this conversion mechanism we have demonstrated nearly 50% efficient classical conversion at dilution refrigerator temperatures, added noise near 10 photons/s/Hz, and the ability to harness electro-optic correlations for suppression of added thermal noise [1]. I will also discuss current efforts to reduce the converter noise and to introduce a superconducting qubit as a modular element.

References

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Approaches and limits to networking quantum machines

Wentao Jiang, Felix Mayor, Kevin Multani, Timothy McKenna, Hubert Stokowski, Chris Sarabalis, Jason Herrmann, Agnetta Cleland, Alex Wollack, Jeremy Witmer, Rishi Patel, Raphael Van Laer, Marek Pechal, Amir H. Safavi-Naeini

Stanford University, Stanford, CA, USA

Currently, several quantum information processing systems are being developed that use microwave photons to store and process information. Networking these systems will likely require transducers that convert information from the microwave domain to a higher energy photons that are more robust thermal decoherence. In this talk, I will outline some of the approaches and associate challenges with developing these transducers. In particular, I will focus on three device approaches which we are actively developing: quantum electro-optic converters [1-2], quantum piezo-optomechanical converters [3], and mm-wave-to-microwave transducers [4-5].

References

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Microwave-optical transduction with integrated gallium phosphide devices

Paul Seidler[1]

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Electromechanically actuated optomechanical resonators offer an attractive route to coherent interconversion of microwave and optical photons. Such devices could enable optical interconnection of quantum computers based on qubits operating at microwave frequencies, providing both scalability and added functionality. In this talk, I will describe a novel platform for microwave-to-optical conversion utilizing an optical cavity made of gallium phosphide (GaP) integrated on prefabricated microwave circuits and present early results demonstrating coherent transduction.

GaP possesses an attractive combination of a large refractive index ($n > 3$) and a wide electronic bandgap (2.26 eV) [1]. These values offer the possibility of creating devices with strong light confinement, enhanced light-matter interaction, and low two-photon absorption at telecommunication wavelengths. In addition, GaP has a non-centrosymmetric crystal structure and is thus piezoelectrically active. The main challenge has been the lack of methods for integrating GaP on low-refractive-index substrates and patterning it into structures with nanometer precision while maintaining good material quality. We have developed the necessary processes to address these issues [2,3].

The fabricated device comprises a quasi-one-dimensional photonic crystal cavity made of single-crystal GaP [4] integrated on niobium circuits on an intrinsic silicon substrate. We exploit spatially extended, sideband-resolved mechanical breathing modes at $\sim$3.2 GHz, with vacuum optomechanical coupling rates up to 300 kHz. The mechanical modes are driven by the niobium electrodes via the inverse piezoelectric effect. We estimate that the system could achieve an electromechanical coupling rate to a superconducting transmon qubit of $\sim$200 kHz.

This work represents a first step towards integration of GaP electro-opto-mechanical transducers with superconducting quantum processors.

References

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Waveguide optomechanics – coherent control of traveling acoustic waves

B. Stiller

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Optical and traveling acoustic waves can interact over stimulated Brillouin scattering (SBS), which is a third-order nonlinear effect and a coherent process. SBS has been of crucial importance for applications in optical fiber sensing, microwave photonics, Brillouin lasers and signal processing. The latter includes calculus operations and signal amplification but also light storage of signal streams [1]. By using traveling acoustic waves, we recently showed proof-of-principle experiments of Brillouin-based light storage [2–7], such as the tunable delay and coherent retrieval of an optical signal [2], as well as cascaded storage at different spatial positions [3].

A particularity of Brillouin-based light storage is the strict phase-matching condition. This allows for different features: nonreciprocal storage over a large bandwidth [4] and simultaneous storage at multiple wavelengths with negligible crosstalk [5], which distinguishes our waveguide approach from optomechanical resonators. The delay time of this technique has so far been limited to the acoustic lifetime of about 10 ns.

In recent results though, we were able to experimentally demonstrate how to reinforce acoustic phonons to overcome the obstacle of the limited acoustic lifetime. We showed for the first time the storage of amplitude and phase of an optical signal via stimulated Brillouin scattering up to 40 ns, which can potentially be further expanded [6]. Another interesting topic is the optoacoustic interaction of short pulses whose bandwidth is well beyond the Brillouin linewidth. We have experimentally demonstrated the SBS interaction of optical pulses down to 150 ps and achieved a time-delay in Brillouin-based memory of 100 pulse-widths [7].

In this talk, I will give an overview about our recent results, speak about the challenges and chances of using SBS for signal processing and present recent achievements in more exotic types of waveguides: liquid-filled capillary fibers and twisted photonic crystal fibers.

References

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AlN cavity electro-optic circuit for microwave-to-optics conversion in the quantum ground state

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Microwave-to-optical quantum converters represent an indispensable component for quantum communication in future quantum networks. To maintain quantum coherence, it is critical for such devices to operate at milli-Kelvin temperatures in the quantum ground state. However, integrating photonics with superconductors at milli-Kelvin temperatures is particularly challenging since the optical excitation leads to unavoidable heating and excess microwave noise, thus placing the device systems in a thermal state as opposed to the desired ground state. In this work, we demonstrate efficient bidirectional microwave-to-optical conversion with an electro-optic device fabricated on an integrated AlN photonic platform in a milli-Kelvin environment. Our device operates near its quantum ground state and meanwhile offers 0.12% conversion efficiency – a rate that is suitable for building two-node quantum network through heralding protocols.[1] This fully integrated converter offers advantages including tunability, scalability, and high pump power handling capability. Harnessing a pulsed drive scheme, we suppress the microwave resonator's thermal occupancy by 30 dB to as low as 0.09±0.06 quanta (92±5% ground state probability). By studying microwave noise thermodynamics, we unravel the underlying light-induced noise generation mechanisms, which provide important guidelines for future deployment of chipscale electro-optical devices as quantum links between superconducting quantum computers. [2,3]

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Operating Microwave Quantum Links between Superconducting Circuits over Meter-Scale Distances

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Superconducting circuits are a strong contender for realizing quantum computing systems. Constructing such systems with many thousands, possibly millions of superconducting qubits will likely require linking several computing nodes housed in their dedicated cryogenic systems into a larger networked cluster. Such networks could operate at optical frequencies using fiber links but would require large bandwidth and high-fidelity microwave-to-optical conversion. At ETH Zurich, in a radically different approach, we have designed, realized, and tested a first quantum microwave link which allows superconducting-circuit-based quantum processors located in different systems to directly exchange quantum information [1] over distances of up to 30 meters. This link, for a quantum computer, takes the role of a network transferring data between computing nodes located in a high-performance computing data center. However, unlike its conventional counterparts, our data link is operated at ultra-low temperatures, close to the absolute zero. This allows our quantum data link to directly connect to quantum processors operating at the same temperature [2]. Using this system, we transfer qubit states and generate entanglement on demand with high transfer and target state fidelities. The system we have constructed is a first of its kind in the world and could play an important role in both growing the power of quantum computers in the future and allowing for fundamental quantum science experiments.

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Abstracts of Posters

(in alphabetical order)

3D Cavity Microwave-to-Telecom Transduction

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We report progress towards the design and fabrication of high quality factor optomechanical crystals (OMCs) with an end goal of obtaining high-efficiency transductions between telecom and microwave frequencies. Previously [1], the Davis lab has had success with microwave transduction in a triply resonant system involving a gallium arsenide (GaAs) OMC and a 3D microwave cavity. Placing the OMC in the electric field maximum of the 3D microwave cavity enabled coupling between the microwave cavity and the mechanical breathing mode of the OMC through the piezoelectric effect. The OMC is designed such that there is a large mode overlap between the mechanical breathing mode and the telecom optical mode, so information such as phase and amplitude can be read out using an optical homodyne measurement scheme. This system had a transduction efficiency of 10^{-15}, but to be competitive with current low frequency classical microwave-to-telecom converters this must be improved.

We propose two routes towards improving transduction efficiency. Development of new fiber coupling methods, such as edge coupling [2], will allow for better 3D microwave cavity geometries, reducing radiative losses and increasing overlap between the OMC and microwave electric field maximum. Additionally, we will be moving to a new material: Lithium Niobate (LN). LN boasts larger photoelastic and piezoelectric coefficients [3], which will produce better optomechanical and piezoelectric coupling respectively. To date, the Davis lab has no fabrication experience with LN, but upon optimization of the fabrication process we predict that our single photon transduction efficiency will increase significantly. Combining the improved 3D microwave cavity and new OMCs we predict the single photon transduction efficiency will increase to $\sim 10^{-8}$.

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A two-node trapped-ion quantum computer with photonics interconnects

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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.**

Currently, we are working 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.

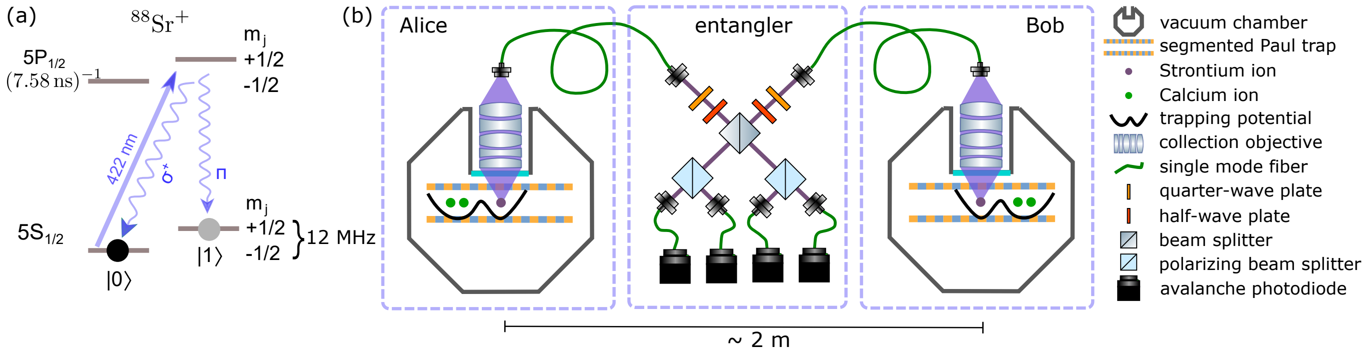

Figure 1: Two-node trapped-ion quantum computer with photonic connections.a) Photons emitted spontaneously at 422 nm are entangled with the state of the ion after the emission (|0⟩ or |1⟩). b) Two identical ion trap systems, 'Alice' and 'Bob', are equipped with micro-fabricated segmented traps. Each system can trap both ^{43}Ca$^+$ and ^{88}Sr$^+$ 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.

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Cavity Optomechanics with Bulk Acoustic Waves

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The field of quantum optomechanics shows great potential as for applications in quantum information storage and quantum transducers, as well as studies of the fundamental interaction between light and mechanical motion on a quantum level. In bulk optomechanical systems the Brillouin interaction is utilised to couple optical modes and bulk acoustic modes in a millimetre sized crystal, allowing to study the interaction between light and sound, down to the quantum level [1].

In our system we investigate this interaction with light at telecom wavelength and the acoustic modes in a quartz crystal. As a proof of concept, the Brillouin scattering is first investigated at room temperature with a flat-flat crystal placed in a high finesse optical cavity. The reflective surfaces of the crystal create a system with several coupled cavities and thus an asymmetric FSR spectrum which can be exploited to differentiate between the Stokes and anti-Stokes Brillouin interactions. At room temperature the coherence length of the phononic acoustic modes is only a few 100 microns. This coherence length can be greatly enhanced by placing the system in a milli-Kelvin environment. By curving one side of the crystal, many roundtrips of the acoustic mode within the crystal can be established in this combined optical/acoustic cavity. An outlook on the design and implementation of the system functioning at milli-Kelvin temperatures will be presented as well.

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Optical Investigation of GeV Center in Diamond Observation of Energy Level Fluctuations and Blinking

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Point defects in diamond are promising candidates in the solid-state for a wide range of application in quantum information processing. Among different defects with allowed optical transitions, the germanium-vacancy center (GeV) is an attractive one as it has good optical properties at room temperature including a narrow zero-phonon line and low emission into the phonon sideband. Some of the GeV center intrinsic physical properties are yet unknown. In this contribution, we focus on the optical investigation of single GeV centers deeply implanted into a synthetic diamond crystal at a cryogenic sample temperature of 4K. Applying a resonant optical excitation scheme, we report on the observation of energy level fluctuations and blinking. The behavior of single GeV centers is monitored both by collecting photons emitted in the phonon side band and in the zero-phonon line using a cross-polarization scheme. The energy level fluctuations occur over hundreds of MHz as determined by successive resonant photoluminescence scans. Similar observations were previously made for SiV centers and attributed to the presence of P1 centers, effectively causing level shift by the Stark effect. Our investigations show that the rate and amount of energy level fluctuations are individual, and we also identify a statistically significant number of GeV without level fluctuations. Further experimental efforts with varying substrate material and preparation methods are required to reveal in detail the underlying processes.

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Quantum coherent microwave-optical transduction using high overtone bulk acoustic resonances

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A device capable of converting single quanta of the microwave field to the optical domain is an outstanding endeavour in the context of quantum interconnects between distant superconducting qubits, but likewise can have applications in other fields, such as radio astronomy or, in the classical realm, microwave photonics. A variety of transduction approaches, based on optomechanical or electro-optical interactions, have been proposed and realized, yet the required vanishing added noises and an efficiency approaching unity, have not yet been attained. Here we present a new transduction scheme that could in theory satisfy the requirements for quantum coherent bidirectional transduction. Our scheme relies on an intermediary mechanical mode, a high overtone bulk acoustic resonance (HBAR), to coherently couple microwave and optical photons through the piezoelectric and strain-optical effects. Its efficiency results from ultra low loss and high intracavity photon number sustaining integrated silicon nitride photonic circuits, combined with the highly efficient microwave to mechanical transduction offered by piezoelectrically coupled HBAR. We develop a quantum theory for this multipartite system by first introducing a quantization method for the piezoelectric interaction between the microwave mode and the mechanical mode from first principles (which to our knowledge had not been presented in this form), and link the latter to the conventional Butterworth-Van Dyke model. The HBAR is subsequently coupled to a pair of hybridized optical modes from coupled optical ring cavities via the strain-optical effect. We analyze the conversion capabilities of the proposed device using signal flow graphs, and demonstrate that quantum coherent transduction is possible, with realistic experimental parameters at optical input laser powers of the order of hundreds of milliwatts. Combined with the high thermal conduction via the device bulk, heating effects are mitigated, and the approach does not require superconducting resonators that are susceptible to absorption of optical photons.

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A Spectrally-Multiplexed Long-Lived Quantum Memory in a Thulium-Doped Crystal

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Abstract: Rare-earth ion-doped materials [1] with long optical coherence lifetimes can serve as frequency-multiplexed, long-lived optical quantum memories [2], which are of an essential requirement towards building frequency multiplexed quantum repeaters [3] for long-distance quantum communications. Towards this end, we investigate a thulium-doped crystal (Tm: YGG) [4, 5] at temperatures as low as 500 mK and low magnetic fields. This crystal offers an optical coherence lifetime exceeding one millisecond and a ground-state Zeeman level lifetime as long as tens of seconds. We take advantage of such exceptional features to show several key demonstrations; storage of optical pulses for up to 100 µs of optical storage time, frequency-multiplexed storage of 11 distinct frequency modes, a proof of principle demonstration of frequency-selective read-out of 3 distinct stored frequency modes. Our results suggest that Tm: YGG can be a potential candidate to be used as an optical quantum memory in frequency multiplexed quantum repeater architecture.

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An aligned optical cavity at mK temperatures for microwave-to-optical transduction

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Superconducting circuits are one of the most sophisticated architectures for quantum information processing to date. Their operation at microwave (MW) frequencies, however, confines these circuits to the base stages of dilution refrigerators. MW-to-optical conversion in the quantum regime could enhance the scalability and range of applications of superconducting circuits, since optical photons can be used as noise-free carriers of quantum information that connect circuits in different refrigerators. This requires a conversion process that is coherent, efficient, and with minimal added noise, which has not been demonstrated yet.

We present our advances in developing a cryogenic cavity optomechanical device based on a bulk-acoustic-wave (BAW) mechanical resonator, which can act as an essential part of a MW-to-optical transducer. Strong coupling to BAWs has been demonstrated both for microwave photons [1] and for optical photons [2]. Building on these works, we are developing an optomechanical cavity for operation at mK temperatures inside a dilution fridge that is also compatible with coupling to superconducting circuits. We discuss the cavity design and introduce a method for alignment at mK temperatures.

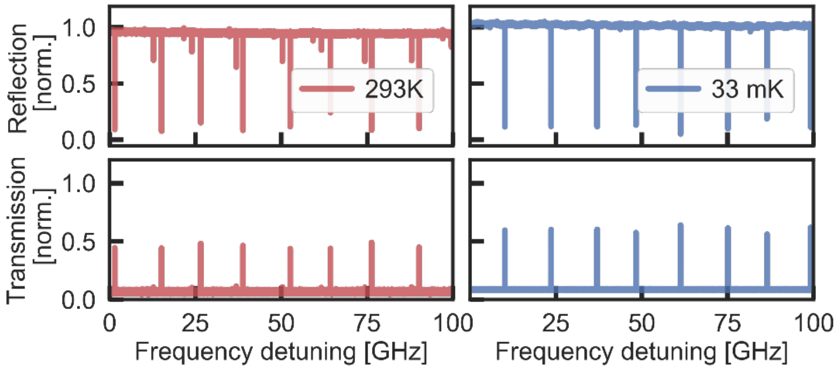

Figure 1: Reflection and transmission spectra of our optomechanical cavity at room temperature (left, red) and at dilution refrigerator base temperature (right, blue). The cavity moves into alignment during the cooldown.

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A Quantum Network Node Based on a Nanophotonic Interface for Atoms in Optical Tweezers

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Efficient interfaces between photons and memory qubits constitute fundamental building blocks for quantum networking and large-scale quantum information processing. Our approach utilizes a photonic crystal cavity to realize such optical interfaces for atoms in optical tweezers. With this platform, we observe strong coupling between two atoms mediated by the cavity. Combining this observation with coherent manipulation and non-destructive measurements, we implement a protocol for generating Bell pairs that remain entangled when transported away from the cavity structure. These results present prospects for additional capabilities, such as rapid non-destructive readout and flexible connectivity, to neutral atom quantum information processors with integrated optical interconnects.

ORGANIC MOLECULES WITH LONG-LIVED QUANTUM COHERENCE

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Single organic molecules in the solid-state are one of the promising optical platforms for realizing quantum networks owing to their remarkable coherent properties [1]. Such a high-degree of coherence resulting from strong zero-phonon lines with Fourier-limited linewidths is limited to nanosecond timescales, which implies a great challenge for practical implementations of quantum networks.

In this theoretical work, we propose a new molecular system with quantum coherences up to millisecond timescales by exploiting the optomechanical character of single molecules in the solid state [2]. The proposed schema consists of a single organic molecule in a host matrix with structured phononic environments that suppress its phononic decay. We show that the resulting long-lived vibrational states facilitate reaching strong optomechanical regimes at single photon level. We exploit the long optomechanical coherence time of the molecule to store and retrieve optical information with proper pulse excitation up to millisecond timescales. The proposed system shows the prospects of organic molecules for reaching unexplored optomechanical regimes and realizing long-lived quantum memories.

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Cavity electro-optics in thin-film lithium niobate for microwave-to-optical transduction

Jeffrey Holzgrafe[1], Neil Sinclair[1,2], Di Zhu[1,3], Amirhassan Shams-Ansari[1], Marco Colangelo[3], Yaowen Hu[1], Mian Zhang[1,4], Karl K. Berggren[3], Marko Loncar[1]

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Cavity electro-optics is a promising approach for quantum transduction between microwave and optical fields because it provides a wide transduction bandwidth and may be capable of low-power operation, high efficiency and low noise. Here we present a cavity electro-optic transducer in a thin-film lithium niobate platform, which provides strong nonlinearity and low optical loss. We demonstrate on-chip photon transduction efficiency of more than 10^{-5} with a bandwidth larger than $10\ \mathrm{MHz}$ and characterize the impact of optical absorption in the superconducting microwave resonator on the transducer. Finally, we describe recent efforts to improve this transducer for higher efficiency and lower noise, as well as near-term goals for creating a system capable of optically-heralded remote entanglement between microwave modes.

Rare-Earth Ions for the Upconversion of Microwave Photons

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Department of Physics, University of Otago, New Zealand

Superconducting qubits are particularly promising, but their tendency to couple to microwave photons means that interconnecting quantum computers is difficult. One method to coherently convert these microwave photons to optical photons is to use a three-level system in a sum-frequency-generation arrangement: to the microwave photon, add an optical pump photon, which generates an output optical photon[2].
The rare-earth ions are well suited to this method, having narrow optical transitions, and easily accessible microwave transitions. Erbium in particular is ideal, with optical transitions around the lowest-loss window in silica fibre at 1550 nm, and with sufficient magnetic moment to allow microwave Zeeman splitting at reasonable (∼100 mT) applied fields. In the past, we have used erbium at natural isotopic abundance to obtain a conversion efficiency of 10^{-5} at 4 K[1]. Two of the limits on the efficiency were thermal population of the higher microwave state, and re-absorption by the ^{167}Er isotope, which occurs at 24% abundance and has non-zero nuclear spin, giving absorptive hyperfine energy levels in between those levels we use.
We have characterised the properties of an isotopically pure sample of ^{170}Er:YSO, and have made measurements of it at temperatures well below 1 K in order to determine the extent to which temperature and parasitic re-absorption limit the conversion efficiency. In doing so, we measured strong coupling between the Er^{3+} ions and the microwave resonator, both in purely microwave (electron spin resonance) measurements, and in Raman heterodyne upconversion measurements. We also have plans to quantify the conversion efficiency with both a microwave resonator and an optical resonator, to resonantly enhance the conversion.

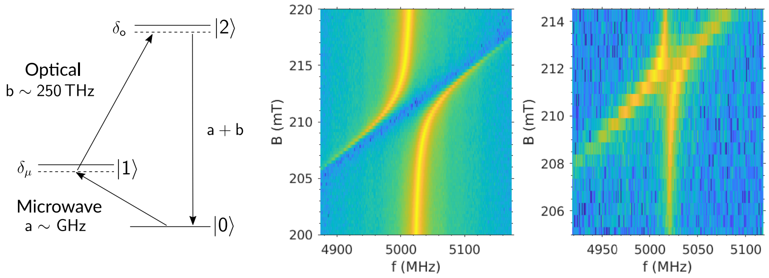

Figure 1: Three-level system used for upconversion (left), strong coupling between the ions and cavity seen by electron spin resonance (centre), and by Raman heterodyne spectroscopy.

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Intrinsic Entanglement Thresholds of a Single Doubly-Parametric Quantum Transducer

Akira Kyle[1,2], Curtis Rau[1,2], Alex Kwiatkowski[1,2], Ezad Shojaee[1,2], John Teufel[2], Konrad Lehnert[1,2,3], Tasshi Dennis[2]

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Doubly-parametric quantum transducers, such as electro-opto-mechanical devices, are quickly approaching quantum operation as decoherence mechanisms such as thermal noise, loss, and limited cooperativities are improved. Hence, the exact requirements on these parameters in order for these transducers to provide a link between quantum information contained in the optical and microwave domains needs to be characterized. We derive closed-form expressions for the necessary and sufficient conditions under which doubly-parametric transducers are capable of entangling optical and microwave modes. Our analysis treats the transducer as a bosonic Gaussian channel capable of both beamsplitter-type and two-mode squeezing-type interactions. Under the beamsplitter interaction, we find explicit entanglement-breaking parameter thresholds for both distillable and bound entanglement. By contrast, the two-mode squeezing interaction produces distillable entanglement without any restrictions on temperature, cooperativities, and losses. These differences between the entanglement thresholds of the beamsplitter-type and two-mode squeezing-type interactions are then important considerations in the construction of larger quantum networks that integrate multiple transducers.

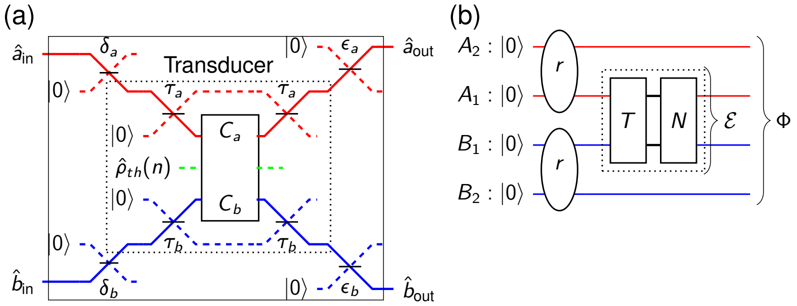

Fig. 1: **a)** Doubly-parametric transducer circuit diagram of the central frequency mode in resolved sideband limit depicting coupling losses τ_i, transmission losses δ_i, ϵ_i, and cooperativities C_i. Environmental modes are represented with dashed lines. Optical, microwave, and mediating modes are denoted red, blue, and green respectively. **b)** The Choi–Jamiołkowski isomorphism gives state Φ corresponding to channel $\mathcal{E}$ when channel acts on input modes maximally entangled with ancillas via infinite two-mode squeezing ($r \to \infty$). The dashed box represents transducer described by matrices T and N.

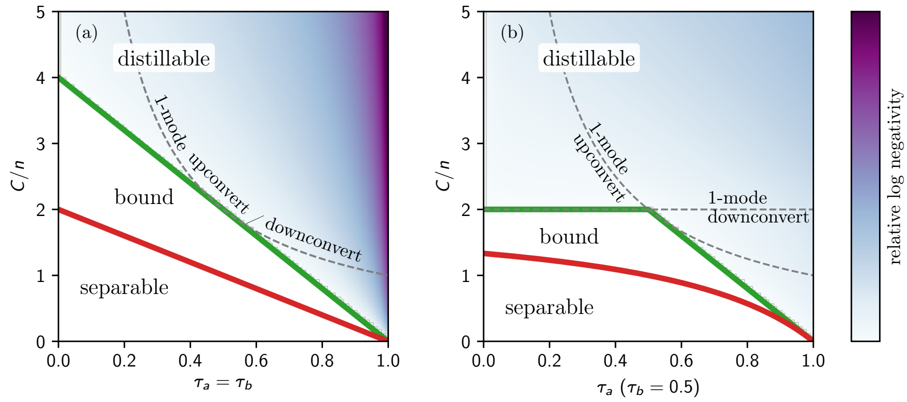

Fig. 2: Plots of entanglement-breaking thresholds with equal cooperativites ($C = C_a = C_b$) and no transmission losses ($\delta_a = \delta_b = \epsilon_a = \epsilon_b = 1$). Here, the thresholds can be characterized simply by C/n_{th} which is related to the average thermal occupation of the mediating mode due to radiation pressure cooling

Fabrication of ultra high quality factor WGM resonators for two-mode squeezing of microwave and optical fields

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Electro-optic transducers based on bulk Lithium Niobate whispering gallery mode resonators are promising candidates for coherent and low-noise microwave-optics conversion with MHz bandwidth [1]. Using a pulsed optical pump we reach full time domain control and near unity efficiencies that are only limited by coupling losses [2]. Recent efforts in the Fink group aim at designing and fabricating a new generation of electro-optics converters using a clamped in the middle architecture realized with a new combination of thin-film technology and conventional mechanical polishing that is optimized for even lower dissipation rates and improved packaging. Alongside these fabrication methods we present preliminary results towards a demonstration of two mode squeezing between optical and microwave output fields [3]. Potential applications include quantum state transfer and deterministic entanglement generation between remote superconducting circuits via microwave-optical quantum teleportation.

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$^{170}Er:Y_2SiO_5$ Whispering Gallery Mode Resonator Electro-Optic Conversion

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Transferring quantum states encoded in microwave frequency excitations to optical domain greatly enrich superconducting qubits as a platform for quantum information processing. Whispering gallery mode (WGM) resonator is a promising approach to build such an electro-optic conversion system to manipulate information. We embed a high-quality $^{170}Er:Y_2SiO_5$ WGM optical resonator into a 3D microwave cavity to achieve the microwave to optical photons up-conversion.

The microwave resonator is a copper cavity with two protruded rings facing each other to clamp the WGM resonator. By a tuning plate, the microwave resonance can be changed from 12.7 GHz to 13.2 GHz. The $^{170}Er:Y_2SiO_5$ WGM resonator is a convex-shaped disk and has an optical free spectral range of 12.7 GHz with the quality factor of $\sim 10^7$. After assembled the cavities together, the hybrid resonant system, as shown in the photograph of Fig. 1, was put into the cryostat at the temperature of ~4K. With the appropriate magnetic field, the erbium ions can simultaneously couple to the microwave and optical cavities. When the microwave resonance and optical free spectral range match to each other, the ions can be driven by the resonators to achieve the microwave to optical photon up-conversion. In experiment, we got some preliminary up-conversion signals, and there is at least hope of making the efficiency higher.

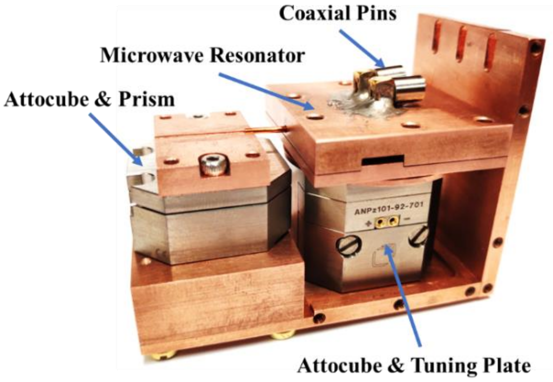

Figure 1. A photograph of the hybrid resonant system.

Gigahertz Phononic Integrated Circuits on Thin-Film Lithium Niobate on Sapphire

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Acoustic devices play an important role in classical information processing for delaying, filtering, and storing of electric signals at radio and microwave frequencies. To further improve the control of phonons on a chip and enable larger scale circuits and systems [1,2], we seek a platform with robust guiding and efficient transduction of mechanical motion. Inspired by integrated photonics, we utilize the phononic analogue of index-guiding in a 1 µm wide waveguide on a thin film of lithium niobate on sapphire (LiSa). The strong piezoelectric effect of $LiNbO_3$ allows us to demonstrate a compact and efficient transducer. Combined with the phononic waveguide, we realize acoustic delay lines, racetrack resonators and meander line waveguides. Losses in the racetrack resonators are further characterized at 4 K for potential quantum applications. Finally, we demonstrate microwave-mechanics three-wave mixing and all-mechanical four-wave mixing in the phononic waveguide.

The demonstrated phononic platform may find applications in emerging microwave quantum technologies at cryogenic temperatures. There have been numerous proposals for using phonons in quantum networks to interconnect physically distant resonators or qubits [3]. The demonstrated gigahertz-frequency phononic circuits can be coupled to superconducting qubits via piezoelectric transducers [4,5]. Long delays and high quality factors, and the compatibility of sapphire with high-*Q* superconducting circuits make LiSa a promising platform for such hybrid quantum systems.

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Measuring Thermal Noise in Electro-Optic Devices at Cryogenic Temperatures

May 23, 2021

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Abstract

The characteristic signal frequency of superconducting computers is in the gigahertz regime. Outside the refrigerator, at room temperature, a photon at such a gigahertz frequency could be completely swamped by thermal photons. Consequently, gigahertz radiation cannot be used to link two quantum machines through the ambient environment; however, visible or near infrared photons are of much higher energy and are known to be able to carry quantum information over long distances at room temperature. Transduction from microwave to optical frequencies is therefore a potential enabling technology for quantum devices. However, in such a device the optical pump can be a source of thermal noise and thus degrade the fidelity; the similarity of input microwave state to the output optical state. In order to investigate the magnitude of this effect we model the sub-Kelvin thermal behavior of an electro-optic transducer based on a lithium niobate whispering gallery mode resonator. We find that there is an optimum power level for a continuous pump, whilst pulsed operation of the pump increases the fidelity of the conversion [1].

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Development of a microwave-to-millimeter-wave quantum frequency converter

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Over the last decade, microwave-optical (M-O) quantum transduction has garnered great interest. Efficient conversion of photons between these two frequencies can be a solution for scaling quantum computation by building a quantum communication network. Most of the effort in this space has been aimed at direct M-O transduction. The end-goal of our work is to develop a two-stage transduction scheme. First, from microwave-millimeter wave (M-MMW) and second, from millimeter wave-optical (MMW-O). In this work, we focus on the M-MMW transducer. M-MMW transduction provides a way to link quantum systems through a channel between 1 K - 4 K temperatures. At these elevated temperatures, the cooling power in cryogenic systems is ~100 milliwatts, compared to ~30 microwatts at 10 millikelvin. This provides us with a greater power budget when driving a M-MMW transducer– which can lead to a lower energy per converted qubit than current transducers[1]. The M-MMW transducer will utilize the kinetic inductance nonlinearity to drive a four-wave mixing process between a microwave photon (~5 GHz) and a millimeter-wave photon (~105 GHz) with two pump photons (50 GHz). We have demonstrated superconducting devices that support 50 GHz and 105 GHz modes which have large current distribution overlap, a requirement to optimize the nonlinear interaction rate. In this work, we discuss the design of the transducer, progress in experimental set up and the fabrication of the proposed transducer.

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Holonomic quantum computation and quantum communication in semiconductor Wannier qubits

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Non-local communication between position-based qubits is described for a system of a quantum electromagnetic resonator entangled to two semiconductor electrostatic qubits via an interaction between matter and radiation by Jaynes-Cummings tight-binding Hamiltonian [1]. Principle of quantum communication between position-dependent qubits is given [2]. The obtained results bring foundation for the construction of quantum internet and quantum communication networks between position-based qubits that are implementable in semiconductor single-electron devices that can be realized in current CMOS technologies. The case of two semiconductor position-dependent qubits interacting with quantum electromagnetic cavity is discussed and general form of tight-binding Hamiltonian is derived with renormalized tight-binding coefficients. The anticorrelation principle is pointed for the situation of mutual qubit-qubit electrostatic interaction [3-5].

The protection against quantum decoherence in Wannier qubits is presented with use of Berry phase concept [6] with presence of quantum electromagnetic cavity[7-8]. Finally examples of holonomic quantum computation [4], [6-7] are given in case of semiconductor Wannier qubits and coupled Wannier qubit single-electron lines [9].

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Localized stimulated Brillouin scattering in hot CS2-filled liquid-core optical fibers

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Liquid-core optical fibers are an auspicious platform for combining highly nonlinear materials with excellent handling capacities and long interaction lengths of fibers. In this work, we present measurements of integrated and distributed stimulated Brillouin scattering (SBS) inside CS2-filled liquid core fibers [1] at various temperatures. The design of the fiber with spliced patch-cords enables us to heat the fiber far beyond the CS2 boiling point of 46.3°C without phase transition, enabling us to investigate a large temperature range.

For our integrated analysis, we use 50ns-long pulses at 1549 nm with an average optical power of 10 mW, where the backscattered SBS signal is detected by a heterodyne measurement setup. We probe a temperature range from 20°C to 136°C, allowing us to monitor the SBS spectrum of CS2 and the influence of temperature and pressure on the phononic interaction properties of the material.

To further explore the fiber platform, we use Brillouin Optical Correlation Domain Analysis (BOCDA) to generate a localized SBS interaction inside the fiber with a spatial resolution of 3 cm. To discriminate the pressure and temperature response we heat half of the fiber and leave the other part at room temperature. We observe that the two parts of the fiber mimic the previously detected behavior, while the rate of Brillouin frequency shift change depends on the length of the fiber which is heated. We observe that the temperature change inside the fiber is localized, while the pressure change in the fiber is extended to the entire liquid-core.

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Superconducting microwire single-photon detectors fabricated with laser lithography

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To measure light down to the single-photon level, superconducting nanowire single-photon detectors (SNSPDs) have become the go-to devices, due to their near unity detection efficiency [1], high-speed and low noise. An important figure of merit is the internal detection efficiency (IDE). To achieve a saturated IDE for detectors based on WSi, wire widths of the order 100 nm are typically required. Nevertheless, recent experiments have shown that functional detectors can be fabricated with wire widths up to 4 µm [2-5]. A higher silicon content of the films combined with a smaller film thickness enables wider wires. Increasing the wire width allows for bigger fabrication tolerances which enables the fabrication with optical lithography.

In our work we present micron-wide detectors based on WSi that were fabricated with a direct laser lithography system and show saturated IDE at 775nm and 1550 nm. Various detector geometries with changing size and detector width (0.6-1.4 µm) were characterized. The direct laser lithography offers fast and flexible fabrication compared to e-beam lithography and is compatible with other laser-lithographically written structures such as titanium-indiffused waveguides in lithium niobate. Integrating wider wires on waveguides may also increase the system detection efficiency of superconducting detectors on waveguides.

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Thresholds for Establishing Remote Microwave Entanglement over an Optical Link Using Two Doubly-Parametric Quantum Transducers

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Doubly-parametric quantum transducers, such as electro-opto-mechanical devices, show promise as quantum links between arbitrary frequencies as disparate as the optical and microwave domains. However, when considered as components in a larger quantum network, the decoherence mechanisms they introduce of thermal noise, loss, and limited cooperativities may render the network unable to transmit quantum information or entangle its end users. We study how two doubly-parametric transducers can be used to establish remote two-mode microwave entanglement over an optical link using various entanglement distribution and swapping topologies. We derive closed-form expressions for thresholds on the decoherence parameters in order to successfully entangle the remote microwave nodes. We find the thresholds are dependent on the given topology, along with the available entanglement resources and measurement capabilities. Furthermore, having two transducers capable of quantum operation is not sufficient to establish remote microwave entanglement, since the available network capabilities impose more stringent thresholds on transducer performance.

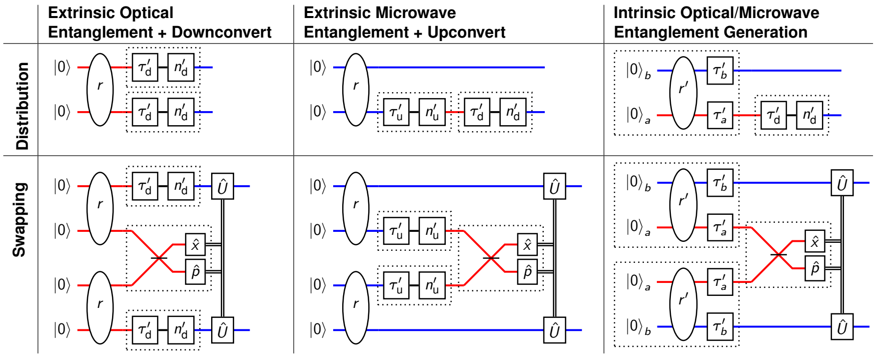

Fig. 1: Circuit diagrams for the 8 topologies considered. Dashed box – Effective Transducer or Homodyne Measurement; Ellipse – Squeezer; Optical – Red; Microwave – Blue.

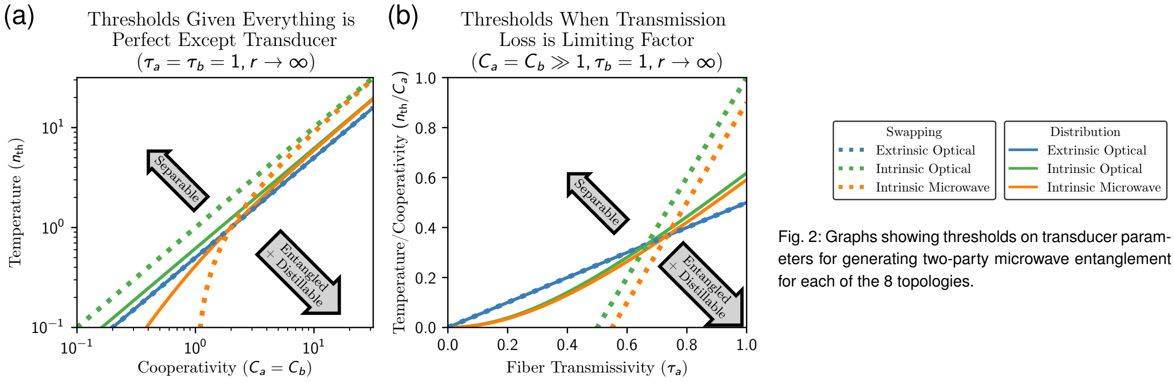

Fig. 2: Graphs showing thresholds on transducer parameters for generating two-party microwave entanglement for each of the 8 topologies.

A Quantum Photonic Interface for Tin-Vacancy Centers in Diamond

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Building photonic quantum networks requires efficient coupling of solid-state quantum emitters to photonic devices. Group-IV color centers in diamond have emerged as promising candidates for quantum information processing applications. In particular, the tin-vacancy center (SnV) has attracted much interest for having long spin coherence times at temperatures above 1 K. This is in contrast to the more mature silicon-vacancy and germanium-vacancy color centers which require dilution refrigerator temperatures. Employing SnV as an optically addressable qubit requires integration with photonic structures to both route the emitted photons and enhance the light-matter interaction.

Here, we report the enhancement of coherent emission of SnV centers via coupling to a nanophotonic waveguide resonator [1]. We observe strong intensity enhancement of the photon emission when the cavity is resonant with the color center. Time-resolved photoluminescence measurements confirm that this improvement is caused by radiative Purcell enhancement of the spontaneous emission into the zero-phonon transition. Emission into the cavity is established to be the predominant channel of decay. Furthermore, we have demonstrated electrical tuning of SnV centers in diamond nanopillars via the Stark effect, which can be used to overcome small detunings between different emitters and facilitate multi-emitter experiments [2]. Our results constitute a significant leap on the route toward the implementation of quantum repeaters and integrated photonic networks, based on color centers in diamond operating at liquid helium temperature.

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Low-loss all-optical ns-switching for scalable quantum photonic links

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Quantum information processing is set to play a large role in future communication technology. Promising realizations for long-distance quantum communication are based on photons. Due to the prospect of moving them out of the lab and toward scalable real-world applications, photonic integrated circuits (PICs) have attracted significant attention. Mature foundry-based PIC platforms based on silicon[1] and silicon nitride[2] have the potential to be a stepping-stone in this development. Especially for necessary switching and routing of single photons including nanosecond delay lines, achieving ultralow losses[3] is key and switching bandwidths should match the single-photon generation rate, which is typically in the MHz to GHz regime for quantum-dot based sources[4].

All-optical switches based on silicon nitride microring resonators are evaluated for their integration with gigahertz single-photon sources. Requirements for the resonator characteristics and control signal waveform are obtained from the Kerr nonlinear dynamics and travelling-wave simulations, and demonstrate the feasibility for single-photon switching in a mature foundry-based PIC platform.

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

M. Ruf, M. Weaver, N. Codreanu, S. B. Van Dam, R. Norte, S. Groeblacher, and R. Hanson

Future quantum networks will enable technologies such as communications secured by the last of nature and distributed quantum communication. Color centers in diamond are promising node candidates for such a network, due to their excellent spin coherence time and access to local nuclear spin memory qubit registers. To realize large-scale quantum networks that can generate entanglement with high rates, efficient spin-photon interfaces are required. A promising way to realize such interfaces is to embed color centers into optical cavities, making use of the Purcell effect. Here, we report on our latest results regarding two strategies to enhance the spin-photon interface of color centers in diamond: open, fiber-based micro-cavities, and photonic crystal cavities in diamond.

We show that embedding a microns-thin diamond membrane in an open, fiber-based cavity allows to preserve the optical coherence of near-surface NV centers in cavities, as required for entanglement generation. This allows us to demonstrate resonant addressing of individual, fiber-cavity-coupled NV centers, and collection of their Purcell-enhanced coherent photon emission, thus overcoming a major roadblock on the path towards efficient NV-based quantum networks [1]. We extract Purcell factors of up to 4, consistent with a detailed theoretical model that shows the potential for increasing entanglement generation rates by up to two orders of magnitude for NV-based systems using realistic, near term improvements to our setup.

We additionally present our latest results regarding the design and fabrication of all-diamond photonic crystal cavities that are promising to enhance the spin-photon interface of group-IV color centers in diamond. Due to their first order insensitivity to electric field fluctuations, these color centers are compatible with nanophotonic integration, in contrast to the NV center. In particular, we demonstrate that such structures can be created via a crystal-plane dependent dry reactive-ion-etch process, and we report on the optical properties of our fabricated devices.

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Quantum-enabled microwave optical interface with unity internal efficiency

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Superconducting qubits are one of the most promising candidates for universal scalable quantum computers [1]. However, quantum networking with these qubits remains a challenge because the fragile microwave photons lose their quantum information at high temperatures. Optical photons, on the other hand, are resilient to thermal noise at room temperature and can be transported with little loss via optical fibers. As a result, the interest in microwave-optical transducers have grown significantly over the last few years [2-5]. An ideal transducer must have a high conversion efficiency while maintaining low thermal added noise [6]. This is a significant challenge since optical photons almost inevitably negatively affect the lower frequency microwave cavities or components. In this talk, we will present a bulk microwave-optical transducer based on electro-optic properties of Lithium Niobate [5]. Our transducer can reach unity cooperativity while keeping the microwave cavity close to its ground state. The resilience to high power optical fields enables not only quantum-enabled high conversion efficiencies, it also allows to explore new physics in electro-optic devices.

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Ultra-coherent electro-mechanics in the quantum regime

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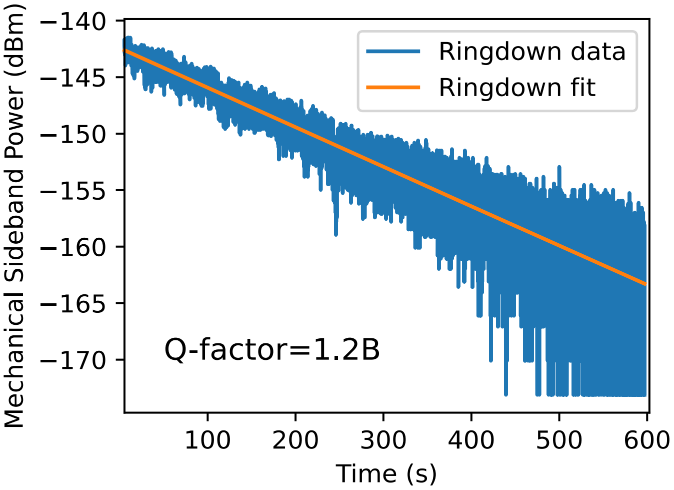
We present the characterisation at milli-Kelvin temperatures of a microwave electro-mechanical system featuring an ultra-coherent phononic-crystal membrane[1]. The mechanical dissipation rate is measured down to 30mK reaching a Q-factor of 1.2 billion, at 1.485MHz mode frequency. Then we perform resolved sideband cooling on the mechanical mode close to its motional ground state[2].



We thus show the operation of an electromechanical system in the quantum regime, where its coherence time is estimated to be ~100ms. We also show light-induced mechanical broadening up to 630Hz, reaching manipulation speeds on the order of state-of-the-art superconducting qubits coherence times [3] making our device a candidate for microwave quantum memories[4].

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Optomechanical interface between telecom photons and spin quantum memory

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We demonstrate optomechanical manipulation of nitrogen-vacancy electron spins in a diamond cavity for the first time. Our work paves the way for the realization of quantum networks at room temperature based on phonon-spin coupling.

Optically active defects in solids are one of the most promising platforms for implementing quantum technologies. Their spin degrees of freedom serve as quantum memories that in some cases can operate at room temperature. Their control can be achieved with microwave spin control and resonant optical excitation but is hindered by the broadening of optical transitions from thermal phonons and spectral diffusion. Furthermore, spin-qubit optical transitions are often outside the telecommunications wavelength band required for long-distance fiber optic transmission. Harnessing the coupling between mechanical degrees of freedom and spins has emerged as an alternative route for controlling spin-qubits [1, 2]. However, connecting spin-mechanical interfaces to optical links to realize a spin-photon interface has remained a challenge. Here we demonstrate such an interface (Fig. 1a) using a diamond optomechanical cavity that does not depend on optical transitions and can be applied to a wide range of spin qubits.

Our device consists of a diamond microdisk resonator studied in Ref. [3]. The microdisk is fabricated from optical grade diamond that contains ensembles of nitrogen-vacancy (NV) centres ($\sim 10^{14}\,\mathrm{cm}^{-3}$). The mechanical mode that we use to couple to the NV spin state is a radial breathing mode with a frequency of around 2.1 GHz with the quality factor $Q_\mathrm{m} = 4\mathrm{k}$. We use an optical mode at 1564 nm with the quality factor $Q_\mathrm{o} = 150\mathrm{k}$ that enables optomechanical self-induced oscillations for sufficiently high optical input power of a blue detuned laser (Fig. 1b). These oscillations can produce the stress of a few MPa (Fig. 1b), large enough to drive the ground-state electron spins of NV centers at room temperature (Fig. 1d). To demonstrate optomechanical manipulation of NV spins, we use a standard diamond NV confocal microscope to initialize and read out the $|0\rangle$ state with the 532 nm laser and MW pulses to transfer the population between $|-1\rangle \leftrightarrow |0\rangle$ and $|+1\rangle \leftrightarrow |0\rangle$ state. We prepare $|+1\rangle$ state to mechanically drive $|+1\rangle \rightarrow |-1\rangle$ for 0.7 μs (Fig. 1e) and measure the population p_{+1} remaining in $|+1\rangle$ state and population p_{-1} transferred to $|-1\rangle$ state.

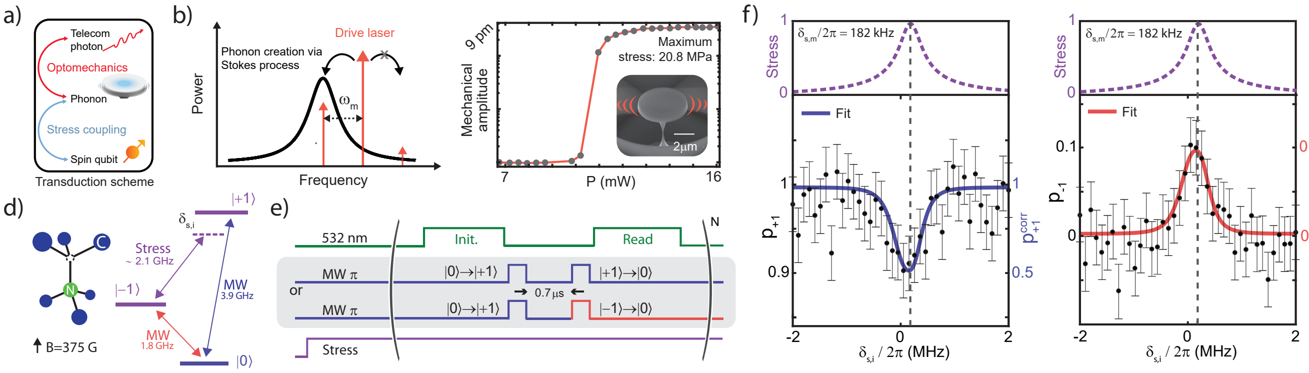

Fig. 1: a) Transduction scheme used here. b) Phonon lasing and measured amplitude of the optomechanically amplified RBM for microdisk. c) NV ground state energy level at a magnetic field of 375 G along the NV axis. d) Pulse sequence used to drive NV spins optomechanically e) Measured population of $|\pm1\rangle$ states for varying optomechanically induced stress with detuning.

We observe a coinciding dip in the $|+1\rangle$ population and a peak $|-1\rangle$ population (Fig. 1f), that verifies that the spins are being optomechanically driven. On calibrating this signal with the MW Rabi contrast and the background signal, we estimate a driving rate of $2\pi\times170$ kHz and $\sim$ 45% transfer of spin population between $|\pm1\rangle$ states. Feasible improvements in device geometry will increase the optomechanically-induced driving rate by a few orders of magnitude allowing for coherent control of NV spins using an optomechanical resonator.

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Electrical Control of Gigahertz Surface Acoustic Wave on Lithium Niobate

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Acoustic waves at microwave frequencies are emerging as a versatile interface between quantum systems such as superconducting circuits, defect centers, and optical devices. However, dynamic control of acoustic waves in a low-loss and scalable manner remains an outstanding challenge, which hinders the development of phononic integrated circuits. Here we present electrical control of traveling acoustic waves on an integrated lithium niobate platform [1] at both room and millikelvin temperatures. We electrically tune the material elasticity to modulate the phase and amplitude of the acoustic waves. In addition, we demonstrate an acoustic serrodyne frequency shifter with efficiency over 92%. Furthermore, we show reconfigurable nonreciprocal modulation by tailoring the phase matching between acoustic and quasi-traveling electric fields. Our scalable electro-acoustic platform comprises the fundamental elements for arbitrary acoustic signal processing and manipulation of phononic quantum information.

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Narrow-band and efficient Fabry-Perot cavities for electro-opto-mechanical transducers

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Superconducting microwave qubits are promising quantum computational platforms, but high thermal occupancies of microwave fields at room temperatures pose a significant challenge to establishing distributed superconducting networks. Faithful transfer of qubit states to the optical domain would facilitate network connections that are much less sensitive to this thermal noise. A promising candidate for quantum electro-optic conversion couples microwave and optical fields to the same mechanical mode of a MHz-frequency SiN membrane via radiation pressure. Using this design, we have shown conversion efficiencies approaching 50%.

Of central importance in our convertor devices are narrow-band and efficient Fabry-Perot cavities. We will discuss recent technical progress in robust cavity design and implementation in our convertor and post-conversion filtering networks. We detail a cavity design with improved stability and robustness based upon integrating one of the Fabry-Perot mirrors with the membrane device. We also discuss progress towards incorporating cascaded cavities in the readout chain in order to spectrally resolve pump signals from converted signals, with the eventual goal of performing single photon counting experiments in the optical domain on converted microwave signals.

Generalized Matching Condition for Efficient N-Stage Quantum Transduction

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Coherently converting quantum states between distinct elements via quantum transducers remains a crucial yet challenging task in quantum science. Especially in demand is quantum transduction between optical frequencies, which are ideal for low-loss transmission across long distances, and microwave frequencies, which admits high-fidelity quantum operations. We present a generic formalism for N-stage quantum transduction that covers all the leading microwave-to-optical linear conversion approaches such as electro-optics, electro-optomechanics, optomagnonics, and atomic ensembles. We then identify a generalized matching condition for achieving maximum conversion efficiency. The generalized matching condition requires resistance matching as well as frequency matching beyond the usual resonant assumption, with simple impedance matched transmission interpretation. Our formalism provides a universal toolbox for determining experimental parameters to realize efficient quantum transduction that can fulfill various practical requirements, and suggests new regimes of non-resonant conversions that can outperform all-resonant ones.

Towards quantum networks with erbium dopants in silicon

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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 [2] at telecommunication wavelengths. So far the long lifetime of the excited state (several ms) made it difficult to spectrally resolve and control individual ions in order to harness them for quantum networks.

To overcome this challenge, we use silicon nanophotonic waveguides and resonators implanted with erbium [3]. At optimized implantation parameters, we find narrow (< 1 GHz) fluorescence lines that originate from erbium ensembles which are well integrated into the silicon lattice. We measured the optical lifetime, coherence and the crystal field splitting of these lines. We then fabricated photonic crystal cavities that should allow us to reduce the lifetime by several orders of magnitude and thus to optically observe and control individual dopants.

This would open unique prospects for the realization of entanglement between spins over distances exceeding 100 km using a novel frequency-multiplexed quantum network architecture.

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On-chip microwave to optical transduction using erbium in YVO_4

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Converting microwave photons to optical photons is essential for linking superconducting circuits inside a large-scale quantum network. Rare-earth ion (REI) doped crystals are one of the potential platforms to achieve microwave to optical transduction at the quantum level. Among the REIs, erbium is of particular interest because of its optical transitions within the low-loss telecom band.

Here, we present an on-chip REI-based transducer that incorporates both a nanophotonic optical resonator and a superconducting microwave resonator on an erbium-doped yttrium orthovanadate crystal. Initial calibration of the transducer performance at low temperatures in continuous-wave and pulsed mode will be presented.

The authors acknowledge support from Army Research Office (ARO/LPS) (CQTS) grant number W911NF1810011, NSF QII TAQS, 1936350, Office of Naval Research Award No. N00014-19-1-2182, Air Force Office of Scientific Research grant number FA9550-18-1-0374

Stimulated Brillouin scattering of helical Bloch modes in 3-fold rotationally symmetric chiral 4-core photonic crystal fibre

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Stimulated Brillouin scattering (SBS) in optical fibres, in which guided light is parametrically reflected by coherent acoustic phonons, provides a powerful and flexible mechanism for controlling light, and has recently been demonstrated with orbital angular momentum (OAM) modes in a special annular-core fibre. Helically twisted photonic crystal fibre (PCF) robustly supports circularly-polarised helical Bloch modes (HBMs) and displays OAM birefringence. Here we report for the first time SBS of circularly-polarised HBMs in a chiral 4-core PCF with 3-fold symmetry.

A pump-probe method is used to measure the wavelength dependence of the SBS gain. Both pump and probe signals are derived from a narrow linewidth 1550 nm CW laser, the probe light being frequency tuned using a single side-band modulator (SSBM). The two signals are boosted in EDFAs and spatially modulated by OAM-generating modules (OGMs) consisting of polariser, quarter- and half-waveplates and a Q-plate. The amplified probe signal is analysed by heterodyning with a local oscillator (LO). In 3-fold rotationally symmetric PCFs the number of complete periods of phase progression around the azimuth, for fields evaluated in cylindrical coordinates, is the azimuthal order $\ell_A^{(m)} = \ell_A^{(0)} + 3m$ (always an integer and robustly conserved) in the m-th Brillouin zone, and for circularly-polarised fields the topological charge $\ell^{(m)}$ is given by $\ell^{(m)} = \ell_A^{(m)} - s$ ($s = 1$ for left-circular polarisation, LCP). Fig. 1(a) shows a scanning electron micrograph (SEM) of fibre cross-section. Fig. 1(b) shows experimental and calculated mode profiles for HBMs.

We first measure the spontaneous Brillouin spectrum by pumping with $(\ell_A^{(0)}, s) = (1, 1)$ and $(\ell_A^{(0)}, s) = (-1, -1)$. Several Brillouin peaks appear, each related to a different guided acoustic mode in the twisted PCF. We then focus on the peaks at 10.82 GHz and 10.59 GHz using pump-probe measurement system. The results are shown in Fig. 1(c) and (d). Peaks only appear when the pump and probe modes have equal and opposite values of ℓ_A and s.

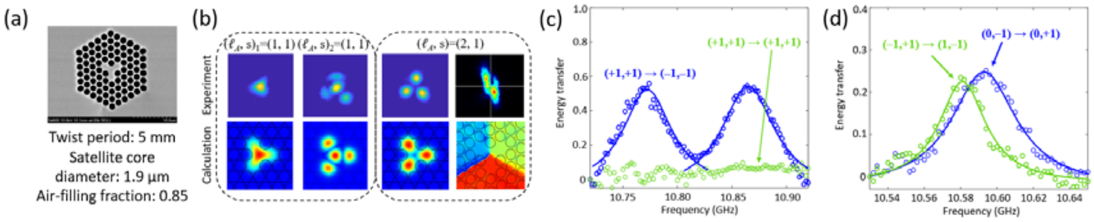

Fig. 1 (a) SEM of fibre cross-section; (b) Measured and calculated mode intensity patterns for $(\ell_A^{(0)}, s) = (1, 1)$ and $(\ell_A^{(1)}, s) = (2, 1)$; (c) and (d) Pump-probe measurement results

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