WE-Heraeus Symposium

Japanese-German Symposium on Applications of Quantum Computers

11 November 2024

at the
Berlin Brandenburgische Akademie der Wissenschaften (BBAW), Berlin

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

WE-Heraeus Symposium:

The goal of this symposium is to outline the state-of-the-art of quantum computation and existing challenges concerning potential disruptive applications. A focus lies on quantum computing activities in Germany and Japan. Invited experts from both countries will share insights into challenges, progress and future perspectives. The discussion will center around the realization of scalable quantum processors, error correction mechanisms, and the integration of quantum computers into existing systems.

The symposium emphasizes the 30st anniversary of the Berlin-Tokyo city partnership. It is also generously supported by the Japanese Science and Technology Agency (JST) through the MEXT - Quantum Leap Flagship Program and the Moonshot Research and Development Program.

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Berlin Brandenburgische Akademie der Wissenschaften (BBAW)
Markgrafenstraße 38
10117 Berlin, Germany

Program

Program Monday 11 November 2024

09:00 – 09:15	Oliver Benson Kohei Itoh	**Welcome & Introduction**
	Stefan Jorda WE-Heraeus-Stiftung	**Welcome Words**
09:15 – 09:45	Yasunobu Nakamura	**High-fidelity control and readout of superconducting qubits**
09:45 – 10:15	Hendrik Bluhm	**Ingredients for spin-shuttling-based quantum processors in Si/SiGe**
10:15 – 10:45	Makoto Negoro	**Controller and software for superconducting quantum computer system**
10:45 – 11:15	*Coffee Break*	
11:15 – 11:45	Fedor Jelezko	**Spin qubits in diamond**
11:45 – 12:15	Tim Schröder	**Diamond spin defects as resource for photonic quantum computation**
12:15 – 12:45	Robert Raußendorf	**Computational Phases of Quantum Matter**
12:45 – 14:00	*Lunch Break*	
14:00 – 14:30	Nayuta Takemori	**New Developments in Computational Condensed Matter Physics for Quantum Computing**
14:30 – 15:00	Akira Furusawa	**Optical quantum computers with quantum teleportation**
15:00 – 15:30	Stephanie Barz	**Photonic quantum technologies: from unravelling quantum foundations to advancing quantum integration and developing applications in quantum networks and computing**
15:30 – 16:15	*Coffee Break*	

Program Monday 11 November 2024

16:15 – 16.45	Kae Nemoto	**Quantum Computation and machine learning**
16:45 – 17:15	Naoki Yamamoto	**Some extensions of phase estimation algorithm**
17:15 – 17:45	Tadashi Kadowaki	**Quantum CAE (computer-aided engineering) and AI for Science**
17:45 – 19:00	**Poster Session**	
19:00	**Closing**	

Posters

Poster Session – 17.45 h – 19:00 h

Xavier Barcons Planas	**Efficient heralding of pure single-photons at telecom wavelength from pulsed cavity-enhanced SPDC**
Mohamed Belhassen	**Investigation of microwave spin control of unstrained negatively charged group-IV color centers in diamond**
Daniel Ceglinski	**Applications of the DLR Quantum computing initiative in science and industry**
Kuldeep Gautam	**Quantum-Enhanced Image Classification: A Hybrid Quantum-Classical Neural Network Approach**
Felipe Gewers	**Multi-color continuous variables quantum teleportation: from near-infrared to telecommunications' L-band**
Luis Javier Gonzalez Martin del Campo	**Spectral Engineered Squeezed Light source for Time-bin Encoded Quantum Information Processing**
Anton Halaski	**Quantum feedback control for quantum error correction on superconducting qubits**
Johannes Jung	**Encoding Architecture Search**
Koray Kaymazlar	**Experimental Quantum Strong Coin Flipping with Single Photons**
Maximilian Klonz	**Growth, fabrication, and characterization of site-controlled quantum dots based on buried-stressor approach**
Aris Koulas-Simos	**Towards scalable quantum circuits based on microlaser-pumped quantum emitters**
Imad Limame	**High-quality single InGaAs/GaAs quantum dot growth on a silicon substrate for single-photon-based quantum computing**

Poster Session – 17.45 h – 19:00 h

Samuele Pedrielli	**Adaptive Observation Cost Control for Variational Quantum Eigensolvers**
Gregor Pieplow	**Generation of cluster states with group-IV color centers in diamond**
Siavash Qodratipour	**Towards time-bin entangled photon cluster states**
Arno Rauschenbeutel	**Emergence of second-order coherence in superfluorescence**
Leo Roche	**Numerical Investigation of a Coupled Micropillar - Waveguide System for Integrated Quantum Photonic Circuits**
Stephan Schuster	**Real-time measurement error mitigation for one-way quantum computation**
Marco Stucki	**The Sawfish cavity: an efficient spin-photon interface for photonic quantum computing**
Maarten van der Hoeven	**Large-Scale Localization and Characterization of Diamond Color Centers for Deterministic Fabrication of Nanophotonic Spin-Photon Interfaces**

Abstracts of Lectures

(in alphabetical order)

Photonic quantum technologies: from unravelling quantum foundations to advancing quantum integration and developing applications in quantum networks and computing

Stefanie Barz[1,2]

[1]*University of Stuttgart, Germany*
[2] *Center for Integrated Quantum Science and Technology, IQST*

I will explore various facets of photonic quantum systems and their application in photonic quantum technologies. Firstly, I will discuss quantum interference, a key element in photonic quantum technologies. I will highlight how the distinguishability and mixedness of quantum states influence the interference of multiple single photons – and demonstrate novel schemes for generating multipartite entangled quantum states [1,2,3]. I will then address photonic quantum computing, specifically focusing on the building blocks of photonic quantum computers [4]. This includes the generation of resource states essential for photonic quantum computing. I will then shift to photonic quantum networks, covering both their hardware aspects and showcasing quantum-network applications that extend beyond bi-partite quantum communication [5]. Lastly, I will outline how photonic integration facilitates the scalability of these systems and discuss the associated challenges.

References

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Distinguishability and mixedness in quantum interference
Phys. Rev. A 108, 053701 (2023)

[2] S. Kumar, D. Bhatti, A. E. Jones, S. Barz
Experimental entanglement generation using multiport beam splitters
New Journal of Physics 25, 063027 (2023)

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Generating Greenberger-Horne-Zeilinger States Using Multiport Splitters
Phys. Rev. A 107, 033714 (2023)

[4] M. Bayerbach, S. D'Aurelio, P. van Loock, S. Barz
Bell-state measurement exceeding 50% success probability with linear optics
Science Advances 9, eadf4080 (2023)

[5] L. Rückle, J. Budde, J. de Jong, F. Hahn, A. Pappa, S. Barz
Experimental anonymous conference key agreement using linear cluster states, Phys. Rev. Research 5, 033222 (2023)

Ingredients for spin-shuttling-based quantum processors in Si/SiGe

Hendrik Bluhm[1,2,3]

[1]RWTH Aachen University, Germany
[2]Forschungszentrum Jülich GmbH, Jülich, Germany
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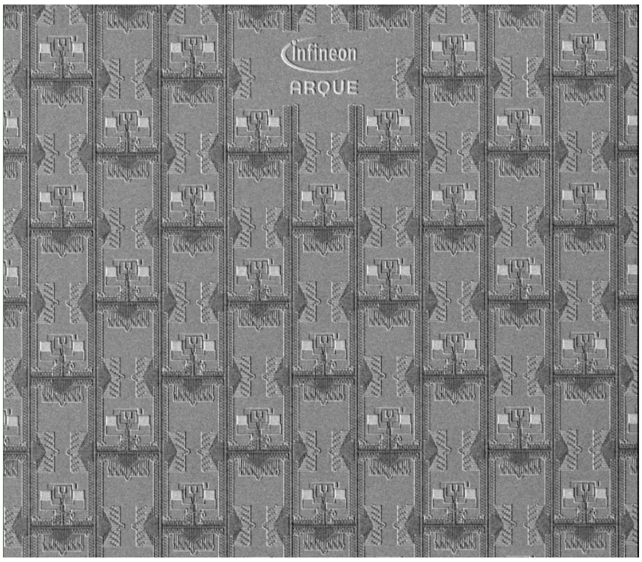
Semiconductor qubits carry the promise to leverage CMOS fabrication technology for realizing large scale quantum computers. While semiconductor qubit operations approach the fidelities required for error corrections, living up to this promise also requires an architecture that can be implemented in industrial foundries. One challenge is to overcome the limitations such as crosstalk and wiring density of dense spin qubit arrays, which have been used so far to realize small scale quantum processors.
I will survey progress in realizing the proposed SpinBus architecture [1] for spin qubits in Si/SiGe heterostructures, which addresses this challenge. A key ingredient is the spin-coherent shuttling of electrons to enable micron scale coupling between qubits. Charge transfer exhibits an experimental fidelity of at least 99.7±0.3 % over a distance of 10 µm [2]. Spin-coherent shuttling with a derived fidelity of 99.3 % over about 500 nm limited by nuclear spins in natural Si [3] shows significant improvement in isotopically purified material.
Variations in the energy splitting between the two low-lying conduction band valleys of Si due to alloy disorder are expected to be the main limitation for the shuttling performance [4]. Experiments using electron shuttling to map this splitting [5] underpin a proposed mitigation approach based on adjusting the shuttling pathway [4].
Largely industrial wafer scale fabrication tuned to the realization of the spin-bus architecture yields devices with very good stability, noise performance and charge shuttling fidelities.



Fabrication test of the of the SpinBus architecture in industrial Si/SiGe technology (without wiring layers)

References

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[4] M. P. Losert *et al.*, arXiv:2405.01832.
[5] M. Volmer *et al.*, Npj Quantum Inf **10**, 61 (2024).

Optical quantum computers with quantum teleportation

Akira Furusawa[a,b]

[a] Department of Applied Physics, School of Engineering, The University of Tokyo
[b] RIKEN Center for quantum computing

We did the first experiment of unconditional quantum teleportation at Caltech in 1998 [1]. Then we did various related experiments like quantum teleportation network [2], teleportation of Schrödinger's cat state [3], and deterministic quantum teleportation of photonic qubits [4].

We invented the scheme of teleportation-based quantum computing in 2013 [5]. In this scheme, we can multiplex quantum information in the time domain and we can build a large-scale optical quantum computer only with four squeezers, five beam splitters, and two optical delay lines [6].

For universal quantum computing with this scheme, we need a nonlinear measurement and we invented the efficient way [7]. We recently succeeded in the realization [8].

Our present goal is to build a super quantum computer with 100GHz clock frequency and hundred cores, which can solve any problems faster than conventional computers without efficient quantum algorithms like Shor's algorithm. Toward this goal we started to combine our optical quantum computer with 5G technologies [9].

For the realization of fault-tolerance with our optical quantum computers, we use Gottesman-Kitaev-Preskill (GKP) qubits [10]. We recently succeeded in the generation [11] and invented an efficient way for the generation [12].

We built a real machine of optical quantum computer in Riken and will put it on the cloud in October, 2024. We launched a new start-up company OptQC in September, 2024 which is working on building a large-scale neural network based on optical quantum computers.

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[11] S. Konno et al., Science 383, 6680 (2024).
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Spin qubits in diamond

Fedor Jelezko[1]

[1]*Institute Institute for Quantum Optics, Ulm University*

Optically active spin qubits in diamond have recently emerged as a candidate material for a range of quantum-based applications, including quantum information processing, quantum communication and quantum sensing. In this talk, we will show the realisation of a spin-based solid-state architecture for a scalable quantum register consisting of strongly dipolarly coupled electron spins associated with NV centres and nuclear spins. Elements of quantum networks and quantum light-matter interface enabled by single GeV colour centres will be presented.

References

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[2] Joas, T., F. Ferlemann, R. Sailer, P.J. Vetter, J. Zhang, R.S. Said, T. Teraji, S. Onoda, T. Calarco, G. Genov, M.M. Müller, and F. Jelezko arXiv:2406.04199 (2024).

Quantum CAE (computer-aided engineering) and AI for Science

Tadashi Kadowaki[1,2]

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[2] DENSO CORPORATION, Aichi, Japan

Computer-aided engineering (CAE) has been widely employed across various industries to efficiently design superior products. It involves evaluating the characteristics of a product through simulation, followed by optimization of the product's design. Traditionally, high-performance computing has been utilized for these tasks. One of the ultimate goals of engineering assistance is to automate the product design process. For this purpose, data-driven optimization frameworks, such as Bayesian optimization, can be leveraged. This process is divided into three computational tasks: (1) computer simulation, (2) data modeling [machine learning], and (3) solving the inverse problem [optimization]. These computationally intensive tasks are known to be accelerated by quantum computing.

We have demonstrated the automation of the product design process using both conventional and quantum computers [1,2]. The problems we addressed are combinatorial optimization problems, making them ideal candidates for acceleration with quantum computers. In our previous studies, we utilized quantum computers primarily for the optimization task. Our ongoing research includes developing quantum algorithms for simulation, such as the Lattice Boltzmann Method (LBM) [3], and quantum machine learning algorithms for Quantum CAE.

There are numerous similarities between Quantum CAE and AI for Science. Both aim to realize automation of processes, adding new value to both industry and academia. This presentation will explore these similarities and discuss how we leverage them to combine these two research areas.

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High-fidelity control and readout of superconducting qubits

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[2]Department of Applied Physics, Graduate School of Engineering,
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Quantum computing demands an unprecedentedly high level of precision in the control and readout of quantum states encoding quantum information in a large Hilbert space. Therefore, in parallel with the pursuit of scalability, persistent efforts are being made to improve the control and readout fidelities of qubits. We are developing two-dimensionally integrated superconducting qubit arrays for quantum computing. This talk will focus on new techniques for achieving high-fidelity readout [1] and entangling gates [2] based on circuit quantum electrodynamics and microwave quantum optics.

References

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[2] R. Li *et al*., arXiv:2402.18926 (2024).

Controller and software for superconducting quantum computer system

M. Negoro[1,2]

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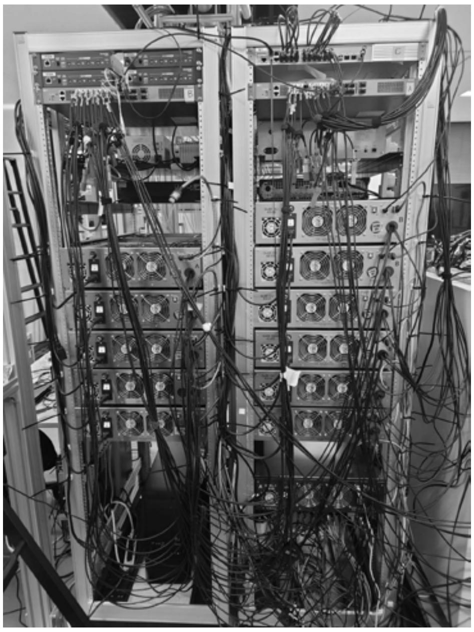
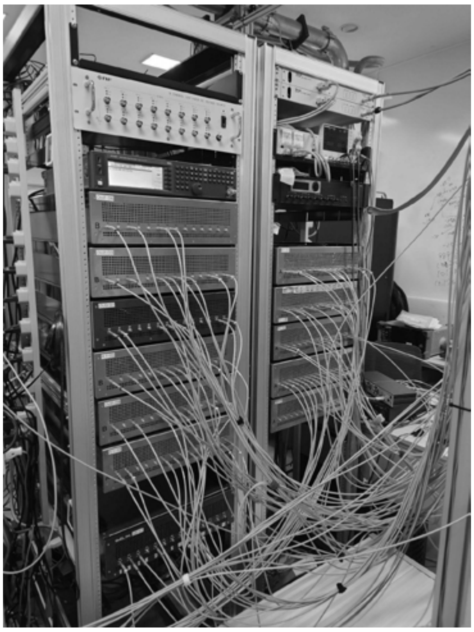
[2] *QuEL, Inc. Tokyo, Japan*

In 2023, Japan has developed national superconducting quantum computers. They are superconducting qubit chip types, developed by Prof. Nakamura, RIKEN. The superconducting quantum computer system consists not only of a qubit chip but also a controller and software, which a team led by Osaka University developed. The controller communicates microwave pulses at X-band with each qubit according to the instructions on the calculation that users want to solve. To control 64 qubits, we have developed a system with 96 output and 16 input channels, as shown in Figure [1]. All channels are synchronized with the relative phase fluctuation of ~1°. The channel bandwidth is broad at > 1.5 GHz. This can cover different frequencies for one- and two-qubit gates and excitation to a higher energy state of transmon qubits. Our team developed a software toolchain for translating user instructions to microwave pulses. Most of those are made public in github [2]. In the system at Osaka University, we obtain the fidelities at 99.9% and 98% for one- and two-qubit gates. We are utilizing the system through cloud access to explore use cases with 40 companies and educate students. The demonstration results such as quantum chemical calculation will be presented at the event.





References

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Quantum Computation and machine learning

Kae Nemoto

OIST (Okinawa Institute of Science & Technology),
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In the last several years we have seen the rapid growth in the size of quantum processors. These quantum processors do not work as "computer", yet, however it has been shown that they can create complexity intractable with the conventional computational technology. A question of how such quantum systems contribute computation still remains. In this talk, we discuss types of computation suitable and validity of the machine learning approach with today's quantum computational technology.

Computational Phases of Quantum Matter

Robert Raussendorf[1]

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In measurement-based quantum computation, the computational power hinges on the resource quantum state. Some states give universal computational power, but most states provide no computational power at all [1]. This picture changes in the presence of symmetry. Namely, for phases of ground states of symmetric Hamiltonians, i.e., symmetry-protected topological (SPT) phases, it has been found that computational power is uniform across those phases. This observation gave rise to the term `computational phases of quantum matter' [2,3]. In my talk, I give a short history of this line of research, and then present examples of symmetry protected quantum phases that have universal computational power [4 - 6].

Joint work with: C. Okay, DS Wang, DT Stephen, and HP Nautrup

References

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New Developments in Computational Condensed Matter Physics for Quantum Computing

N. Takemori[1]

[1] Center for Quantum Information and Quantum Biology, Osaka University, 1-2 Machikaneyama, Toyonaka, Osaka, 560-0043, Japan
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The exploration of quantum computing applications in condensed matter physics has garnered significant interest, driven by the need for efficient and accurate computational methods. This presentation delves into recent advancements in computational techniques for quantum computing, with a focus on condensed matter physics. First, we introduce the development of an optimized error-balancing strategy for fermionic reduced density matrix (RDM) estimation [1]. By leveraging cumulant expansion and quantum subspace methods, we demonstrate how these techniques mitigate errors and enhance the accuracy of excited-state calculations in strongly correlated electron systems. These findings reveal the benefits of cumulant-based biased estimations over traditional unbiased methods. Secondly, we discuss the integration of *ab initio* downfolding methods with quantum algorithms, proposing an extended Hubbard model specifically tailored for quantum computation of molecular electronic structures [2]. This model significantly reduces computational complexity, enabling quantum computations with fewer qubits and reduced circuit depth. These developments represent a significant step toward harnessing the full potential of quantum computing for the exploration of complex quantum systems.

References

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Some extensions of phase estimation algorithm

N. Yamamoto

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In this talk I will present some extensions of the phase estimation algorithms, one of the most important subroutines in quantum computation. The first one is to apply the entanglement-assisted phase estimation algorithm to calculating dynamical response functions [1]. The second is the Heisenberg-limited adaptive gradient estimation for multiple observables [2]. The last one is a tensor-network-based realization of phase difference estimation algorithm for large-scale experimental demonstration [3].

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Abstracts of Posters

(in alphabetical order)

Efficient heralding of pure single-photons at telecom wavelength from pulsed cavity-enhanced SPDC

Xavier Barcons Planas[1,2], **Helen M. Chrzanowski**[1,2], **Leon Messner**[2], **and Janik Wolters**[2,3]

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Entangled quantum states of multiple photons are crucial for pushing the boundaries of photonic quantum technologies. The generation of large multi-photon entangled states demands light sources that provide highly pure photons with high efficiency (either deterministic or heralded), as these factors limit scalability. A popular approach is to herald single-photons from photon-pair sources based on spontaneous parametric down-conversion (SPDC). Despite the spatial and spectral multimode emission of the process, potentially constraining the heralding efficiency and purity, the emitted photons can be engineered with single-mode characteristics, through waveguide geometries [1], group velocity matching techniques [2] or cavity resonators [3]. Here, we present a narrowband (170 MHz) single-photon source at the C-band based on pulsed SPDC in a monolithic crystal cavity. Pure and fiber-compatible single-photons have been generated with 85% heralding efficiency.

References

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Investigation of microwave spin control of unstrained negatively charged group-IV color centers in diamond

G. Pieplow[1], M. Belhassen[1] and T. Schröder[1,2]

[1] *Department of Physics, Humboldt-Universität zu Berlin, Germany*
[2] *Ferdinand-Braun-Institut, Berlin, Germany*

Negatively charged group VI color centers in diamond have great potential for use in quantum applications due to their ability to host a long-lived spin qubit. In this work, we theoretically examine microwave control of the spin-qubit and analyze the fidelity of the resulting spin gates. Beyond showing that strain has a significant impact on the Rabi frequency, we investigate the interplay between strain and the applied DC and AC magnetic field orientations. We find that optimizing their orientations is crucial for maximizing the efficiency of spin control. The most efficient field configuration is achieved when the DC magnetic field is orthogonal to the symmetry axis of the color center, and the AC magnetic field is parallel to it. We also show that this unconventional choice of field orientation can still be used for optical initialization and read-out of the spin.

Reference

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Applications of the DLR Quantum Computing Initiative in Science and Industry

D. Ceglinski[1] and P. Ranitzsch[1]

[1]*DLR Quantum Computing Initiative, Hamburg, Germany*

The DLR Quantum Computing Initiative (QCI) is a comprehensive program aimed at advancing quantum computing technology funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK). The initiative focuses on the entire development spectrum, from hardware and software to applications. The QCI aims to facilitate technology transfer by working closely with industry and business to accelerate the development and commercialization of quantum computing technologies. Using different platforms such as ion traps, neutral atom, photons and more, the DLR QCI awarded contracts to build 17 quantum computers over the course of four years. In more than 20 projects the potentials of quantum computing are explored and leveraged.

This poster will present the latest advancements and applications of the DLR QCI, including:

- Materials Science: By utilizing quantum algorithms for simulating complex molecules and materials, new possibilities for developing innovative materials emerge.

- Artificial Intelligence: Quantum computing has the potential to revolutionize machine learning and artificial intelligence by enabling faster and more efficient algorithms.

- Optimization Problems: Many industrial applications, such as route planning and logistics, benefit from the quantum computer's ability to solve complex optimization problems more efficiently.

We will showcase exemplary results from ongoing DLR QCI projects and discuss future perspectives and challenges in integrating quantum computers into existing technologies.

References

[1] https://qci.dlr.de/

Title: Quantum-Enhanced Image Classification: A Hybrid Quantum-Classical Neural Network Approach

Kuldeep gautam

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Abstract: Image classification has become a critical component in various fields, including autonomous vehicles and medical imaging, due to its role in object detection, tracking, and disease diagnosis. However, conventional deep learning techniques such as convolutional neural networks (CNNs) face significant computational challenges with growing visual data volumes. This study investigates the use of a hybrid classical-quantum neural network (QNN) to address these challenges. Utilizing a dataset of 500 paintings from two artists, images were reduced from 224x224 RGB to 16x16 grayscale through a convolutional autoencoder, followed by amplitude encoding into quantum states. A variational ansatz with quantum gate rotations (Rx, Ry, Rz) was implemented using Qiskit's EstimatorQNN module and PyTorch for hybrid model simulation. After training over 100 epochs, the model achieved an average test loss of 0.0042 and an accuracy of 96%. These results demonstrate the potential of hybrid QNNs in enhancing image classification performance, suggesting that quantum technologies can effectively overcome classical computational bottlenecks. This research contributes to the growing field of quantum machine learning, offering scalable solutions for complex image classification tasks and paving the way for future advancements.

Multi-color continuous variables quantum teleportation: from near-infrared to telecommunications' L-band

Felipe Gewers[1,*], Gabriel Borba[1], Beatriz Moura[1], Tulio Brasil[2], Rayssa B. De Andrade[3], R. Medeiros de Araújo[4], Igor Konieczniak[5], Paulo Nussenzveig[1], and Marcelo Martinelli[1]

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Quantum teleportation is the basis for numerous quantum applications, with the continuous variables (CV) protocol having the significant advantage of being unconditional and deterministic, allowing every input state to be teleported [1]. Quantum channels connecting different wavelengths can be used in quantum hybrid networks, linking several quantum platforms with distinct purposes that interact with light at specific wavelengths [2].

Our approach to building these continuous variable quantum channels is through quantum teleportation between the fields' quadratures at different frequencies. For that, we used a triply resonant parametric optical oscillator (TROPO), in the above threshold regime, as a source of two-mode entangled states. Pumping with an Nd:YAG second harmonic laser (532nm), we generated intense beams at near-infrared (793nm) and telecommunications' L-band (1616nm), with a frequency separation of more than one octave.

Here we report the first demonstration of a multi-color CV quantum teleportation protocol between intense beams sideband modes that violate the classical limit fidelity. For a coherent input state with non-zero mean quadrature values, without the corrections for Alice and Victor's detection losses, we achieved a fidelity of 56.2(5)% for the protocol's gain of 0.970(3), indicating a violation of the classical limit of 50% by more than ten standard deviations. We hope this demonstration will inspire the development of connecting devices in quantum hybrid systems.

References

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Spectral Engineered Squeezed Light source for Time-bin Encoded Quantum Information Processing

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Engineering the spectral characteristics of squeezed light sources is crucial for advancing quantum computing and communication technologies. A notable application is Gaussian Boson Sampling (GBS) [1], which focuses on the statistical properties of output states rather than specific spectral correlations. Conversely, these spectral correlations are vital for maintaining the fidelity of quantum states in measurement-based quantum computing (MBQC) [2]. Achieving high spectral purity typically involves filtering or manipulating the light; however, this method can unintentionally reduce the spectral correlations within the system. Thus, balancing spectral purity and correlations is essential for optimizing quantum information processing protocols.

In this work, we demonstrate that by employing the cavity-enhanced spontaneous parametric down-conversion (SPDC) process [3], we can optimize squeezed light generation for various applications. Our system (Fig. 1) is designed to effectively integrate a pulsed or continuous wave squeezed light source to work effectively with both photon number resolving (PNR) detectors and balanced homodyne detection (BHD), while preserving their intrinsic characteristics.

This source is compatible with a Quantum Processing Unit (QPU) for experiments like GBS, MBQC and generation of non-gaussian states. The QPU is composed of a Variable beamsplitter where the polarization degree of freedom of light is used to perform transformations to the quantum states.

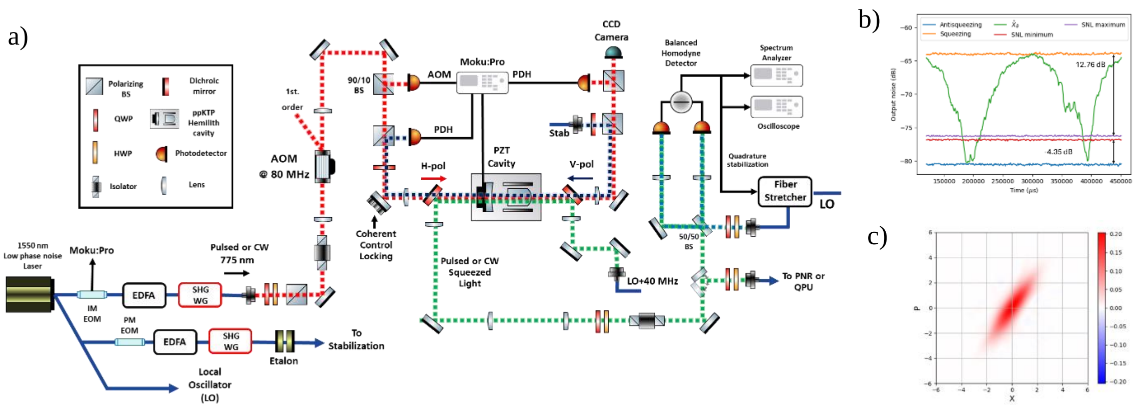

Fig. 1 a) Experimental implementation for the generation of squeezed light source compatible with PNR and BHD detection systems. b)Squeezing level of the source with CW pump light taken at 5 MHz with RBW: 300 KHz and VBW: 300 Hz. c) Wigner function reconstruction of the state by using Quantum State Tomography.

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Quantum feedback control for quantum error correction on superconducting qubits

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Continuous quantum error correction (QEC) is required in many situations in which the limit of a strong projective measurement cannot be applied. Recently, Atalaya et al. [1] proposed a continuous QEC scheme for quantum information applications which involve continuously varying Hamiltonians. This scheme relies on a sufficiently strong and continuous two-qubit parity measurement to extract the error syndromes.
To implement such a measurement is particularly challenging, since one has to perform a fast, nonlocal measurement while at the same time not introducing any errors to the information encoded in the qubits. We investigate to what extent this task can be accomplished using current circuit QED architecture.
Recent proposals for continuous parity measurements in this field rely on the so-called dispersive regime in which the transmons are far detuned from a resonator which acts as the meter for the parity measurement. As a result, transmons and resonator are only weakly coupled and the measurement is slow. We explore how one can achieve speedups by going to the quasi-dispersive regime.
Measurements based on the quasi-dispersive regime could then be utilized to enhance the resilience of Atalaya et al.'s and future QEC protocols.

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Encoding Architecture Search

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Quantum Architecture Search (QAS) [1] involves identifying the optimal quantum circuit structure or an Ansatz for a given problem. Traditionally, QAS (for e.g. machine learning tasks) is performed after the problem parameters have been encoded into the quantum circuit. The encodings chosen are typically predefined protocols like angle encoding [2], amplitude encoding [3], or schemes from image representation techniques. These are developed with the intent to, for example, implement image processing algorithms [4], and not targeted at machine learning tasks. In this work, we introduce **Encoding Architecture Search (EAS)**, which can be considered either a part of QAS or a precursor that focuses on finding the optimal encoding strategy for a given problem. Prior work has already demonstrated that the encoding method influences the performance of a quantum machine learning model [5]. We aim to improve the overall performance of quantum machine learning models by focusing on finding an improved encoding scheme.

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Experimental Quantum Strong Coin Flipping with Single Photons

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Strong coin flipping (SCF) is a protocol to allow two distrustful parties namely Alice and Bob to agree on randomly generated bits. In this work, we implement a quantum strong coin flipping protocol that yields lower cheating probabilities than its classical counterpart [1]. For this, we dynamically modulate polarization states of single photons generated by a semiconductor quantum dot. We report the performance of our quantum strong coin flipping implementation, which is the first with single photons, resulting in a single photon advantage compared to previous demonstrations with attenuated laser pulses.

To generate single photons a quantum dot in a CBG cavity is excited quasi-resonantly by picosecond laser pulses with a repetition rate of 80 MHz and the trion emission line @921 nm is spectrally selected. To encode the quantum state on Alice's side, the collected single photons are directed to a fiber-based electro-optic modulator (EOM) driven by a four-level random voltage waveform via custom-built electronics based on a field programmable gate array (FPGA) and a digital to analog converter (DAC). Single photons leave the EOM in four different polarization states chosen to optimize the SCF protocol after numerical simulations. After passing a 30 cm free-space quantum channel, the polarization states are analyzed on Bob's side. A classical link allows to compare sent and detected states to complete the protocol.

Our results show that the system produces successful coin flipping with a rate of 1.8 KHz. The average quantum bit error ratio (QBER) is calculated to be lower than 3%, sufficient to realize a quantum advantage.

Results clearly show the quantum advantage compared to classical counterparts. The QSCF was shown to be fair and balanced, as needed for various applications and can be also integrated into other cryptographic protocols.

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Growth, fabrication, and characterization of site-controlled quantum dots based on buried-stressor approach

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The buried-stressor approach is one of the pivotal methods for the growth of site-controlled quantum dots (SCQDs). This growth technique makes use of the strain from a partially oxidized AlAs layer to induce site-selective nucleation of InGaAs quantum dots. This versatile technique has a broad spectrum of applications including nanophotonic devices such as single-photon sources (SPSs) [1], microlasers [2], and their integration into quantum information and computing systems [3]. Here, we report on the growth, fabrication, and surface as well as optical characterization of SCQD microcavity arrays acting as SPSs. The epitaxial growth of the samples is conducted using metal-organic chemical vapor deposition (MOCVD) with the motive of achieving position, number, and emission energy control of QDs. A systematic investigation of the effects of variation of SCQD growth parameters on QDs density, surface morphology, and optical properties is done using atomic force microscopy (AFM), cathodoluminescence (CL), and micro-photoluminescence (µPL) spectroscopy. Furthermore, quantum optical characterizations such as second-order autocorrelation are also performed on these SCQD arrays. The comprehensive understanding of the intricacies involved in the growth and characterization of SCQDs offers a roadmap for the advancement of nanophotonic technologies and quantum information.

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Towards scalable quantum circuits based on microlaser-pumped quantum emitters

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We report on activities towards the development of a scalable technology platform for integrated quantum photonic circuits (IQPCs) based on semiconductor quantum dots acting as single-photon emitters. Photons, generated by these on-demand quantum emitters, serve as flying qubits in quantum communication systems and as input states for photonic quantum computing [1]. The proposed scalable quantum nanophotonic platform relies on individual semiconductor quantum dots integrated deterministically into quantum circuits that are based on photonic waveguides. Complex IQPCs circuits are fabricated using innovative manufacturing techniques such as in-situ electron beam lithography [2] and are optically excited by integrated microlasers to enable high quantum functionality in a scalable IQPC concept [3]. To demonstrate the platform's practical viability, a fiber-coupled module is developed as a demonstrator and incorporated into a compact, user-friendly cryocooler.

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High-quality single InGaAs/GaAs quantum dot growth on a silicon substrate for single-photon-based quantum computing

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Classical computers have revolutionized our lives thanks to their scalability, energy efficiency, and low costs. However, they are nearing their limits in calculation speed and capacity. In contrast, emerging quantum computers, leveraging quantum mechanics, offer the potential to outperform even the most powerful classical supercomputers.

Among quantum computing methods, photonic quantum computing is notable for using photons as information carriers, which resist decoherence, require minimal cooling, and integrate with existing communication networks. Single-photon sources (SPS) based on InGaAs quantum dots (QDs) are key components for this [1], offering high photon purity, indistinguishability, and entanglement fidelity. Their integration into tunable cavities improves brightness and emission rates, enabling the scalable fabrication of integrated quantum photonic circuits.

To further reduce costs, improve scalability, and shrink the size, we propose directly growing InGaAs single-photon emitters on silicon (Si) substrates using a GaP intermediate layer [2]. These emitters can be integrated into nanobeam cavities and be connected to an on-chip active demultiplexer, linear optical network [3], and superconducting nanowire single-photon detectors (SNSPDs), enabling gate-based general purpose photonic quantum computation [1].

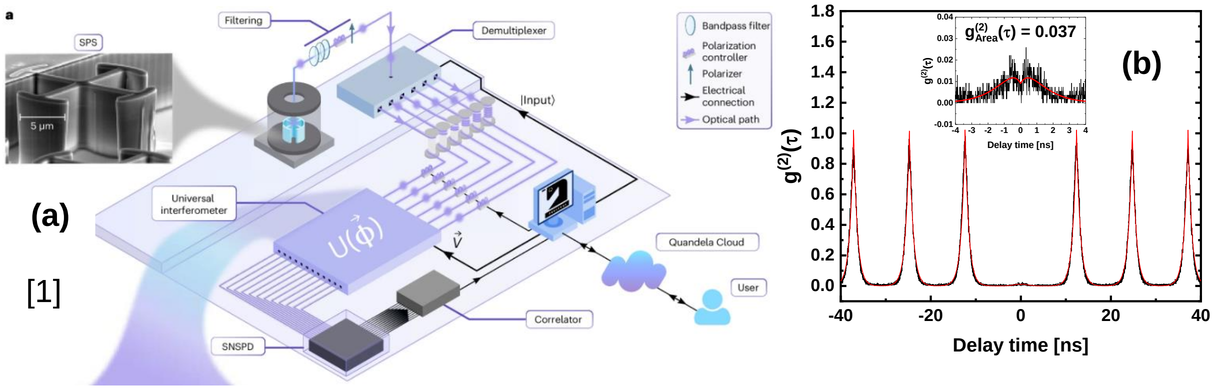

Figure 1: (a) Overview of the architectural design for the six single-photon quantum computer. **(b)** Second-order photon correlation function for the investigated QD.

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Adaptive Observation Cost Control for Variational Quantum Eigensolvers

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The objective to be minimized in the variational quantum eigensolver (VQE) has a restricted form, which allows a specialized sequential minimal optimization (SMO) that requires only a few observations in each iteration. However, the SMO iteration is still costly due to the observation noise---one observation at a point typically requires averaging over hundreds to thousands of repeated quantum measurement shots for achieving a reasonable noise level. In this paper, we propose an adaptive cost control method, named subspace in confident region (SubsCoRe), for SMO. SubsCoRe uses the Gaussian process (GP) surrogate, and requires it to have low uncertainty over the subspace being updated, so that optimization in each iteration is performed with guaranteed accuracy. Adaptive cost control is performed by setting the required accuracy according to the progress of the optimization, and identifying the minimum number of measurement shots, as well as their distribution, satisfying the SubsCoRe requirement.

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Generation of cluster states with group-IV color centers in diamond

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This work [1] introduces a novel platform for generating cluster states using Group-IV vacancies in diamond (G4Vs), including silicon (SiV), tin (SnV), and germanium (GeV) vacancies [2]. Cluster states are a key resource for measurement-based quantum computing [3]. We propose an emission-based protocol for generating linear cluster states and provide a detailed analysis of Raman single-qubit gates for controlling solid-state spin systems. We also examine the impact of nanophotonic crystal cavities, which are essential for coupling emitted photons into a well-defined optical mode and for minimizing photon losses.

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Towards time-bin entangled photon cluster states

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Single photons are ideal carriers of quantum information due to the lack of interaction with each other. However, manipulating and controlling them for quantum computing becomes a difficult task. One-way quantum computation [1] overcomes this challenge by avoiding non-linear two-qubit interaction and instead uses highly entangled states called "cluster states". Together with single qubit measurements and feed-forward a scalable universal quantum computer can be implemented [2].
The aim of our research is to realize a cluster state by fusion of few photon qubits which are time-bin encoded (early and late time-bins) in optical fibres. In this presentation, we will report on the generation of time-bin entangled photon pairs at 1560 nm and the subsequent characterization of the energy-time and time-bin entanglement by two photon interference [3]. We will also outline how we implement interferometric phase stability and arbitrary phase point control which are necessary to achieve a reproducible and deterministic interference. Scalability of our approach will be discussed as well.

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Emergence of second-order coherence in superfluorescence

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We experimentally investigate the second-order quantum coherence function of a superradiant burst in a cascaded quantum system. We chirally (i.e. direction-dependently) couple roughly 900 cesium atoms to the forward propagating mode of an optical nanofiber. We then prepare the ensemble in the maximally inverted state, where the subsequent collective emission of a burst is known as superfluorescence. Here, we observe that second-order coherence emerges in the course of the decay [1]. This is a clear feature of the underlying collective dynamics that is also at the origin of the superradiant burst itself. We furthermore study the dynamics of the second-order coherence function of the emission in dependence on the initial average dipole moment of the ensemble. In addition, by correlating the detection of early and late photon emission events, we obtain evidence for fundamental shot-to-shot fluctuations in the delay of the start of the burst emission. Our findings reveal that, despite the fundamentally different coupling Hamiltonian, superradiance in cascaded and symmetrically coupled systems feature a strikingly large number of similarities.

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Numerical Investigation of a Coupled Micropillar - Waveguide System for Integrated Quantum Photonic Circuits

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The on-chip resonant excitation of single quantum dots (QDs) via integrated microlasers represents an effective and scalable method for integrated quantum photonics applications based on on-demand single-photon emitters. In this study, the design and numerical optimization of the evanescent coupling between whispering gallery modes (WGMs) of a micropillar resonator and a nearby single-mode ridge waveguide in the Al(Ga)As/GaAs material system are presented. In this study, such systems are examined within a wavelength range of 930 nm, which is suitable for resonant excitation of typical self-assembled InGaAs quantum dots. In particular, the coupling and the transmitted optical power of a WGM resonator to a ridge waveguide are examined for a range of gap spacings, with the objective of optimizing the photon coupling efficiency and Q-factor of the monolithically integrated nanophotonic system. The findings of this study enable to identify the best device parameters for subsequent device fabrication. The findings establish a foundation for the production of highly effective photonic quantum circuits through the use of WGM microlasers integrated into evanescently coupled waveguide systems, including resonantly excited single quantum dots.

Real-time measurement error mitigation for one-way quantum computation

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We propose a quantum error mitigation scheme for single-qubit measurement errors, particularly suited for one-way quantum computation. Contrary to well established error mitigation methods for circuit-based quantum computation [1,2], that require to run the circuits several times, our method is capable of mitigating measurement errors in real-time, during the processing measurements of the one-way computation. For that, an ancillary qubit register is entangled with the to-be-measured qubit and additionally measured afterwards. By using a voting protocol on all measurement outcomes, occurring measurement errors can be mitigated in real-time while the one-way computation continues.
We provide an analytical expression for the probability to detect a measurement error in dependency of the error rate and the number of ancilla qubits. From this, we derive an estimate of the ancilla register size for a given measurement error rate and a required success probability to detect a measurement error. Additionally, we also consider the CNOT gate error in our mitigation method and investigate how this influences the probability to detect a measurement error. Finally, we show in a proof-of-principle simulation, considering a hardware noise model, that our method is capable of reducing the measurement errors significantly in a one-way quantum computation with only a small number of ancilla qubits.

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The Sawfish cavity: an efficient spin-photon interface for photonic quantum computing

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Color centers in diamond are promising candidates for creating photonic clusters states, which are entangled resource states that find application in photonic quantum computing as well as in quantum repeater schemes. These color centers are individually addressable spin systems, which generally show long coherence times and couple to optical transitions [1]. For these applications, a high rate of indistinguishable photons is required, which translates to coherent photons generated by the zero-phonon line (ZPL) transition. Due to the interaction with the surrounding solid-state environment, however, only a limited percentage of photons are emitted into the ZPL. In order to increase this percentage, the color centers can be embedded in photonic crystal cavities that are resonant with the ZPL transition [2]. Here, we show the characterization of the first generation of suspended Sawfish cavities in bulk diamond [3]. The Sawfish cavity is a newly proposed photonic crystal cavity that can reach Purcell factors up to 46 and a coupling efficiency into a single-mode fiber of up to 88% for a negatively-charged tin vacancy embedded in a cavity fabricated with realistic parameters (quality factor Q=17000) [4]. Quality factors of up to 3800 were already achieved in the first generation of Sawfish cavities, which shows that the above-mentioned enhancements are attainable with just minors improvements in fabrication.

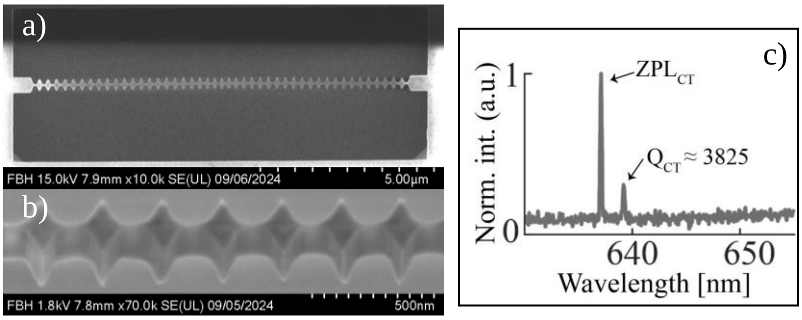

Fig 1: a) top view scanning electron microscope (SEM) image of suspended Sawfish cavity. b) 30° tilted zoomed in SEM image of Sawfish cavity. c) spectrum of a Sawfish cavity at cryogenic temperature.

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Large-Scale Localization and Characterization of Diamond Color Centers for Deterministic Fabrication of Nanophotonic Spin-Photon Interfaces

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Quantum photonic circuits are fundamental building blocks for quantum information applications, like secure communication or quantum computing. In the past decades, it has been demonstrated that color centers in diamond have excellent properties to serve as qubits in such systems [1]. To create an efficient spin-photon interface, the color centers have to be coupled to nanostructures. The scalable fabrication of such devices with high yield and optimal performance requires deterministic fabrication techniques [2]. Our approach is to use a widefield fluorescence microscope to localize tens of color centers per image frame and thousands of color centers per diamond sample. This is achieved with a high-accuracy and -precision localization resulting in positional uncertainties of a few tens of nanometers [3]. Furthermore, all localized color centers are characterized such that the ones with the most suitable properties can be chosen for integration into nanophotonic devices.

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