Progress in Photonic Quantum Computing

843. WE-Heraeus-Seminar

21 - 24 Sept 2025

at the Physikzentrum Bad Honnef, Germany

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 843. WE-Heraeus-Seminar:

The last years have seen impressive progress on realizing quantum information processing with photons. On the one hand this was enabled by the development of new theoretical tools and algorithms, on the other hand by improvement of hardware components, e.g. small processors, highly efficient non-classical light sources and single photon detectors. However, putting together all the required high-fidelity components to demonstrate a persistent photonic quantum advantage remains challenging. In this context we try to develop a vision for the field of photonic quantum information processing at the crossover from academia to industry.

This seminar will showcase the impressive progress made and will bring together leading experts from academia and industry to discuss the prospects and challenges of joint international/European research efforts on photonic quantum computers and simulators. The involved discussions will be highly beneficial not only for advancing the field, but also will support early-stage researchers in their progress on becoming experts themselves.

Scientific Organizers:

Prof. Dr. Janik Wolters	DLR, Germany E-Mail: Janik.Wolters@dlr.de
Prof. Dr. Jasmin Meinecke	Technische Universität Berlin, Germany E-Mail: jasmin.meinecke@tu-berlin.de
Prof. Dr. Klaus Jöns	Universität Paderborn, Germany E-Mail: klaus.joens@uni-paderborn.de

Introduction

Administrative Organization:

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Elisabeth Nowotka

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 21 September 2025

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 22 September 2025

08:00	*BREAKFAST*	
09:00 – 09:25	Scientific organizers Video	**Welcome words** **About the WE-Heraeus-Foundation**
09:25 – 10:10	Fabio Sciarrino	**Quantum machine learning with hybrid photonics platform**
10:10 – 10:55	Kai Müller	**Superconducting nanowire single-photon detectors for photonic quantum technologies**
10:55 – 11:20	*COFFEE BREAK*	
11:20 – 12:05	Fabian Wiesner	**The influence of experimental imperfections on photonic GHZ state generation**
12:05 – 12:50	Tobias Guggemos / Iris Agresti	**Experimental photonic quantum computing for machine learning tasks**
12:50	*LUNCH*	

Program

Monday, 22 September 2025

14:20 – 15:05	Mamoru Endo	**Key Technologies toward ultrafast optical quantum computation**
15:05 – 15:50	Sophia Economou	**Photonic resource state generation from quantum emitters**
15:50 – 16:10	Tobias Huber-Loyola	**Quantum dots in cavities for photon state generation**
16:10 – 16:40	*COFFEE BREAK*	
16:40 – 17:00	Angela Sara Cacciapuoti *(online)*	**On the quantum internet architecture**
17:00 – 17:45	Guillaume Dauphinais	**Quantum computing with photonic GKP qubits**
17:45 – 18:10	**Poster flashes 1**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:00 – 22:15	**Poster discussion 1**	

Program

Tuesday, 23 September 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Robert Raußendorf	**Fault-tolerant quantum computation with 3D cluster states**
09:45 – 10:30	Pascale Senellart	**Hybrid photonic quantum computing with semiconductor quantum dots**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Stephanie Barz	**Ingredients for photonic quantum computing: entanglement, fusions, and integration**
11:45 – 12:30	Jelmer Renema	**Integrated photonic quantum information processing**
12:30	*LUNCH*	
14:00 – 14:20	Alcides Montoya	**Quantum photonics in Latin America: landscape, gaps, and opportunities**
14:20 – 14:50	Karla Loida	**The QCI's quantum computing ecosystem and its photonic contribution**
14:55 – 16:00	**Panel discussion**	

Program

Tuesday, 23 September 2025

16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Falk Eilenberger	**Integrated active platforms for photonic quantum computing**
17:15 – 17:35	Michael Stefszky	**PaQS - The Paderborn Quantum Sampler**
17:35 – 18:00	**Poster flashes 2**	
18:00	*DINNER*	
19:30 – 22:00	**Poster discussion 2**	

Program

Wednesday, 24 September 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Christine Silberhorn	**Scaling photonic systems for quantum information science**
09:45 – 10:30	Tim Schröder	**Diamond nanophotonic spin defects: A promising resource for photonic quantum computation**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Ian Walmsley	**Lighting the quantum future**
11:45– 12:30	Jens Eisert	**Thoughts on photonic quantum information processing**
12:30 – 12:45	Scientific organizers	**Closing words**
12:45	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday; however, a self-service breakfast will be provided on Thursday morning

Posters

Posters

Mohamed Ahmed	**Training-based error mitigation in photonic variational quantum circuits**
Bedirhan Alkan	**Quantum state tomography**
Dina Atwa Khalil	**Nonlinear optical properties of hexagonal boron nitride nanosheet thin films: A femtosecond Z-scan study**
Eugenio Caruccio	**Fully-reconfigurable photonic integrated circuit for experimental validation of Threshold Quantum State Tomography**
Dario Cilluffo	**Operator-basis matrix product state formalism for optical circuits**
Antariksha Das	**Cavity-enhanced on-demand efficient quantum memory**
Patrícia De Assis Almeida	**Thermodynamic quenches in an extended hubbard model**
Edward Deacon	**An integrated source of pure single-mode squeezing**
Serge Deside	**Detecting genuine non-Gaussian entanglement**
Christoph Engelberg	**SPDC photon pair source for quantum random walk application on an integrated quantum photonic processor**
Ibrahim Ergün Bedirhan Alkan	**Spatiotemporal multiplexer design for nearly-deterministic high-visibility single-photon generation**
Imogen Forbes	**Hybrid path-transverse electric mode qudit encoding on an integrated photonic chip**
Sitotaw Eshete Gebremeskel	**Quantum metrology with click-counting measurements**
Felipe Gewers	**Quantum teleportation of multi-color continuous-variable states: from near-infrared to telecommunications bands**

Posters

Oliver Green	**Monolithic generation and detection of squeezed vacuum on an integrated photonic chip**
Thomas Haeffner	**Fusion of time-bin GHZ-states**
Irina Ivanova	**Probing relaxation dynamics of two-electron spin states in a quantum dot molecule**
Marcin Klaczak	**Quantum computation and machine learning for cancer detection**
Iurii Konyshev	**Calculating vibronic spectra with a linear algorithm based on gaussian boson sampling**
Jatin Kumar	**Toward spectral engineering of squeezed light in high gain parametric down conversion**
Sanjeet Kumar	**On-chip electro-optic modulation in the UV regime**
Jonas Lammers	**Resource efficient universal photonic processor based on time-multiplexed hybrid architecture**
Andreas Lehr	**High-precision time tagging for scalable photonic quantum experiments**
Zizheng Li	**Hybrid integration of amorphous silicon carbide for quantum photonics**
Arkajyoti Maity	**Polarisation shaped light for optimal two photon entanglement from quantum emitters**
Alessio Miranda	**Cross waveguide design for color-centers in diamond for photonic quantum computing**
Isabell Mischke	**Loss profiling of a massively multiplexed superconducting nanowire photon-number-resolving detector**
Haim Nakav	**Quantum CNOT gate with actively synchronized photon pairs**

Posters

Inmaculada Pérez Pérez	**Towards new hybrid schemes for photon generation**
Marcel Augusto Pinto	**Non-Markovian dynamics of a qubit due to accelerated light in a lattice**
Léo Pioge	**Anomalous bunching in multiphoton interferences**
Konstantinos Rafail Revis	**Statistical analysis of qutrit graph states under local complementation and local scaling**
Atzin David Ruiz Perez	**Towards scalable quantum photonics: preliminary investigations on LNOI-based components**
Carlos Sevilla	**Efficient coupling of SPDC enhanced by nonlinear interference**
Darshit Suratwala	**Quantifying quantum key randomness: statistical testing of QKD Keys**
Khalid Talbi	**Extractable work as a tool for testing witnessing in three-level lasers**
Priyanshu Tiwari	**Deterministic generation of light–matter entangled state for realization of quantum repeaters**
Hrachya Zakaryan	**Orbit classification of qutrit graph states under local complementation and local scaling**

Abstracts of Talks

(in alphabetical order)

Ingredients for photonic quantum computing: entanglement, fusions, and integration

S. Barz[1]

[1]Institute for Functional Matter and Quantum Technologies - University of Stuttgart, Stuttgart, Germany
[1]Centre for Integrated Quantum Science and Technology - University of Stuttgart, Stuttgart, Germany

In this talk, I will present recent progress in photonic quantum computing across three central areas: entanglement generation, fusion operations, and photonic integration. First, I will discuss schemes for the generation of resource states, enabling the creation of large-scale entangled photonic states that underpin measurement-based and fusion-based quantum computing. I will then introduce novel approaches to fusion operations that significantly enhance the success probabilities of entangling gates, reaching values close to 70%, a key step towards the practical realisation of fusion-based quantum computing. These improvements allow for more efficient construction of large photonic cluster states and reduce the overhead associated with fault tolerance. Finally, I will discuss issues of scalability and recent developments in photonic integration, including advances in on-chip platforms, and outline steps towards the implementation of fully optical quantum networks.

Quantum computing with photonic GKP qubits

Guillaume Dauphinais

Xanadu Quantum Technologies, Toronto, Canada

I will present Xanadu's proposal for a scalable and fault-tolerant photonic quantum computer along with relevant new results. Gottesman-Kitaev-Preskill bosonic qubits for this architecture are generated all-optically with high probability; a shallow network of static beamsplitters then creates universal resources with arbitrary connectivity for fault-tolerant quantum computation. Computation, syndrome data extraction, and final measurement readouts are all achieved using homodyne detectors, which are fast, reliable, accurate, and operate at room temperature. The architecture is based on modular, easy-to-network integrated photonic chips compatible with scalable fabrication and operation. Long-range connectivity between physical qubits is a feature of this approach that enables more efficient quantum error correction and implementation of fault-tolerant gates.

Photonic resource state generation from quantum emitters

Sophia E. Economou

Department of Physics and Center for Quantum Information Science and Engineering, Virginia Tech

Photonic resource states are entangled states of photons in particular graph structures. They are resources for measurement- and fusion- based quantum computing and for quantum networks. I will discuss the challenges in generating these states and focus on the protocols we developed toward determinist photonic resource state generation using quantum emitters.

Thoughts on photonic quantum information processing

Jens Eisert

FU Berlin, Germany

Photonic architectures offer exciting platforms for quantum information processing—not least because photons do not interact, making them particularly promising for scalable quantum computing. In this talk, after a brief introduction to set the stage, we will reflect on three aspects that possibly sometimes receive less attention than they deserve. First, we will consider the role of quantum error mitigation in sampling schemes [1]. After outlining some general obstacles [2], we will explore how error mitigation strategies might nevertheless be feasible in the context of boson sampling [3]. Second, we will highlight the importance of tools for certifying properties of quantum states in photonic systems. This includes fidelity witnesses [4], as well as a discussion of the fundamental challenges that prevent full tomography in continuous-variable photonic systems [5]. Finally, in an outlook, we will emphasize the central role of quantum error correction in enabling scalable photonic platforms [6].

[1] Reviews of Modern Physics 95, 035001 (2023).
[2] Nature Physics 20, 1648 (2024).
[3] arXiv:2505.00102 (2025).
[4] Nature Communications 14, 3895 (2023).
[5] arXiv:2405.01431, Nature Physics (2025).
[6] Nature Communications 16, 8214 (2025).

Key Technologies toward Ultrafast Optical Quantum Computation

M. Endo[1,2], A. Furusawa[1,2,3]

[1] *Department of Applied Physics, School of Engineering, The University of Tokyo, Tokyo, Japan*
[2] *RIKEN Center for Quantum Computing, Saitama, Japan*
[2] *OptQC Corp., Tokyo, Japan*

Continuous-variable optical quantum information processing—where quantum information is encoded in the quadrature phase amplitudes of an electromagnetic field of light—offers a path to quantum computers that operate at room temperature and atmospheric pressure [1]. By harnessing large-scale cluster states generated through time-domain multiplexing as the core of a quantum processor [2,3], we exploit light's inherently high carrier frequency to realize ultrafast operations beyond tens of gigahertz [4, 5]. Recent advances in low-loss optical circuits and high-resolution photon-number-resolving detectors have brought practical error-correctable logical qubit generation within reach [6]. In this talk, we will describe our integration of state-of-the-art optical communication techniques to fully leverage these advantages of light [7], enabling both our quantum processor and logical qubit source to operate at ultrafast speeds [6,7]. Ultimately, our goal is to build an all-optical quantum computer that processes information entirely in the optical domain—without any electrical signals—and performs computation at a 10-THz clock frequency.

References

1. S. Takeda and A. Furusawa, APL Photonics 4, 060902 (2019)
2. S. Yokoyama et al., arXiv:2506.16147 (2025)
3. H. A. Rad et al., Nature 638, 912-919 (2025)
4. A. Kawasaki et al., Nature Photonics 19, 271-276 (2025)
5. T. Yamashima et al., Optics Express 33, 5769-5780 (2025)
6. M. V. Larsen et al., Nature 642, 587-591 (2025)
7. A. Kawasaki et al., Nature Communications 15, 9075 (2024)
8. M. Endo et al., arXiv:2502.08952 (2025)

Experimental Photonic Quantum Computing for Machine Learning Tasks

T. Guggemos[1,2], I. Agresti[1]
[1]*University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), Vienna, Austria*
[2] *German Aerospace Center, Remote Sensing Technology Inst., Wessling, Germany*

Quantum computing is emerging as a transformative approach in the analysis of remote sensing data, with can be applied to practical tasks. Recent research demonstrates quantum algorithms that outperform classical methods in certain scenarios, notably by achieving higher accuracy in data analysis while requiring fewer features [1].
In this framework, photonic platforms have proven to be especially effective platforms, able to operate efficiently with limited resources, delivering high single-photon rates critical for scalable quantum computation [2]. Moreover, advances in integrated photonics have led to the development of compact, on-chip platforms capable of realizing quantum enhancement in given machine learning applications [3]. Photonic quantum platforms are resilient and adaptable to challenging environments. Unlike many other quantum systems that require cryogenic temperatures and delicate shielding, photonic devices can function at room temperature and withstand harsh conditions such as vacuum and elevated radiation - circumstances encountered in space, which makes them a leading candidate for quantum communication in satellite-based networks [4].
We leverage the features of photonic platforms to design hybrid classical-quantum machine learning protocols that can be applied to useful tasks, within reach of the state-of-the-art of quantum technologies. We outsource the non-linear computation, which is required by learning processes, to the quantum hardware, while classical algorithms perform the final linear classification. We show this in two recent works [5,6].
On the hardware side, we explore deploying photonic quantum processors on satellites for in-orbit data analysis. Their durability and computational strength enable us to present the design, operational experience, and challenges of using photonic quantum computing in space. These findings offer key insights for advancing quantum technologies in Earth observation and resource-efficient data processing.

References

[1] Fan, F., Shi, Y., Guggemos, T., & Zhu, X. X. (2023). Hybrid quantum-classical convolutional neural network model for image classification. IEEE
[2] Carosini, L., Oddi, V., Giorgino, F.,… & Walther, P. (2024). Programmable multiphoton quantum interference in a single spatial mode. Science Advances
[3] Yin, Z., Agresti, I., de Felice, G. et al. (2025). Experimental quantum-enhanced kernel-based machine learning on a photonic processor. Nat. Photonics
[4] Liao, S. K., Cai, W. Q., Liu, W. Y., Zhang, L., Li, Y., Ren, J. G., ... & Pan, J. W. (2017). Satellite-to-ground quantum key distribution. Nature, 549(7670)
[5] Mauser, Martin FX, et al. "Experimental data re-uploading with provable enhanced learning capabilities." arXiv preprint arXiv:2507.05120 (2025).
[6] Selimović, Mirela, et al. "Experimental neuromorphic computing based on quantum memristor." arXiv preprint arXiv:2504.18694(2025).

Tobias Huber-Loyola 1,2

1 Julius-Maximilians-Universität Würzburg, Technische Physik, Würzburg, Germany

2 Karlsruher Institut für Technologie, Institute for Photonics and Quantumelectronics, Karlsruhe, Germany

Solid-state single emitters are promising sources of single and entangled photons for quantum information technologies. Many of these emitters feature high internal quantum efficiency, strong emission into the zero-phonon line, and controllable single charge spins—making them ideal candidates for quantum memories or for generating entangled photon strings. However, their integration into photonic systems is challenged by the high refractive index of the host material, which limits photon extraction. To overcome this, nanophotonic structures such as waveguides and microcavities are employed to enhance photon outcoupling. In this talk, I will present our approach for integrating microcavities around pre-selected quantum dots using hyperspectral imaging combined with electron-beam lithography. I will also discuss how the precision of emitter-cavity alignment influences key photon properties, depending on the specific type of cavity used.

The QCI's Quantum Computing ecosystem and its photonic contribution

Dr. Karla Loida, German Aerospace Center, Linder Höhe, 51147 Köln, Germany

The Quantum Computing Initiative (QCI) of the German Aerospace Center (DLR) accelerates the development of quantum computers together with partners from industries by commissioning quantum computing protoypes. We generate a market, having start-ups, SMEs and established industry compete [1].
We are pooling infrastructure, expertise and resources at our innovation centres in Hamburg and Ulm. Industry and research come together at these innovation centres and jointly develop quantum computers, the necessary enabling technologies, software and use cases with a focus on our main areas of research which are space, aviation, energy, transport and security. To this end, we provide quantum start-ups and industrial consortia with laboratories, workshops and office space and create a highly attractive location with shared areas for efficient technology transfer, effective collaboration and an environment in which groundbreaking progress is possible.
At the quantum computing initiative, we are pursuing various technological approaches in order to benefit from a wide spectrum of expertise and evaluate where the quantum race will lead us. Our quantum computers include ion trap, neutral atom, photonic, diamond and other spin-based technologies. DLR pursues various activities in photonic quantum computing including industrial full stack prototypes [2], research in photonic sources [3], analogue quantum machines [4] and photonic quantum computing in space [5].

References

[1] DLR quantum computing initiative website: https://qci.dlr.de/en/homepage/

[2] UPQC project profile: https://qci.dlr.de/en/upqc/ (2022)

[3] PiQ project profile: https://qci.dlr.de/en/piq/ (2023)

[4] AQuRA project profile https://qci.dlr.de/en/aqura/ (2022)

[5] Pressemitteilung https://www.dlr.de/de/aktuelles/nachrichten/2025/mini-quantencomputer-ins-all-gestartet (2025)

Quantum Photonics in Latin America: Landscape, Gaps, and Opportunities — Poster Abstract

Alcides Montoya Cañola[1]

1 Departamento de Física, Universidad Nacional de Colombia - Sede Medellín, Medellín, Colombia. Director - Center for Excellence in Quantum Computing & AI (CECCIA)

This poster surveys the emerging landscape of quantum photonics across Latin America and outlines near-term opportunities for coordinated growth. We structure the region's activity along four pillars: (i) integrated photonics and on-chip optics; (ii) single-photon sources and detectors for quantum key distribution (QKD) and quantum sensing; (iii) testbeds and field deployments for metro-scale quantum-secure networking; and (iv) cross-cutting enablers including workforce development, open tooling, standards, and shared infrastructure. Strengths include longstanding academic leadership in quantum optics, robust training pipelines, and cost-aware prototyping practices. Key gaps remain in specialized cryogenic characterization and in sustained, multi-year funding for longitudinal testbeds. Building on these findings, we propose a staged roadmap: short-term actions emphasize curriculum micro-tracks in quantum photonics, open reference designs, and instrument-sharing agreements; mid-term steps prioritize university–industry partnerships, cloud-accessible measurement services, and interoperable, multi-city QKD pilots; long-term goals converge on regionally coordinated, standards-compliant quantum-secured networks and application-oriented photonic processors. The poster will also present an up-to-date map of the most relevant research groups, laboratories, and ongoing investigations in the region to facilitate collaboration.

Superconducting nanowire single-photon detectors for photonic quantum technologies

K. Müller[1]

[1]*Technical University of Munich, School of Computation Information and Technology and Center for QuantumEngineering, Garching, Germany*

Superconducting Nanowire Single Photon Detectors (SNSPDs) are a crucial building block for photonic quantum technologies due to their ability to detect single photons with high efficiency, low dark counts and low timing jitter.
In this talk, I will review how the superconducting material and detector design can be tailored to optimize the performance for applications in quantum technologies [1-4]. In addition, I will present how the local irradiation of SNSPDs with He-ions can be used to modify their properties which can be used to increase scalability, enhance the performance and enable current-crowding free SNSPDs [5-7]. Finally, I will discuss the potential of SNSPDs based on 2D van-der-Waals materials [8-9].

References

[1] R. Flaschmann et al., Nanoscale, 2023,15, 1086-1091 (2022)
[2] R. Flaschmann et al., Materials for Quantum Technology 3, 035002 (2023)
[3] L. Zugliani et al., 10.1109/GCWkshps58843.2023.10465075 (2023)
[4] S. Grotowski et al., Scientific Reports 15, 2438 (2025)
[5] S. Strohauer et al., Advanced Quantum Technologies 6, 2300139 (2023)
[6] S. Strohauer et al., Science Advances 11, eadt0502 (2025)
[7] S. Strohauer et al., APL Quantum 2, 026131 (2025)
[8] P. Metuh et al., arXiv:2503.22670 (2025)
[9] L. Zugliani et al., under review (2025)

Fault-tolerant quantum computation with 3D cluster states

Robert Raußendorf
Universität Hannover

Abstract: We describe a comprehensive circuit architecture and protocol for realizing 3D cluster states through photonic-measurement-based donor-spin-qubit entanglement and readout. The basic building blocks and protocol are chosen to be compatible with a fully-integrated photonic circuit implem entation, using Se+ as the photonically-coupled matter qubit. The basic operational building blocks of this universal quantum computing machine are local measurements and unitaries, plus an entangling m easurement of non-local Pauli operators. By analyzing several sources of error, we estimate a theoretical fault-tolerant threshold value on the order of 1%, and point to literature where required components have already been realized in integrated silicon circuits, albeit not all on the same chip, that suggest the threshold is within reach.

Joint work with Xiruo Yan, Warit Asavanant, Hirsh Kamakari, Jingda Wu, Jeff Young

Diamond nanophotonic spin defects: A promising resource for photonic quantum computation

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Measurement-based quantum computing (MBQC) is a model of quantum computation that relies on quantum measurements rather than unitary operations to implement algorithms [1,2]. In MBQC, a highly entangled state, a so-called resource graph state, is prepared initially. Algorithms are then executed by performing a sequence of adaptive single-qubit measurements on this state. Each measurement outcome determines the basis for subsequent measurements, allowing complex computations to unfold without the need for direct gate operations. This approach is particularly interesting because it separates the preparation of entanglement from the computation process, offering potential advantages in fault-tolerant quantum computing and making it compatible with various physical implementations of quantum processors.

In this presentation I will introduce the fundamental concepts of MBQC through ongoing research my group is conducting, focusing on the physical implementation with *photonic* graph states [3,4]. There are two main challenges that the scientific community as well as commercial companies a presently facing towards the implementation of MBQC. The first one is the creation of the required resource state consisting of photons that are entangled with each other in at least two dimensions. For the creation of such graph states [5], we are exploring the suitability of atom-like optically active spin defect centers in diamond nanostructures [6]. To this end, we theoretically investigate the achievable resource state size [7] and the required gate operations for graph state creation [8,9]. Experimentally, we demonstrate optical and microwave qubit control gates [10]. To provide the required high photon creation efficiencies, we have developed an efficient spin-photon interface with up to 99% creation-to-fiber coupling efficiency [11,12]. The second challenge is the implementation of adaptive single-qubit measurements on the photons of the entangled state [2] which requires photonic integrated circuits with feed-forward operations. Towards this goal we have made progress in using AlGaN as photonic platform [13] and are developing feed-forwarding methods.

By addressing both of these challenges, our group explores photonic graph states as fascinating entangled objects and the required physical systems to turn them into resources for quantum information.

References

[1] R. Raussendorf and H. J. Briegel, "A One-Way Quantum Computer," Phys. Rev. Lett. 86, 5188 (2001).
[2] H. J. Briegel et al., "Measurement-based quantum computation," Nature Physics 5, 19–26 (2009).
[3] I. Schwartz et al., "Deterministic generation of a cluster state of entangled photons," Science 354, 434 (2016).
[4] P. Thomas et al., "Efficient generation of entangled multiphoton graph states from a single atom," Nature 608, 7924 (2022).
[5] J. Borregaard et al., "One-Way Quantum Repeater Based on Near-Deterministic Photon-Emitter Interfaces," PRX 10, (2020).
[6] T. Schröder et al., "Quantum nanophotonics in diamond [Invited]," Journal of the Optical Society of America B 33, B65 (2016).
[7] G. Pieplow et al., "Deterministic Creation of Large Photonic Multipartite Entangled States with Group-IV Color Centers in Diamond," arXiv:2312.03952 (2023).
[8] L. Orphal-Kobin et al., "Coherent microwave, optical, and mechanical quantum control of spin qubits in diamond," Advanced Quantum Technologies, 2300432 (2024).
[9] G. Pieplow et al., "Efficient Microwave Spin Control of Negatively Charged Group-IV Color Centers in Diamond," Phys. Rev. B 109, 115409 (2024).
[10] C. G. Torun et al., "SUPER and subpicosecond coherent control of an optical qubit in a tin-vacancy color center in diamond," arXiv:2312.05246 (2023).
[11] J. M. Bopp et al., "'Sawfish' Photonic Crystal Cavity for Near-Unity Emitter-to-Fiber Interfacing in Quantum Network Applications," Advanced Optical Materials, 2301286 (2023).
[12] T. Pregnolato et al., "Fabrication of Sawfish photonic crystal cavities in bulk diamond," APL Photonics 9, 036105 (2024).
[13] S. Gündogdu et al., "AlGaN/AlN heterostructures: an emerging platform for integrated photonics," npj Nanophotonics 2, 1 (2025).

Quantum machine learning with Hybrid photonics platform

Fabio Sciarrino

Quantum Lab, Dipartimento di Fisica, Sapienza Università di Roma

The implementation of large-scale universal quantum computation represents a challenging and ambitious task on the road to quantum processing of information. In recent years, an intermediate approach has been pursued to demonstrate quantum computational advantage via non-universal computational models. This presentation highlights recent progress in photonic quantum information processing with a focus on intermediate computational models. We introduce in particular the model of Adaptive Boson Sampling, which combines linear optics evolution and adaptivity, and present our work on implementing quantum machine learning by emulating adaptivity through post-selection on femtosecond laser-written circuits. Furthermore, we introduce the photonic quantum convolutional neural network (PQCNN), employing particle-number preserving circuits and state injectionl. Our experiments, using a quantum dot-based single-photon source and programmable interferometers, validate the PQCNN for binary image classification. These advancements showcase the potential of adaptive photonic systems for scalable quantum computing and machine learning.

References

[1] F. Hoch, E. Caruccio, G. Rodari, T. Francalanci, A. Suprano, T. Giordani, G. Carvacho, N. Spagnolo, S. Koudia, M. Proietti, C. Liorni, F. Cerocchi, R. Albiero, N. Di Giano, M. Gardina, F. Ceccarelli, G. Corrielli, U. Chabaud, R. Osellame, M. Dispenza, F. Sciarrino. Quantum machine learning with Adaptive Boson Sampling via post-selection, Nature Communications 16, 902 (2025)

[2] G. Rodari, C. Fernandes, E. Caruccio, A. Suprano, F. Hoch, T. Giordani, G. Carvacho, R. Albiero, N. Di Giano, G. Corrielli, F. Ceccarelli, R. Osellame, D. J. Brod, L. Novo, N. Spagnolo, E. F. Galvão, F. Sciarrino. Experimental observation of counter-intuitive features of photonic bunching, PRX Quantum 6, 020340 (2025)

[3] G. Rodari, T. Francalanci, E. Caruccio, F. Hoch, G. Carvacho, T. Giordani, N. Spagnolo, R. Albiero, N. Di Giano, F. Ceccarelli, G. Corrielli, A. Crespi, R. Osellame, U. Chabaud, F. Sciarrino. Observation of Lie algebraic invariants in Quantum Linear Optics (2025) [arXiv:2505.03001]

[4] L. Monbroussou, B. Polacchi, V. Yacoub, E. Caruccio, G. Rodari, F. Hoch, G. Carvacho, N. Spagnolo, T. Giordani, M. Bossi, A. Rajan, N. Di Giano, R. Albiero, F. Ceccarelli, R. Osellame, E. Kashefi, F. Sciarrino. Photonic Quantum Convolutional Neural Networks with Adaptive State Injection (2025) [arXiv:2504.20989]

Hybrid photonic quantum computing with semiconductor quantum dots

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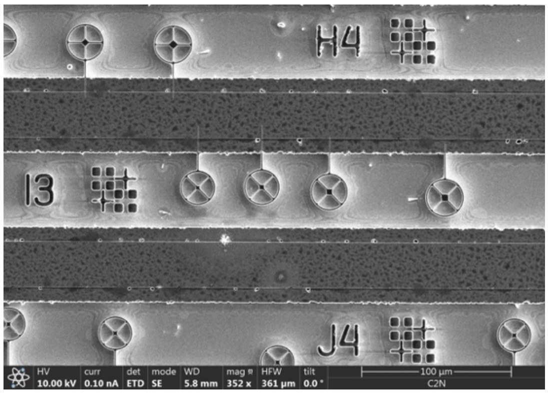
In this talk, I will present our contribution to the development of hybrid photonic quantum computing platform exploiting single InGaAs quantum dots in cavities. We will first see how we have progressively developed efficient sources of highly indistinguishable single photons [1] and turned them into plug and play devices [2]. We will virtually visit our first quantum computing platform, based on single photons and integrated photonic chips and present first proof of concept applications [3]. We will then discuss various possible roadmaps for scaling up, all pertaining to the category of measurement-based quantum computing and requiring photonic graph states. Exploiting the spin degree of freedom of an electron trapped in a quantum dot, we recently achieved an important milestone in this context, with the generation of various spin-multi -photon entangled states [4,5].
We will finally discuss the potential of this hybrid approach of quantum computing, exploiting both spins and photons. As a first example, we will study the resources needed to generate a typical state sought for implementing a logical qubit, comparing the full photonic approach to the hybrid one [6].



SEM image of spin-photon interfaces based on quantum dot in cavities.

[1] N. Somaschi, V. Giesz et al, Nature Photonics 10, 340 (2016)
[2] N. Margaria et al, arXiv:2410.07760 – Nature Communications in press
[3] N. Maring et al., Nature Photonics 18, 603 (2024)
[4] N. Coste et al., Nature Photonics 17, 582 (2023)
[5] H. Huet et al, Nature communications 16 (1), 4337 (2025)
[6] S. C. Wein et al, arXiv:2412.08611

Scaling photonic systems for quantum information science

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Quantum technologies promise a paradigm shift across many applications, most notably high-performance computing and large-scale simulations. Realizing systems of practical scale, however, demands highly complex photonic architectures. In photonics, scalability hinges on precise control of many optical modes together with multi-photon quantum states.

We review experimental approaches for future photonic quantum computing, including Gaussian boson sampling and time-frequency multiplexing. Our focus spans nonlinear integrated quantum devices, engineered photon sources, pulsed temporal modes, and mode-multiplexed architectures.

Nonlinear integrated devices with multiple channels and tailored functionality are essential for implementing suitable quantum circuits, combining high-brightness sources and fast electro-optic modulation on compact monolithic platforms. We explore thin-film lithium niobate (TFLN) circuits and introduce concepts toward a toolbox of integrated components optimized for quantum applications.

For advanced quantum-light engineering, pulsed photonic temporal modes offer an attractive, inherently high-dimensional encoding. These field-orthogonal superpositions arise naturally in contemporary nonlinear sources and have can be engineered for the realization of high-dimensional circuits. We also show how precise control of pulsed time-frequency modes can be harnessed to realize efficient quantum network architectures based on quantum interference.

Finally, we discuss our Gaussian boson sampling (GBS) platforms and outline the requirements for fully integrated and functional quantum computing implementations, together with strategies for benchmarking GBS toward future applications.

PaQS, the Paderborn Quantum Sampler

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Gaussian Boson Sampling (GBS) has advanced rapidly since it was first conceived [1] and was subsequently demonstrated on a large scale [2]. Not only was GBS the first system to provide compelling evidence of quantum computational advantage [2], but the scheme has also driven advancements in photonic technology, and investigations into universal photonic quantum computing. It has subsequently been shown that a number of graph-based problems can be encoded into the GBS architecture, leading to possible applications in, for example, drug discovery [3].
Constructing a GBS system requires a number of highly specialised and carefully designed components: engineered squeezed state sources, low-loss reconfigurable beamsplitter networks, and high efficiency photon-number-resolved (PNR) detection. Differing implementations of these key components provide unique benefits and disadvantages.
Here, we present the GBS architecture that has been constructed at Paderborn University. The squeezed light generation is achieved via temporal multiplexing in a nonlinear waveguide, the interferometer is implemented using a fully programmable integrated photonic processor, and intrinsic photon-number resolution is accomplished using superconducting nanowire single-photon detectors (SNSPDs) [4]. These design decisions result in a system with a total system efficiency of 7% while maintaining full programmability of the 12-mode interferometer. The integrated source is capable of producing extremely bright single-mode vacuum squeezing (up to 40,000 photons per pulse). We will present recent results highlighting the versatility of the chosen architecture and investigations into quantifying nonclassicality in the system.

References

[1] C. S. Hamilton *et* al, *Phys. Rev. Lett.,* ***119****,* 170501, (2017).
[2] H-S. Zhong *et* al, *Science,* ***370****,* 6523, (2020).
[3] S. Yu *et* al, *Nat Comput Sci.,* ***3****,* 839-848, (2023).
[4] T. Schapeler *et* al, *Phys. Rev. Applied,* ***22****,* 014024, (2024).

Lighting the Quantum Future

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Light is a critical medium for quantum technologies, providing the capability both to encode a large capacity of information and to preserve quantum features, such as entanglement and reduced noise, at ambient conditions. Photonics has proven to be an effective means to engineer quantum systems that can perform tasks efficiently in both analog simulation and digital architectures. The challenge is to build a quantum state of sufficient complexity, both in the number of photons and the number of modes, that useful applications can be addressed. I will discuss how optical platforms can provide potential advantage in hybrid protocols, even without full error correction, and consider their role as a machine learning platform.

The Influence of Experimental Imperfections on Photonic GHZ State Generation

Fabian Wiesner[1], **Helen M. Chrzanowski**[2,3], **Gregor Pieplow**[3], **Tim Schröder**[3,4], **Anna Pappa**[1], **Janik Wolters**[2,6]

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While the advantages of photonic quantum computing, including direct compatibility with communication, are apparent, several imperfections such as loss and distinguishability presently limit actual implementations. These imperfections are unlikely to be completely eliminated, and it is therefore beneficial to investigate which of these are the most dominant and what is achievable under their presence. In this work, we provide an in-depth investigation of the influence of photon loss, multi-photon terms and photon distinguishability on the generation of photonic 3-partite GHZ states via established fusion protocols. We simulate the generation process for SPDC and solid-state-based single-photon sources using realistic parameters and show that different types of imperfections are dominant with respect to the fidelity and generation success probability. Our results indicate what are the dominant imperfections for the different photon sources and in which parameter regimes we can hope to implement photonic quantum computing in the near future.

Abstracts of Posters

(in alphabetical order)

Training-Based Error Mitigation in Photonic Variational Quantum Circuits

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Linear photonic quantum computers are constrained by the low success probability of CNOT gates. While the KLM protocol enables scalability, it requires many modes and error-correcting codes. Variational quantum circuits (VQCs) offer intrinsic error mitigation, but typically rely on costly post-processing with repeated executions. This work studies VQC-based classifiers under probabilistic photonic CNOT nois. We find that CNOT failures affect states unevenly, with certain error-immune states enabling training-based error mitigation. We also identify parameter subspaces where errors can be suppressed through parameter corrections, avoiding post-processing. Simulations on binary classification tasks across varying CNOT success probabilities show that VQCs maintain acceptable accuracy, highlighting the potential of linear photonics for quantum machine learning.

References

[1] E. Knill, R. Laflamme, and G. J. Milburn, “A scheme for efficient quantum computation with linear optics,” nature, vol. 409, no. 6816, pp. 46–52, 2001.

[2] A. Peruzzo, J. McClean, P. Shadbolt, M.-H. Yung, X.-Q. Zhou, P. J. Love, A. Aspuru-Guzik, and J. L. O’brien, “A variational eigenvalue solver on a photonic quantum processor,” Nature communications, vol. 5, no. 1, p. 4213, 2014.

Quantum State Tomography

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In this work, a quantum state tomography setup was implemented for a one-qubit system using Pauli gates, in an optical bulk system with a Spontaneous Parametric Down-Conversion (SPDC) photon source. Pauli gates X, Y, and Z were applied to manipulate the quantum state of the photon, which was then measured in the computational basis.

Optical components, including beam splitters, wave plates, and polarizers, were used to perform the Pauli gates and the tomography. Measurement data were collected and processed using maximum likelihood estimation (MLE) and linear inversion, enabling the reconstruction of the photon's density matrix. This setup provides a method for quantum state characterization in optical systems and demonstrates the potential for state reconstruction with single-photon sources.

References

[1] Altepeter, J., Jeffrey, E., & Kwiat, P. (2005). Photonic state tomography. In Advances in atomic, molecular, and optical physics (pp. 105–159)

[2] Toninelli, E., Ndagano, B., Vallés, A., Sephton, B., Nape, I., Ambrosio, A., Capasso, F., Padgett, M. J., & Forbes, A. (2019). Concepts in quantum state tomography and classical implementation with intense light: a tutorial. Advances in Optics and Photonics, 11(1)

Spatiotemporal Multiplexer Design for Nearly-Deterministic High-Visibility Single-Photon Generation

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Highly deterministic streams of indistinguishable single photons are essential for a wide range of quantum technologies, from scalable quantum computing to quantum key distribution. Quantum dots are prominent platforms to generate nearly-deterministic single photons. However, their broad emission spectra lead to a trade-off between indistinguishability and deterministic single photon generation[1]. On the other hand, parametric sources generate high purity heralded photons via probabilistic processes. To overcome the probabilistic nature of parametric sources, spatial, temporal and spatiotemporal multiplexing architectures have been developed. Each approach offers distinct advantages and limitations in terms of scalability, optical loss and complexity. In this work, we build upon existing analyses[2] of multiplexed SPDC systems to evaluate their performance in enabling high fidelity Bell-State measurements. We propose a spatiotemporal multiplexing architecture that combines the strengths of temporal and spatial designs to maximize the nearly-deterministic generation of high-visibility single photons.

References

[1] D. K. Thapa, S. Biswas, Nanoscale **17**, 7651 (2025)

[2] F. Kaneda, P. G. Kwiat, Sci. Adv. **5**, eaaw8486 (2019).

"Nonlinear Optical Properties of Hexagonal Boron Nitride Nanosheet Thin Films: A Femtosecond Z-scan Study"

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Hexagonal boron nitride nanosheets (h-BNNs) have emerged as promising two-dimensional materials with exceptional optical properties, yet their nonlinear optical (NLO) characteristics remain largely unexplored. This study presents the first comprehensive investigation of the NLO properties of h-BNN thin films using the Z-scan technique with femtosecond laser excitation. h-BNN thin films were fabricated via mechanical exfoliation and characterized using UV-visible spectroscopy, transmission electron microscopy, and Raman spectroscopy to confirm their morphology and crystal structure. The nonlinear optical response was systematically evaluated using 100 fs laser pulses across excitation wavelengths ranging from 740 to 820 nm at a fixed average power of 1 W. The results demonstrate a linear decrease in the nonlinear absorption coefficient with increasing excitation wavelength. The h-BNN thin films exhibited remarkable optical limiting behavior characterized by reverse saturable absorption, indicating strong potential for laser protection applications. These findings establish h-BNNs as viable candidates for next-generation optical limiting devices and highlight their promise as sensitive optical components in photonic applications. The wavelength-dependent nonlinear response observed in h-BNN thin films provides valuable insights into their optical properties and opens new avenues for their implementation in advanced optical systems requiring precise power regulation and laser safety protocols.

Fully-reconfigurable photonic integrated circuit for experimental validation of Threshold Quantum State Tomography

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Quantum State Tomography (QST) enables reconstruction of a state with resources that scale exponentially with the system size. Threshold Quantum State Tomography (tQST) [1] is a method that determines the optimal number of measurements needed for accurate reconstruction, without a prior knowledge of the state. In this work, we experimentally reconstruct the density matrices of path-encoded quantum states with up to four photons, implementing tQST on a fully reconfigurable photonic integrated circuit (PIC) [2]. We show that tQST achieves state reconstruction with accuracy comparable to standard QST, while significantly reducing the number of required projectors. Our experimental setup [3-4] employs a semiconductor quantum dot source, combined with a time-to-spatial demultiplexer, to generate multi-photon Fock states. These are injected into an eight-mode fully reconfigurable PIC. Dual-rail path encoding, post-selection and single qubit projectors are used to prepare and measure n-qubit quantum states. n-fold coincidence events are detected by a superconducting detection system connected to a time-to-digital converter. The tQST protocol was first validated on sets of 2,3-qubit states and then applied to maximally entangled states. For the 4-photon GHZ state, tQST requires only 66 projectors compared to 256 for standard QST. The fidelity between the reconstructed density matrices for $|GHZ_4\rangle$ is ~95%, indicating that tQST achieves high-quality reconstruction with limited information loss. In conclusion, tQST provides a resource-efficient alternative to QST, maintaining comparable reconstruction accuracy. This substantial reduction in measurement overhead makes it particularly promising for scaling up quantum state tomography in high-dimensional quantum systems.

References

[1] D. Binosi, APL Quantum **1**, 036112 (2024)
[2] E. Caruccio, arXiv:2504.05079v1 [quant-ph] (2025)
[3] G. Rodari, PRX QUANTUM **6**, 020340 (2025)
[4] F. Hoch, Nature Communications **16**, 902 (2025)

Operator-basis Matrix Product State formalism for optical circuits

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Tensor network formalisms have emerged as powerful tools for simulating quantum state evolution [1,2]. While widely applied in the study of optical quantum circuits, such as Boson Sampling [3], existing tensor network approaches fail to address the complexity mismatch between tensor contractions and the calculation of photon-counting probability amplitudes. Here, we present an alternative tensor network framework, the operator-basis Matrix Product State (OBMPS) [4], which exploits the input-output relations of quantum optical circuits encoded in the unitary interferometer matrix. Our approach bridges the complexity gap by enabling the computation of the permanent -- central to Boson Sampling -- with the same computational complexity as the best known classical algorithm based on a graphical representation of the operator-basis MPS that we introduce. Furthermore, we exploit the flexibility of tensor networks to extend our formalism to incorporate partial distinguishability and photon loss, two key imperfections in practical interferometry experiments. This work offers a significant step forward in the simulation of large-scale quantum optical systems and the understanding of their computational complexity.

[1] R. Orús, Nature Reviews Physics 1, 538 (2019).
[2] U. Schollwöck, Annals of Physics 326, 96 (2011).
[3] S. Aaronson and A. Arkhipov, arXiv:1011.3245 (2010).
[4] D. Cilluffo, M. Kost, N. Lorenzoni and M. B. Plenio, arXiv:2502.01737 (2025).

Cavity-Enhanced On-Demand Efficient Quantum Memory

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The development of large-scale quantum networks critically depends on the ability to distribute entanglement over long distances. Quantum repeaters offer a promising solution by enabling entanglement distribution across continental scales, and most repeater architectures require reliable quantum memories to store quantum states temporarily. Rare-earth ion-doped crystals are arguably ideal candidates for building optical quantum memories, as they offer excellent coherence properties, long storage times, and high multiplexing capabilities. In our work, we demonstrate a high-efficiency spin-wave quantum memory using the atomic frequency comb (AFC) protocol in a $Pr^{3+}:Y_2SiO_5$ (Pr:YSO) crystal embedded within an impedance-matched optical cavity. The memory features on-demand read-out and operates at the single-photon level, achieving storage efficiencies of up to 40%. We verify the quantum nature of the memory by storing heralded single photons from a non-degenerate SPDC source, confirming non-classical correlations. Our results represent a significant step forward in advancing solid-state quantum memories for scalable quantum repeater networks.

References

[1] S. Duranti et al, Optics Express 32 (15), 26884-26895 (2024)
[2] M. Afzelius et al, Phys. Rev. A, 79, 052329 (2009)
[3] M. Afzelius and C. Simon, Phys. Rev. A, 82, 022310 (2010)

THERMODYNAMIC QUENCHES IN AN EXTENDED HUBBARD MODEL

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This work investigates the thermodynamic quenches in an extended Hubbard model, emphasizing entanglement properties, concurrence measures, and phase diagrams using time-dependent density matrix renormalization group (tDMRG) methods [1]. The extended Hubbard model, which incorporates interactions beyond nearest neighbors, provides a rich framework for exploring non-equilibrium dynamics in strongly correlated systems. Using tDMRG simulations, we compute entanglement entropy and concurrence to evaluate quantum correlations throughout the quench dynamics. Phase diagrams obtained from the simulations highlight transitions between entangled and decoherent regimes, offering a deeper understanding of information spreading and thermalization. Preliminary results indicate distinct dynamical regimes governed by interaction strength and initial state configuration. The concurrence evolution exhibits non-trivial behavior, revealing correlations between electronic states, while entanglement dynamics provide insights into coherence and decoherence effects. Our findings suggest that extended interactions significantly shape the post-quench evolution, offering new perspectives on non-equilibrium phenomena in condensed matter physics. This study contributes to bridging traditional condensed matter techniques with quantum information theory, leveraging computational methods to explore fundamental aspects of quantum correlations and dynamical phase transitions.

References

[1] S. Kirino, T. Fujii, J. Zhao, K. Ueda, J. Phys. Soc. Jpn. 77, 084704 (2008)

An Integrated Source of Pure Single-mode Squeezing

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Presented here is an integrated photonic source whose design is based on linearly uncoupled and nonlinearly coupled (LUNC) microring resonators (MRRs) [1] optimised for the generation of pure single-mode squeezed vacuum (SMSV) using dual pump spontaneous four-wave mixing (DP-SFWM). LUNC MRRs have several benefits for the generation of SMSV states including the ability to suppress parasitic FWM processes like single pump (SP-)SFWM and Bragg scattering (BS-)FWM which induce deleterious thermal noise and loss to the desired SMSV state.

SFWM and stimulated SP-FWM have been demonstrated in LUNC MRRs [2,3] including the suppression of parasitic SP-SFWM while performing DP-SFWM [4]. To date, no measurements nor optimization of spectral purity have been performed for squeezed states generated in LUNC MRRs. In this work, we use independent tuneable couplings on each MRR of the source implemented with Mach-Zehnder interferometers (MZIs) in conjunction with spectrally broad pulsed pumps to achieve high spectral purity. We perform stimulated emission tomography (SET) of the joint spectral intensity (JSI) obtaining purities >98%. In addition, we demonstrate the suppression of parasitic SP-SFWM by >16 dB via photon counting measurements.

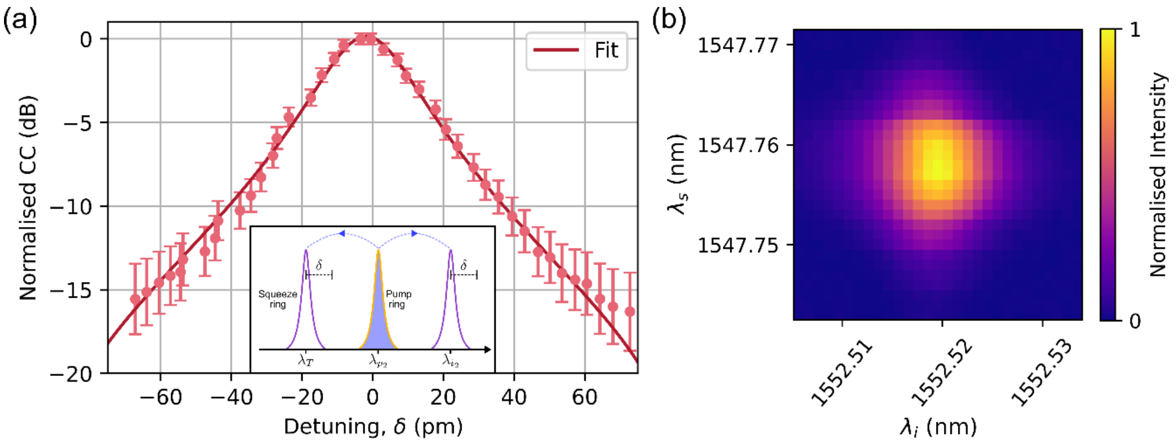

Figure 1: (a) Suppression of SP-SFWM via resonance detuning (see inset) observed via a reduction in photon coincidence counts (CC). (b) JSI measured via SET with a purity of >98%.

References

[1] M. Menotti, *et al.*, Phys. Rev. Lett. **122**, 013904 (2019)
[2] K. Tan, *et al.*, Opt. Lett. **45** 873-876 (2020)
[3] F. A. Sabatolli, *et al.*, Appl. Phys. Lett. **121** (20): 201101 (2022)
[4] F. A. Sabattoli, *et al.*, Phys. Rev. Lett. **127**, 033901 (2021)

Detecting genuine non-Gaussian entanglement

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Efficiently certifying non-Gaussian entanglement in continuous-variable quantum systems is a central challenge for advancing quantum information processing, photonic quantum computing, and metrology. Here [1], we put forward continuous-variable counterparts of the recently introduced entanglement criteria based on moments of the partially transposed state, together with simple readout schemes that require only a few replicas of the state, passive linear optics, and particle-number measurements. Our multicopy method enables the detection of genuine non-Gaussian entanglement for various relevant state families overlooked by standard approaches, which includes the entire class of NOON states. Further, it is robust against realistic experimental constraints (losses, noise, and finite statistics), which we demonstrate by extensive numerical simulations.

Reference

[1] Serge Deside, Tobias Haas, and Nicolas J. Cerf, arXiv:2504.15831 (2025).

SPDC Photon Pair Source for Quantum Random Walk Application on an Integrated Quantum Photonic Processor

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Photonic quantum computing (PQC) is emerging as a promising approach to quantum computing due to photons' near-decoherence-free nature, room temperature operation and high-precision manipulation [1]. One crucial component for PQC are quantum light sources, which can be realized by spontaneous parametric down-conversion (SPDC) photon pair sources. A key requirement for such sources is a high indistinguishability of the photons [2].

In this work, an SPDC photon pair source at telecom wavelength is set up and characterized with an on-chip integrated quantum photonic processor (QPP). Furthermore, its practical suitability and performance for a potential use in the field of PQC is confirmed. By further performing spectral filtering, a Hong-Ou-Mandel (HOM) interference visibility of 98.41% was achieved. A high indistinguishability of the photons is thereby shown.

A possible PQC application are quantum random walks (QRWs) on a QPP, where a pair of indistinguishable photons is passed through a linear optical network [3]. In a future step, this photon pair source will be used to experimentally and simulatively investigate the influence of the source properties on the performance of QRWs.

References

[1] C. Taballione, et al., Quantum 7, 1071 (2023)
[2] J. Pan, et al., Light: Science & Application 9, 1-24 (2020)
[3] A. Peruzzo, et al., Science 329 (5998), 1500-1503 (2010)

Hybrid Path-Transverse Electric Mode Qudit Encoding on an Integrated Photonic Chip

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Hybrid encoding, or using multiple degrees of freedom (DOFs) to simultaneously encode information within a quantum state, increases the dimensionality of the Hilbert space without increasing particle number [1]. We demonstrate generation and verification of states using this encoding on an integrated photonic device, shown in Figure 1(a). Experimentally, we generate a hyperentangled state and a GHZ_4-style state. We reconstruct the density matrices for each state using quantum state tomography, as shown in Figure 1(b) and (c). The hyperentangled state has a fidelity of $67.3 \pm 0.2\%$ and the GHZ_4-style state has a fidelity of $85.2 \pm 0.4\%$. Our hyperentangled state can also be used in entanglement distillation [2]. By encoding our information across multiple DOFs and distilling down to a single DOF using a deterministic CNOT with the control and target in different DOFs, we can increase the fidelity of our state in the presence of errors [3], as shown in Figure 1(d). By using DOFs which are highly compatible with integrated photonic devices, these states have exciting potential for use in future quantum information processing and computing technologies.

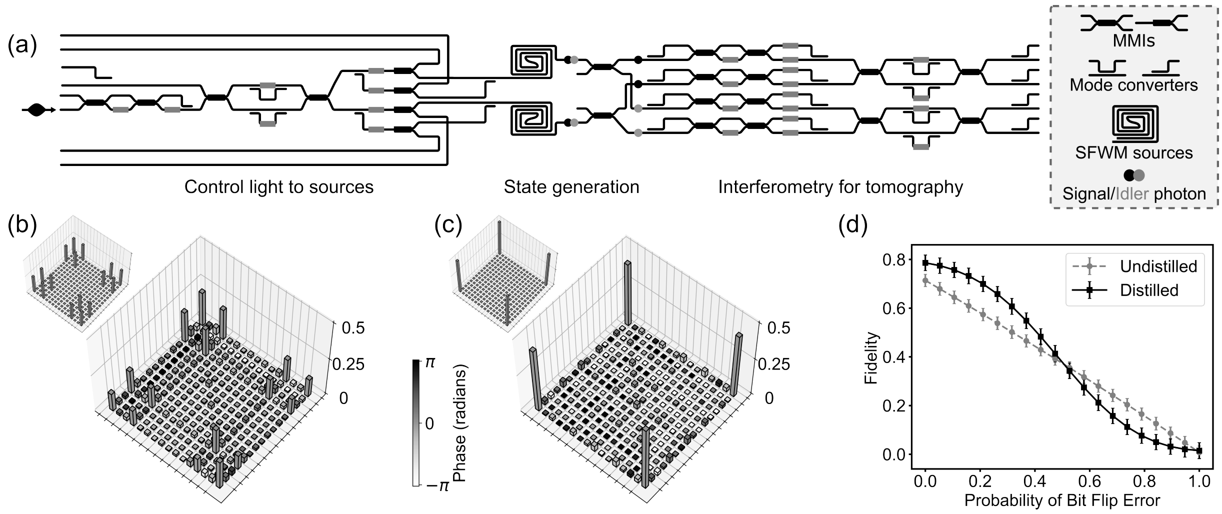

Figure 1: (a) shows a schematic of the device used. (b,c) show the reconstructed density matrices for the hyperentangled and GHZ_4-style states respectively, with an inset of the ideal state. (d) compares the fidelity of a Bell state, with and without single-copy entanglement distillation in the presence of bit-flip errors.

References

[1] J. T. Barreiro *et. al*, Phys. Rev. Lett. **95**, 260501 (2005)
[2] C. H. Bennett *et. al*, Phys. Rev. Lett. **76**, 722 (1996)
[3] S. Ecker *et. al*, Phys. Rev. Lett. **127**, 040506 (2021)

Quantum metrology with click-counting measurements

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Ideal NOON states constitute the optimal quantum states for phase estimations via Mach–Zehnder interferometers within the realms of quantum metrology and precision measurement. Their phase sensitivity is governed by the Heisenberg scaling in accordance with the mean photon number. The meticulous design of the associated scheme and the method of generation poses a significant challenge within the field of quantum metrology. Specifically, true photon-number resolution for the generation and detection is typically not available and may be replaced with click-counting devices, in practice. Therefore, in this work, we provide the theory for click-detection-based counterparts of NOON states and their interferometer propagation (polynomial decomposition of NOON states [1, 2]). In addition, the determination of quantum Fisher information through click-counting is derived, leading to minimal phase detection uncertainties below the Heisenberg limit. Also the fidelity of the click-NOON state to the ideal one is evaluated and shows a good approximation and correct limit as the number of measurable clicks increases.

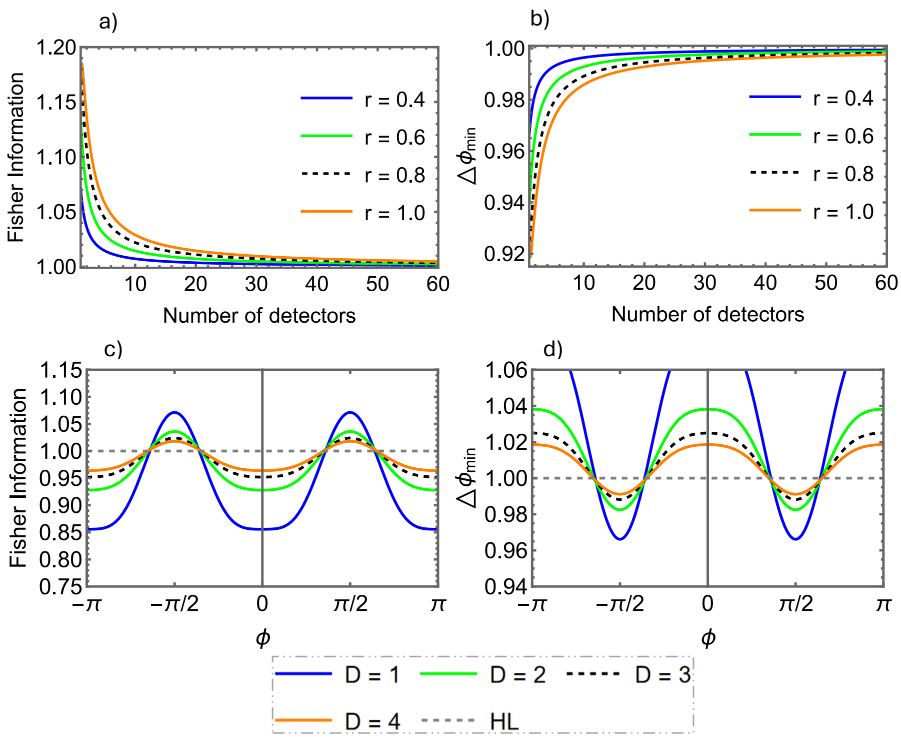

Figure 1: a) Fisher information as a function of the number of detectors D for different squeezing parameters r of the heralded source. b) Fisher information as a function of the interferometer phase for different numbers of detectors. c) minimum phase uncertainty against the number of detectors. d) minimum phase uncertainty against the phase of the interferometer. (HL: Heisenberg limit) All simulated figures are provided for 99.9% quantum efficiency to show click-resolution behavior rather than efficiency limitations.

References

[1] P. Kok, Opt. Spectrosc. **111**, 520 (2011).

[2] J. Yoshikawa, M. Bergmann, P. v. Loock, M. Fuwa, M. Okada, K. Takase, T. Toyama, K. Makino, S. Takeda, and A. Furusawa, Phys. Rev. A **97**, 053814 (2018).

Quantum teleportation of multi-color continuous-variable states: from near-infrared to telecommunications bands

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Quantum teleportation is a foundational element for many quantum applications. The continuous-variable (CV) protocol offers a distinct advantage by being unconditional and deterministic, enabling any input state to be reliably teleported [1]. In the context of quantum networks, quantum channels connecting different wavelengths can be used in quantum hybrid technologies, linking different quantum platforms with distinct purposes that interact with light at specific wavelengths. Our research focuses on creating these CV quantum channels by using teleportation to link the quadratures of light fields at widely separated frequencies.

To accomplish this, we utilize a triply resonant optical parametric oscillator (TROPO) that operates above its threshold to generate two-mode entangled states. The system is pumped by a 532 nm laser, which in turn produces intense, entangled light beams at 794.4 nm (near-infrared, compatible with the rubidium D1 line) and 1611 nm (telecommunication L-band). The frequency gap between these beams is a massive 191 THz, which is more than an octave. By implementing a resonator-assisted auto-homodyne technique [2], we successfully execute the teleportation protocol, transferring a displaced coherent state from the infrared beam to the telecommunication beam. A scheme of the experimental setup is illustrated in Figure 1.

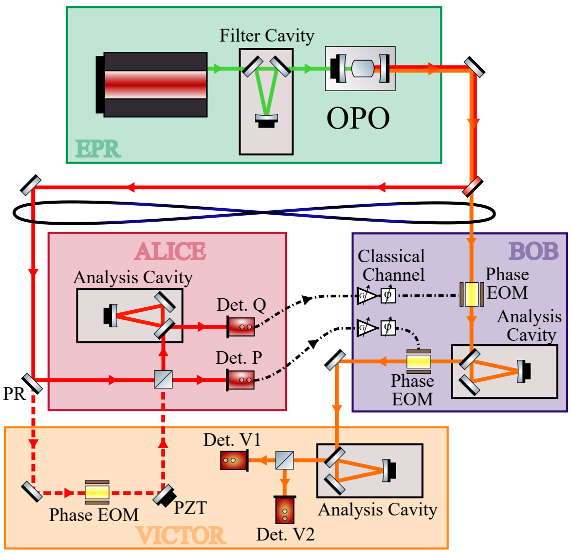

Fig. 1: Scheme of the multi-color unconditional teleportation experimental setup.

This work provides the first demonstration of multi-color CV quantum teleportation across distinct frequency bands. By violating the classical limit, this achievement confirms a quantum advantage and paves the way for enhanced connectivity in hybrid quantum systems.

References

1. A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik, "Unconditional quantum teleportation," science **282**, 706–709 (1998).
2. A. S. Villar, "The conversion of phase to amplitude fluctuations of a light beam by an optical cavity," Am. J. Phys. **76**, 922–929 (2008).

Monolithic generation and detection of squeezed vacuum on an integrated photonic chip

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The ability to generate and detect squeezed state of light is integral for the development of quantum technologies that operate in the continuous variable (CV) paradigm, including quantum enhanced sensing and quantum information processing. Recent efforts to develop the building block of CV quantum technologies on chip has led to high quality sources of squeezing and integrated homodyne detectors yet combining these two on a single chip has proved challenging. Here we present the first demonstration of the generation and detection of squeezed vacuum on a single silicon on insulator photonic chip with layout shown in fig 1a. Single mode squeezing is generated by a dual pulsed pump scheme in a spiral waveguide with the squeezing routed to on chip homodyne detectors of the type reported in [1]. To ensure phase coherence between the squeezing and local oscillator, all pulses are carved from a single fs pulsed laser, fig 1b. By modulating the phase of the local oscillator we are able to directly measure 0.2 dB of squeezing, fig 1c. This work demonstrates a platform capable of the generation and detection of quantum states of light at room temperature and represents a significant step forward in achieving monolithic, scalable CV quantum technologies.

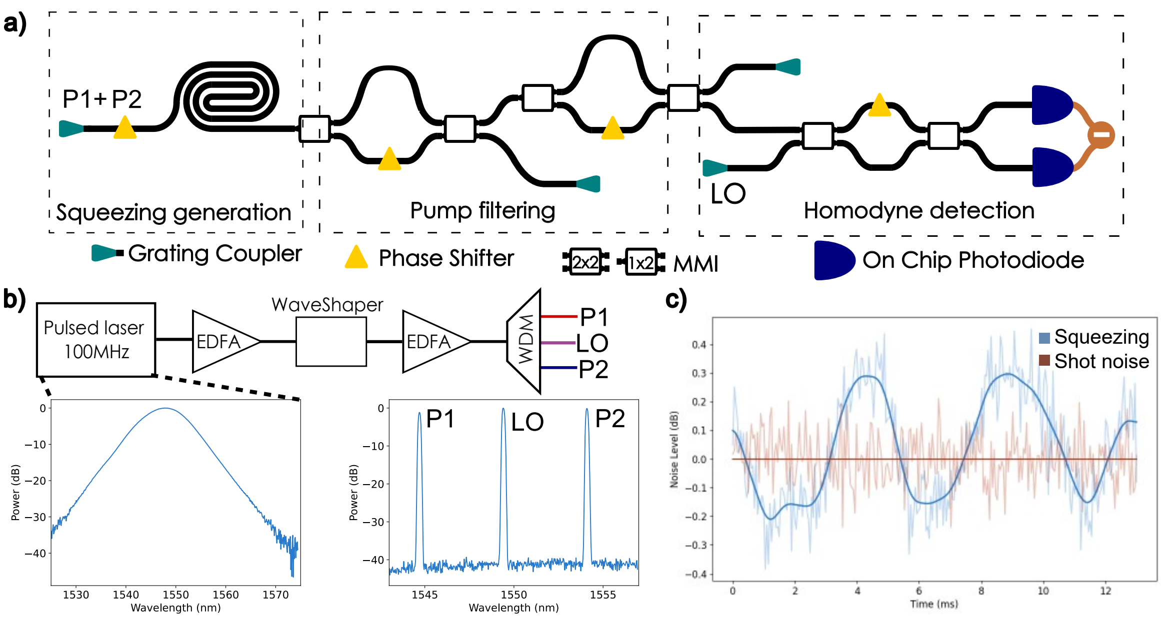

Figure 1: a) Layout of the Silicon on insulator chip used for squeezed light generation. b) Preparation of pump and local oscillator tones by spectral carving a spectrally broad fs laser. c) Output of homodyne detector normalized to shot noise level as oscillator phase is swept. 0.2dB of squeezing is directly measured.

References

[1] J.F Tasker *et. al*, Nat. Photonics **15**, 11–15 (2021).

Fusion of Time-bin GHZ-States

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Time-bin encoding is a robust and scalable platform for photonic quantum information processing, particularly suited for integrated and fiber-based implementations [1]. We present progress toward the fusion-based generation of time-bin GHZ-states, as a resource for fusion-based linear optical quantum computing. Laser pulses from a TiSapph are doubled in a unbalanced Mach-Zehnder-Interferometer (uMZI) and subsequently pump a type-II periodically poled $LiNbO_3$ waveguide. Through spontaneous parametric down-conversion, time-bin entangled photon pairs are generated [2]. Two such pairs are interfered in a stabilized unbalanced Mach–Zehnder interferometer to create a three-photon time-bin GHZ state, with the fourth photon serving as a herald of a successful fusion. Long-term phase stability of the uMZI, which is essential for high-visibility interference, is achieved through active feedback and fast relative phase modulation of frequency-stabilized reference laser pulses. We report on the achieved phase stability, fidelity of the entangled states and the visibility of multi-photon interference. These results mark an important step toward scalable, fiber-based fusion gates for large-scale time-bin cluster state generation.

[1] Bartolucci, S. et al. Nat Commun **14**, 912 (2023)
[2] Tanzilli, S. et al.. Eur. Phys. J. D **18** (2002)

Probing relaxation dynamics of two-electron spin states in a quantum dot molecule

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Semiconductor quantum dots are a promising platform for photonic quantum technologies. Quantum dot molecules (QDMs) - consisting of two vertically stacked, tunnel-coupled quantum dots - can host two-electron singlet-triplet qubits, which have enhanced coherence times [1] and are suitable for ultrafast optical spin control [2]. These features make electrically tunable QDMs of interest for realizing photonic cluster states with multi-dimensional entanglement structures [3].

To study the dynamics of the two-electron system, we use a device that enables us to deterministically prepare two electrons by combining optical excitation with electric field control [4]. We conduct a series of pump-probe measurements, in which we optically drive the doubly charged trion transition, to pump the orbital state into the configuration, for which a single electron resides in each dot, denoted (1,1). The relaxation time of this state back to the initial state with two electrons in the bottom dot (2,0) is significantly longer than for a singly charged molecule, which implies spin correlations between the electrons.

We demonstrate the dependence of the relaxation time on gate voltage and applied magnetic field. Our results give us insight into the properties of the hybridized two-electron states, which are important for optical spin control, and demonstrate the potential QDMs have as spin-photon interfaces for quantum communication applications.

References

[1] J. R. Petta et al., Science 309, 2180-2184 (2005)
[2] D. Kim et al., Nature Physics 7, 223-229 (2011)
[3] M. Gimeno-Segovia et al., Phys. Rev. Lett. 123, 070501 (2019)
[4] F. Bopp et al., Adv. Quantum Technol. 5, 2200049 (2022)

Quantum computation and machine learning for cancer detection

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Cancer is the second biggest cause of human deaths. Early diagnosis is a key element of full recovery or long overall survival. Liquid biopsies are excellent alternatives to traditional biopsies and imaging for cancer detection as they are minimally invasive and their cost is decreasing. In recent years, there has been a growing interest in machine learning techniques and models regarding liquid biopsy analysis. Both fields of artificial intelligence and quantum computation are growing rapidly in recent years. Intersection between machine learning and quantum computation promises great possibilities. It this work I am presenting the machine learning methods in its classical version and in the version enriched by quantum computation. I am comparing both approaches and presenting applications of quantum computation and machine learning in biomedical research.

References

[1] M.Jopek et al., Improving platelet-RNA-based diagnostics: a comparative analysis of machine learning models for cancer detection and multiclass classification, Molecular Oncology 18 (2024) 2743–2754.

Calculating Vibronic Spectra with a linear algorithm based on Gaussian Boson Sampling

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Accurately simulating molecular vibronic spectra remains computationally challenging due to the exponential scaling of required calculations. In this work, we show that employing the linear coupling model within the Gaussian Boson Sampling (GBS) framework effectively addresses this limitation [1]. We implement the algorithm for simulating the pentacene molecule with 8 vibrational modes through three distinct approaches, using a numerical simulation on a classical computer and experimentally using two optical setups equipped with different photon detectors (SNSPD and SPAD). High fidelity (F > 0.999) was achieved between the simulated Franck–Condon profiles and analytically calculated profiles obtained by enumerating all possible transitions within the linear coupling model. Furthermore, simulations were performed for larger molecular systems using 48 vibrational modes of naphthalene and 64 vibrational modes of anthracene. Comparison with experimental data confirms that the simulated spectra accurately reproduce both the positions and shapes of the measured spectral bands. A notable advantage of our algorithm is its scalability, requiring only a fixed minimal set of optical components irrespective of the size of the studied system, and it can be executed efficiently on a standard laptop, providing spectroscopists with an accessible and effective tool.

References

[1] I. Konyshev *et al.*, arXiv: 2508.03943 (2025).

Toward Spectral Engineering of Squeezed light in High Gain Parametric Down Conversion

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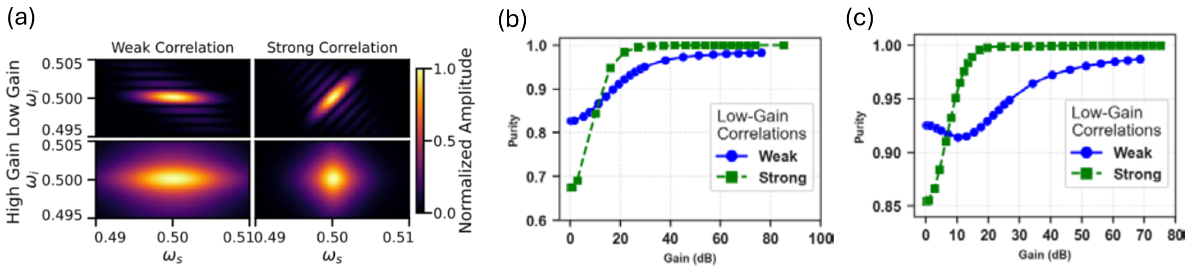
Squeezed states are fundamental quantum resources whose spectral properties are critical for quantum communication, computation, and sensing, and therefore require precise control over these properties. Integrated nonlinear waveguides (WGs) are promising in this context, providing robust sources of squeezed light via high-gain parametric down-conversion (PDC) and offering versatile opportunities for spectral engineering [1]. In this work, we aim to deepen the understanding of integrated waveguide PDC sources in the high-gain regime, where strong nonlinear dynamics substantially affect the spectral structure of the generated light.



We study the spectral purity of the output of a nonlinear WG as a function of parametric gain, as well as the dependence of this behaviour on the initial (low-gain) spectral correlations. Figure (a) shows the joint spectral amplitudes (JSAs) for two cases of dispersion-engineered correlations in both low- and high-gain scenarios. While both yield nearly pure states at high gain, the gain-dependence of the purity differs. This is shown in Fig. (b–c) for an unapodized (b) and apodized (c) WG. In both, states with strong initial correlations reach high purity more rapidly. Apodized WGs also display non-monotonic behaviour in the nearly uncorrelated case, where purity first decreases before recovering at higher gain. We provide a physical interpretation of these gain-dependent behaviours and demonstrate that spectral correlations in squeezed light can be dynamically tuned through tailored combinations of dispersion engineering and gain [2], enabling optimized integrated photonic sources for emerging quantum technologies.

References

[1] S. Slussarenko and G. J. Pryde, Applied Physics Reviews 6, 041303 (2019).
[2] Kumar, J., Krstić, A., Setzpfandt, F., and Saravi, S., manuscript in preparation.

ON-CHIP ELECTRO-OPTIC MODULATION IN THE UV REGIME

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Many problems in science and economics, such as optimisation in logistics and the simulation of molecules or solids, remain beyond the reach of classical computers. Quantum computers promise faster solutions by using qubits, which can exist in superpositions and enable efficient computation [1]. Neutral atoms form a scalable qubit platform, where Rydberg states allow long-range interactions and quantum gates controlled by local laser beams [2]. Integrated photonic devices, including waveguide-integrated electro-optic modulators, provide precise on-chip light control for addressing large qubit arrays [3].

Within the framework of the Munich Quantum Valley Initiative, the consortium MUNICQ ATOMS aims to realize a neutral atom-based quantum processor with up to 400 qubits encoded in strontium atoms. Our contribution is to develop integrated optical switches for high-precision single-atom addressing. To implement two-qubit gates by coupling to Rydberg states, the desired photon wavelength is in the ultraviolet (UV) range at 316 nm, corresponding to the electronic transition $^3P_0$ to $^3S_1$ within a strontium atom. In the UV regime, technology is catching up for on-chip electro-optic modulation. In an integrated photonic circuit, a suitable waveguide material for this wavelength is Aluminium Gallium Nitride ($Al_{0.73}Ga_{0.27}N$) on AlN on sapphire, which has a large bandgap in the UV regime. For electro-optic modulation, four parts have to come together: waveguides, splitters, electrodes and in- and out-couplers.

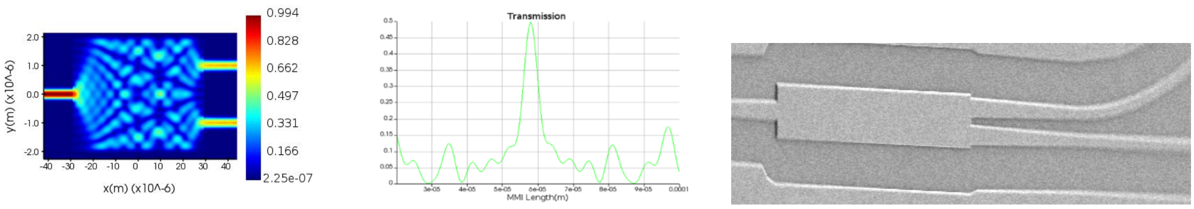

Figure 1: Left to right shows E-field Intensity distribution, Transmission with length and fabricated MMI

A multimode Interferometer (MMI) is used to split and combine light. It is the key component of the Mach-Zehnder interferometer. The electric field intensity distribution in the designed MMI on the AlGaN platform at 317 nm wavelength is shown in Figure 1. Currently, we are characterising the devices with a free-space optical setup in our Lab.

References

[1] Massimo Bertaccini.CryptographyAlgorithms.Packt Publishing, 2022.

[2] ThomasFGallagher. “Rydbergatoms”. In: ReportsonProgress in Physics 51.2(1988), p.143.

[3] Richard Jr. Osgood and Xiang Meng. Principles of Photonic Integrated Circuits. Materials, Device Physics, GuidedWaveDesign.SpringerCham,2021.

Resource efficient universal photonic processor based on time-multiplexed hybrid architecture

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Over the last years the field of photonic quantum information processing has taken strong leaps building on the scalability of optical systems. Experiments centered around Gaussian boson sampling (GBS) as one of the most promising platforms from the current noisy intermediate scale quantum era (NISQ) have involved record breaking numbers of photons and optical modes demonstrating quantum computational advantage [1]. At the heart of the GBS platform lies the photonic processor, a device capable of implementing linear transformation matrices between a large number of optical modes. To this date most universal photonic processors encode the underlying mode structure on only a single degree of freedom (DoF). The most prevalent photonic processor architectures utilize the spatial DoF, demonstrating low loss and high fidelity operations, but come with a scaling problem in terms of mode numbers [2]. Using time-multiplexing, where the mode structure is encoded in time-bins, one can overcome this scaling problem and introduce the possibility of probing the system during its evolution. However as optical field feature a variety of different DoF, it is possible to encode the mode structure on multiple DoF resulting in a hybrid architecture. Here we put forward such a hybrid architecture that leverages both time-multiplexed and the multiple DoF of light in order to realize a universal photonic processor that is highly resource efficient and strongly resilient against experimental imperfections.

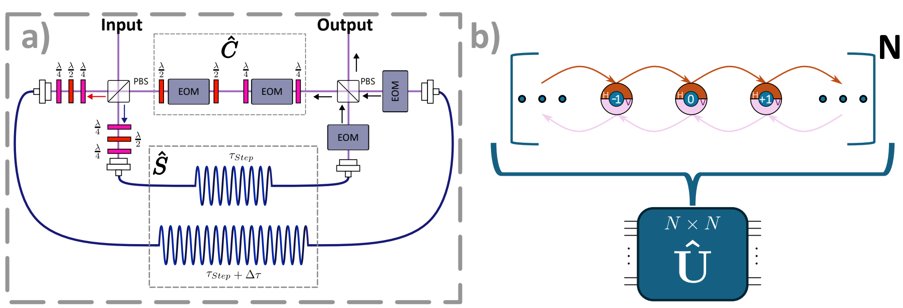

FIG. 1. (a) Sketch of our hybrid architecture utilizing both the polarization and time degree of freedom. (b) The underlying graph structure which after N repetitions represents any $N \times N$ target unitary $\hat{U}$.

Fundamentally, it consists of an encoding operation ($\hat{C}$) acting on an arbitrary internal DoF and a delay operation ($\hat{S}$) exchanging the internal DoF between time-bins using temporal delays. Here we map this process to a graph structure, where each node represents a time-bin featuring all internal DoF and the edges represent the delay operation. From there we show how to map the spread of a photon over such a graph structure to an arbitrary unitary for a two-dimensional internal DoF. We further proof that we can implement any $N \times N$ target unitary by performing N iterations of the encoding and delay operations. As each time-bin contains all internal DoF, this results in a linear reduction of the photonic processors temporal footprint allowing for higher experimental repetition rates. Furthermore, we provide analytical proof that our proposed and implemented time-multiplexed hybrid architecture is strongly resilient against experimental imperfections such as phase noise and or losses. Finally we introduce our experimental system implementing the time-multiplexed hybrid architecture using polarization as the internal DoF and show recent results. Our architecture paves the way towards large scale noise resilient photonic processors for use in boson sampling in the time-domain allowing for feed-forward protocols.

[1] Madsen, L. S., et al., “Quantum computational advantage with a programmable photonic processor.", Nature 606, 75–81 (2022).
[2] Clements, W. R., et al., “Optimal design for universal multiport interferometers", Optica 3, 1460-1465 (2016).

High-Precision Time Tagging
for Scalable Photonic Quantum Experiments

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Timing precision, scalability, and real-time data processing are central challenges in photonic quantum computing. PicoQuant's latest developments in time-tagging electronics are tailored for photonic quantum applications, including time-bin encoding, correlation measurements, and integrated quantum photonics. Our FPGA-based time-tagging systems achieve few-ps timing resolution and jitter as well as sub-ns dead time across up to 65 synchronized input channels. Flexible trigger methods including constant fraction discriminators, real-time external FPGA processing, and WhiteRabbit long-distance synchronization enable precise and efficient time stamping at system count rates exceeding 1.6 Gcps.

We demonstrate the relevance of this technology through a collaborative work integrating a 64-channel waveguide-integrated SNSPD receiver with our most recent time tagging platforms. This combination enables high-throughput quantum key distribution and time-bin encoded qubit analysis across multiple parallel channels, as reported in recent studies. [1, 2] The time tagger's architecture allows flexible interfacing with multi-channel cryogenic detectors, overcoming key bottlenecks in bandwidth, latency, and synchronization.

Our contribution underscores the essential role of advanced timing electronics in scaling photonic quantum technologies. The demonstrated system opens pathways toward multiplexed, chip-integrated quantum processors, Boson sampling, and complex quantum state analysis – solidifying time tagging as a core enabling technology in the photonic quantum computing stack.

References:

[1] M. Häußler et al., Rev. Sci. Instrum. **94**, 013103 (2023)
[2] R. Terhaar et al., Opt. Express **31**, 2675 (2023)

Hybrid integration of amorphous silicon carbide for quantum photonics

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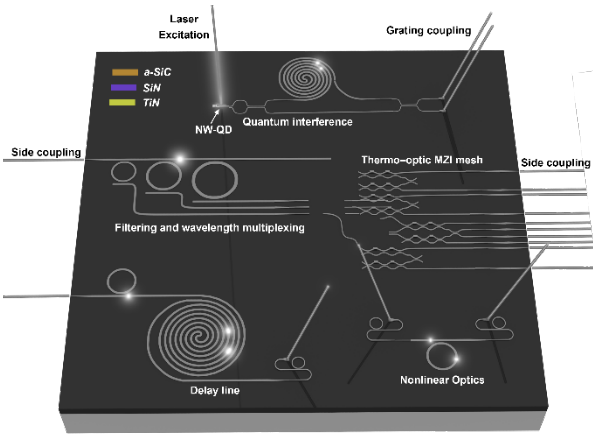
On-chip single photon generation, manipulation, and detection are essential for the scaling up of quantum photonics experiments and applications. Despite the blooming advancements over the decades in integrated photonics, it hitherto remains an unsettled question to combine all these three functionalities on a single chip. This has been the major driving force for exploring novel hybrid integration methods.



Amorphous silicon carbide (a-SiC) has emerged as a compelling candidate in integrated photonics, known for its high refractive index, high optical quality, large thermo-optic coefficient, and strong third-order nonlinearities[1]. In addition, a-SiC can be easily deposited via CMOS-compatible chemical vapor deposition techniques, allowing for supreme compatibility when integrating with other photonics platforms. We heterogeneously combine the a-SiC photonics with SiN and lithium niobate ($LiNbO_3$) photonics, monolithically enable low-loss, wide transparent window, strong Kerr nonlinearity, compact, electro-optical tunable and thermo-optical tunable photonic platforms[2-4].

Furthermore, we pick-and-place nanowire quantum dots on to our hybrid photonic platforms, realizing deterministic on-chip quantum light generation[2]. Leveraging the ultra-low-loss property of SiN and the electro-optical tuning of $LiNbO_3$, we aim for on-chip quantum light generation and detection. Superconducting nanowire single photon detectors will also be integrated on the same chip for quantum detection.

References

[1] ACS photonics, 2023, **10** (10): 3748-3754.
[2] Materials for Quantum Technology, 2024, **4** (3) 035401.
[3] APL Photonics 2025, **10** (1): 016120.
[4] arXiv preprint arXiv:2507.10312, 2025.

Polarisation shaped light for enhanced two photon entanglement from quantum emitters

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Entangled photon pairs are essential for quantum technologies, with semiconductor quantum dots serving as promising on-demand sources. While removing excitonic fine-structure splitting helps, entanglement is still limited by finite-duration laser pulses, which induce a dynamic splitting of exciton states during the excitation process. This effect caps the achievable concurrence in a four-level emitter driven via two-photon resonance. To overcome this, we employ Bayesian optimization to shape the laser's polarisation dynamically, achieving higher concurrence than with static polarisation.

References

[1] T.Seidelmann et.al Phys. Rev. Lett.129, 193604 (2022)

Cross Waveguide Design for Color-Centers in Diamond for Photonic Quantum Computing

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Color centers in diamond are receiving an increasing interest as platform for quantum computing applications because of their optical and spin properties[1]. To overcome the cost and technological limitations of diamond, it is convenient to separate the tiny diamond chiplet containing the color center(s) from the rest of the circuit (fabricated on another platform) and then heterogeneously integrate the two (e.g. by pick and place, P&P)[1,2,3]. The diamond chiplet consists of a multimode interferometric (MMI) cross waveguide, eventual Bragg filters, and tethers to a supporting frame; the receptor on the other platform consists of adiabatic couplers to those of the chiplet, and the remaining photonic components. In addition to P&P, this design is suitable for other integration schemes (transfer printing or DOI monolithic).

Each of the components must be designed synergistically with the others in terms of excitation to emission conversion, transmission efficiency, working bandwidth, fabrication feasibility and tolerance. Here we propose a methodology to optimize all the components of chiplet, receptor and their combination: after a comparison of the alternatives presented in the literature, we show a complete study for the chosen solution. Apart from quantum computing, this methodology is relevant for a wider audience interested in the optimization of commonly used components in Photonics.

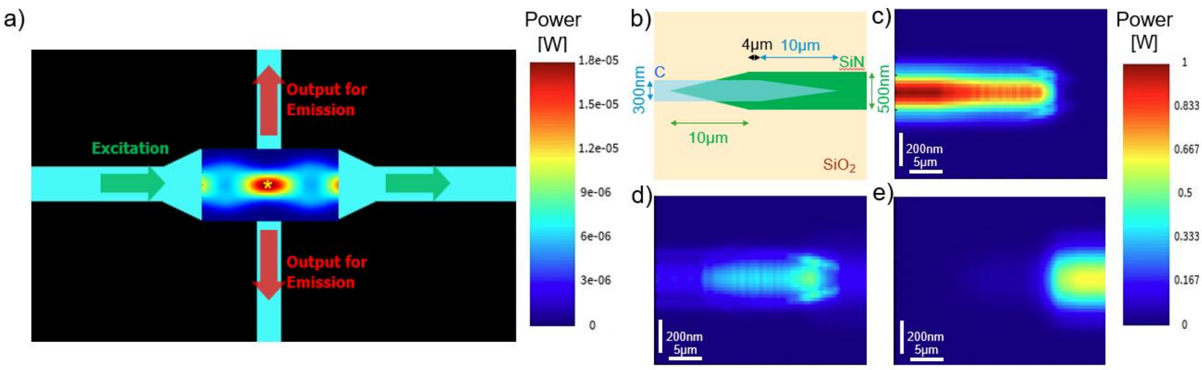

Figure 1. a) structure and excitation power distribution of a cross waveguide with tapered MMI, b) structure of diamond/SiN adiabatic couplers and power distribution in c) diamond coupler, d) interface between the couplers, e) SiN coupler.

We gratefully acknowledge support from the joint research program “Modular quantum computers” by Fujitsu Limited and Delft University of Technology, co-funded by the Netherlands Enterprise Agency under project number PPS2007.

References

[1] M. Ruf, et al., J. Appl. Phys. 130, 070901 (2021).
[2] N. H. Wan, et al., Nature 583, 226 (2020).
[3] R. Ishihara, et al., IEEE International Interconnect Technology Conference (IITC) and IEEE Materials for Advanced Metallization Conference (MAM), 1 (2023).

Loss Profiling of a Massively Multiplexed Superconducting Nanowire Photon-Number-Resolving Detector

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Intrinsic photon-number resolution (PNR) has been shown by analyzing the rising edge of superconducting nanowire single-photon detector (SNSPD) electrical signals, which leads to easy accessibility of photon-number resolved measurements [1]. Nevertheless, the overlap of the underlying distributions for different photon numbers limits the number of resolvable photons per SNSPD up to a few photons. Our work scales PNR up to thousands of photons by combining the intrinsic PNR of SNSPDs with temporal and spatial multiplexing [2]. Specifically, we use eight spatial bins with 128 temporal bins each, for a total of 1024 bins. Each bin can resolve up to four photons [3].
With detailed data analysis, the losses per bin can be calculated to determine the efficiency of the system. We conducted a simulation of the multiplexing architecture to characterize and quantify multiple sources of loss. To extract key parameters, a minimization routine was applied to determine the beam splitter efficiencies and splitting coefficients. This knowledge will enable further investigations of PNR detection in the future.

[1] Schapeler et al., *Physical Review Applied*, 22(1), 014024 (2024)

[2] Cahall et al., *Optica*, 4(12), 1534-1535 (2017)

[3] Sidorova et al., *arXiv preprint arXiv:2503.17146* (2025)

Quantum CNOT Gate with Actively Synchronized Photon Pairs at Room Temperature

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Reliable synchronization of photons from probabilistic sources is a critical bottleneck for scalable photonic quantum technologies [1]. In this work [2], we present the experimental realization of a probabilistic entangling gate [3, 4] operating on actively synchronized photon pairs enabled by a quantum memory based on warm atomic vapor [5, 6, 7]. This approach achieves a truth-table fidelity exceeding 85% and successfully violates the Bell inequality for all four Bell states. We identify that the reduction in Hong-Ou-Mandel (HOM) interference visibility, as introduced by the storage process, is the primary factor limiting gate fidelity. Crucially, we derive a universal quantitative relation between HOM visibility and gate fidelity for pure single photons, applicable across all interference-based photonic gates. These results mark a significant step toward scalable, memory-assisted quantum networks and provide a broadly relevant framework for evaluating the performance limits of photonic entangling operations.

References

[1] J Nunn, NK Langford, WS Kolthammer, TFM Champion, MR Sprague, PS Michelberger, X-M Jin, DG England, and IA Walmsley. Enhancing multiphoton rates with quantum memories. *Physical review letters*, 110(13):133601, 2013.

[2] Haim Nakav, Tanim Firdoshi, Omri Davidson, Bankim Chandra Das, and Ofer Firstenberg. Quantum cnot gate with actively synchronized photon pairs. *arXiv preprint arXiv:2505.03960*, 2025.

[3] Nikolai Kiesel, Christian Schmid, Ulrich Weber, Rupert Ursin, and Harald Weinfurter. Linear optics controlled-phase gate made simple. *Physical review letters*, 95(21):210505, 2005.

[4] Laflamme R Milburn G. J Knill, E. A scheme for efficient quantum computation with linear optics. *Nature*, 409:46–52, 2001.

[5] Omri Davidson, Ran Finkelstein, Eilon Poem, and Ofer Firstenberg. Bright multiplexed source of indistinguishable single photons with tunable ghz-bandwidth at room temperature. *New Journal of Physics*, 23(7):073050, 2021.

[6] Omri Davidson, Ohad Yogev, Eilon Poem, and Ofer Firstenberg. Fast, noise-free atomic optical memory with 35-percent end-to-end efficiency. *Communications Physics*, 6(1):131, 2023.

[7] Ran Finkelstein, Eilon Poem, Ohad Michel, Ohr Lahad, and Ofer Firstenberg. Fast, noise-free memory for photon synchronization at room temperature. *Science advances*, 4(1):eaap8598, 2018.

Towards new hybrid schemes for photon generation

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Optical quantum technologies, especially quantum computing, often rely on single photons as their elementary unit. Pure single photons can be produced using atom-like solid-state emitters such as quantum dots or color centers. However, hardly two sources share identical spectral properties since their emission lines vary as they couple to their environment. Consequently, additional solutions are required to achieve indistinguishability between different sources, such as photon de-multiplexing or active tuning. These solutions, however, are challenging to scale for large-scale quantum protocols. Alternatively, photon-pair sources avoid reproducibility and temperature constraints but require low-gain operation for high photon fidelity, making generation probabilistic and limiting their use in many quantum applications.

With the goal of circumventing the drawbacks of these two types of photon sources, we work towards a new photon generation scheme, a source of pure and indistinguishable single photons on demand, which also is scalable, reproducible and tunable. Specifically, we combine a nonlinear medium with a single photon absorber, both embedded in a photonic cavity. In this hybrid system, photon pairs are generated via nonlinear processes, while the optical cavity and the single photon absorber modulate the generation rate through the Purcell effect, enhancing spontaneous emission into selected modes and ensuring that only one photon-pair is generated at a time. Our previous theoretical studies [1] have already shown that, when excited with controlled pump pulses, this scheme can generate tunable quantum states of light with probabilities close to one.

We are now exploring the use of transition-metal dichalcogenide (TMD) thin films as a potential nonlinear material to host the generation of photons in our proposed hybrid systems. The aim of this work is to study nonlinear processes in such cavity scheme and learn more about the limitations and possibilities for the future implementation of our hybrid photon sources. In this present contribution, we discuss the fundamentals behind this hybrid scheme, as well as the theoretical and experimental advances towards its realization and the challenges to be faced.

References

[1] A. Krstic, P. Tiwari, F. Höhe et al. Phys. Rev. Lett. **133**, 203605 (2024)

Non-Markovian dynamics of a qubit due to accelerated light in a lattice

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We study the spontaneous emission of a qubit weakly coupled to a one-band coupled-cavity array, where an engineered gradient in the cavity frequencies induces a synthetic force F that effectively accelerates photons. This force gives rise to a discrete, equally spaced energy spectrum known as the Wannier-Stark ladder, with level spacing set by F. As a result, the system exhibits two distinct dynamical regimes depending on the strength of the force.

In the strong-force regime, we see clear Rabi oscillations on the qubit population, and the system is well described by an effective Jaynes-Cummings model. This leads to a chiral, time-periodic excitation that spreads across an extensive region of the array, either to the left or right of the qubit depending on its transition frequency.

Conversely, in the weak-force regime, the qubit undergoes a complex, non-Markovian decay characterized by pronounced revivals. These dynamics resemble those seen in standard waveguides with mirrors, even though no actual mirrors are present. The effect is instead due to the finite bandwidth of the photonic energy band, which confines the emitted photon.

Remarkably, in an appropriate parameter regime, the decay can be accurately modeled by a delay differential equation formally equivalent to that governing the decay of an atom inside a multi-mode cavity. In this analogy, the Bloch oscillation amplitude and period play roles analogous to the cavity length and photon round-trip time, respectively.

References:

[1] Pinto, M. A., Sferazza, G. L., Di Bernardis, D. & Ciccarello, F., **arXiv:2503.1902** (2025)

Models and limits of anomalous bunching

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Anomalous bunching is a paradoxical quantum interferometric phenomenon in which partially distinguishable photons exhibit a higher probability of bunching into a few modes than fully indistinguishable photons [Nat. Photon. **17**, 702 (2023)]. The underlying mechanism of this multiphoton-multimode process remains poorly understood, so that the precise conditions under which it may occur in experimental conditions are still unclear. In particular, since fluctuating time delays between pulses is a major source of mode mismatch in current photonic platforms, it is important to determine whether the resulting photon distinguishability can lead to anomalous bunching. In this work, we begin by introducing a new physical interpretation of this effect, which helps clarify its seemingly paradoxical character and restores the expected link between photon bunching and indistinguishability. This new perspective also uncovers additional facets of this phenomenon, which are all captured in a unified manner. We predict situations where a decrease in pairwise indistinguishability actually enhances the bunching probability. Moreover, we identify a broad class of interferometric configurations in which anomalous bunching is ruled out, helping us to pinpoint where to look for it. As an answer to our question on time-delayed photons, we exhibit a specific interferometric setup where time-delay–induced distinguishability enhances boson bunching, offering new insights into the complex role of distinguishability in multiphoton interference.

Statistical analysis of qutrit graph states under local complementation and local scaling

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Graph states and their entanglement properties are pivotal for the development of quantum computing and technologies. For qubits, local complementation, a graphical rule that connects all the equivalent states under Local Clifford (LC) operations, was used for the complete characterization of all the LC equivalence classes up until 12 particles, assisting applications in quantum error correction and state preparation protocols optimization. This concept has been extended for qudits. In this work, we provide a complete characterization of the entanglement classes up until 7 qutrits, mapping each class into an orbit. The graph-theoretic properties of the orbits are studied, illuminating the rich structure they have. Clear connections between the connectivity of the orbits and the entanglement properties are observed. The correlations between the graph-theoretic properties and the Schmidt measure provide useful insights regarding qudit state preparation and fault-tolerance. The aim of this poster is to present the information about the entanglement properties obtained if the graph properties of the orbits are known. The strong interplay between quantum theory and graph theory is well-known and extensively studied for qubits. The presented result provides practical tools to assist this endeavor for the qudit case.

References

[1] A. Cabello, L. E. Danielsen, A. J. López-Tarrida, and J. R. Portillo. Optimal preparation of graph states. Phys. Rev. A, 83:042314, Apr 2011

[2] J. C. Adcock, S. Morley-Short, A. Dahlberg, and J. W. Silverstone. Mapping graph state orbits under local complementation. Quantum, 4:305, August 2020

[3] K. Revis, H. Zakaryan and Z. Raissi. Orbit classification and analysis of qutrit graph states under local complementation and local scaling. arXiv:2506.05478

Towards Scalable Quantum Photonics: Preliminary Investigations on LNOI-based Components

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Multimode-interference (MMI) splitters are of interest due to their compactness and tolerance, but their performance depends on (i) accurate control of the beat length and (ii) low-loss interfaces between single-mode access guides and the multimode section.

Here we investigate lithium-niobate-on-insulator (LNOI) MMIs, with C^1-continuous tapers (continuous first derivative) that eliminate corner discontinuities that are liable to induce losses. Exponential or raised-cosine transitions like these offer first-derivative continuity and reduce mode mismatch losses [1,2].

Simulations show that C^1 profiles, while keeping the total device footprint around ~15 µm in length [3,4], reduce end-facet scattering and reshape the local field to stay away from the sidewalls, mitigating losses. Those tapers recover ~0.3–0.7 dB and improve imbalance and phase error. This is consistent with the physics of bent waveguides, where the fundamental mode migrates toward the outer radius under effective “centrifugal” index gradients [5].

These preliminary results highlight the importance of careful taper design for ensuring low-loss and reproducible operation, a requirement for scalable quantum photonic applications.

References

[1] J. R. Ong, et al., Opt. Express 21, 17413 (2013).

[2] W. Bogaerts, et al., IEEE J. Sel. Top. Quantum Electron. 16, 33 (2010).

[3] Y. Ding, et al., Opt. Lett. 39, 5348 (2014).

[4] S. Dwivedi, et al., Opt. Express 20, 27277 (2012).

[5] A. W. Snyder and J. D. Love, Optical Waveguide Theory, Springer (1983).

Efficient coupling of SPDC enhanced by Nonlinear Interference

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Photon-pair sources based on spontaneous parametric down-conversion (SPDC) are the workhorse of experimental quantum optics. Achieving high pair collection efficiency—quantified by brightness and heralding efficiency—is crucial for loss-sensitive quantum applications such as device-independent protocols, quantum-enhanced sensing, and photonic quantum computing. Type-II SPDC in KTP at telecom wavelengths is widely used to generate spectrally uncorrelated photons, enabling high-visibility multi-photon interference experiments like Gaussian Boson Sampling (GBS). However, this configuration typically sacrifices brightness by up to an order of magnitude to reach heralding efficiencies above 95% [1]. A recent GBS demonstration employed a stimulated-SPDC source architecture to enhance brightness by a factor of four [2]. This design uses two cascaded Type-II crystals with intermediate polarization rotation and phase control. Building on this, we show that the same architecture achieves a significantly improved trade-off between brightness and heralding efficiency: our implementation yields over 15× brighter output for the same heralding efficiency [3]. We theoretically model it by looking at the different spatio-temporal modes in each SPDC process and how they interfere differently in such nonlinear interferometer, enhancing the desired modes while partially suppressing unwanted modes. Furthermore, we also show how this source can produce near to spectrally pure state by simply changing the temperature of the nonlinear crystal, eliminating the need for more complex solutions like aperiodic poling [3]. We experimentally confirm our model and predictions via stimulated-emission tomography, by scanning independently the wavelength and spatial mode of the signal and idler seed beams.

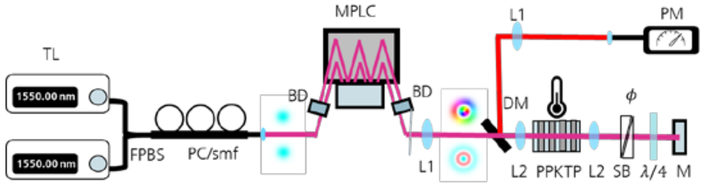

Figure 1 Setup for performing stimulated-emission tomography of the spatio-spectral state after the Nonlinear interferometer

References

[1] Ryan S. Bennink, "Optimal Collinear Gaussian Beams for Spontaneous Parametric Down-Conversion," *Phys. Rev. A* **81**, 053805 (2010).

[2] Han-Sen Zhong "Phase-Programmable Gaussian Boson Sampling Using Stimulated Squeezed Light," *Phys. Rev. Lett.* **127**, 180502 (2021).

[3] Carlos Sevilla-Gutiérrez et.al. in preparation

Quantifying Quantum Key Randomness: Statistical Testing of QKD Keys

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SENTRY-Q is a unified, practical framework for evaluating the randomness of keys produced by BBM92-based QKD systems. It integrates NIST SP 800-22, ENT, Dieharder, PractRand, min-entropy estimation, Lempel–Ziv complexity, compression-based tests, and Borel normality into a single toolchain for comprehensive, multi-dimensional assessment. Experiments show that BBM92 final keys (after privacy amplification) are strongly random under ideal conditions, yet noise, loss, and adversarial interference can introduce detectable anomalies, underscoring the need for empirical testing alongside security proofs. The tool supports both batch and single-key validation and functions as an operational diagnostic by flagging low-entropy or biased sequences early, enabling system tuning and greater trust in the final key. Planned extensions include support for additional QKD protocols that generate batches of 256-bit keys, with parameter and suite adaptations to reflect added post-processing and photon-source considerations. We also aim to integrate SENTRY-Q into live QKD systems for real-time randomness monitoring during key generation, enabling adaptive post-processing and fault detection. By bridging statistical validation and operational deployment, SENTRY-Q provides a practical path to more robust, trustworthy, and accountable quantum-secure communication.

Analysis:

- Key Index 3/9999
- Original (Encoded):
/h6pFGy3+yaRCXcJBEUR8x2HMTA6uXHmNV+uU6OYnZs=
- Bin:
1111111000011110101010010001010001101100101101111111101100100110100100010000100101110111000010010000010001000101000100011111001100011101100001110011000100110000001110101011100101110001111001100011010101011111101011100101001110100011100110001001110110011011

- Results:
PASS Min-Entropy (Score: 253.126)
PASS Lempel-Ziv Complexity (Score: 59)
PASS Borel Normality (k=1,2) (Score: 0.005)
PASS Serial Correlation Coefficient (Score: 0.012)

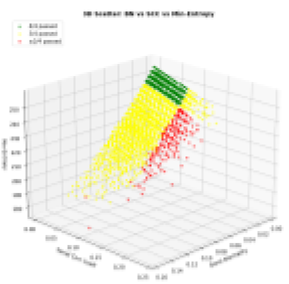

Figure 1: Relationship of Tests that Pass and Fails the statistical Analysis of 256 bit keys.

- Key Index 8557/9999
- Original (Encoded):
LAZ4AEyFgSOGYEQfaAIUIEikGWKMnD6B+a7NPOcBBmg=
- Bin:
0010110000000110011110000000000000100110010000101100000010010001110000110011000000100010000011111011010000000000100001010010010100010010001010010000011001011000101000110010011100000111110100000011111100110101110110011010011110011100111000000010000011001101000

- Results:
FAIL Min-Entropy (Score: 178.232)
PASS Lempel-Ziv Complexity (Score: 57)
FAIL Borel Normality (k=1,2) (Score: 0.154)
PASS Serial Correlation Coefficient (Score: 0.105)

References

[1] C.H. Bennett, G. Brassard, N.D. Mermin, Quantum cryptography without Bell's theorem. Phys. Rev. Lett. 68, 557–559 (1992).

[2] N.Gisin, G. Ribordy, W. Tittel, H. Zbinden, Quantum cryptography. Rev. Mod.S. Phys. 74, 145–195 (2002).

[3] National Institute of Standards and Technology, A Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications, SP 800-22 rev1a, 2010. [7]G. Marsaglia, "Diehard: A Battery of Tests of Randomness," 1996. http://stat.fsu.edu/geo/diehard.html

EXTRACTABLE WORK AS A TOOL FOR TESTING WITNESSING IN THREE-LEVEL LASERS

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Abstract

Information is now recognized as a thermodynamic resource that can fuel energy extraction through measurement and feedback control. Additionally, the amount of work that can be extracted from correlated bipartite quantum states has been shown to serve as a means to distinguish entanglement from separability. In this work, we introduce an operational criterion, denoted as E_W, for detecting entanglement based on the extractable work from a thermal bath using a Szilard-like engine, where a two-mode Gaussian state ρ_{AB} acts as the working medium. The two modes, A and B, are generated during successive transitions in a nondegenerate three-level laser and are coupled to a shared two-mode thermal bath. We demonstrate that E_W remains zero for product states, reaches its maximum when ρ_{AB} is coupled to a vacuum bath, and decreases under thermal noise. Furthermore, we show that the entanglement detected by E_W can be modulated through atomic coherence in the laser system. Finally, a comparison with logarithmic negativity (a faithful entanglement measure) confirms the consistency of E_W in identifying entanglement within ρ_{AB}.

Keywords: TMGS, Extracted Work, Szilard-like engine.

Reference

[1] E.A. Sete and H. Eleuch, J. Opt. Soc. Am. B 32, 971 (2015).

[2] J.E. Qars, Ann. Phys. (Berlin) 534(6), 2100386 (2022).

[3] M. Bekele, T. Yirgashewa, and S. Tesfa, Phys. Rev. A 105(5), 053502 (2022).

[4] S. Tesfa, Phys. Rev. A 74, 043816 (2006).

[5] H. Xiong, M.O. Scully, and M.S. Zubairy, Phys. Rev. Lett. 94, 023601 (2005).

[6] N.A. Ansari, J. Gea-Banacloche, and M.S. Zubairy, Phys. Rev. A 41, 5179 (1990).

[7] H.-T. Tan, S.-Y. Zhu, and M.S. Zubairy, Phys. Rev. A 72, 022305 (2005).

[8] C.A. Blockley, D.F. Walls, Phys. Rev. A 43, 5049 (1991)

Deterministic Generation of Light–Matter Entangled States for Realization of Quantum Repeaters

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Quantum repeaters require sources that generate light–matter entangled states on demand. Conventional approaches, based on nonlinear photon-pair generation with storage of one photon in a quantum memory, are limited by the probabilistic nature of pair production and low coupling efficiencies [1].

To overcome these obstacles, we propose a hybrid nonlinear system, schematically shown in Fig. (a), consisting of a $\chi^{(2)}$ medium embedded in a cavity along with a multilevel quantum memory (e.g., a trapped ^{87}Rb atom), whose level structure is shown in Fig. (b). The cavity supports two degenerate idler modes and two degenerate signal modes, each pair having orthogonal circular polarizations. The idler modes couple to the two degenerate excited states of the memory. When the nonlinear cavity is driven by an off-resonant pump, the cavity modes are only virtually populated. The atom virtually absorbs the idler-mode excitation and is promoted to its excited state, after which a π-polarized control pulse transfers the excitation to the metastable states and the control field. As a result, the intracavity state evolves into a deterministic light–matter entangled state, where the atom's metastable states are entangled with the polarization degree of freedom of the signal photon, as shown in Fig. (c). Most notably, tuning the cavity parameters and pump frequency allows the signal photon to match fiber and free-space communication channels.

$|\Psi\rangle = \frac{}{\sqrt{2}}|\sigma_s, m_1\rangle - \frac{}{\sqrt{2}}|\sigma_s', m_2\rangle$ Time ($\frac{}{\Omega}$)

References

[1] X. Liu et al., Nature 594, 41–45 (2021).

Orbit classification of qutrit graph states under local complementation and local scaling

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Graph states and their entanglement properties are pivotal for the development of quantum computing and technologies. For qubits, local complementation, a graphical rule that connects all the equivalent states under Local Clifford (LC) operations, was used for the complete characterization of all the LC equivalence classes up until 12 particles, assisting applications in quantum error correction and state preparation protocols optimization. This concept has been extended for qudits. We provide the tools for finding the equivalence classes, also called orbits, of qudit graph states up to isomorphisms. We find that the scaling of the problem is exponentially worse in the qudit case, due to the graphs including weighted edges, meaning powers of controlled-Z operations. Due to this, even for qutrits the space required in memory to study graphs with 8 vertices is over 50GB, requiring the use of High Performance Clusters (HPC). Therefore, we provide the full orbits of qutrit graphs of up to 7 vertices, as well as the representatives of each orbit, which are based on the minimum number of edges and the lowest total weight in the orbit. This number of vertices is lower than the one achieved for the qubit case, however, it is still enough for considering optimal preparation strategies for graph states as well for the study of loss-tolerance. We believe in the future with the use of an HPC at least 9 vertices for qutrits is achievable.

References

[1] A. Cabello, L. E. Danielsen, A. J. López-Tarrida, and J. R. Portillo. Optimal preparation of graph states. Phys. Rev. A, 83:042314, Apr 2011

[2] J. C. Adcock, S. Morley-Short, A. Dahlberg, and J. W. Silverstone. Mapping graph state orbits under local complementation. Quantum, 4:305, August 2020

[3] K. Revis, H. Zakaryan and Z. Raissi. Orbit classification and analysis of qutrit graph states under local complementation and local scaling. arXiv:2506.05478