Optical Information Processing – from Quantum Computing to Artificial Intelligence

751. WE-Heraeus-Seminar

25 - 27 August 2021
ONLINE

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 751. WE-Heraeus-Seminar:

Digital computers are visibly approaching their physical limits. Thus, there is a growing interest in post-digital computing approaches. This covers quantum information processing (QIP) and artificial neural networks (ANN) implemented in specialized hardware. Recent years have seen tremendous progress in both fields, both in theory and in experiments. The first QIP systems have demonstrated advantages compared to classical supercomputers for specific tasks, while ANNs showed capability for machine learning (ML), e.g. in pattern recognition. Research towards the realization of both is motivated by the unique opportunities across a range of intellectual and technical frontiers. Speech recognition, home automation, and autonomous driving are typical problems for ML, while QIP is expected to change our notions of physics, combinatorial problems, and possibly even biological systems. The common goal of both is to solve a variety of computational tasks that are inefficient to solve on digital computers.

Optical platforms have high potential for both QIP and ANNs. The first components for optical QIP have been realized, e.g. small processors, highly efficient non-classical light sources, superconducting single photon detectors. Similar components enabled chip-integrated optical artificial neural networks (ONNs), which are in principle composed of linear optical networks and non-linearities. However, putting together all required components to demonstrate large scale photonic computers that outperform today's digital hardware remains challenging: given the variety and complexity of experimental and theoretical approaches, it is nearly impossible to unite expertise from all involved fields within one single research team. This seminar will bring together experts from different communities in order to discuss the prospects and challenges of combining their fields within a joint research effort on photonics for post-digital computers. The involved discussions will be highly beneficial not only for advancing the field, but also for supporting early stage researchers in their progress on becoming experts themselves.

Introduction

Scientific Organizers:

Prof. Dr. Janik Wolters	DLR Berlin, Germany E-mail: janik.wolters@dlr.de
Dr. Anna Pappa	TU Berlin, Germany E-mail: anna.pappa@tu-berlin.de

Administrative Organization:

Dr. Stefan Jorda Mojca Peklaj	Wilhelm und Else Heraeus-Stiftung Postfach 15 53 63405 Hanau, Germany Phone +49 6181 92325-18 Fax +49 6181 92325-15 E-mail peklaj@we-heraeus-stiftung.de Internet: www.we-heraeus-stiftung.de

Program

Program *(CEST)*

Wednesday, 25 August 2021

09:00 – 09:15	Janik Wolters Anna Pappa	**Welcome**
Chair: Daniel Brunner		
09:15 – 09:55	Ulrik L. Andersen	**Continuous Variable Optical Quantum Computing**
09:55 – 10:35	Heike Riel	**The Future of Computing – Bits & Neurons & Qubits**
10:35 – 10:50	*BREAK*	
10:50 – 12:10	*MINGLING (speed networking) on the MeetAnyway platform*	
12:10 – 13:10	*LUNCH BREAK*	
Chair: Ulrik L. Andersen		
13:10 – 13:50	Michael Kues	**Photonic Frequency-Domain Circuits for Quantum State Generation and Processing**
13:50 – 14:30	Benjamin Brecht	**Time-Frequency Quantum Walks**
14:30 – 14:40	*BREAK*	
Chair: Janik Wolters		
14:40 – 15:00	Nora Tischler (Contributed Talk)	**Provable Accuracy Advantage in Machine-Learned Quantum Models of Classical Stochastic Processes**
15:00 – 15:20	Markus Gräfe (Contributed Talk)	**Quantum Sensing With Undetected Light**
15:20 – 15:40	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
15:40 – 15:50	*BREAK*	
Chair: Pascale Senellart		
15:50 – 16:30	Hui Cao	**Massive-Parallel Ultrafast Random Bit Generation with a Semiconductor Laser**
16:30 – 17:10	Kai Müller	**Dynamics of Generation and Detection of Single Photons**
17:10	Poster 1 & Networking (bring your own beer & snacks)	

Program *(CEST)*

Thursday, 26 August 2021

Chair: Anna Pappa

09:15 – 09:55	Jens Eisert	**Rigorous Approaches to Quantum-Assisted Machine Learning**
09:55 – 10:35	Daniel Brunner	**Towards Autonomous Optical Neural Networks Leveraging 3D Integration**
10:35 – 10:50	*BREAK*	

Chair: Kai Müller

10:50 – 11:10	Oleksandr Kyriienko (Contributed Talk)	**Differentiable Quantum Circuits for Solving Nonlinear Differential Equations**
11:10 – 11:30	Felix Bussieres (Contributed Talk)	**Photon-Number Resolving Superconducting Nano-Strip Single-Photon Detectors for Quantum Optical Information Processing**
11:30 – 12:10	Pascale Senellart	**Efficient Photon Sources for Optical Quantum Computing**
12:10 – 13:10	*LUNCH BREAK*	

Chair: Christoph Becher

13:10 – 13:50	Alexander Szameit	**Laser-Written Photonic Quantum Circuits**
13:50 – 14:30	Elham Kashefi	**QML-based Cryptanalysis**
14:30 – 14:40	*BREAK*	

Chair: Janik Wolters

14:40 – 15:00	Tobias Stollenwerk (Contributed Talk)	**Quantum Approximate Optimization for Real-World Planning Problems**
15:00 – 15:20	Gerd Leuchs (Contributed Talk)	**Towards a Free Space Atomic Quantum Gate**
15:20 – 15:50	*BREAK*	

Chair: Vedran Dunjko

Program *(CEST)*

15:50 – 16:30	Stefanie Barz	**Networked Communication and Hybrid Computing with GHZ States**
16:30 – 17:10	Wolfram Pernice	**Towards Brain-Inspired Photonic Computing**
17:10	Poster 2 & Networking (bring your own beer & snacks)	

Program *(CEST)*

Friday, 27 August 2021

Chair: Anna Pappa

09:15 – 09:55	Vedran Dunjko	**Toward Quantum Advantages for Reinforcement Learning**
09:55 – 10:35	Anthony Laing	**The First Photonic Quantum Computers and their Applications**
10:35 – 10:50	*BREAK*	

Chair: Stefanie Barz

10:50 – 11:10	Jelmer Renema (Contributed Talk)	**A 12-mode Universal Photonic Processor for Quantum Information Processing**
11:10 – 11:50	Christoph Becher	**Towards Generation of Cluster States with Color Centers in Diamond for Photonic Quantum Computing**
11:50	Janik Wolters Anna Pappa	**Closing comments and best poster award**

Posters

Poster Session 1 – 25 August – 5.10 PM

1	Meritxell Cabrejo Ponce	**Toward High-Dimensional Frequency Entanglement Certification for Quantum Information Processing**
2	Radhakanta Dash	**Finite Element Method Modeling of an Optical Ring Resonator**
3	Jacob Hastrup	**Generation of Optical Gottesman-Kitaev-Preskill States with Cavity QED**
4	Alisa Javadi	**Ultra-bright Source of Coherent Single Photons**
5	Fatemeh Khastehdel Fumani	**Quantum Correlations in the Spin-1/2 XXZ Chain with Modulated Dzyaloshinskii-Moriya Interaction**
6	Gregor Pieplow	**Aspects of the Generation of Cluster States with Group-4 vacancies in Diamond**

Poster Session 2 – 26 August – 5.10 PM

1	Frederik Hahn	**Simulating Quantum Repeater Strategies for Multiple Satellites**
2	Johann A. Preuß	**Large Arrays of hBN Single-Photon Emitters Fabricated by Capillary Assembly**
3	Elizabeth Robertson	**A Scheme for Optical Reservoir Computers with Atomic Memory**
4	Benjamin Schiffer	**Faster Adiabatic Ground State Preparation with Few Measurements**
5	Otgonbaatar Soronzonbold	**A Quantum Annealer for Subset Feature Selectionand the Classification of Hyperspectral Images**
6	Philipp Stammer	**High Photon Number Entangled States and Coherent State Superposition from Extreme-UV to Far-IR**
7	Abhinav Verma	**Non Gaussian Cluster States**

Abstracts of Lectures

(in alphabetical order)

Continuous variable optical quantum computing

Mikkel V. Larsen, Jonas S. Neergaard-Nielsen and Ulrik L. Andersen
Center for Macroscopic Quantum States (bigQ), DTU Physics, Denmark

Continuous variable (CV) measurement-based quantum computation (MBQC) shows great potential for scalable quantum information processing. It has in recent years witnessed an increasing interest due to the simplicity in generating the foundational states – the cluster states – deterministically and in a scalable manner (1,2). There are still numerous steps to be taken towards realizing universal quantum computation but some of the critical steps are the realization of single and two-mode gates, the generation of the Gottesman-Kitaev-Preskill (GKP) states and development of robust quantum error correcting codes.

In MBQC, quantum gates are implemented through simple Gaussian measurements of the cluster state: High-efficiency homodyne detection suffices to realize a complete gate set in the two-dimensional sub-space of the GKP qubits. GKP qubits are of particular interest as they allow for the implementation of non-Clifford gates via Gaussian transformation and they are error-correctable by Gaussian transformations (3).

Here we discuss our recent progress on executing a complete set of measurement-based Gaussian single- and two-mode gates in a large two-dimensional cluster state (4). The fully programmable gates are also combined into a small-scaled circuit, demonstrating the programmability and flexibility of the setup. Moreover, we discuss new cluster state architectures that allow for both correction of continuous variable quadrature noise as well as discrete qubit errors (3). We also discuss new schemes for the realization of GKP states (5,6). These demonstrations and theoretical considerations are important steps towards realizing a universal quantum processor based on continuous variables.

References

(1) Larsen et al, Science **366**, 369 (2019)
(2) Warit et al, Science **366**, 373 (2019)
(3) Larsen et al, arxiv:2101.03014
(4) Larsen et al, arxiv:2010.14422
(5) Hastrup et al, npj Quantum Info 7, 1 (2021)
(6) Hastrup and Andersen, arXiv: 2104.07981

Networked communication and hybrid computing with GHZ states

Stefanie Barz [1,2]

[1] Institute for Functional Matter and Quantum Technologies, Universit ̈at Stuttgart, 70569 Stuttgart, Germany

[2] Center for Integrated Quantum Science and Technology (IQST), Universit ̈at Stuttgart, 70569 Stuttgart, Germany

In this talk I will discuss novel applications of GHZ states in quantum communication and computing.

First, I will present a recent experiment that shows quantum communication in a multipartite network. Here, I show how GHZ states allow achieving security in the communication – and also keeping the identities of the participating parties private [1]. Second, I will show how GHZ states can act as a resource for computation and that, vice versa, computation can be used as a tool to test quantum correlations [2].

References

[1] C. Thalacker, F. Hahn, J. de Jong, A. Pappa, Stefanie Barz, Anonymous and secret communication in quantum networks, arXiv:2103.08722 (2021)

[2] B. Demirel, W. Weng, C. Thalacker, M. Hoban, S. Barz, Correlations for computation and computation for correlations, npj Quantum Information 7, 29 (2021)

Towards generation of cluster states with color centers in diamond for photonic quantum computing

J. Görlitz[1], R. Morsch[1], B. Kambs[1], P. Fuchs[1], D. Herrmann[1], and C. Becher[1]

[1]*Universität des Saarlandes, Fachrichtung Physik, Saarbrücken, Germany*

Photonic cluster or graph states [1], i.e. multi-partite entangled states of photons, are considered an essential resource for photonic quantum computing [2,3] where quantum algorithms are performed by measurement of individual photonic qubits and fast feed-forward operations on (some of) the remaining qubits. Creating large photonic cluster states, however, remains a challenge where the most efficient scheme (sometimes labeled “cluster state machine gun”) builds upon repeated periodic emission and collection of single photons from individual quantum emitters where each photon is entangled with an internal degree of freedom of the emitter, e.g. an electron spin [4]. The general requirements for the individual quantum emitter are: (i) suitable level scheme and transition rules, (ii) efficient emission and collection of single photons with a high degree of indistinguishability, (iii) efficient single qubit (spin) rotations and (iv) long spin coherence time.

In recent years color centers in diamond, in particular the nitrogen-vacancy (NV) center and centers based on group IV impurities (e.g. silicon-vacancy (SiV) centers), have emerged as qubit systems fulfilling all requirements (i)-(iv). We here focus on the latter class of defect centers, exhibiting optically addressable spins with long coherence times and bright emission of single, close to transform limited photons [5,6]. We report on first experiments on Hong-Ou-Mandel interferometry of single photons from tin-vacancy (SnV) centers showing high visibilities and pointing towards small spectral instabilities. We also discuss photonic elements to enhance the photon collection from SnV centers, in particular planar metallo-dielectric optical antennas based on thin diamond membranes [7].

References

[1] H.J. Briegel and R. Raussendorf, Phys. Rev. Lett. **86**, 910 (2001).
[2] R. Raussendorf and H.J. Briegel, Phys. Rev. Lett. **86**, 5188 (2001).
[3] D.E. Browne, and T. Rudolph, Phys. Rev. Lett. **95**, 010501 (2005).
[4] N.H. Lindner and T. Rudolph, Phys. Rev. Lett. **103**, 113602 (2009).
[5] J.N. Becker and C. Becher, Phys. Status Solidi A **214**, 1700586 (2017).
[6] J. Görlitz et al., New J. Phys. **22**, 013048 (2020).
[7] P. Fuchs et al., arXiv: 2105.10249

Time-frequency quantum walks

S. De[1], V. Ansari[1,2], J. Sperling[1], S. Barkhofen[1], B. Brecht[1], and C. Silberhorn[1]

[1]Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

[2]E. L. Ginzton Laboratory, Stanford University, 348 Via Pueblo Mall, Stanford, California 94305, USA

Photonic quantum walks are an appealing platform for quantum simulation and, prospectively, quantum computation applications. They benefit from the inherent strengths of the photonics platform: long coherence times, fast experiments, and potential scalability. The latter is particularly pronounced for time-multiplexed quantum walks [1, 2], where an increase in system complexity does not entail increasing physical and technical resources. There remain, however, two challenges that must be addressed. Losses are a major issue for photonics applications; they scale exponentially with and ultimately limit the system size. Further, most photonic quantum walks to date are limited to one-dimensional lattices and two-dimensional coins, and no system goes beyond two-dimensional lattices, owing to the technical complications of realising larger dimensionality.

I will discuss a novel approach to quantum walks – measurement-based time-frequency quantum walks. In our system, the quantum walk evolution is encoded in an appropriate rotation of the measurement basis, where frequency bins take the role of the internal and external degrees of freedom of the quantum walker. This naturally addresses both the loss and dimensionality issues. Using this approach, we demonstrate Grover walks on four-dimensional lattices, a prerequisite for walk-based quantum computation. Further, we demonstrate quantum walks with periodic and reflecting boundary conditions with up to 400 steps. The approach of measurement-based time-frequency quantum walks thus adds novel functionality to the quantum walk platform, which offers potential for future applications in both simulations and computations.

References

[1] A. Schreiber et al, Phys. Rev. Lett. **104**, 050502 (2010).

[2] A. Schreiber et al, Science **336**, 55 (2012)

Towards autonomous optical neural networks leveraging 3D integration

D. Brunner

Institut FEMTO-ST, Université Bourgogne Franche-Comté, CNRS UMR6174, Besançon, France

Neural networks differ from classical, algorithmic computing in a number of fundamental aspects. These differences result in equally fundamental, severe and relevant challenges for neural network computing using current computing substrates. Neural networks urge for parallelism across the entire processor and for a co-location of memory and arithmetic, i.e. beyond von Neumann architectures.

We have recently realized a fully parallel and fully implemented photonic neural network using spatially distributed modes of an efficient and fast semiconductor laser [1]. Importantly, all neural network connections are embedded in hardware, and the processor produces results without pre- or post-processing. Such a system is scalable to large sizes, to bandwidths in excess of 20 GHz and has the potential to surpass electronic neural networks in energy efficiency.

To embed such parallel neural network systems in integrated circuits faces a further, fundamental challenge. The number in connections comprising a neural network scale with o(N^2) for N neurons, which contests the scalability of classical 2D integration. We have recently demonstrated 3D photonic integration based on 3D printing leveraging two photon polymerization [2]. With such an approach photonic integrated tensor processing units with a far superior integration density and scaling become possible. Both technologies combined could indicate a scalable path for high performance integrated photonic neural networks to overcome the approaching technology road block.

References

[1] Porte, et al., J. Phys. Photonics **3**, 024017 (2021).
[2] Moughames, et al., Optica **7**, 640 (2020).

Photon-number-resolving superconducting nanostrip single-photon detectors for quantum optical information processing

F. Bussières[1,2], M. Perrenoud[2], G. Gras[2], L. Stasi[1,2]

[1] *ID Quantique SA, Carouge, Switzerland*
[2] *Group of Applied Physics – Quantum Technologies, University of Geneva, Switzerland*

PNR detectors have been identified as a core enabling technology for optical quantum information processing since the early beginnings. The KLM approach relied on such detectors, and more recent examples such as cluster-states [1,2], fusion-based quantum computation [3] and squeezed states combined with non-Gaussian operations also rely on the need for excellent PNR detectors [4].

To address this need, transition edge sensors (TES) have been successfully used to reach close to unity efficiency per photon, combined with the ability to discriminate from a few photons per device, and up to ~20 by multiplexing of several devices [4]. TES can however suffer from long recover times and rather poor time resolution when compared to what conventional superconducting nanostrip single-photon detectors (SNSPDs) can achieve. Moreover, TES typically require operation at tens of mK, putting a burden on the cryogenics.

Recent progress on SNSPDs have shown also that close to unity efficiency is possible. Such devices can therefore potentially reach the necessary requirements to find use for optical quantum information processing, and possibly provide performances as good as what TES can do. We approach this using parallel SNSPDs, in which several pixels are connected in parallel and read out by a single coaxial line [5]. In this talk, I will show how this direct approach can fail due to latching if the cross-talk between the pixels is not properly managed, and how it can be mitigated with to unleash the potential of SNSPDs towards multi-photon PNR detectors. I will report on devices reaching SDEs close to 90% efficiency with the ability to resolve between 0 to 8 simultaneous detections, without any latching. This opens new possibilities towards SNSPDs reaching very high efficiencies, ultra-low dead times, small jitter and a PNR ability reaching tens of photons.

References

[1] M.V. Larsen *et al.*, *Science* **366**, 369–372 (2019).
[2] Asavanant, W. et al., *Science* **366**, 373–376 (2019).
[3] S. Bartolucci *et al.*, arXiv:2101.09310 (2021).
[4] M. Perrenoud *et al.*, *Superconducting science and Technology* **34**, 024002 (2021).

Parallel ultrafast random bit generation with a semiconductor laser

Kyungduk Kim[1], Stefan Bittner[1,2], Yongquan Zeng[3], Stefano Guazzotti[4], Ortwin Hess[4], Qi Jie Wang[3], Hui Cao[1]

[1]*Dept. of Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Chair in Photonics, LMOPS EA-4423 Laboratory, CentraleSupélec and Université de Lorraine, 2 rue Edouard Belin, Metz 57070, France*
[3]*Center for OptoElectronics and Biophotonics, School of Electrical and Electronic Engineering & School of Physical and Mathematical Science and the Photonics Institute, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore*
[4]*School of Physics and CRANN Institute, Trinity College Dublin, Dublin 2, Ireland*

Random numbers are widely used for information security, cryptography, stochastic modeling, and quantum simulations. Key technical challenges for physical random number generation are speed and scalability. We demonstrate a method for ultrafast generation of hundreds of random bit streams in parallel with a single laser diode. Spatio-temporal interference of many lasing modes in a specially designed cavity is introduced as a scheme for greatly accelerated random bit generation. Spontaneous emission, caused by quantum fluctuations, produces stochastic noise that makes the bit streams unpredictable. We achieve a total bit rate of 250~Tb/s with off-line post-processing, which is more than two orders of magnitude higher than the current post-processing record. Our approach is robust, compact, energy efficient, and should impact applications in secure communication and high-performance computation.

References

[1] K. Kim, S. Bittner, Y. Zeng, S. Guazzotti, O. Hess, Q. J. Wang, H. Cao, Science, **371**, 948 (2021).

Toward quantum advantages for reinforcement learning

Vedran Dunjko[1]
[1]Leiden Institute of Advanced Computer Science, Leiden, The Netherlands

Machine learning is nowadays often highlighted as one of the most likely domains where generally useful quantum advantages may be obtained. One of the most popular approaches is to employ variational quantum circuit (VQC) methods in this context, as they may lead to algorithms that work despite various restrictions of near-term quantum computing devices.

In recent times, we have made substantial advances in our understanding of such VQC methods in the context of supervised and unsupervised learning. However, for reinforcement learning, which is the arguably hardest mode of machine learning and where a quantum boost may be very valuable, far fewer results are known.

In this talk, I will present our recent results in quantum-enhanced reinforcement learning, and demonstrate a few proposals showcasing now quantum techniques can lead to better reinforcement learning performances.

Specifically I will discuss quantum variational algorithms for policy gradients, Q-learning, and give examples of separations statements between classical and quantum learning agents that can be proven. This talk is based on [1,2].

References

[1] Variational quantum policies for reinforcement learning, S Jerbi, C Gyurik, S Marshall, HJ Briegel, V Dunjko, arXiv preprint arXiv:2103.05577 (2021)
[2] Quantum agents in the Gym: a variational quantum algorithm for deep Q-learning, A Skolik, S Jerbi, V Dunjko, arXiv preprint arXiv:2103.15084 (2021)

Rigorous approaches to quantum-assisted machine learning

J. Eisert

[1]*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14192 Berlin, Germany*

Recent years have enjoyed an increased interest in notions of quantum-assisted machine learning and artificial neural networks, driven by the hope that quantum algorithms could fare better than classical ones in instances of learning tasks. These advantages could refer to computational speedups, but also to better generalization and other figures of merit. Optical architectures have been suggested that could potentially make use of such enhanced capabilities. In this talk, we will have a look at what can be rigorously said about aspects of quantum-assisted machine learning. In the first part of the talk, we will discuss the comparative power of classical and quantum learners for generative modelling within the probably approximately correct (PAC) framework, for which we prove a separation between the quantum and classical settings [1]. In a second part, we discuss the theoretical properties of model classes derived from parameterized quantum circuits by deriving generalization bounds which depend explicitly on the strategy used for data-encoding. Apart from allowing one to obtain bounds on the performance of trained parameterized quantum circuit models on unseen data, such bounds also facilitate the selection of optimal data-encoding strategies via structural risk minimization [2]. If time allows, we will briefly mention ideas of classical control of variational quantum circuits as they can be implemented in integrated optical circuits [3,4] and of machine-learning inspired quantum-aided quantum design [5], again referring to variational quantum circuits. We will make the point that such efforts are important to gauge what approaches to quantum assisted machine learning are expected to be promising in the realm of optical noisy intermediate scale quantum devices.

References

1. On the quantum versus classical learnability of discrete distributions, R. Sweke, J.-P. Seifert, D. Hangleiter, J. Eisert, Quantum 5, 417 (2021).
2. Encoding-dependent generalization bounds for parameterized quantum circuits, M. C. Caro, E. Gil-Fuster, J. J. Meyer, J. Eisert, R. Sweke, arXiv:2106.03880 (2021).
3. Stochastic gradient descent for hybrid quantum-classical optimization, R. Sweke, F. Wilde, J. Meyer, M. Schuld, P. K. Faehrmann, B. Meynard-Piganeau, J. Eisert, Quantum 4, 314 (2020).
4. Single-component gradient rules for variational quantum algorithms, T. Hubregtsen, F. Wilde, S. Qasim, J. Eisert, arXiv:2106.01388 (2021).
5. A variational toolbox for quantum multi-parameter estimation, J. J. Meyer, J. Borregaard, J. Eisert, Nature Partner Journal Quantum Information 7, 89 (2021).

Quantum Sensing With Undetected Light

M. Gilaberte Basset[1], S. Töpfer[1], J. R. León Torres[1,2], J. Fuenzalida[1], and M. Gräfe[1,2]

[1]*Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena, Germany*

[2] *Institute of Applied Physics, Abbe Center of Photonics, Jena School for Microbial Communication (JSMC), Friedrich-Schiller University Jena, Jena, Germany*

Nowadays, quantum physics turned from purely fundamental science to a research field with real-life applications. In particular, quantum photonics promises novel approaches for quantum enhanced-imaging and sensing. Most of them rely on interferometric settings, like quantum optical coherence tomography [1,2], superresolving sensing with N00N states [3,4], and quantum imaging with "undetected photons" [5]. The ladder one is a highly attractive approach where interaction with a sample and detection can be spectrally separated. Based on Mandels induced coherence [6,7], with nonlinear interferometers it becomes possible to extract information about an object with light that never interacted at all with the object. It is worth mentioning explicitly that in stark contrast to Ghost imaging, here, neither any coincidence detection is necessary nor any detection of the light that interacted with the object. By exploiting non-degenerated spontaneous parametric down conversion, photon pairs with large wavelength difference can be harnessed. The obvious advantage of this technique is that the wavelength of the idler photons can be tailored to match the interesting spectral range of the object (e.g., far IR, THz, deep UV). At the same time, the signal photons, which are actually detected, can stay in the VIS range where, e.g., Si-based detectors are optimized. The talk will be devoted on recent advances in the field and related scientific findings and technical achievements. Moreover, a link towards on-chip integration and sources similar as for photonic quantum computing will be drawn.

References

[1] Abouraddy et al., Phys. Rev. A 65, 053817 (2002)
[2] Nasr et al., Phys. Rev. Lett. 91, 083601 (2003)
[3] Boto et al., Phys. Rev. Lett 85, 2733 (2000)
[4] Afek, Ambar, and Silberberg, Science 328, 879 (2010)
[5] Lemos et al., Nature 512, 409 (2014)
[6] Wang, Zou, and Mandel, "Phys. Rev. A 44, 4614 (1991)
[7] Zou, Wang, and Mandel, Phys. Rev. Lett. 67, 318 (1991)

QML-based Cryptanalysis

Elham Kashefi

University of Edinburgh, Scotland& CNRS Sorbonne Université, Paris, France

Cryptography designs are based on security by construction with strong security arguments but cryptanalysis remains a crucial part of a cipher's validation process. Meanwhile more and more cipher proposals are emerging and the task of cryptanalysis remains a challenging low-rewarding task. Hence various techniques have been deployed for automating as much as possible the tasks of an attacker. In recent years classical machine learning has been also successfully exploited for black-box cryptanalysis, in this talk we present two examples of similar approaches that have been used for quantum cryptanalysis based on quantum machine learning applications.

Photonic frequency-domain circuits for quantum state generation and processing

Michael Kues

[1]*Institute of Photonics, Leibniz University Hannover, Germany*

A key challenge in today's quantum science relies in the realization of large-scale complex non-classical systems to enable, e.g., accelerated computations. Optical quantum frequency combs, characterized by many equidistantly spaced frequency modes, allow the storage of a large amount of quantum information. The combination with control techniques, embodied by e.g. electro-optical frequency shifting, can represent a powerful frequency-domain quantum circuit and an approach towards realizing large-scale controllable quantum systems. In this presentation, we will discuss the efficient realization of quantum frequency combs in on-chip waveguide structures and micro-resonators as well as demonstrate their used for the realization of quantum states with considerably enhanced complexity, particularly generating and manipulating on-chip multi-photon as well as high-dimensional quantum states. These frequency-domain circuits permitted the first realization of discrete high-dimensional cluster states, laying at the basis of measurement based-quantum computing, as well as the frequency-domain Hong-Ou-Mandel interference of independent photons, fundamental to quantum information processing. Microcavity-based photonic frequency comb states and their control using accessible telecommunications infrastructure can open up new venues for reaching the processing capabilities required for meaningful quantum information science.

Differentiable quantum circuits for solving nonlinear differential equations

Oleksandr Kyriienko[1,2], **A. E. Paine,**[1, 2] **V. E. Elfving**[2]

[1] *1Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom*

[2] *Qu & Co B.V., PO Box 75872, 1070 AW, Amsterdam, The Netherlands*

Quantum machine learning based on parametrized circuits became the leading paradigm for near-term quantum computing when applied to data processing. In this case, classical data is encoded using quantum feature maps (variable-depend circuits), adjusted with a variation ansatz, and read out as a sum of expectation values. Motivated by the development of classical neural networks and deep learning, this approach was applied to solve various problems ranging from classification to generative modelling [1]. The advantage comes from the rich expressivity of quantum models that can be designed using the exponentially increasing Hilbert space.

In the talk, I will show how to differentiate quantum circuits with feature maps and thus embed derivatives of multidimensional functions. The approach relies on automatic differentiation to represent derivatives in an analytical form, thus avoiding inaccurate finite difference procedures. We refer to the underlying circuits as differentiable quantum circuits (DQCs) [2]. I will describe the proposed hybrid quantum-classical workflow where DQCs are trained to satisfy nonlinear differential equations and specified boundary conditions. First, I will show how it performs on simple systems of nonlinear differential equations. Next, I will apply the algorithm to solve a problem from computational fluid dynamics. This corresponds to the fluid flow in a convergent-divergent nozzle (described by Navier-Stokes equations), where we predict density, temperature and velocity profiles for the stiff system of equations that can challenge classical solvers. Finally, I will also show that DQCs can provide an advantage for generative modelling from stochastic differential equations, giving access to sampling from financially relevant models.

References

[1] M. Benedetti, E. Lloyd, S. Sack, and M. Fiorentini, Quantum Sci. Technol. **4**, 043001 (2019).

[2] O. Kyriienko, A. E. Paine, V. E. Elfving, Phys. Rev. A **103**, 052416 (2021).

[3] A. E. Paine, V. E. Elfving, O. Kyriienko, arXiv:2108.03190 (2021).

The first quantum computers and their applications

Anthony Laing
Quantum Engineering and Technology Labs, University of Bristol, UK

Remarkable progress has been made in the development of quantum computing hardware. As a platform for quantum computing, integrated photonics has enabled significant leaps for integrating many components, including programmable circuitry, photon sources and detectors. However, fault tolerant digital quantum computing still appears to be a long way off for all platforms, including photonics. Yet there are reasons to be optimistic that intermediate scale photonic devices can achieve quantum advantage in solving certain interesting problems. We discuss these recent advances, including work to sharpen our understanding of where the boundary for quantum advantage lies. We also touch upon some of the fundamental hardware advances that could deliver scalable quantum computing with photonics.

References

[1] The Boundary for Quantum Advantage in Gaussian Boson Sampling, Bulmer, Bell, Chadwick, Jones, Moise, Rigazzi, Thorbecke, Haus, Vaerenbergh, Patel, Walmsley, Laing, arXiv:2108.01622

[2] A scheme for universal high-dimensional quantum computation with linear optics, Paesani, Bulmer, Jones, Santagati, Laing, Phys. Rev. Lett. 126, 230504 (2021)

[3] Error protected qubits in a silicon photonic chip, Vigliar, Paesani, Ding, Adcock, Wang, Morley-Short, Bacco, Oxenløwe, Thompson, Rarity, Laing, arXiv:2005.09579, Nature Physics (in press)

[4] Near-ideal spontaneous photon sources in silicon quantum photonics, Paesani, Borghi, Signorini, Maïnos, Pavesi, Laing, Nature Communications 11, 2505 (2020)

[5] Integrated Photonic Quantum Technologies, Wang, Sciarrino, Laing, Thompson, Nature Photonics 14, 273 (2020)

[6] Generation and sampling of quantum states of light in a silicon chip, Paesani, Ding, Santagati, Chakhmakhchyan, Vigliar, Rottwitt, Oxenløwe, Wang, Thompson, Laing, Nature Physics 15, pages 925–929 (2019)

[7] Simulating the vibrational quantum dynamics of molecules using photonics, Sparrow, Martín-López, Maraviglia, Neville, Harrold, Carolan, Joglekar, Hashimoto, Matsuda, O'Brien, Tew, Laing, Nature 557, 660 (2018)

Towards a free space atomic quantum gate

G. Leuchs

Max Planck Institute for the Science of Light, Erlangen, Germany
and University of Erlangen-Nürnberg, Germany
Email: gerd.leuchs@mpl.mpg.de

A single atom in free space can serve as a quantum gate for both continuous as well as discrete quantum variables. The challenge is reaching the optimal efficiency. Progress in this direction will be discussed.

References

[1] M. Fischer, B. Srivathsan, L. Alber et al., Appl Phys B **123**, 48 (2017)
[2] M. Sondermann, M. Fischer, G. Leuchs, Adv Quant Techn **3**, 2000022 (2020)

Dynamics of generation and detection of single photons

L. Hanschke[1], F. Sbresny[1], E. Schöll[2], K. Boos[1], W. Rauhaus[1], J. J. Finley[1], K. Jöns[2] and K. Müller[1]

[1]*Walter Schottky Institut, Technical University of Munich, 85748 Garching, Germany*
[2]*University of Paderborn, 33098 Paderborn, Germany*

Single photons are key ingredients for many applications in quantum technologies. In this talk, I will discuss the dynamics of generating single photons using semiconductor quantum dots and recent progress in the development of highly-efficient superconducting single photon detectors. Due to their excellent optical properties, such as fast emission rates and nearly transform-limited linewidth, semiconductor quantum dots are promising as single-photon sources. Here, the fundamental limits of the single-photon purity and photon indistinguishability for resonantly driven two-level systems and three-level ladder systems will be discussed [1-3], as well as a novel scheme that circumvents the intrinsic limitations [4]. In addition, I will present recent progress in the engineering of superconducting nanowire single photon detectors.

References

[1] K. A. Fischer, et al., Nature Physics 13, 649-654 (2017).
[2] L. Hanschke et al., npj Quantum Information 4, 43 (2018)
[3] E. Schöll et al., Physical Review Letters 125, 233605 (2020)
[4] F. Sbresny et al., arXiv:2107.03232 (2021)

Towards brain-inspired photonic computing

Wolfram Pernice, University of Münster, Germany

Optical computing methods are seeing a resurgence of popularity due to recent advances in integrated photonics and neuromorphic engineering. Photonic systems are very suitable for analog computing approaches with moderate accuracy, yet very high processing speed. These features hold promise for implementing photonic accelerator systems for computationally expensive tasks such as matrix vector multiplications (MVM). Here I will introduce a nanophotonic approach for realizing chip-scale MVM-units. Using phase-change photonic devices allows for creating parallel processing circuits in which analog multiplications can be carried out at high speed in parallel. In combination with the development of novel light sources, photonic approaches offer new opportunities for creating brain-inspired hardware for artificial intelligence applications.

A 12-mode Universal Photonic Processor for Quantum Information Processing

C. Taballione[1], R. v.d. Meer[2], H. Snijders[1], P. Hooijschuur[2], J. P. Epping[1], M. de Goede[1], B. Kassenberg[1], P. Venderbosch[1], C. Toebes[2], H. v.d. Vlekkert[1], P. Pinkse[2], J. Renema[1,2]

1. *QuiX BV, Hengelosestraat 500, 7521 AN Enschede, The Netherlands*
2. *Adaptive Quantum Optics group, University of Twente, Drienerlolaan 5,7522 NB Enschede, The Netherlands*

Recently, a quantum advantage over classical computation has been claimed using photons [1]. To control photonic quantum computations, large-scale quantum processors are needed [2,3]. To realize scalable and robust photonic quantum processors, integrated photonics is a key technology.

Here, we present a universal 12-mode quantum photonics processor which is the largest of its kind to date, based on silicon nitride waveguides [4]. The presented quantum photonic processor is fully reconfigurable by using a matrix of 156 thermally tunable Mach-Zehnder interferometers (see Fig 1a-b for the functional design).

Our processor achieves a transformation fidelity of 98% (see Fig. 1c for a few example transformations), and optical losses of 2.5 dB. To validate the functionality of the processor for quantum optical experiments, we characterized the Hong-Ou-Mandel interference of every single MZI of our processor.

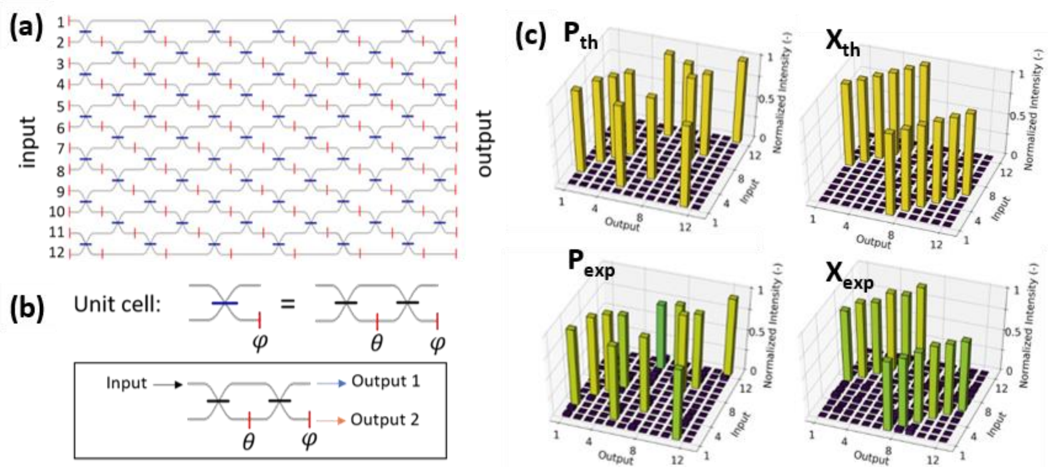


Fig. 1 (a) Functional design of the photonic processor: tunable Mach-Zehnder interferometer (blue), 50:50 directional couplers (black), and phase shifters (red). (b) Unit cell of the processor. (c) Theory (top) vs experimental (bottom) of a random permutation matrix, P, and Pauli-X gate, X[6].

References

[1] H.-S. Zhong, *et al*, Science 370, 1460 (2020).
[2] J. Carolan, *et al*, Science 349, 711 (2015).
[3] C. Taballione, *et al*, Opt. Express 27, 26842 (2019).
[4] C. G. H. Roeloffzen, IEEE J. Sel. Top. Q. Electron. 24(4), 4400321 (2018).
[5] C. Taballione *et al*, arXiv:2012.05673 (2021).

The Future of Computing – Bits & Neurons & Qubits

Heike Riel

IBM Research Europe – Zurich, Rüschlikon, Switzerland

For decades Moore's law has been the driving force of semiconductor technology and the enabler of today's information technology. Smaller devices, resulting in faster chips and consequently cheaper microprocessors – this was the economic law of this first of a kind revolution in IT. However, nowadays, despite of a lot of innovation in materials, devices, device scaling and architectures, progress is continuously slowing down and new approaches to computing are in demand.
With the explosion of available data, the internet-of-things and the increasing demand for machine learning, deep learning and artificial intelligence (AI), the computational workloads are significantly changing. Therefore, there is a growing need for specialized hardware which should be able to handle these different computational workloads which today's computers cannot handle efficiently.
In that regard completely new computing paradigms are explored and developed such as quantum computing and specialized hardware for AI including non-von Neumann architectures.

In this talk I will give an overview of our research activities in the field of extending the core technology roadmaps and in the new computing paradigms of cognitive hardware technologies and quantum information processing. This includes the discussion of the technology roadmaps we pursue comprising several approaches such as approximate computing and analog in-memory computing for AI HW as well as our Quantum Computing Development roadmap.

Efficient photon sources for optical quantum computing

P. Senellart

Center for Nanoscience and Nanotechnology, C2N CNRS – University Paris Saclay, 10 Bd. Thomas Gobert, 91120, Palaiseau, France

Optical quantum computing has recently gained great momentum with the recent demonstration of quantum computational advantage in a Gaussian Boson sampling experiment. Both discrete and continuous variables approaches are showing spectacular progresses. However, in both cases, the future scalability and universality of the computation lies in the possibility to efficiently generate non-gaussian quantum light states.

Recently, semiconductor quantum dots have emerged as excellent single-photon sources, showing near unity quantum purity and unparalleled efficiency [1]. In this talk, I will briefly discuss our recent progresses in the development of semiconductor single photon sources and discuss how we recently gained a factor of 2 in the source brightness by exploiting phonon assisted excitation schemes [2]. I will then explain how, by revisiting the spontaneous emission of a single emitter, we demonstrated the possibility to directly generate both quantum superpositions in the photon-number basis [3] and photon number entanglement distributed in two time bins [4]. The latter scheme can be extended to multiple time bins and could lead to applications in both discrete variable and continuous variables.

References

[1] Somaschi et al., Nature Photonics 10 (5), 340-345 (2016), P Senellart, G Solomon, A White, Nature nanotechnology 12 (11), 1026-1039 (2017)
[2] S. E. Thomas et al., Physical Review Letters 126 (23), 233601 (2021)
[3] J.C. Loredo et al, Nature Photonics 13 (11), 803-808 (2019)
[4] S.C. Wein et al, arXiv:2106.02049 (2021)

Quantum Approximate Optimization for Real-World Planning Problems

Tobias Stollenwerk[1]

[1]*Quantum Computing Group, Institute for Software Technology, German Aerospace Center, Linder Hoehe, 51147 Cologne, Germany*

There are few candidates for quantum algorithms which might outperform classical approaches, while being amenable to NISQ devices. Beside quantum simulation algorithms, quantum algorithms for approximate optimization are promising candidates. The target application for such approaches is finding approximate solutions to combinatorial optimization problems. In this talk I will report on our recent efforts to map a particular real-world planning problem, the flight-gate assignment problem, to a quantum approximate optimization algorithm [1].

References

[1] T. Stollenwerk, S. Hadfield and Z. Wang, "Toward Quantum Gate-Model Heuristics for Real-World Planning Problems," in *IEEE Transactions on Quantum Engineering*, vol. 1, pp. 1-16, 2020, Art no. 3101816, doi: 10.1109/TQE.2020.3030609.

Laser-written photonic quantum circuits

Alexander Szameit

Institute for Physics, University of Rostock

Integrated photonic devices fabricated by femtosecond lasers exhibit numerous advantages regarding stability, robustness, and miniaturization. In particular in the field of quantum photonics they provide an excellent testbed for exploring novel physical effects that may play a significant role in innovative applications.

In this presentation, I will discuss three recently explored phenomena implemented in laser-written integrated photonic devices: Photonic Boson sampling as an inherent quantum computation task, the observation of non-Hermitian $\mathcal{PT}$-symmetric quantum optics as an extension of common Hermitian quantum optics, and three-dimensional quantum walks on complex graphs exploring higher-dimensional physics.

Provable accuracy advantage in machine-learned quantum models of classical stochastic processes

N. Tischler[1], C. Yang[2], A. Garner[2], F. Liu[3], J. Thompson[4], M.-H. Yung[3], M. Gu[2,4] and O. Dahlsten[3]

[1] *Freie Universität Berlin, Berlin, Germany*
[2] *Nanyang Technological University, Singapore*
[3] *Southern University of Science and Technology, Shenzhen, China*
[4] *National University of Singapore, Singapore*

Stochastic process models serve to describe a wide variety of natural and social phenomena, such as the weather, traffic congestion, and atomic decay. The simulation of stochastic processes provides valuable information about the dynamics of complex systems. However, highly complex processes require a vast amount of memory for simulation. If the amount of available memory is limited, this can lead to inaccuracies in the simulation [1].

It has previously been shown that quantum information processors can reduce the memory required to accomplish exact simulation [2,3]. Thereby, stochastic process simulation has been established as a new application that can benefit from quantum resources. However, until now, all quantum works in stochastic process simulation assumed knowledge about the process to be modelled and considered only exact simulation. This can be unrealistic, particularly in noisy real-world scenarios.

Here (the submission is based on [4]), we show how quantum information processing provides an advantage in accuracy, given constrained memory resources. We introduce a learning algorithm, which discovers dimensionally reduced quantum models that achieve greater accuracy than their optimal classical counterparts. Our algorithm directly uses the output data of a stochastic process, instead of requiring knowledge about the underlying model. The results provide a rare case in quantum machine learning where the quantum advantage is rigorously provable.

References

[1] J. P. Crutchfield, Physica D **75**, 11-54 (1994)
[2] F. Ghafari, N. Tischler, J. Thompson, M. Gu, L. Shalm, V. B. Verma, S.-W. Nam, R. Patel, H. Wiseman, and G. Pryde, Phys. Rev. X **9**, 041013 (2019)
[3] F. Ghafari, N. Tischler, C. Di Franco, J. Thompson, M. Gu, and G. Pryde, Nature Commun. **10**, 1630 (2019)
[4] C. Yang, A. Garner, F. Liu, N. Tischler, J. Thompson, M.-H. Yung, M. Gu, O. Dahlsten, arXiv:2105.14434 (2021)

Abstracts of Posters

(in alphabetical order)

Toward High-Dimensional Frequency Entanglement Certification for Quantum Information Processing

M. Cabrejo Ponce[1], A. L. M. Muniz[1], and F. O. Steinlechner[1, 2,*]

[1]Emerging Technologies Dept., Fraunhofer IOF, Jena, Germany
[2]Abbe Center of Photonics, Friedrich Schiller University Jena, Jena, Germany

High-dimensional quantum states (known as qudits, with dimension $d > 2$), can store and process more information than the 2-dimensional qubits [1], and have proven to be more resistant to noise in quantum communication scenarios [2]. Such advantages can be exploited in more complex algorithms for quantum information processing or more noise-resilient quantum communication. Frequency-domain encoded quantum information has key advantages: huge parallelization and universal quantum gates with standard telecommunication devices. However, due to the physical limitations of the available components, complete entanglement certification has only been possible for a handful of discretized frequency modes [3].
In this work, we show the steps toward massive entanglement certification of photons in the frequency degree of freedom. Building on the methods presented in [4,5], our approach achieves local frequency superposition using electro-optic modulators. Such a method allows to partially reconstruct the full state only with knowledge of the energy correlations (the computational basis) and the coherence information between neighboring modes, to finally lower bound the dimensionality of the state. With these tools, we explore the high-dimensionality of frequency modes over a 60 nm spontaneous parametric down-converted (SPDC) spectrum of a periodically poled lithium niobate (ppLN) waveguide. Although the spectrum contains a continuum of frequencies, mode discretization occurs inevitably at the measurement step. Here, we chose a mode distance of 25 GHz with the same bandwidth and investigate the two-photon interference between first-neighbor (j and $j+1$) and second-neighbor (j and $j+2$). We achieve consistent visibilities above 94% and 96% respectively for all modes (without subtraction of accidentals). These results pave the way toward practical processing of massive high-dimensional entanglement in the frequency domain.

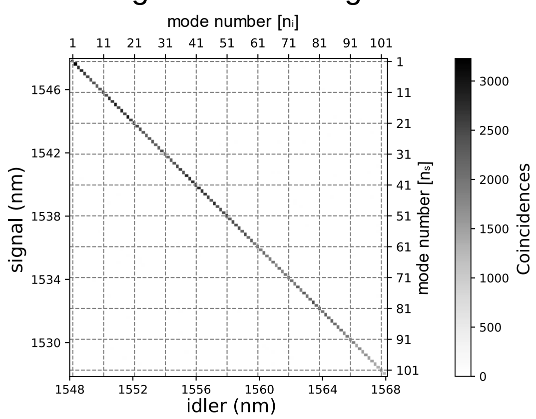


Figure: 100-dimensional state in the frequency basis.

References

[1] Y. Wang et al. Frontiers in Physics **8**, 24 (2020)
[2] S. Ecker et al. Physical Review X 9, 041042 (2019)
[3] M. Kues et al. Nature **546**, 622–626 (2017)
[4] A. Tiranov et al. Physical Review A **96**, 040303(R) (2017)
[5] A. Martin et al. Physical Review Letters **118**, 110501 (2017)

Finite Element Method Modeling of an Optical Ring Resonator

R. Dash[1,*] and S. Jena[2]

[1]*College of Engineering and Technology (Autonomous), Ghatikia, Bhubaneswar, INDIA*

[2]*Atomic & Molecular Physics Division, Bhabha Atomic Research Centre, Mumbai, INDIA*

**Email: radhakanta.physics@gmail.com*

An optical ring resonator is a looped optical waveguide and it is coupled to an adjacent bus waveguide by evanescent coupling for functional applications. A resonance occurs when the optical path length of the resonator is exactly an integer number of wavelength and the light power stored in the ring builds up and these resonant wavelengths are coupled to the output waveguide. In this paper we have studied the spectral properties of an Yttrium Vanadate based optical micro-ring resonator by finite element method and analysed its performance as an optical notch filter for a resonant wavelength of 1.55 µm.

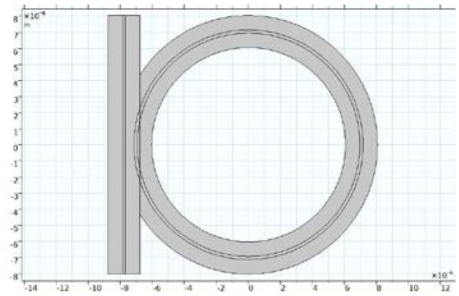


Fig. 1 Design of the ring resonator

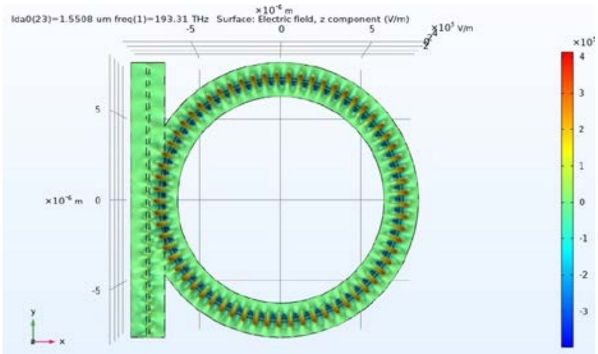


Fig. 2 *Electric field for the resonant wavelength.*

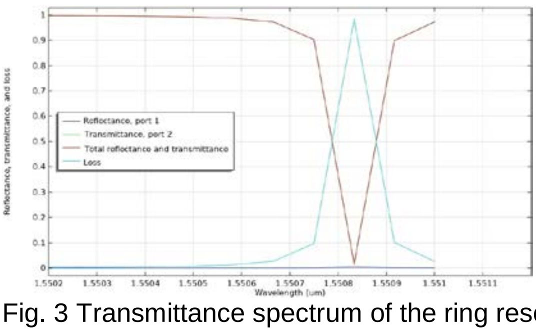


Fig. 3 Transmittance spectrum of the ring resonator

Table 1. Design Parameters of Ring Resonator

Core width	0.2 µm
Cladding width	2 µm
Radius of curvature	7.053 µm
Core (YVO_4) refractive index	2.9488
Clad (SiO_2) refractive index	1.444
Separation between waveguides	0.727 µm

References

[1] Stokes, L.F., Chodorow, M., Shaw, H.J.: All-single-mode fiber resonator. Opt. Lett. 7(6), 288–290 (1982) .

[2] Choi, J.M., Lee, R.K., Yariv, A.: Control of critical coupling in a ring resonator–fiber configuration: application to wavelength-selective switching, modulation, amplification, and oscillation. Opt. Lett. 26(16), 1236–1238 (2001)

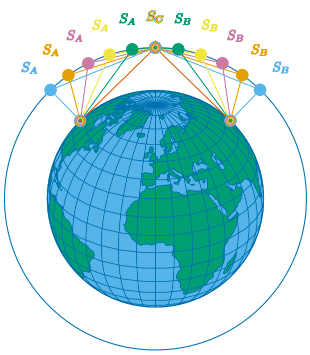
[3] Van, Vien - Optical microring resonators_ theory, techniques, and applications, CRC Press (2017).

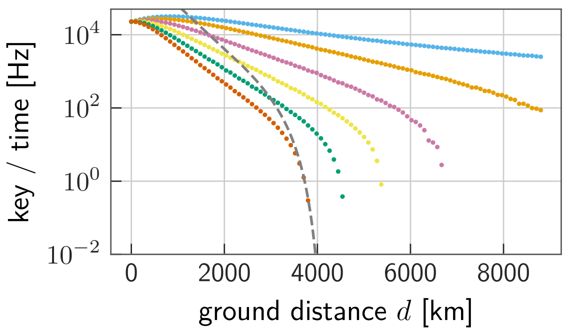
Simulating quantum repeater strategies for multiple satellites

Julius Wallnöfer[1], Frederik Hahn[1], Fabian Krüger[1], Mustafa Gündogan[2,3], Jasminder Sidhu[4], Nathan Walk[1], Jens Eisert[1,5], and Janik Wolters[3,6]

[1]Dahlem Center for Complex Quantum Systems,Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany
[2] Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, Berlin 12489, Germany
[3] Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute of Optical Sensor Systems, Rutherfordstr. 2, 12489 Berlin, Germany
[4] SUPA Department of Physics, University of Strathclyde, John Anderson Building, 107 Rottenrow East, Glasgow, G4 0NG, UK
[5] Helmholtz-Zentrum Berlin für Materialien und Energie, Hahn-Meitner-Platz 1, 14109 Berlin, Germany
[6] Technische Universität Berlin, Institut für Optik und Atomare Physik, Str. des 17. Juni 135, 10623 Berlin, Germany

A global quantum communication network with satellite-based links is likely to have advantages over fiber- based networks in terms of long-distance communication, since the photon losses introduced by optical fibers are too detrimental for distances beyond a few hundred kilometers. We have developed an event- based Monte Carlo simulation to simulate quantum repeaters with multiple memories that can faithfully represent loss and imperfections in these memories. Here, we simulate quantum key distribution (QKD) rates achievable in various satellite and ground station geometries for realistic experimental parameters.





References

1. J. Wallnöfer et. al., "Simulating quantum repeater strategies for multiple satellites", In preparation (2021).
2. M. Gündogan et. al., "Space-borne quantum memories for global quantum communication", arXiv:2006.10636 (2020)

Generation of optical Gottesman-Kitaev-Preskill states with cavity QED

J. Hastrup and U. L. Andersen

Technical University of Denmark, Department of Physics, 2800 Kgs Lyngby, Denmark

Gottesman-Kitaev-Preskill (GKP) [1] states are a central resource for fault-tolerant optical continuous-variable quantum computing. However, their realization in the optical domain remains to be demonstrated. Here we propose a method for preparing GKP states using a cavity QED system which can be realized in several platforms such as trapped atoms, quantum dots or diamond color centers. We then further combine the protocol with the previously proposed breeding protocol by Vasconcelos et al. [2] to relax the demands on the quality of the QED system, finding that GKP states with more than 10 dB squeezing could be achieved in near-future experiments.

References

[1] D. Gottesman, A. Kitaev and J. Preskill, Phys. Rev. A **64**, 012310 (2001)
[2] H. M. Vasconcelos, L. Sanz and S. Glancy, Optics Letters **35**, 3261 (2010)

Ultra-bright Source of Coherent Single Photons

A. Javadi[1], N. Tomm[1], N. Antoniadis[1], A. Korsch[1,2], D. Najer[1], M. C. Löbl[1], R. Schott[2], S. R. Valentin[2], A. D. Wieck[2], A. Ludwig[2] and R. J. Warburton[1]
[1] Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
[2] Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany
Author e-mail address: alisa.javadi@unibas.ch

Single-photon sources represent an invaluable resource in photonic quantum technologies, with applications in optical quantum computing and quantum key distribution. Single-photon generation efficiency (η) is critical for these applications as the complexity and the success rate of quantum protocols increase exponentially with the number of photons ($\propto\eta^N$). The established approach based on parametric down-conversion is probabilistic and inherently has low end-to-end efficiency. In this work, we break the established paradigms for single-photon generation by employing a quantum dot in an open microcavity [1]. We achieve an end-to-end efficiency of 53%, which is 2.3 times higher than the previous state-of-the-art. Given the exponential scaling of quantum protocols, our source would enable a 10^7 speed-up of 20-photon boson sampling experiment. Moreover, the observed efficiency is higher than the threshold for loss-tolerant photonic quantum computing for the first time. Crucially, the other metrics of our source match the state-of-the-art, i.e., HOM visibility 97.5% and $g^{(2)}(0)<2\%$.

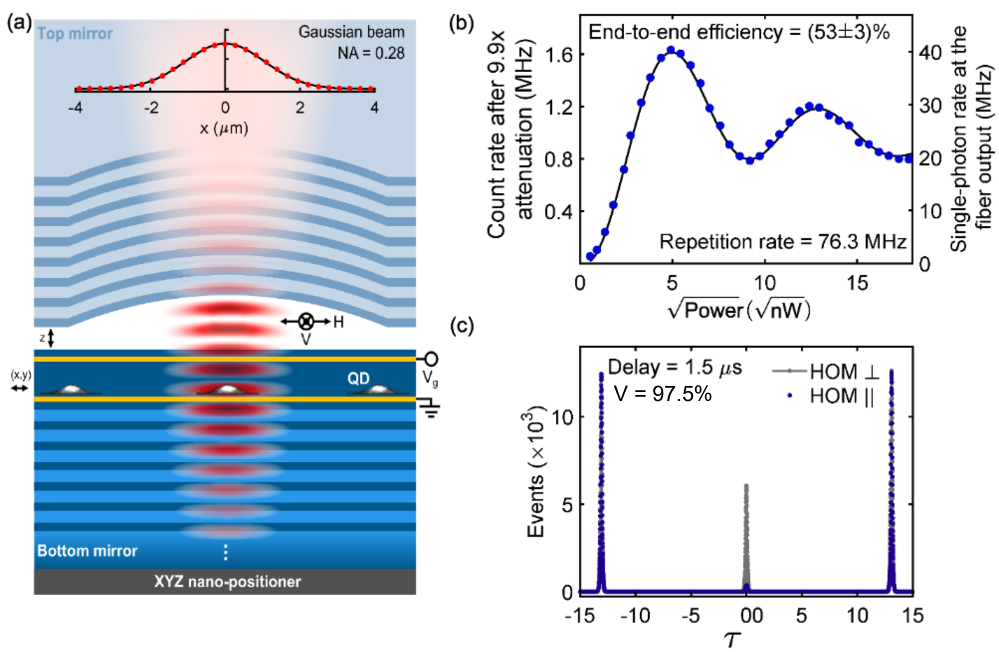


Figure 1 (a) The structure of the microcavity. (b) The output rate of the source. (c) Hong-Ou-Mandel interference between the photons that are generated 1.5 μs apart.

References

[1] N. Tomm, A. Javadi, N. Antoniadis, N. Najer, M. C. Löbl, A. R. Korsch, R. Schott, S. R. Valantin, A. D. Wieck, A. Ludwig, and R. J. Warburton, Nat. Nanotechnol. **16**, 399 (2021).

Quantum correlations in the spin-1/2 XXZ chain with modulated Dzyaloshinskii-Moriya interaction

F. Khastehdel Fumani[1], S. Mahdavifar[2], and G. I. Japaridze[3]

[1]*Department of Basic Sciences, Langarud branch, Islamic Azad University, Langarud, Iran*

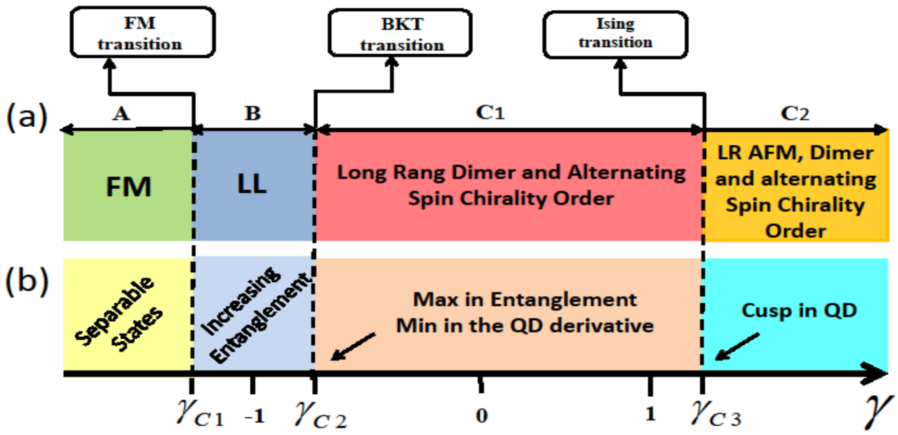
[2]*Department of Physics, University of Guilan, 41335-1914 Rasht, Iran*

[3]*Ilia State University, Faculty of Natural Sciences and Medicine, 0162 Tbilisi, Georgia*

Identification of quantum phase transition (QPT) is a complicated task in quantum many-body systems. Recently, it is widely argued that distinguishing QPTs can be obtained by analysis of the quantum correlation measures like entanglement and quantum discord (QD). In this work, we have investigated the ground state (GS) phase diagram of a one-dimensional spin-1/2 XXZ Heisenberg model with alternating Dzyaloshinskii-Moriya interaction, given by the Hamiltonian:

$$H = \mathrm{J}\sum_{n} S_n^x S_{n+1}^x + S_n^y S_{n+1}^y + \gamma S_n^z S_{n+1}^z + i(d_0 + (-1)^n d_1)(S_n^x S_{n+1}^y - S_n^y S_{n+1}^x)$$

According to Ref. [1], for $d_0 d_1 \geq 0$, depending on the value of the exchange anisotropy parameter, γ, the GS phase diagram of the above model contains three quantum critical points (QCPs) (see part (a) of Figure). Here, we reexamine the same problem using numerical Lanczos method for chains up to N = 26 sites and explicitly detect positions of QCPs by investigating the quantum correlations as the entanglement and the QD. Results show that the detection of the first critical point, as a discontinuity can be done by both entanglement and the QD. Probing the location of the maximum created in the entanglement, we found a Berezinskii- Kosterlitz-Thouless (BKT) phase transition. Moreover, we have successfully extracted the location of the BKT transition by consideration of the first derivative of the QD. Furthermore, it was shown that the QD can distinguish another QPT between two composite phases C1 and C2. (see part (b) of Figure)



[1] N. Avalishvili, G. I. Japaridze, G. L. Rossini, Phys. Rev. B **99**, 205159 (2019).

Aspects of the Generation of Cluster States with Group-4 vacancies in Diamond

Gregor Pieplow[1], Joseph H. D. Munns[1], Mariano I. Monsalve[1] and Tim Schröder[1]

[1]Integrated Quantum Photonics, Department of Physics, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany

One of the biggest challenges in photonic quantum computation is creating deterministic interactions between the photons that constitute the qubits in the computing architecture. This problem can be addressed by shifting the difficulty of producing entanglement between individual qubits to the generation of a universal resource state, enabling measurement-based quantum computation. Measurement-based quantum computation only relies on local operations and measurements, and does not require additional entangling operations to function. The difficult entangling of individual photons and creation of so-called cluster states as a computational resource are thus separated from the details of the computation and can be studied separately. Here we address the generation of a linear cluster state with group four vacancies such as the Silicon Vacancy (SiV) and Tin Vacancy (SnV) in diamond and some of the challenges that have to be overcome in order to for these systems to generate a highly entangled multi-photon state.

Large arrays of hBN single-photon emitters fabricated by capillary assembly

Johann A. Preuß[1], Eduard Rudi[1], Johannes Kern[1], Robert Schmidt[1], Rudolf Bratschitsch[1], Steffen Michaelis de Vasconcellos[1]

[1]*Institute of Physics and Center for Nanotechnology, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany*

Quantum photonic technologies require large numbers of robust and efficient quantum light sources. Recently, bright and stable single-photon emitters have been discovered in the 2D material hexagonal boron nitride (hBN), which efficiently emit single photons even at room temperature [1]. Gaining control over the positioning of nanocrystals hosting these light emitters is an important technique for the bottom-up fabrication of functional nanostructures.

Here, we demonstrate the fabrication of large rectangular arrays formed by tens of thousands of hBN nanoplatelets [2]. With the simple, yet effective technique of capillary assembly, we arrange commercially available hBN nanopowder (<150 nm diameter, multilayer platelets) suspended in water in large arrays as shown in Fig. 1a. The PMMA layer is removed after positioning to obtain arrays of freestanding hBN platelets.

Positioning yields of >95% are achieved on individual fields, as illustrated in Fig. 1b. After thermal annealing of the sample and upon optical excitation of the particles with a 532 nm laser we find stable and spectrally narrow quantum optical light emitters in 16% of the positions. Our preparation method opens the way for a systematic optical characterization of many easily addressable single-photon emitters in hBN. In addition, the array of quantum light emitters provides a platform for fabricating integrated photonic chips, which can provide thousands of single-photon sources at different emission energies.

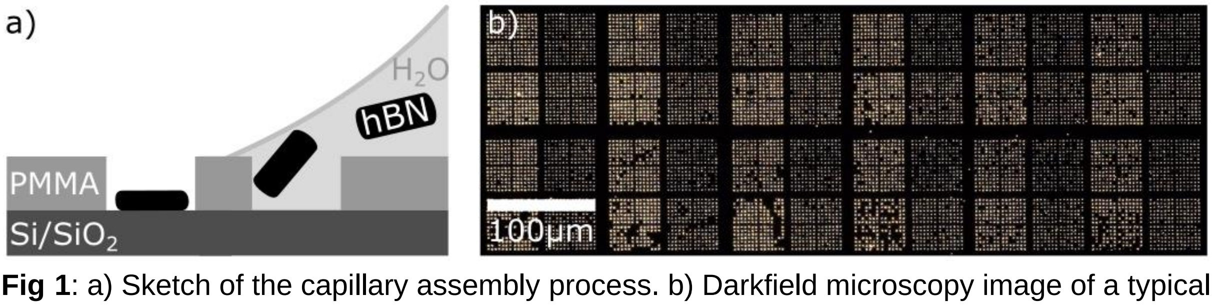


Fig 1: a) Sketch of the capillary assembly process. b) Darkfield microscopy image of a typical sample with a high yield of positioned hBN nanoplatelets after removal of the PMMA.

References

[1] T. T. Tran, K. Bray, M. J. Ford, M. Toth, and I. Aharonovich, Nature Nanotechnology 11, 37–41 (2015)

[2] J. A. Preuß *et al.*, 2D Materials 8, 035005 (2021)

A Scheme for Optical Reservoir Computers with Atomic Memory

Elizabeth Robertson[1,2], **Lina Jaurigue**[2], **Luisa Esguerra-Rodriguez**[1,2], **Guillermo Gallego**[2], **Kathy Lüdge**[2], **Janik Wolters**[1,2]

1. Deutsches Zentrum f ür Luft- und Raumfahrt e.V. (DLR), Rutherfordstr. 2, 12489 Berlin, Germany

2.Technische Universit ät Berlin, Str. des 17. Juni 135, 10623 Berlin, Germany

Email: elizabeth.robertson@dlr.de

Optical systems have been identified as one of the promising alternative hardware implementations for machine learning applications due to low latency, high bandwidth and lower energy consumption from the use of passive optics [1]. Reservoir computers (RCs) are interesting as they are versatile and easily trained recurrent neural networks - preforming particularly well on time series data [2]. RCs lend themselves particularly well an optics implementation, as the the reservoirs remained fixed, and the trained weights exchanged, allowing for reuse of one reservoir for multiple problems. It has been demonstrated that optic-to-electric conversion introduces uncertainty and time delay in the implementation of optical reservoir computers [3], thus motivating research into all-optical RCs. First implementations of an all-optical RC used feedback loop laser setups with fixed delay and dynamics, limiting state space which can be represented in the reservoir, but allowing quick data throughput [2,4]. We propose an all-optical setup with the internal states of the reservoir which are stored in an optical memory, allowing for more complex internal dynamics. We present an electro-optical implementation as first result, and outline how this can be implemented all-optically by using atomic vapor based memories [5].

Using an electro-optic modulator (EOM), we encode the internal states of a RC using pulses from an external cavity diode laser of 894nm. These pulses are then detected using an avalanche photo-diode (APD), where the internal state values are measured, the reservoir output x_{out} is calculated and then propagated through the reservoir. The reservoir outputs are used to train a classifier to learn the logical XOR gate. To train the network, we used a Ridge Regression classifier and 5-fold cross validation, on a training and test set size of 50 bits. We achieved a test accuracy of 80% without reservoir or training process optimisation. Building on this toy model we propose a re-configurable all-optical RC based on multi-cell optical memories.

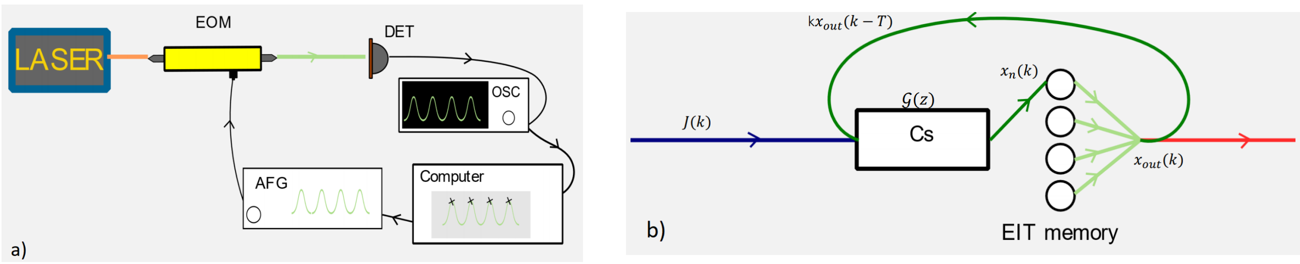


Fig. 1 a) Basic setup of the electro-optical RC. The node states are encoded on to the pulse amplitude by an EOM. The pulses are detected by an APD, and the detected signal is electrically passed on to the computer for updating the memory states. b) A schematic of all-optical reservoir with optical memory. The state of the network nodes x_n is encoded in the amplitudes and stored in a multi-cell atomic memory. The memory cells are partially read out, and the read out inputs combined to give the output of the network $x_{\text{out}}(k+1)$. One fraction of the output intensity is directed to the detector, the other fraction is combined with new input to the system J and is given as an input to a non-linear function $G(X)$, implemented the saturation absorbtion of a cesium vapor. The output from the non-linearity is then read into one of the memory cells, overwriting any information stored in the cell. By iterating the process, the RC evolves over time.

References

[1] X. Sui, Q. Wu, J. Liu, Q. Chen and G. Gu, "A Review of Optical Neural Networks," in IEEE Access, **vol. 8**, pp. 70773-70783, (2020)

[2] Van der Sande, G., Brunner, D., Soriano, M. C. 'Advances in photonic reservoir computing', Nanophotonics, **6(3)**, 561-576. (2017).

[3] Brunner, D. et al. Ṕarallel photonic information processing at gigabyte per second data rates using transient states.' Nat Com **4**, 1364 (2013).

[4] Paquot, Y., Duport, F., Smerieri, A. et al. 'Optoelectronic Reservoir Computing'. Sci Rep **2**, 287 (2012).

[5] Wolters J., Buser G., Horsley A., et al. 'Simple Atomic Quantum Memory Suitable for Semiconductor Quantum Dot Single Photons.' Physical Review Letters, ;119(**6**):060502. (2017)

Faster adiabatic ground state preparation with few measurements

Benjamin F. Schiffer,[1,2,*] Jordi Tura,[3,1,2] and J. Ignacio Cirac[1,2]

[1] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*

[2] *Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 Munich, Germany*

[3] *Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands*

Preparing the ground state of a Hamiltonian is a problem of great significance in physics with deep implications in the field of combinatorial optimization. The adiabatic algorithm is known to return the ground state for sufficiently long preparation times which depend on the a priori unknown spectral gap. We present the concept of a variational quantum adiabatic algorithm (VQAA) for optimized adiabatic paths [1]. We aim at combining the strengths of the adiabatic and the variational approaches for fast and high-fidelity ground state preparation while keeping the number of measurements as low as possible. Our algorithms build upon ancilla protocols which we present that allow to directly evaluate the ground state overlap. We benchmark for a non-integrable spin-1/2 transverse and longitudinal Ising chain with N = 53 sites using tensor network techniques. Using a black box, gradient-based approach, we report a reduction in the total evolution time for a given desired ground state overlap by a factor of ten, which makes our method suitable for the limited decoherence time of noisy-intermediate scale quantum devices.

[1] B. F. Schiffer, J. Tura, and J. I. Cirac, Adiabatic spectroscopy and a variational quantum adiabatic algorithm, arXiv preprint arXiv:2103.01226 (2021).

* Correspondence: Benjamin.Schiffer@mpq.mpg.de

A Quantum Annealer for Subset Feature Selection and the Classification of Hyperspectral Images

S. Otgonbaatar and M. Datcu

German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Hyperspectral images showing objects belonging to several distinct target classes are characterized by dozens of spectral bands being available. However, some of these spectral bands are redundant and/or noisy, and hence, selecting highly informative and trustworthy bands for each class is a vital step for classification and for saving internal storage space; then the selected bands are termed a highly-informative spectral band subset. We use a Mutual Information (MI)-based method to select the spectral band subset of a given class and two additional binary quantum classifiers, namely a quantum boost (Qboost) and a quantum boost plus (Qboost-Plus) classifier, to classify a two-label dataset characterized by the selected band subset. We pose both our MI-based band subset selection problem and the binary quantum classifiers as a quadratic unconstrained binary optimization (QUBO) problem. Thus, we adapted our MI-based optimization problem for selecting highly-informative bands for each class of a given hyperspectral image to be run on a D-Wave quantum annealer. After the selection of these highly-informative bands for each class, we employ our binary quantum classifiers to a two-label dataset on the D-Wave quantum annealer. In addition, we provide a novel multi-label classifier exploiting an Error-Encoding Output Code (ECOC) when using our binary quantum classifiers. As a real-world dataset in Earth observation, we used the well-known AVIRIS hyperspectral image (HSI) of Indian Pine, northwestern Indiana, USA.

References

[1] Otgonbaatar, Soronzonbold und Datcu, Mihai (2020) Quantum Machine Learning for Earth observation. **Phi-Week 2020**, 28. Sept. - 2. Okt. 2020.

[2] E. Farhi, J. Goldstone, S. Gutmann, and M. Sipser, “Quantum computation by adiabatic evolution,” **arXiv:0001106**, Jan 2000.

[3] S. Sarmah and S. K. Kalita, “Mutual information-based hierarchical band selection approach for hyperspectral images,” in Advances in Electronics, Communication and Computing, A. Kalam, S. Das, and K. Sharma, **Eds. Singapore: Springer Singapore, 2018**, pp. 755–763.

[4] A. Radoi and M. Datcu, “Multilabel annotation of multispectral remote sensing images using error-correcting output codes and most ambiguous examples,” IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing**, vol. 12**, no. 7, pp. 2121–2134, 2019.

High photon number entangled states and coherent state superposition from extreme-UV to far-IR

P. Stammer[1] and J. Rivera-Dean[1], T. Lamprou[2], E. Pisanty[3], M.F. Ciappina[4], P. Tzallas[2] and M. Lewenstein[1]

[1]*ICFO – Institute of Photonic Science, Castelldefels (Barcelona), Spain*
[2] *Foundation of Research and Technology - Hellas, Heraklion (Crete), Greece*
[3] *Max-Born-Institute, Berlin, Germany*
[4] *Guangdong Technion, Shantou, China*

We present a theoretical study on the generation of entangled coherent states and of coherent state superpositions, with photon numbers and energies, orders of magnitude higher than those provided by the current technology [1]. This is achieved by utilizing a quantum mechanical multimode description of the single- and two-color intense laser field driven process of high harmonic generation in atoms. It is found that all field modes involved in the high harmonic generation process are entangled, and upon performing a quantum operation, leads to the generation of high photon number non-classical coherent state superpositions spanning from the extreme-ultraviolet to the far infrared spectral region. These states can be considered as a new resource for fundamental tests of quantum theory and quantum information processing.

References

[1] P. Stammer *et. al,* arXiv:2107.12887

Non Gaussian Cluster States

Abhinav Verma*[1], Subhashish Barik[2], Mikkel Larsen[3], Jonas S. Neergaard Nielsen[4], and Ulrik L. Andersen[5]

[1,2,3,4,5]Center for Macroscopic Quantum States (bigQ), Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark.

This poster sheds light on the study of non-Gaussian multi-mode entangled states conducted as a Master's thesis. The study consists of a theoretical portion which investigates the different methods of generation of non-Gaussianity in multi-mode entangled states by subtraction of a single photon. The theoretical portion also studies and shows, in agreement with previous research works [1,2], the dissipation of non-Gaussian features within a cluster state by the use of Wigner function formalism. The study also undertook the investigation of non-Gaussianity induced within smaller 6-mode models of cluster states with the goal of understanding the propagation of non-Gaussianity and developing methods of generation of non-Gaussian clusters. The idea of Hilbert-Schmidt distance [3] is used to quantify the degree of non-Gaussianity. The experiment consists of photon subtraction performed on a larger Gaussian 2D cluster state [4] to generate a 200 mode non+Gaussian cluster and the results show an increase in variances in the mode where the photon is subtracted and the neighbouring modes. It is also demonstrated how excess Kurtosis takes negative values at the site of subtraction and at neighbouring sites, thus indicating non-Gaussianity, and the metric sharply decreases away from where it peaks.

References

[1] *Non-Gaussian quantum states of a multimode light field., Ra, YS., Dufour, A., Walschaers, M. et al, Nat. Phys. 16, 144–147 (2020).*

[2] *Tailoring Non-Gaussian Continuous-Variable Graph States, Mattia Walschaers, Supratik Sarkar, Valentina Parigi, and Nicolas Treps, Phys. Rev. Lett. 121, 220501 (2018).*

[3] *Quantifying non-Gaussianity for quantum information, Marco G. Genoni and Matteo G. A. Paris, Phys. Rev. A 82, 052341 (2010).*

[4] *Continuous variable cluster state computation, Mikkel Vilsbøll Larsen, DTU Physics. (2021).*

*Corresponding author.