Photonics for Information Processing

811. WE-Heraeus-Seminar

02 – 05 June 2024

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 811. WE-Heraeus-Seminar:

Photonics is an evolving field with immense potential to address the ever-increasing demands of information processing and data transmission. Despite promising breakthroughs, current developments and research efforts are slowed down by moderate device efficiencies as well as detrimental reliability and production time of device fabrication. The demonstration of the full advantage of photonics in information processing still requires addressing several challenges. These include developing new more efficient materials, rapid-prototyping manufacturing techniques and design approaches, and in turn improving the efficiency and reliability of photonic integrated devices, and advancing photonic-electronic interfaces and control at the system level for improving and implementing operating algorithms.

Within this workshop, we want to cover the topic of photonics in information processing in a broad overview with a combination of expert lectures, and discussions, complemented by contributed short-talks and poster presentations. The workshop focuses on sharpening the view for scalability in the context of materials, design and fabrication and investigate the latest and upcoming trends. By fostering collaboration, interdisciplinary discussions, and transfer of knowledge, the seminar seeks to push the boundaries of photonic information processing beyond the current horizon to establish potentially novel research directions. At the same time, we will give young scientists an insight into the current problems and proposed research directions and enable networking with leading experts.

Scientific Organizers:

Prof. Dr. Michael Kues, Leibniz University Hannover
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Introduction

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Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (16:30 h - 21:00 h) and Monday morning

Program

Program

Sunday, 02 June 2024

16:30 – 21:00	Registration	
18:30	*BUFFET SUPPER and informal get-together*	

Monday, 03 June 2024

08:00	*BREAKFAST*	
08:55	Scientific organizers	**Welcome**
09:00 – 10:00	Isabelle Staude	**Active Dielectric Metasurfaces for Diffractive Deep Neural Networks**
10:00 – 11:00	Peter Bienstman	**Optical Computing with Silicon Photonic Reservoirs**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 11:45	Gabriele Cavicchioli	**Recursive Integrated Photonic Processor for All-optical Matrix Inversion**
11:45 – 12:00	Nikolay Lukin	**Volume Holographic Optical Elements for Applications in Optical Computing**
12:00 – 12:15	Fiodar Marozka	**Optoelectronic Reservoir Computer with In-situ-optimized Digital Delayed Feedback**
12:15 – 12:30	Josefine Bjørndal Robl	**Clustering Using Gaussian Boson Sampling**
12:30 – 14:00	*LUNCH BREAK*	

Program

Monday, 03 June 2024

14:00 – 15:00	Alina Karabchevsky	**Integrated Photonics for On-chip Computing**
15:00 – 16:00	Daniel Brunner	**Towards Autonomous Optical Neural Networks Leveraging 3D Integration**
16:00 – 16:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:15	**Poster Pitches** (first half)	
17:15 – 18:45	**Poster Session 1 & Networking**	
18:45	*DINNER*	

Program

Tuesday, 04 June 2024

08:00	*BREAKFAST*	
09:00 – 10:00	Clivia M. Sotomayor Torres	**Coupled Photons-phonons for Information Processing**
10:00 – 11:00	Birgit Stiller	**Photonic Computation with Sound Waves**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Bhavin J. Shastri	**Neuromorphic Photonic Computing: Applications, Cassical to Quantum**
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 15:00	Rachel Grange	**Integrated or Random Nonlinear Optical Generator for Machine Learning**
15:00 – 15:15	Shreya Kumar	**Multiphoton Interference and Entanglement Using Multiport Beam Splitters**
15:15 – 15:30	Yannik Mahlau	**Efficient Inverse Design for Photonic Integrated Circuits**
15:30 – 15:45	Frederik Kofoed Marqversen	**Impact of Finite Squeezing on Measurement-based Quantum Computations Using GKP Qubits**
15:45 – 16:00	Sina Saravi	**Towards Truly Deep All-optical Diffractive Neural Networks**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:00	**Poster Pitches** (second half)	
17:00 – 18:30	**Poster Session 2 & Networking**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 05 June 2024

08:00	*BREAKFAST*	
09:00 – 10:00	Henning Menzel	**Orientational Order of Photoactive Colloidal 2D Nanoplatelets in Polymer Fibers**
10:00 – 11:00	Maurizio Burla	**Integrated Photonics Processing for Phased Array Antenna Beamforming**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 11:45	Maira Pérez Sosa	**Nanophotonic Metasurfaces for Optical Wireless Communication**
11:45 – 12:00	Ilker Oguz	**Programming Optical Propagation in Multimode Fibers for High Speed, Ultra-Low Power Computing**
12:00 – 12:15	Fan Tongmiao	**Biphoton Polarization Bell States from an InGaP Nonlinear Metasurface**
12:15 – 12:30	Frank Brückerhoff-Plückelmann	**Photonic Probabilistic Computing**
12:30 – 12:40	Scientific Organizers	**Closing**
12:40	*LUNCH BREAK*	

End of the seminar and departure

Posters

Poster Session 1, Monday, 3 June, 17:15 (CEST)

Sadeq Bahmani	Photonic Inverse Design for Directivity Enhancement of Quantum Emitters
Yassine Ben Chaabane	Inverse Design and 3D Printing of Polymer Metalenses on Optical Fiber Facets
Ivonne Bente	Adaptive Optical Neural Networks
Steven Becker	High-speed Coherent Photonic Random-access Memory in Long-lasting Sound Waves
Richard Bernecker	Optimized Photon Pair Generation in Parametric Down-conversion for High-dimensional Maximally Entangled States
Shi Bin	On-chip Parallelisms to Accelerate Photonic Convolutional Operations
Hadir Borg	Cryogels from Pt/γ-Fe2O3 and Pd/γ-Fe2O3 NPs as Promising Electrocatalysts for Ethanol Oxidation Reaction
Bruno Chaves	Spectro-temporal Control of Supercontinuum Generation Using a Photonic Integrated Chip
Glitta Rosalia Cheeran	Nonlinear Phase Wrapping for Linear Information Forwarding
Sarah Dean	Metasurface-Enabled Polarimetry with Redundancy for Satellite Imaging
Abhrodeep Dey	Polarization Dependant Unidirectional Excitation of Surface Plasmon Polaritons Using Actively Tunable Dielectric Loaded Plasmonic Metasurfaces

Poster Session 1, Monday, 3 June, 17:15 (CEST)

Dirk Dorfs	Alternative Plasmonic Materials – Colloid Chemical Synthesis, Characterization and Properties
Masoumeh Goudarzi	Nanophotonic Metasurfaces for Optical Wireless Communication
Min Jiang	Giant and Broadband Optical Chirality Enhancement in 3D Plasmonic Archimedean
Anahita Khodadad Kashi	Spectral Hong-Ou-Mandel Effect between a Heralded Single-photon State and a Thermal Field: Multiphoton Contamination and the Nonclassicality Threshold
Yilin Li	Spatio-Spectral Tailoring of Plasmonic Modes for Surface-Enhanced Coherent Anti-Stokes Raman Scattering (SECARS)
Saravanan Mani	Synthesis and Characterization of Linear/Nonlinear Optical Properties of Graphene Oxide and Reduced Graphene Oxide- Au-Fe2O3 Nanocomposite
Jesus Humberto Marines Cabello	Deep Context Processing with an Optoacoustic Recurrent Operator
Liam McRae	LNOI Based Architecture for Local Time-Wavelength Multiplexing
Luis Mickeler	HYBRAIN: Electronic-photonic Architectures for Brain-inspired Computing

Poster Session 2, Tuesday, 4 June, 17:00 (CEST)

Alessio Miranda	**Arbitrary Ratio Power Splitters Using Bent MultiMode Interference Couplers**
Mehmet Müftüoğlu	**Efficient Techniques for Supervised Output Training on Photonic Reservoirs and Extreme Learning Machines**
Abhishek Nanda	**Inverse Design for Integrated Polymer 3D Optical Circuits**
Alfonso Nardi	**Intensity Statistics Resulting from a Large Ensemble of Nonlinear Optical Operations Performed by a Disordered Photonic Medium**
Alexandra Rittmeier	**Combining Two-Photon Polymerization and Inverse Design to Enable the Fabrication of Tailored Nanophotonic Components**
Julius Römer	**Development of Record High-speed Quantum Key Distribution System**
Karthika S Sunil	**Numerical Demonstration of Archimedean Spiral with Highest Dissymmetry Factor**
Mohammad Sobhi Saeed	**Neuromorphic Information Processing in Nonlinear Optical Fibers**
Lorenz Sauerzopf	**Broadband Inverse Design Grating Couplers for Fast-Prototyping and Efficient Coupling**
Larissa Schoske	**Magnetic Aerogels from FePt and CoPt3 Directly from Organic Solution**
Naresh Sharma	**Photonic Integrated Scanning Microscopy**
Duarte Silva	**Towards a High Speed and Low Loss InP Electro-optical Phase Modulator for Heterogeneous Integration with SiN Photonics**

Poster Session 2, Tuesday, 4 June, 17:00 (CEST)

Grigorii Slinkov	Coherent Multi-frequency Photonic Activation Function
Pia Thomsen	Photoelectrochemical Investigation of Nanoparticle-Based Assemblies
Yu Wang	Polarization Insensitive 40-channel 100 GHz Spacing Fold-back Planar Echelle Grating Mux/Demux for Photonic Integrated Wavelength Selective Switches
Kilian Welz	Experimental Setup for Characterizing Waveguide-integrated Superconducting Nanowire Single-photon Detectors at 1550nm
Wenyong Xie	Tuning Photonic Bandgaps in Porous Anodic Alumina Structures Via Liquid Crystals (LCs)
Mingwei Yang	Optical Systems for Classical and Quantum Computing for Machine Learning in Orbit
Kessem Zamir Abramovich	Low-threshold Lasing with a Stationary Inflection Point in a Three-coupled-waveguide Structur
Yaoyuan Zhang	Design of a Compact and Efficient Silicon-Based Integrated Optical Phased Array

Abstracts of Lectures

(in alphabetical order)

Optical computing with silicon photonic reservoirs

P. Bienstman[1]

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We will discuss how **integrated photonic reservoir computing** is a promising approach for solving a number of problems in telecommunications, e.g. **non-linear dispersion compensation**. We have shown experimentally that using a reservoir consisting of only 20 nodes can achieve sub-FEC error performance on on-off keying (OOK) signals at 32 Gbaud/s. Such a neuromorphic approach has the potential for being a high-speed low-power alternative for traditional electronic DSP [1].

We also showed in simulations that the scheme can be extended from simple modulation formats like OOK to complex coherent formats like **64QAM**. We used the **Kramers-Kronig** (KK) detector configuration to achieve below-FEC-error-limit communications at 64 Gbaud/s, by including the nonlinear KK receiver in the training procedure [2].

Additionally, we have shown experimentally a completely new **self-learning** paradigm of optimising the weights inside a recurrent neural network, without relying on an offline algorithm or on a generated error feedback signal. Our network consists of ring resonators covered by a phase change material. By feeding the network with different binary sequences to be recognised, at powers above the plasticity threshold for the phase change material, we have shown that the network self-organises to better identify these sequences, without external intervention.

References

[1] S. Sackesyn**,** Optics Express **29**, 20, pp. 30991-30997 (2021)
[2] S. Masaad, Nanophotonics, https://doi.org/10.1515/nanoph-2022-0426 (2022)

Photonic Probabilistic Computing

F. Brückerhoff-Plückelmann[1,2] and W. Pernice[1,2]

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Artificial neural networks (ANNs) have achieved remarkable success in areas such as medical diagnosis, autonomous driving, and natural language processing when implemented on deterministic conventional hardware. However, deterministic models only provide point estimates based on known data and fail to consider the complete posterior distribution of the parameters. Bayesian neural networks (BNNs) address this issue by replacing deterministic network parameters with probability distributions to capture the probabilistic nature of inferring from incomplete observed data [1].

Due to the intractability of integrals describing the model, Monte Carlo simulations are used to approximate the output. This requires high-speed random number generation and a suitable processing architecture to efficiently compute BNNs. To tackle this challenge, we have developed a probabilistic photonic processor based on chaotic light as an entropy source. Unlike exploiting random fluctuations in material properties, we can conveniently control the correlation time of the intensity fluctuations by changing the optical bandwidth. With an optical bandwidth of 4 THz, we can deploy spectral multiplexing to sample from the output distributions in parallel.

We train the system by using stochastic variational inference (SVI) to minimize the divergence between the true posterior of the model parameters and the distributions educible by our architecture. To evaluate the system, we use the MNIST dataset of handwritten numbers, but only train the network on numbers zero to eight. By utilizing SVI, we can successfully classify the known numbers, and during testing, the BNN can accurately reject images of the unknown number nine [2].

References

[1] L. V. Jospin, "Hands-on Bayesian Neural Networks – A Tutorial for Deep Learning Users," arXiv (2020).
[2] F. Brückerhoff-Plückelmann, H. Borras, B. Klein, A. Varri, J. Dijkstra, C. D. Wright, M. Salinga, B. Risse, and W. Pernice, "Probabilistic Photonic Computing with Chaotic Light," arXiv (2024).

Towards Autonomous Optical Neural Networks Leveraging 3D Integration

Daniel Brunner
CNRS, University France Comte

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. 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. 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.

Integrated Photonics Processing for Phased Array Antenna Beamforming

M. Burla

TU Berlin, Germany

Phased array antenna control requires flexible, efficient and high-speed processing of the amplitude and phase of many individual antenna signals. Optical approaches for radio frequency antenna beamforming have been first proposed in the early 1990s, to provide solutions offering broad instantaneous bandwidth and large amount of tunable delays for phased array radars.

With the enormous progress of radio frequency integrated circuits, those optical beamforming techniques went out of the spotlight. But today we see a resurgence of interest toward photonic processing approaches, driven by the need of flexible antenna beam control for sub-THz waves in next generation wireless communications and space applications, and by the evolving capabilities offered by photonic integration.

Starting from a brief history of the topic, this talk will provide an insight on the current challenges and discuss where photonic processing can help.

Recursive Integrated Photonic Processor for All-optical Matrix Inversion

G. Cavicchioli[1], D. A. B. Miller[2], N. Engheta[3], A. Melloni[1], and F. Morichetti[1]

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Photonics is emerging as a viable technology for performing information processing task and in the last years we are assisting to the development of programmable optical processors (POPs). These devices can achieve higher throughput and lower latency compared to digital electronic processors, so they could accelerate the solution of specific mathematical problems. In particular, several photonic integrated circuits providing efficient implementation of matrix-vector multiplication have been proposed in the last years [1]. Solving more complex linear algebra problems, though, often requires an electro-optical conversion, which introduces a bottleneck in the performance of POPs. For this reason, all optical implementations of mathematical problems are of critical importance to exploit the full potential of POPs.

In this work, the design of a programmable optical processor performing matrix inversion entirely in the optical domain is presented. Matrix inversion is achieved thanks to a recursive topology based on multiple optical cavities coupled together by a mesh of reconfigurable Mach-Zehnder interferometers (MZIs) [2]. Thanks to this reconfigurability, the elements of the matrix that the device inverts can be programmed by tuning the phase shifters of the MZI mesh. To assess the functionalities of this architecture, a prototype circuit inverting 3x3 matrices was realized using a commercial silicon photonics (SiPh) process and characterized experimentally. The prototype analog bandwidth is in the order of some GHz, so inverting a matrix takes only few nanoseconds. The measurements validate the circuit model and its capability of inverting matrices.

References

[1] H. Zhou et al., “Photonic matrix multiplication lights up photonic accelerator and beyond,” Light: Science & Applications, vol. 11, no. 1, Feb. 2022.
[2] N. Mohammadi Estakhri, B. Edwards, and N. Engheta, “Inverse-designed metastructures that solve equations,” Science, vol. 363, no. 6433, pp. 1333–1338, Mar. 2019.

Integrated or random nonlinear optical generator for machine learning

R. Grange

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Nonlinear devices are present in our daily life with many applications: light sources for microsurgery, green laser pointers, or modulators for telecommunication. Most of them use bulk materials such as glass fibres or high-quality crystals, hardly integrable or scalable. Even the fast developments of thin film lithium niobate face the challenging etching of metal-oxides. Therefore, the quest for a non-centrosymmetric material system, easy to fabricate and to scale up while maintaining its functionality is still ongoing. Here I will present our recent advances in top-down fabrication of lithium niobate devices and bottom-up assemblies of randomly oriented nanocrystals to produce electro-optic, nonlinear and parametric down conversion signals for information processing.

In a first application, we use a 14-mm waveguide in lithium niobate on an insulator as an optical processor to validate the benefit of optical nonlinearity for reservoir computing. Data are encoded on the spectrum of a femtosecond pulse, which is launched into the waveguide [1]. A second approach is based on a disordered polycrystalline slab composed of lithium niobate nanocrystals. Mediated by random quasi-phase-matching and multiple scattering, linear and nonlinear optical speckle features are generated defining a complex neural network in which the second-order nonlinearity acts as internal nonlinear activation functions [2]. Both cases show improved performance across a large collection of machine learning tasks in image classification, regression, and graph classification with varying complexity.

References

[1] M. Yildirim, I. Oguz, F. Kaufmann, M. R. Escalé, R. Grange, D. Psaltis, and C. Moser, "Nonlinear optical feature generator for machine learning," *APL Photonics* **8** (2023).

[2] H. Wang, J. Hu, A. Morandi, A. Nardi, F. Xia, X. Li, R. Savo, Q. Liu, R. Grange, et al., "Large-scale photonic computing with nonlinear disordered media," arXiv:**2310.07690** (2023).

Integrated Photonics for Optoelectronic Physical Reservoir Computing

Alina Karabchevsky

[1]*Iben-Gurion University of the Negev, Beer-Sheva, Israel*

On-chip nanophotonic devices represent a category of tools designed to manipulate light directly on a chip, offering significant performance enhancements compared to conventional components of integrated photonics. These ultra-fast and energy-efficient nanoscale optoelectronic devices target various applications such as high-performance computing, chemical and biological sensing, energy-efficient lighting, environmental monitoring, and beyond. Their growing appeal as fundamental elements in diverse systems stems from their distinctive attributes, including a substantial evanescent field, compact design, and crucially, their adaptability to suit specific application needs through configuration[1].

Here, I will present an on-chip reservoir computing (RC) which adopts a neuromorphic strategy inspired by biological neural systems, utilizing randomized and fixed internal connections to streamline training and enable easy implementation. Optoelectronic oscillators represent a highly promising material platform for physical RC due to their ability to merge the high modulation bandwidth of optics with the robustness, flexibility, and tunability of electronics. We have developed a physical reservoir that achieves cutting-edge performance in tasks such as pattern recognition and time-series prediction through the utilization of delayed feedback. During my talk, I will show that even a single physical node employing FPGA-based delayed feedback demonstrates remarkable results. By integrating digital delay, sufficient delay time is ensured within the reservoir's operational bandwidth, which is compatible with standard electronic hardware. This feature enables fine-tuning and on-the-fly optimization of delay time, resulting in a normalized mean squared error (NMSE) below 0.6 in the NARMA10 time series recovery task.

References

[1] Karabchevsky, A, Katiyi, A., Ang, A. S., Hazan, A. 2020. On-chip nanophotonics and future challenges. Nanophotonics, Invited Review, 9(12), 3733-3753.

Multiphoton interference and entanglement using multiport beam splitters

Shreya Kumar,[1,2] Alex E Jones,[3] Daniel Bhatti,[1,2] Matthias J Bayerbach,[1,2] Simone E D'Aurelio,[1,2] and Stefanie Barz[1,2]

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Quantum interference of photons is essential to many applications in quantum technologies, such as generation of entangled states, quantum metrology, quantum imaging and photonic quantum computing. One of the prerequisites for reliable quantum interference is that the photons are pure and indistinguishable. The visibility of the Hong-Ou-Mandel (HOM) interference dip is usually used to deduce the quality of the interfering photons. In case of two photons, this visibility is reduced by distinguishability and mixedness in the same way. However, in this work, we show that that when scaling up to three photons, despite having similar HOM interference visibilities, one can differentiate between distinguishability and mixedness of the photons by observing the photon statistics after interference at a three-port beam splitters, called a tritter [1]. This shows that the HOM visibility alone is inadequate to discriminate between distinguishability and mixedness of the photons and that it is important to characterize photon state purity, in order to study interference effects in multiphoton experiments.

Additionally, multiphoton entangled states are essential resources to networked quantum communication protocols such as quantum key exchange, quantum secret sharing, and in measurement-based quantum computation. While various experimental approaches have generated different types of photonic entangled states, most setups are optimized to generate a specific state, and require modifications in order to switch between different states. Our approach generates genuine multipartite entangled states belonging to different classes using one setup by sending three independent photons through a tritter [2].

References

[1] A. E. Jones, S. Kumar, S. D'Aurelio, M. Bayerbach, A. J. Menssen, and S. Barz, "Distinguishability and mixedness in quantum interference," Phys. Rev. A **108(5)**, 053701 (2023).

[2] S. Kumar, D. Bhatti, A. E. Jones, and S. Barz, "Experimental entanglement generation using multiport beam splitters," New Journal of Physics, **25(6)**, 063027 (2023).

Volume holographic optical elements for applications in optical computing

N. Lukin[1] and S. Sinzinger[1]

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Holography and the fabrication of holographic optical elements (HOEs) expand the range of manufacturing methods for diffractive optical elements. Compared to classical photolithographic techniques, they offer significant potential in terms of achieving high aspect ratios and diffraction efficiencies, as well as smaller grating periods. Challenges arise regarding the diversity of producible structures and the availability of suitable materials for holographic exposure. Another aspect gaining increasing importance for holographic-optical components is the so-called multiplexing of various structures, which can influence both spatial and spectral parameters of the incident light. These properties open up the use of HOEs for applications such as optical computing. In this contribution, we want to present examples of optical exposure setups in holographic photopolymers and discuss design approaches for elements with a view to their application in optical computing.
In the talk, we would like to demonstrate how holographic optical elements can be used for reservoir computing based on the work by Antonik et al. [1]. We want to demonstrate what characteristics of the particular volume hologram types make it suitable for use as a reservoir and what changes it requires in the training process. Additionally, we would also talk about what functionalities can be realized with the help of volume holograms for optical computing in general. Furthermore, we elaborate on why volume HOEs have potential as a fabrication technique regarding integration on plane substrates as well as scaling by briefly covering the topic of replication of the holograms.

References

[1] P. Antonik, N. Marsal, D. Brunner, D. Rontani. Human action recognition with a large-scale brain-inspired photonic computer. Nature Machine Intelligence, 2019, 1 (11), pp.530-537. 10.1038/s42256-019-0110-8

Efficient Inverse Design for Photonic Integrated Circuits

Frederik Schubert[1], Konrad Bethmann[1] and Yannik Mahlau[1]

[1]*Institute for Information Processing, Leibniz University Hannover, Germany*
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Inverse design methods are essential to accelerate the development of next-generation photonic integrated circuits (PICs) for information processing. However, the computational challenges associated with optimizing 3D PICs are significant, especially as new fabrication techniques for the two-photon polymerization (TPP) process enable more complex multi-material designs. We present an efficient inverse design framework that combines reverse-mode automatic differentiation [1] for FDTD simulations with the scalability of neural networks. Specifically, we utilize a memory efficient gradient calculation by exploiting the reversible nature of FDTD [2].
By constraining the optimization to account for TPP fabrication constraints, our approach enables the practical realization of 3D PICs with enhanced performance. In general, our inverse design approach is able to optimize a design for any desired functionality while accounting for any fabrication constraints. As an example, we apply our framework to the coupling problem in PICs, demonstrating its ability to generate complex structures that improve efficiency.
Our inverse design approach provides a way to overcome current bottlenecks in photonic information processing by facilitating the design of novel high-performance devices.

References

[1] Blondel, M.; Roulet, V. The Elements of Differentiable Programming. (2024)
[2] Tang, R. J.; Lim, S. W. D.; Ossiander, M.; Yin, X.; Capasso, F. Time Reversal Differentiation of FDTD for Photonic Inverse Design. ACS Photonics, **10**, 4140–4150 (2023)

Optoelectronic reservoir computer with in-situ-optimized digital delayed feedback

F. Marożka[1], S. Watad[1], A. Naser[1], A. Calà Lesina[2], A. Novitsky[3], and A. Karabchevsky[1]

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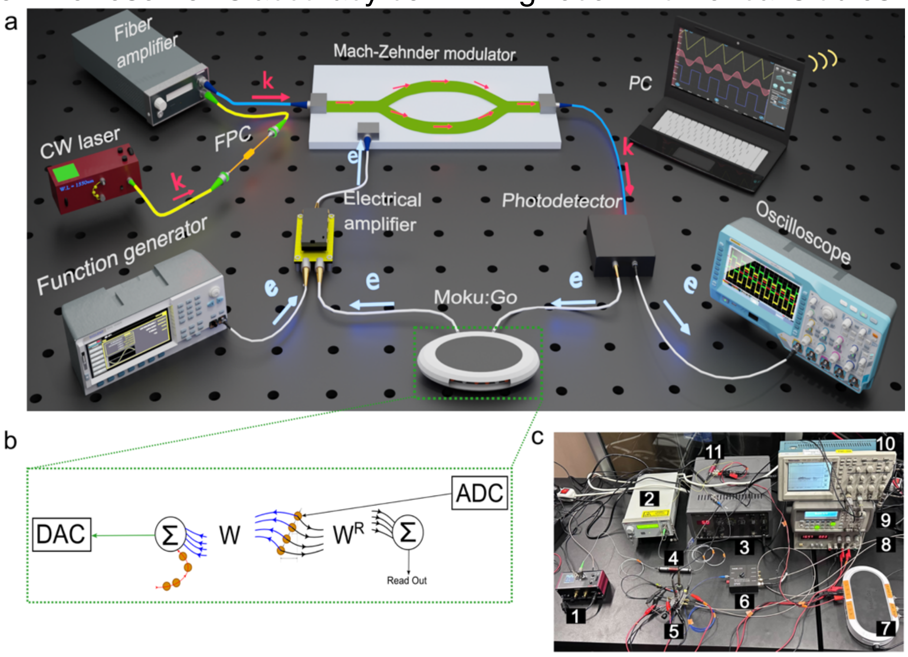
Reservoir computing (RC) is a paradigm in neuromorphic computing that emulates processes in biological neural systems based on randomized and fixed rather than learned neural connections, simplifying the training process, and facilitating energy-efficient hardware realizations[1,2]. The most practical realizations of RC exploit delay systems[3]. Here, we implement a delay-based optoelectronic reservoir computer featuring FPGA-based delay line. Such a choice of delay mechanism provides delay time tuning which enables *in situ* optimization of our reservoir. We perform *in situ* optimization for three diverse benchmark tasks and reveal substantial effect of the delay time on the reservoir's accuracy confirming recent numerical studies[4,5].



References

1. Lukoševičius, M. & Jaeger, H. *Computer Science Review* **3**, 127–149 (2009).
2. Brunner, D. *et al. Journal of Applied Physics* **124**, 152004 (2018).
3. Appeltant, L. *et al. Nat Commun* **2**, 468 (2011).
4. Stelzer, F., *et al. Neural Networks* **124**, 158–169 (2020).
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Impact of finite squeezing on measurement-based quantum computations using GKP qubits

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Our study delves into the potential of the Gottesman-Kitaev-Preskill (GKP) code [1] for realising fault-tolerant qubits within the realm of photonic systems. Leveraging Gaussian operations alongside logical Pauli eigenstates, theoretical frameworks suggest the possibility of fault-tolerant universal quantum computing through measurement-based approaches [2]. However, in the noisy intermediate-scale quantum (NISQ) era, where the technology operates with approximate codewords of suboptimal quality, limited squeezing in generating approximate GKP qubits, and expensive logical error correction, the practical computational limits remain unclear.

To explore near-term applications of GKP Measurement-Based Quantum Computing (MBQC), we introduce a novel numerical approach based on tensor network methods and simulate quantum computations using approximate GKP qubit states. Our investigations focus on logical fidelity [3] with increasing circuit size and varying levels of squeezing in the approximate codewords. We explore these scenarios both with and without continuous-variable GKP error correction, from which a direct comparison can be made. For this purpose, we derive new analytical results about GKP error correction with finite energy logical states that allow for faster simulation but also provide important physical insights into real physical GKP error correction. Using these results we show what are the expected requirements put on hardware in order to perform computations with NISQ photonic devices. Finally, an investigation of the performance of gate-based vs. measurement-based methods is presented. With the Grover search algorithm as a particular example, we highlight the different advantages and disadvantages of both approaches.

This research provides explicit insights into how limited squeezing affects quantum computations with GKP states, contributing to the understanding of challenges on the path to photonic fault-tolerant and universal quantum computing.

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Orientational order of photoactive colloidal 2D nanoplatelets in polymer fibers

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Light-emitting polymer fibers, prepared from polymers embedding chromophores or functional nanoparticles, are suitable for various applications in advanced photonics and sensing technologies. Electrospinning is a promising method for preparation of such active polymeric nanomaterials [1]. However, while electrospinning is a facile process for incorporating dyes or nanoparticles into the fiber matrix material to adjust the optical properties, it is also a delicate process that is influenced by a whole range of parameters. Moreover, although classical electrospinning produces very thin fibers, due to the typical whipping motion they tend to be deposited in a disordered manner as a nonwoven and can then no longer be manipulated easily. However, by adjusting the parameters, electrospinning can also be performed in the stable jet mode, which produces somewhat thicker fibers but deposits them as highly aligned fiber bundles [2]. The method was optimized to produce smooth and uniform fiber surfaces and to control fiber thickness and orientation [3].
Microfibers were prepared by stable jet electrospinning from PMMA with two-dimensional semiconductor nanoplatelets (CdSe@CdS). Highly aligned fibers with an orientation of the NPLs were obtained [4]. Dominant anisotropic emission along the fibers was achieved, which is expected to have superior performance.

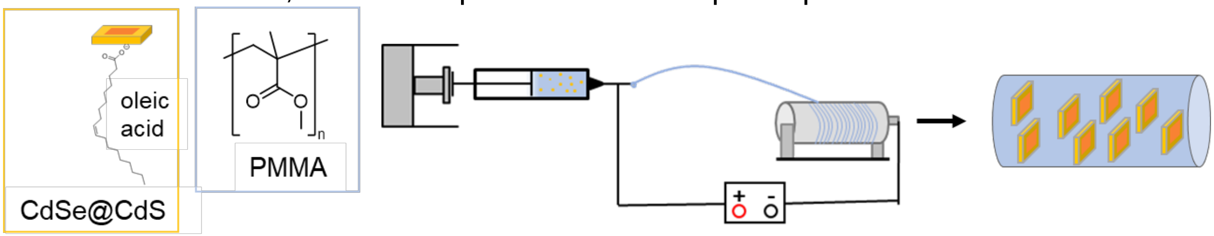

Figure 1: Schematic of the linear jet electrospinning of PMMA with with fluorescent nanoplatelets

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Programming Optical Propagation in Multimode Fibers for High Speed, Ultra-Low Power Computing

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Scattering media, like optical fibers, offer numerous interactions within a small space effortlessly. These interactions can be considered as a physical passive weight bank that its different sets of weights can be utilized by preconditioning the input data [1]. In this study, we experimentally demonstrate that this principle can be put to use for a highly efficient optical computing system for machine learning tasks.

The proposed optical system comprises a digital micromirror device (DMD) to spatially modulate a laser beam with pre-processed input information, a multimode fiber where the beam undergoes an information-processing transform based on the preprocessing of the input data, and a quadrant photodiode to detect the output's center location. By training the preprocessing operation with a digital twin of the system, we achieve all-optical inference results without needing any digital operations post-optical computing.

This configuration enables a high input and output data rate exceeding 1000 frames per second, with a total power consumption of only 2 W, while maintaining task accuracies comparable to digital neural networks. Our optical computing framework is particularly suitable for edge AI applications such as self-driving or patient tracking, where low latency and energy consumption are critical.

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Nanophotonic Metasurfaces for Optical Wireless Communication

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Detectors for optical wireless communication have achieved high electrical bandwidths due to their miniaturization. However, this miniaturization limits their power collection, forcing the use of optical elements to focus the incoming light into small areas. This approach is limited by the fundamental principle of the conservation of the etendue, which describes how well the emission from an extended and divergent source can be focused. Passive optical elements cannot reduce the etendue, which does not allow to focus divergent beams from extended sources into small areas. To overcome this principle, we use active optical elements that absorb omnidirectionally the emission from the source and emit a collimated beam that can be focused onto a small area photodiode. This omnidirectional absorption and directional emission is achieved with photonic metasurfaces [1]. We discuss the metasurface working principle, its design and the limitations of the receiver concept in terms of size, bandwidth and field of view (FoV).

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Clustering Using Gaussian Boson Sampling

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The process of categorising objects with high similarity into groups is deeply embedded in human nature and constitutes a fundamental aspect of daily life, and likewise, it plays a crucial role in research to identify clusters within data. Various clustering algorithms have been developed, one of these being divisive hierarchical clustering which iteratively subdivides the data into smaller groups until it reaches clusters of minimum size, thereby achieving an optimal clustering solution with exponential time complexity. While faster heuristics are available, they sacrifice precision for a reduced time complexity, providing only locally optimal solutions in polynomial time rather than globally optimal solutions in exponential time.

Our research explores the leveraging of quantum properties to devise a clustering method that is both fast and precise; more specifically, the method is based on the recently developed Gaussian boson sampling scheme, which involves sending Gaussian states through an interferometer encoded with the data graph, measuring the number of photons in each output. Utilising that the frequency of sampling an output photon pattern correlates with the number of perfect matchings in that subgraph and in turn the density of its nodes, we propose a divisive hierarchical clustering method providing a guarantee of approaching the globally optimal clustering solution for a considerable yet achievable number of samples. Initial findings suggest that the method provides an exponential speedup over classical sampling by effectively suppressing the sampling of irrelevant subgraphs, however, further research is essential to establish the extend of these results and to benchmarking our algorithm against established divisive hierarchical heuristics.

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Towards truly deep all-optical diffractive neural networks

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Diffractive neural networks (DNNs) are an optical implementation of deep neural networks, which explore the scattering and propagation of light at and between multiple layers of diffractive optical elements [1]. One could potentially map a deep neural network computational algorithm onto a DNN structure, to perform computations with light, which could then benefit from low-energy consumption and light-speed performance of optical systems. The resulting DNNs could be used for complex image classification and analysis tasks, and more generally for creating an all-optical computer, where the input and output to the system is light.
The realization of such a system is critically dependent on having access to diffractive optical elements with a specific class of nonlinear responses. The nonlinear optical elements will play a similar role to nonlinear activation functions in neural network algorithms. The presence of layers with nonlinear responses give a multilayer neural network its true “depth”, because a fully linear multilayer network is equivalent to a linear single-layer network. Using layers with appropriate nonlinear responses in a multilayer configuration gives a deep neural network it “universal approximation” capability, which means it can perform computations with an arbitrary complexity.
However, making diffractive optical elements with the appropriate nonlinear response is highly challenging, mainly because all-optical nonlinearities are notoriously weak, and require high optical intensities, which can make the use of nonlinear DNNs less practical. In this talk, I will first give an overview on the stat-of-the-art approaches in creating nonlinear DNNs. Then, I will present our efforts towards using second-harmonic-generation (SHG) for this goal, where I show how SHG can enhance the classification accuracy of DNNs for object recognition. I will also put a path forward to use second-order parametric processes for reaching the universal approximation capability.

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Neuromorphic photonic computing: applications, classical to quantum

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Artificial intelligence (AI) powered by neural networks has enabled applications in many fields (medicine, finance, autonomous vehicles). Digital implementations of neural networks are limited in speed and energy efficiency. Neuromorphic photonics aims to build processors that use light and photonic device physics to mimic neurons and synapses in the brain for distributed and parallel processing while offering sub-nanosecond latencies and extending the domain of AI and neuromorphic computing applications. We will discuss photonic neural networks enabled by silicon photonics, lasers, detectors, co-integrated electronics, analog memory, and also some recent work on thin-film niobate photonics. We will highlight applications that require low latency and high bandwidth, including wideband radio-frequency signal processing, fiber-optic communications, and nonlinear programming (solving optimization problems). We will briefly introduce a quantum photonic neural network that can learn to act as near-perfect components of quantum technologies and discuss the role of weak nonlinearities.

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Coupled photons-phonons for information processing

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We have investigated optomechanical structures for information transmission and processing, considering scalability, room temperature operation and frequencies in useful communication regimes such as 2-14 GHz.

These Si nanofabricated structures, based on the interplay of photonic and phononic modes, offer a rich spectrum of functions based on non-linear interactions ranging from phonon lasing [1], the generation of frequency combs, synchronisation [2] and extending towards single and multimode operation [3. 4].

We will present our findings and discuss our approach towards the design and realisation of topological phononic waveguides [5].

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Active Dielectric Metasurfaces for Diffractive Deep Neural Networks

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All-optical diffractive deep neural networks (D^2NNs), namely holographic optical elements interconnected by free space light propagation, have become a hot topic in (nano)photonics based on their capability to perform certain classification tasks at almost the speed of light [1]. However, the majority of D^2NNs considered so far was passive and linear, limiting the possibilities for the implementation of trainable models and the effective number of layers.

Metasurfaces composed of designed dielectric nanoresonators arranged in a plane offer unique opportunities for controlling the properties of light fields [2]. Such metasurfaces can e.g. impose a spatially variant phase shift onto an incident light field, thereby providing control over its wave front with high transmittance efficiency. Initially most investigated metasurfaces were linear, and their optical response was permanently encoded into the structure during fabrication. Recently, a growing amount of research is concentrating on active metasurfaces, specifically on the integration of optical nonlinearities into dielectric the metasurfaces, as well as on obtaining dynamic control of their optical response. Such nonlinear and tunable all-dielectric metasurfaces may offer important ingredients to overcome the current limitations of D^2NNs.

This talk will start with a brief introduction into D^2NNs. This will be followed by an overview of our recent advances in nonlinear and tunable all-dielectric metasurfaces [3]. In particular, second harmonic generation in metasurfaces made of, or containing, materials with a high second-order nonlinear susceptibility, such as III-V semiconductors, lithium niobite, and monolayers of transition metal dichalcogenides will be discussed. For dynamic tuning of the metasurface response, we integrate them into nematic-liquid-crystal cells, allowing to modify their linear-optical response using an applied voltage or temperature as control parameters. Alternatively, photoresponsive polymers can be employed as an active material for metasurface tuning [4].

Finally, we speculate on technological implementations allowing to integrate active dielectric metasurfaces into D^2NNs. Altogether, our results illustrate the potential of all-dielectric metasurfaces as nonlinear and tunable components for next-generation D^2NNs.

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Photonic computation with sound waves

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Photonics has the potential to advance modern quantum technologies and high-speed applications such as communications and the processing of large amounts of data. However, to replace or improve the well-established systems with photonic solutions, there is still a way to go. A promising approach to manipulate light all-optically is to use the link of optical waves with acoustic vibrations. Our research experimentally investigates how traveling sound waves can be used to process states of light in the classical and quantum regime.
Via the nonlinear effect of stimulated Brillouin scattering (SBS), acoustic waves can be created all-optically by counter-propagating optical signals. With help of acoustic waves, we implement several building blocks for photonic machine learning, such as a recurrent operator [1] and a nonlinear activation function [2]. We experimentally demonstrate a temporary storage for light information [3] and show how to extend the performance in terms of bandwidth [4] and storage time [5,6]. SBS is also a versatile tool for processing polarization and orbital angular momentum, where we demonstrate a non-reciprocal device [7] and a vortex laser [8]. In order to enter the regime of quantum signal processing, we demonstrate laser cooling of acoustic phonons [9] which then represent a macroscopic object for studying quantum to classical transitions. We investigate photon-phonon entanglement [10] and pulsed optoacoustics in waveguide systems [11]. The fact that acoustic waves are a very different type of wave compared to light allows to access and sense parameters that are not influencing light itself. An example thereof is the investigation of the metastable state of negative pressure in liquids [12].

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Biphoton Polarization Bell states from an InGaP nonlinear metasurface

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Nonlinear dielectric metasurfaces incorporating subwavelength nanostructures are emerging as promising platforms for generating versatile and highly flexible miniaturized photon pair sources via spontaneous parametric down-conversion (SPDC). Unlike conventional nonlinear crystals, metasurfaces can enhance and customize SPDC by leveraging optical resonances in the nanostructures [1,2]. While polarization entanglement was proposed in a multiplexed metasurface [3] and demonstrated in thin films [4,5], the experimental realization in metasurfaces remained an open challenge.

We reveal that enhanced and tailored generation of polarization Bell state can be realized with an InGaP nonlinear metasurface through the SPDC process. The metasurface incorporates nanostructured InGaP film of 500 nm thickness with a high second-order susceptibility of 110 pm/V. The nanostructures support a local optical resonance at 1550 nm, allowing enhanced generation of counterpropagating photon pairs. Our experimental results show that the photon-pair rate is enhanced by 25 times in comparison to unstructured film. Notably, the coincidence-to-accidental ratio is ~8000 due to tailored bandgap and low fluorescence, which is 2-3 orders of magnitude higher than the photon pairs from most semiconductor or van der Waals materials. Furthermore, we select the InGaP crystal orientation as <110>, offering a nonlinear tensor for generating polarization entanglement. The density matrix reconstructed experimentally using quantum tomography confirms the generation of the polarization-entangled state, manifesting a concurrence of 0.92 and fidelity of 95% with the maximally entangled Bell state. More importantly, we observe that the amplitude of polarization entanglement is optically tunable via pump wavelength due to optical mode asymmetry, which is a unique feature unattainable with unstructured nonlinear films. The results establish the first metasurface-based source of tunable polarization entanglement and manifest an important step closer to quantum communications with quantum light sources from metasurfaces.

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Abstracts of Posters

(in alphabetical order)

Photonic inverse design for directivity enhancement of quantum emitters

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Quantum emitters are one of the main building blocks of photonic information processing platforms. They play a crucial role in photonic quantum computing, sensing, and communication. However, their radiation pattern poses a challenge to their coupling to the other components, degrading the performance of the structure. In order to overcome this issue, the radiation pattern of these emitters should be manipulated to enhance their directivity [1] [2].

In this work, we propose an inverse design approach based on topology optimization [3] to design photonic structures coupled to a dipole emitter that can change its radiation pattern. We investigate the directivity and polarization of the radiated field from the optimized structure.

By this method, we can design highly efficient quantum sources that provide the desired radiation pattern and high coupling efficiency for information processing.

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High-speed coherent photonic random-access memory in long-lasting sound waves

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With recent developments in the field of optical computing, the need for novel optical memories becomes more important to harness the full potential of optical computing. Optoacoustic memory based on stimulated Brillouin scattering coherently stores optical information in sound waves while offering quick access (sub-ns) and frequency-selective operation. However, its intrinsic storage time has so far been limited to about 10 ns.
Here we experimentally show an optoacoustic memory that retrieves amplitude and phase information after 120 ns, surpassing the state of the art by one order of magnitude (see Figure 1). To achieve this, we increase the intrinsic phonon lifetime of a highly nonlinear fiber by a factor of six by cooling the fiber down to 4.2K. We demonstrate the performance enhancement of optoacoustic memory by measuring the amplitude and phase information of an initial data pulse and its corresponding retrieved readout pulse using direct and double homodyne detection.
Our work can accelerate photonic computing and has the potential to advance other applications of Brillouin scattering, such as optoacoustic filters in microwave photonics. Furthermore, it is compatible with active acoustic refreshment technique potentially leading to all-optical coherent memory beyond 1 μs.

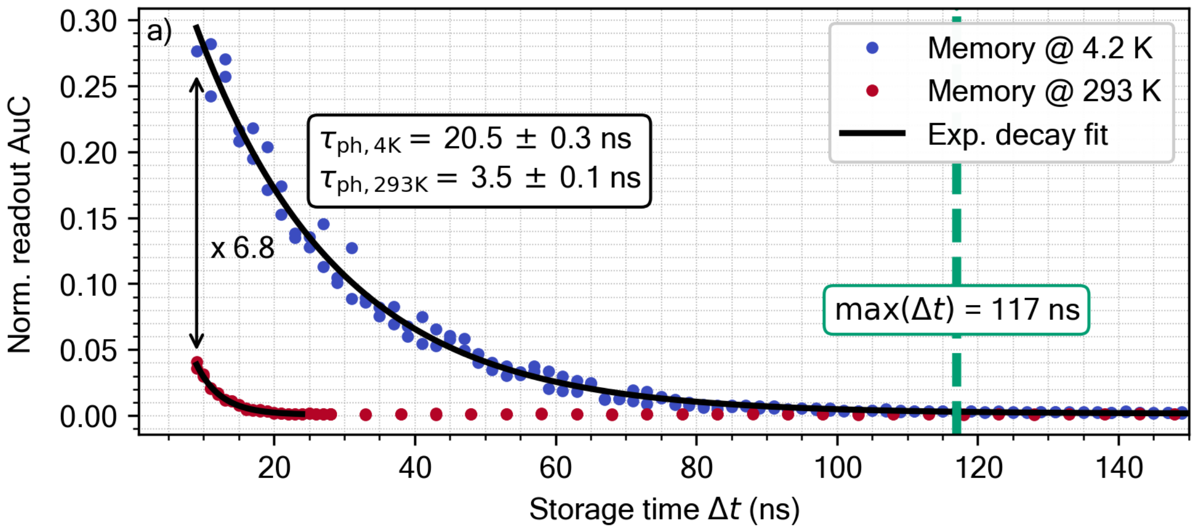

Figure 1: Lifetime analysis of the cryogenic optoacoustic memory. Taken from [1]

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Adaptive optical neural networks

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Brain-inspired or neuromorphic computing approaches are of high interest because of their promising performance regarding energy efficiency when implementing artificial neural networks (NNs). Neuromorphic devices implement NNs in an analog fashion instead of a digital simulation on a conventional computer. The requirements to the hardware of a neuromorphic system are inherent scalability and the requirement of "artificial neurons" for non-linear operations and "artificial synapses" for storing linear connections between neurons. Additionally, synaptic plasticity (adaptive connection strength) and structural plasticity (rewiring of connections) are very important.

We present our adaptive optical neural network made of a large-scale event-driven architecture. It offers synaptic and structural plasticity. The main building blocks are wavelength-addressable phase-change material (PCM) based artificial neurons. The embedded PCM serves both as non-linear activation function and non-volatile memory. Our activation function shows both inhibitory and excitatory responses, as well as a switching contrast of 3.2 dB. This is enabled by placing the PCM on focussing multimode interferometer focussing structures. Our implemented neural network is trained to distinguish between German and English text making use of an evolutionary algorithm. Our large-scale network consists of 736 subnetworks, with each consisting of 16 PCM neurons.
Our adaptive ONN consists of PCM neuros which are individually addressable by different wavelengths. The PCM neurons are connected by a bus waveguide from which light of the required wavelength is coupled into a micro ring resonator after which it passes the PCM, reflected by a Bragg mirror, the light passes the PCM a second time and via the micro ring resonator it is guided back into the bus waveguide. The PCM cell is placed on a focusing MMI structure which improves the light coupling to the PCM. Using the non-volatile properties of the PCM it acts as a multi-level non-volatile memory, therefore, the internal state of the neuron is saved.

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Optimized photon pair generation in parametric down-conversion for high-dimensional maximally entangled states

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Photon pairs generated from spontaneous parametric down-conversion (SPDC) constitute the predominant method to realize entangled photonic bipartite systems. Laguerre-Gaussian modes, which carry orbital angular momentum (OAM), are commonly exploited to create high-dimensional entangled quantum states experimentally. In particular, maximally entangled states (MES) in dimensions d>2 show promising features like improving the capacity and security of quantum communication protocols. However, the direct generation of MES in well-defined high-dimensional subspaces of the infinite OAM basis still remains a considerable challenge. In this theoretical study, we predict conditions for the spatial distribution of the pump beam and the nonlinear crystal profile to generate MES without additional spatial filtering of OAM modes within a subspace. To this end, we have developed a straightforward method to obtain optimal pump and crystal configurations. We illustrate our approach with maximally entangled qutrits (d=3) and ququints (d=5).

On-chip Parallelisms to Accelerate Photonic Convolutional Operations

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This poster introduces an additional on-chip parallelism with combination of space and wavelength domains, provided by cyclic array waveguide grating, to further accelerate the WDM-based convolutional operation. The on-chip parallelisms is simulated with image classification problem. The novel parallelism improves CNN acceleration by 10s times with respecting to other photonic integrated convolutional processors, suggesting up to 40 Tera Operations/s for a chip with 64 weighting elements, using 10 Gsample/s inputs.

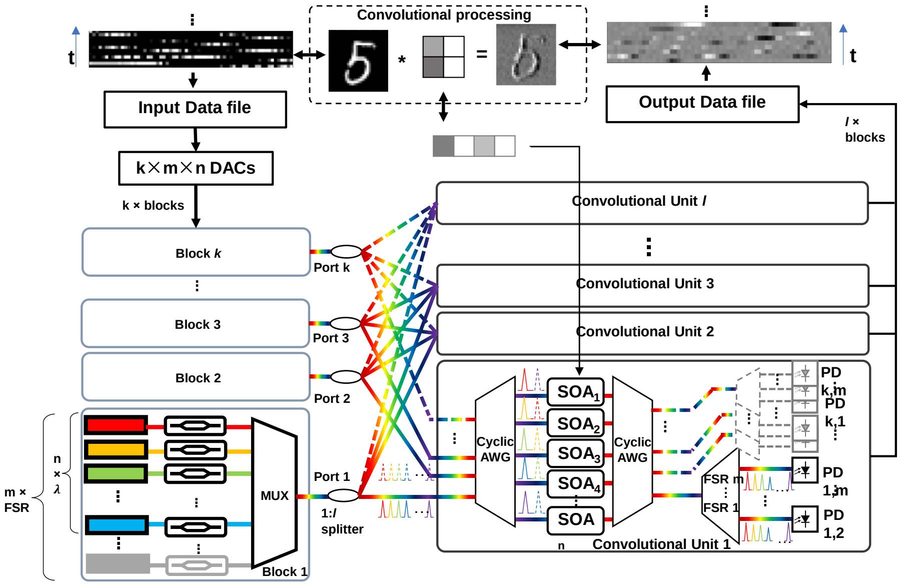

Figure 1. Simulation set-up for the photonic integrated convolutional processor.

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Cryogels from Pt/γ-Fe2O3 and Pd/γ-Fe2O3 NPs as Promising Electrocatalysts for Ethanol Oxidation Reaction

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This study explores nanoparticle-based cryogels, a new type of catalysts that have proven to be highly efficient for application in direct ethanol fuel cells. The catalyst is made in form of a porous thin film containing nanoparticles (NPs) of platinum (Pt) or palladium (Pd) as the structure building blocks, or mixtures of these noble metals with (γ-Fe_2O_3 NPs). Structural and elemental analysis of the samples were performed, along with the measurement and analysis of their catalytic activity. The electrocatalytic activity of the cryogels towards ethanol oxidation reaction (EOR) in alkaline media was evaluated by means of cyclic voltammetry. We have found that these catalysts were just as effective, or even better, at converting ethanol into energy than those made solely from expensive precious metals like Pt or Pd. This is because the porous structure provides more surface area for the reaction to take place, and the iron oxide helps to prevent the catalyst from being poisoned by byproducts of the reaction. Overall, the findings of this study suggest that cryogel catalysts from mixed Pt or Pd NPs with γ-Fe_2O_3 have promising applications in developing more efficient and affordable ethanol fuel cells.

Spectro-temporal control of supercontinuum generation using a photonic integrated chip

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A desirable feature in a neural network architecture is the ability to access a diverse output space. If one wishes to replicate this using photonic systems, demonstrating their ability to achieve diversity is of paramount importance. In our work, we show how the spectro-temporal properties of broadband light can be controlled and reshaped using a programmable photonic integrated chip.

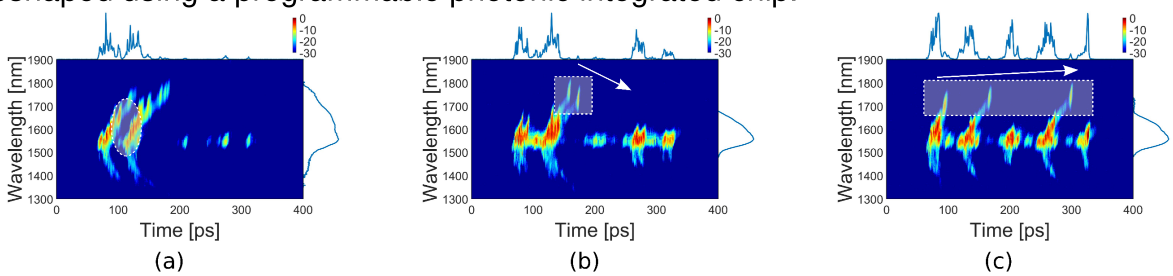

Figure 1: Experimental spectrograms showing spectro-temporally reconfigurable SC.

Specifically, we use an integrated on-chip programmable delay line (PDL) that allows for the adaptive control of the temporal pattern of a light wave. Then, by launching this wave into a highly nonlinear fiber, we generate a broadband supercontinuum whose features depend on the input temporal pattern defined by the PDL. A previous work [1] showed how one can then tailor the spectral profile of the supercontinuum using the PDL. We extend this work to include the temporal aspect, and show that the spectro-temporal profile of the supercontinuum can be shaped. By using an X-FROG (Cross-Correlation Frequency Resolved Optical Gating) setup, we obtain experimental spectrograms which show how the temporal profile defined by the PDL settings allows for a rich spectro-temporal diversity of the supercontinuum. Additionally, optimization results are shown which demonstrate that specific patterns can be produced.

Altogether, our approach opens up the way for both the flexible control of broadband light and the possible use of the spectro-temporal domain in optical data processing.

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Nonlinear Phase Wrapping for Linear Information Forwarding

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The study of nonlinear dynamics in optical fibers has attracted significant attention due to their applications in multi-frequency laser engineering [1] and nonlinear imaging [2]. Recently, it has been demonstrated as a powerful optical system that mimics multi-layer neuromorphic computing [3]. The accuracies of this system in classification tasks outperform other optical approaches, but some tasks remain difficult, such as the classification of the MNIST dataset. In the MNIST task, which involves classifying images of handwritten digits (0 through 9), the system achieves only moderate accuracies ($<$90%). Other demonstrations have achieved higher accuracies ($>$90%) with purely linear digital or mildly nonlinear optical networks [3]. We hypothesized that the strong nonlinear mixing of information by the system could be detrimental in the case of MNIST, as the dataset may require significantly less nonlinearity to become separable. Our objective is to study the phenomenon of nonlinear phase wrapping [4], where the phase-encoded in the input pulse of the system is mapped onto the intensity profile of the output supercontinuum. The aim is to comprehend this linear behavior through numerical methods. We'll study the mapping at different input pulse powers to see where the linear information breaks down, utilizing statistical scores such as Pearson correlation to quantify linearity. The Pearson correlation coefficient is a statistical measure that quantifies the strength and direction of the linear relationship between two variables. Then, we'll utilize these dynamics to define encoding regimes for tasks of varying complexity, including operational regimes tailored for tasks requiring linear information alongside the complex nonlinear mappings in optical neuromorphic systems. The next step is to experimentally see if the linear regime gives a better classification for the MNIST task. The results may pave the way for nonlinear wave processors that feature preserving input information alongside with their nonlinear activation for brain-inspired computing.

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Metasurface-Enabled Polarimetry with Redundancy for Satellite Imaging

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Polarisation imaging is a technique used to enhance or distinguish objects and surface characteristics. Full polarisation state imaging allows complex processes like water glint filtering for remote Earth observations [1]. Small satellites are accessible platforms for remote sensing, however their size and weight limitations cannot accommodate conventional polarisation imaging with bulk optics. We show that metasurface optics can perform complex imaging within a small-form factor, and present a metasurface designed for polarisation remote sensing.

Metasurfaces are photonic devices composed of nanostructured arrays on flat substrates, designed to produce specific optical outputs. We build on previous polarisation imaging metasurfaces [2] by designing a satellite-specific system, accounting for the nontrivial requirements of low-light imaging, field-of-view (FOV) for efficient sensor use, and redundancy for remote error monitoring.

Full polarisation imaging requires a minimum of 4 polarisation measurements. We designed our metasurface for redundancy with 5 measurements; any 4-measurement subset can reconstruct an incident polarisation and reconstructions are compared to monitor errors. Divergence in reconstructions indicates errors in the system, which can be corrected with recalibration.

We adopt freeform topology optimisation to create a diffractive metasurface design, maximising the reconstruction performance of all the measurement subsets. The metasurface is tailored to image a strip perpendicular to satellite movement and diffraction direction so that all measurements are on one camera sensor, and a complete image is built over time as the satellite scans the Earth's surface.

We estimate that for a metasurface area of 1mm^2, imaging at a wavelength of 850nm and a numerical aperture of 0.29, the achievable resolution is over 20,000 samples. Importantly, the imaging resolution limit scales with the fabricated metasurface area, hence the resolution and FOV requirements of small satellites can be achieved.

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Polarization dependant unidirectional excitation of surface plasmon polaritons using actively tunable dielectric loaded plasmonic metasurfaces

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Dedicated optimization of plasmonic geometries in the nanoscale can be employed to efficiently host strongly localized electromagnetic modes in the near field via the satisfaction of momentum-matching condition. The refractive index contrast at the interface, that is pivotal to attain strongly localized mode confinement, can be tailored by employing appropriate dielectric-loaded plasmonic system. In this work, we propose such a system that comprises of a dielectric grating on top of a thin gold film using a phase change material (PCM) known as Stibnite (Sb_2S_3). The usage of PCMs provides useful advantage of drastic optical property change once tuned from their amorphous to crystalline state [1]. Sb_2S_3 can be easily tuned from amorphous to crystalline state at an ultrafast rate using an optical beam or via thermal annealing process [1, 2]. The dielectric grating is designed in a fishbone configuration to exhibit a circular polarization-dependent directional coupling of SPPs [3]. Finite-difference time-domain (FDTD) simulations based on amorphous Sb_2S_3 fishbone grating exhibit strong directional propagation of SPPs, the directionality of which changes when the handedness of circular polarization is changed. Interestingly, when the phase of the material is switched to crystalline Sb_2S_3, the aforementioned handedness-dependent response remains but the directionality gets reduced from 1400 dB (amorphous) to 2.365 dB (crystalline). Furthermore, using the same principle, we also demonstrate a focusing/defocusing of the coupled SPPs depending on the handedness of the circular polarization of incident light.

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Alternative Plasmonic Materials – Colloid Chemical Synthesis, Characterization and Properties

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When discussing plasmonic colloidal nanoparticles, the majority of publications deals with gold or silver nanoparticles. However, many more materials than just these noble metals are capable of showing plasmonic behavior. In this talk, our efforts on the colloid chemical synthesis and structural and optical characterization of such "alternative" plasmonic materials is summarized. Different material classes are invoked such as degenerately doped semiconductors (Cu2-xSe) or metallic compounds (Cu1.1S and NiS compounds). Emergent properties are for example a post synthetically tunable plasmon resonance or also a temperature switchable plasmon resonance. Furthermore, ultrafast plasmon/plasmon interaction in dual plasmonic nanoparticles (Cu1.1S/Au) are discussed.

Nanophotonic Metasurfaces for Optical Wireless Communication

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Detectors for optical wireless communication have achieved high electrical bandwidths due to their miniaturization. However, this miniaturization limits their power collection, forcing the use of optical elements to focus the incoming light into small areas. This approach is limited by the fundamental principle of the etendue conservation, which describes how well the emission from an extended and divergent source can be focused. Passive optical elements can not reduce the etendue, which does not allow to focus divergent beams from extended sources into small areas. To overcome this principle, we use active optical elements that absorb omnidirectionally the emission from the source and emit a collimated beam that can focused onto a small area photodiode [1]. This omnidirectional absorption and directional emission is achieved with photonic metasurfaces. We discuss different metasurfaces and , each offering unique advantages and limitations. Also, we investigate the possible limitations of this new photodetector concept for optical wireless communication regarding size, bandwidth, and detectivity, which could impact the practical implementation of this technology.

In conclusion, while active optical elements and photonic metasurfaces present promising solutions to overcome etendue limitations, the practical implementation of this technology for optical wireless communication necessitates addressing challenges related to size, bandwidth, and detectivity. However, it's important to note that these challenges are not insurmountable. Continued research and development hold the potential to transform these advanced photodetector concepts into a reality in future communication systems, offering a glimpse into the exciting possibilities of the future.

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Giant and broadband optical chirality enhancement in 3D plasmonic Archimedean

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Chirality is ubiquitous in the natural world. As chiral enantiomers with similar physical and chemical properties can play different roles in biochemical processes, chiro-sensitive molecular detection is of strong interest to the emerging fields of chiral sensing and analysis. Circular dichroism is conventionally used to detect optical chirality but it is constrained by the weak and narrowband chiroptical effects of the molecules, thereby, limiting the sensitivity. Our previous work showed that using a metasurface of 3D plasmonic single-arm Archimedean spirals makes it possible to get strongly enhanced and stably localized broadband near-field optical chirality in the middle infrared regime [1]. However, the fabricated structures have proved to be structurally unstable. Furthermore, the spectral regime of operation used in our previous work is not friendly to easily available and highly sensitive optical equipment. This limits the potential applicability in detecting the targeted molecules at extremely low concentrations. To circumvent this, we demonstrate a 3D plasmonic two-arm Archimedean spiral that achieves large broadband optical chirality enhancement in visible to near infrared region and robust structural stability. Numerical calculations of the near-field optical chirality enhancement and transmission have been systematically investigated. Moreover, fabrication of the simulated structures achieved by using focus ion beam milling has been demonstrated.

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Spectral Hong-Ou-Mandel Effect between a Heralded Single-photon State and a Thermal Field: Multiphoton Contamination and the Nonclassicality Threshold

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The heralding technique, commonly used to approximate deterministic single-photon states from the SPDC process, is crucial for the two-photon Hong-Ou-Mandel (HOM) effect. However, the impact of thermal properties of heralded states has not been studied on the HOM effect. In this study, we experimentally implement the spectral HOM effect between a heralded single-photon state and a thermal field, revealing the effect of multiphoton contamination on the HOM visibility. Experimentally, we implemented the HOM effect using electro-optic phase modulation (see Fig. 1a & b), between two independent idler frequency modes from two pulsed-driven SPDC processes and obtained a visibility of Vis = 43.%2 $\pm$ 4.2% (see Fig.1c). The experimentally measured non-delayed three-fold coincidence counts fell below the lower limit of the standard deviation of the minimum predicted counts at zero delay. This observation could be explained by the engagement of multiphoton components (in the heralded state) in the HOM effect with the thermal field and was verified by our newly-derived theoretical relationship for the HOM visibility $\mathrm{V_{theory}} = 1/1 + \left(\bar{n}_{i1,th}^2 + \bar{n}_{i2}^2 + \bar{n}_{i1,th} / \bar{n}_{i1,th}\,\bar{n}_{i2} + \bar{n}_{i2}\right)$**,**as function of the mean photon number in the thermal field, $\boldsymbol{\bar{n}_{i2}}$, and the thermal part of the heralded state, $\bar{n}_{i1,th}$ (See Fig. 1d). Our observation that multiphoton components (in the heralded state) lead to improving the HOM visibility, could question the often-made practice in literature [1] in subtracting the multiphoton components from the total coincidence counts. Moreover, we demonstrate that the degree of nonclassicality of a heralded state can be identified through its HOM effect with a thermal field for which we identified a peak visibility of at least 41.4% under the upper limit of $\bar{n}_{i1,th} < 1$ [2].

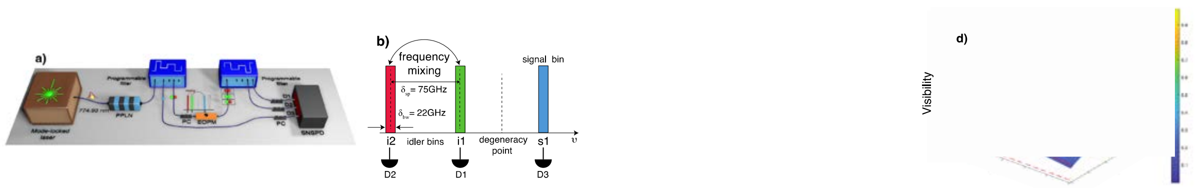

Fig. 1. a) Experimental setup, **b)** spectral configuration, **c)** experimental results, **d)** HOM visibility as function of mean photon number. The dashed arrow points to the intersection of the experimentally measured mean photon numbers $\boldsymbol{\bar{n}_{i1,th}}$ ≈ 0.1±0.033 and $\boldsymbol{\bar{n}_{i2}}$ ≈ 0.098±0.033, in turn corresponding to the theoretical value of the HOM visibility $\mathrm{V_{theory}}$ ≈ 47.30% ± 0.66%.

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Spatio-Spectral Tailoring of Plasmonic Modes for Surface-Enhanced Coherent Anti-Stokes Raman Scattering

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Well-designed plasmonic nanostructures play a crucial role in mediating optical near field and the optical far field, thereby, enhancing light-matter interactions by orders of magnitude [1]. In this study, we explore the nonlinear enhancement of light-matter interactions, particularly surface-enhanced coherent anti-Stokes Raman scattering (SECARS), through plasmonic nanostructures. We introduce a plasmonic azimuthally chirped grating (ACG) platform to experimentally investigate the enhancement effect of plasmonic gratings on the input and output signals of nonlinear surface-enhanced coherent anti-Stokes Raman scattering (SECARS). Our work focuses on optimizing the spatially overlapping resonant plasmonic modes, which match to the different wavelengths involved in the nonlinear optical process, to achieve effective plasmonic enhancement. Furthermore, we investigate the interplay between groove geometry and grating periodicity, which determines the mechanism responsible for field enhancement in the ACG [2]. Overall, our study provides valuable insights into the mechanism of plasmonic gratings for enhancing light-matter interactions.

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Synthesis and characterization of linear/nonlinear optical properties of graphene oxide and reduced graphene oxide- Au-Fe_2O_3 nanocomposite

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The laser stands out as one of humanity's most remarkable inventions, finding extensive applications in both research and the public sector owing to its unique characteristics such as coherence, monochromaticity, energy density, and directionality. In optical realms, lasers induce various effects like nonlinear polarization, absorption, refraction, and scattering. However, exposure to intense laser radiation, whether accidental or direct, poses significant risks to human safety and optical equipment. Therefore, safety measures and optical mitigators are essential to shield individuals and components from such hazards. Optical limiters, in particular, serve as effective safeguards against optical threats in such scenarios. Recent studies have highlighted the exceptional light absorption and broad emission capabilities of graphene oxide and reduced graphene oxides, making them promising candidates for laser damage protection. Combining rGO with Fe2O3 derivatives enhances their nonlinear optical properties and stability. This study aims to identify a superior composite material with enhanced nonlinear optical properties based on these findings. The reduced graphene oxide decorated with gold ferric oxide showed enhanced nonlinear optical behaviour. The complex Au-Fe_2O_3 systems exhibit optical limiting action under ultrafast (800 nm, 80 MHz, 150 fs) and (532 nm, 50 mW) laser excitation. Among the investigated systems, Au-Fe_2O_3-(15 wt%) rGO demonstrated the highest nonlinear optical coefficients and optical limiting action, as well as the highest thermal stability. The detailed investigation shows that the combined contribution of rGO and metal ions present in the Fe_2O_3 system is responsible for the improvement of NLO coefficients and optical limiting action. Thus, the present work is an investigation into the enhancement in nonlinear optical properties through nanocomposite formation and the possibility to utilise them as optical limiters for laser safety devices.

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LNOI based Architecture for Local Time-Wavelength Multiplexing

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The rapid explosion of large-scale computational models has correspondingly prompted a search for architectures which can reduce the power requirement and cost of realizing these systems. Integrated photonic systems appear to be uniquely suited for this challenge, as demonstrated through coherent unitary systems, photonic crossbar arrays, and broadcast and weight systems.[1] However, a further degree of improvement has been identified through employing time-wavelength interweaving, thereby increasing the throughput of data and the calculations that can be achieved for many perceptron and convolutional tasks.[2] We present a system for a small-scale time-wavelength interweaving on single photonic chip using a Lithium Niobate on Insulator platform. With a relatively slow modulator speed of 4 GHz, the system is able to achieve notable performance on traditional image convolution tasks with a relatively small footprint and low Vpi. Moreover, we present the suitability of this architecture for complete on-chip realization of wavelength and temporal multiplexing.

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HYBRAIN: Electronic-photonic Architectures for Brain-inspired Computing

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As artificial intelligence (AI) proliferates, hardware systems that can perform inference at ultralow latency, high precision and low power are crucial and urgently required to deal – especially quasi-locally, i.e. 'in the edge' – with massive and heterogenous data, respond in real time and avoid unintended consequences and function in complex and often unpredictable environments. HYBRAIN's vision is to realize a pathway for a radical new technology with ultrafast and energy- efficient edge AI inference based on a world-first, brain-inspired hybrid architecture of integrated photonics and unconventional electronics. Our approach will take advantage of the ultrahigh throughput and low latency of photonic convolutional processors (PCPs) [1] employing novel phase-change materials in these initial layers to radically speed up processing. Their output is processed using cascaded electronic linear and nonlinear classifier layers, based on memristive (phase-change memory) [2] crossbar arrays and dopant network processing units, respectively [3].

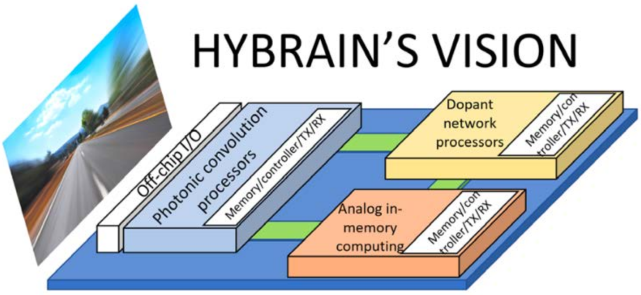

Figure 1 *High-bandwidth, multi- modal input data is fed into the hybrid architecture for low-latency inference. The first bottleneck convolutional layers are photonic. Via high-speed interfaces, a minimum of data is transferred to analog in-memory computing cores for linear classification and to dopant network processing units for nonlinear classification. Peripheral electronics for memory, control, transmitting (TX) and receiving (RX) is indicated.*

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Arbitrary Ratio Power Splitters using Bent MultiMode Interference Couplers

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Integrated Photonics has become a well-established field with applications in information processing and data transmission. It relies on the interaction of basic active and passive components to perform its operations. For many applications there is the need for arbitrary ratio power dividers, and a number of solutions for this has been investigated, such as the use of directional couplers and multimode intereference couplers (MMIs).

MMIs are a fundamental family of photonic components, whose main function is to distribute the incoming light over several output ports, with a well-defined power ratio and phase difference with respect to each other. The working principle is based on self-imaging caused by internal interference of the modes excited and propagating in it. They find a variety of applications in numerous areas of photonics including optical switching, quantum communications, balanced detection, power splitting and many others. Traditionally designed rectangular 1 x 2 or 2 x 2 MMIs however enable power splitting only for fixed power ratios, namely 50/50, 72/28, 85/15, thus limiting the application of MMIs, when other splitting ratios are required. Proposed solutions based on MMI technology rely on connected devices or have significantly more complex geometries compared to the standard MMIs.

In our contribution we present uniformly bent 1x2 or 2x2 MMIs, which allow a design tunable power splitting, proportional to the curvature of the bending, from 50/50 to 80/20 with an overall simulated loss of less than 0.2dB. We investigate the optimization of the device geometry in the L, C and S bands to minimize the insertion losses and we perform a fabrication tolerance analysis. These devices can be implemented in a standard passive fabrication process flow as for standard MMIs, and are useful for applications where a well-defined, low-loss, splitting is required, such as in tap detecting and optical filters.

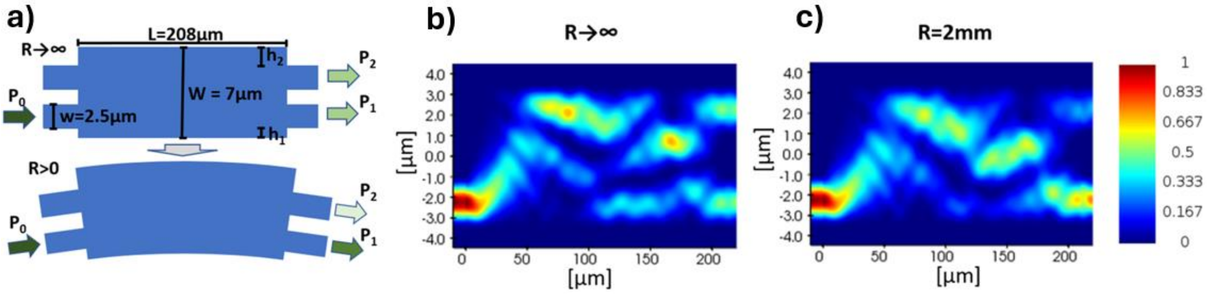

Fig. 1: a) schematics and power distribution for b) straight, and c) bent 2x2 MMI.

Efficient Techniques for Supervised Output Training on Photonic Reservoirs and Extreme Learning Machines

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Extreme Learning Machines (ELM) and Reservoir Computers (RC) are output trainable recurrent neural networks and provide a unique take on neural networks, emphasizing neuromorphic wave computing(NWC)[1] for energy efficiency. We introduce a novel implementation of neuromorphic wave computing paradigm, in-fiber nonlinear NWC[2], utilizing transient nonlinear frequency generation to emulate neural network functions. Nonlinear NWC builds on the nonlinear Schrödinger equation, trainable at the readout layer like ELMs. Its unique architecture embeds a hidden layer within a highly nonlinear optical fiber, leveraging phenomena like higher-order soliton fission and self-phase modulation. In-fiber NWC processes information optically by encoding input in the spectral phase and embedding it in the output spectrum. In-fiber NWC employs conventional ELM training methodologies, such as linear or ridge regression, for weight determination. A search algorithm selects readout bins, akin to hidden layer nodes in ELMs, for task-specific performance. However, reducing node subsets faces challenges due to unclear optimal subset selection and unconstrained weight matrix. To address these, we reformulate the search as a 0-1 multiple Knapsack problem and use approximation algorithms to reduce node count while maintaining task adequacy via linear regression. Additionally, we employ LASSO regression to address the overdetermined weight matrix problem[3]. These approaches reduced nodes from 94 to 40 bins while maintaining performance at 86.7% to 82.6% at the MNIST 10-class classification task with room for improvement. This enhances in-fiber NWC's robustness of the training, practicability of the machine, and interpretability of our approach by demonstrating a more flexible search and a regularized weight matrix approach.

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Inverse design for integrated polymer 3D optical circuits

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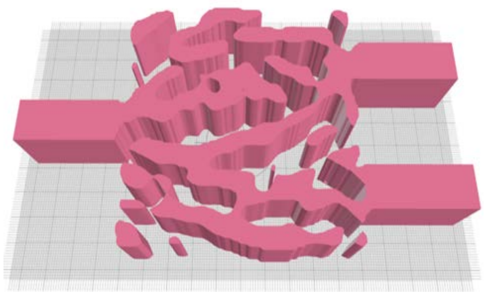
By developing fast and energy-efficient solutions, integrated optics is revolutionizing the fields of computers, telecommunications, and sensors. Meanwhile, traditional designs use basic intuitive geometry and a small set of design attributes. This typically fails to yield an optimal solution. Therefore, inverse design approaches are being employed to explore a larger design space and pursue devices with improved performance.



Additionally, two-Photon Polymerization (2PP) is a novel 3D free-form nano-scale fabrication technique for a wide range of polymer optical devices. To fully harness the potential of this fabrication method, it is imperative to employ efficient inverse design techniques to produce innovative 3D designs. In our work, we utilize topology optimization based on the adjoint method to create miniaturized integrated optical devices with non-intuitive designs on a substrate, such as (de-)multiplexers and polarization converters. Then, these devices are fabricated using 2PP and characterized. By incorporating manufacturing constraints into the optimization process and learning from each fabrication iteration, we establish a feedback loop between the predicted and actual performance of the device.

In future, we intend to leverage our expertise from planar polymer-on-glass devices to develop fully 3D optimized designs with topology optimization and two-photon polymerization. This has the potential to substitute two or more functionalities and unlock unique characteristics, e.g., polarization splitting and conversion in one device, thereby pushing the limits of integration in the field of integrated optics. This endeavour signifies a major advancement in the design and fabrication of polymer optical devices, with potential impacts across various sectors.

Intensity statistics resulting from a large ensemble of nonlinear optical operations performed by a disordered photonic medium

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Nonlinear disordered photonic media (NL-DM) are an emerging platform for photonic computing. They are strongly scattering materials whose nanodomains generate second harmonic (SH) waves with random amplitude and phase when excited by a fundamental beam, effectively behaving as a large ensemble of fully connected nonlinear functions. The complex interference results in a random intensity distribution (the speckle pattern) that can be used to enable large-scale nonlinear optical operators for encryption, all-optical logic gates, and photonic machine learning [1, 2]. However, despite the widespread interest, the statistical properties of the SH generated light, critical due to the random nature of the material, remain scarcely explored.

We analyzed the statistics of the SH light generated by an NL-DM, revealing significant deviations from the predictions of diffusion theory, which describes the scattering of the fundamental light [3]. Considering the interference between different transmission channels, we conclude that the number of open transmission modes for SH light is one order of magnitude lower than for fundamental light. This implies that, when the fundamental beam is strongly focused at the input facet of the medium, the probability of having high intensity speckles for the SH light is orders of magnitude higher than for the fundamental light.

Our result demonstrates the possibility of generating higher SH intensity condensed into fewer speckles. Having fewer, stronger outputs potentially allows for easier control when using the NL-DM in combination with a programmable modulator. Furthermore, the deviations from diffusion theory indicate that for strongly focused fundamental light, which is useful to achieve a higher SH signal, the propagation through the NL-DM cannot be described by a random nonlinear input-output response. Thus, it is essential to consider this effect in applications that exploit the randomness to achieve large-scale nonlinear operations.

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Combining Two-Photon Polymerization and Inverse Design to enable the fabrication of tailored nanophotonic components

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High-resolution 3D printing by means of two-photon polymerization (2PP) facilitates rapid prototyping of on-chip nanophotonic components. In this contribution, we demonstrate the prospects of fabricating optical ridge waveguides by investigating the influence of various printing parameters on the optical properties. In addition, the beneficial fabrication flexibility is exploited by combining 2PP with topology optimization – a rather new approach for inverse designing nanophotonic components featuring non-intuitive shapes. In this context, waveguide-integrated components like wavelength (de-)multiplexers will be presented. This will pave the way for rapid prototyping of chip-scale waveguide-integrated systems with tailored functionalities.

Development of record high-speed quantum key distribution system

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The evolving capabilities of quantum computing present challenges to the security of widely used encryption technologies. While methods such as quantum key distribution (QKD) promise inherent security, they must contend with limitations in achieving practical secret-key rates over long transmission distances[1]. Photonic integrated chips (PICs) offer a scalable solution, offering on-chip state preparation, wavelength-division multiplexing, high-efficiency single-photon detectors, and overall scalability. We present progress in developing a sender module aimed at achieving a high secret key rate in the gigabit per second (Gbit/s) range. Our approach utilizes a hybrid design to address packaging challenges in PICs, incorporating an InP-Chip for on-chip laser-driven qubit preparation and a silicon nitride chip for multiplexing. This design enables the implementation of protocols such as time-bin BB84 or coherent one-way protocols and promises further scalability. Additionally, the receiver utilizes waveguide-integrated superconducting nanowire single-photon detectors to enhance detection efficiency[2].

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Neuromorphic Information Processing in Nonlinear Optical Fibers

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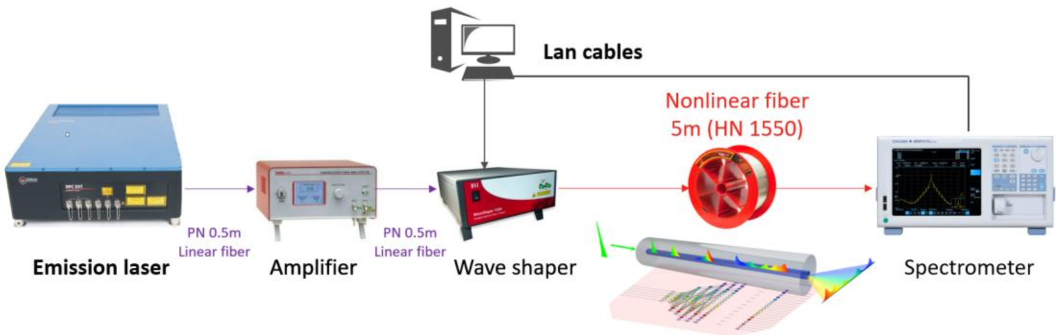
The performance limitations of traditional digital computer architectures have led to a rise in the development of neuromorphic hardware [1], [2], with optical solutions gaining popularity due to their energy efficiency, high speed, and scalability [3]. In recent theoretical and experimental studies, nonlinear interactions between optical spatial modes have been used to emulate basic neural network functionalities. The use of such transient nonlinear dynamics may enable electro-optical limitations to be bypassed in signal conversion, and may also facilitate the development of new approaches towards highly efficient, multi-layer (deep) processing [4].
The main focus of this research work is the exploration and functionalization of highly complex and nonlinear wave dynamics, such as broadband light generation known as supercontinuum generation. Such spectral broadening inside fibers performs an input-output nonlinear mapping similar to the hidden layers of neural networks. Our research addresses the key challenge of identifying benchmarks to reveal the computational power of such analog wave computers.
We build an optical computing system, that enables encoding a dataset into an optical signal via spectral domain phase modulation and its processing in a nonlinear fiber. The system is read out via a spectrometer, following which a weight matrix is trained on this system output to map the high-dimensional space of the system's output to interpretable classification or regression results, a training method known from reservoir computing. We share our benchmark-tests results to identify performance scalability and the system's capability to solve nonlinear problems. The research thus extends our understanding of analog brain-inspired hardware for information processing in the optical domain to help address global challenges such as green computing, Big Data communications, and intelligent medical diagnostics.



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Broadband Inverse Design Grating Couplers for Fast-Prototyping and Efficient Coupling

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Integrated photonics combines high-speed information transfer with scalability. Therefore, in quantum technologies, quantum photonic integrated circuits promise to enable quantum networks and secure key distribution. However, their realization introduces not only new opportunities but also new challenges.

This study explores photonic grating couplers for efficient light coupling into chips, focusing on a hybrid system of amorphous silicon and erbium-doped yttrium orthosilicate (YSO). This combination is promising for quantum memory applications [1] in the C-band at 1550nm, requiring efficient coupling of the fundamental transverse magnetic (TM) mode into a specific waveguide mode.
Specifically, we employed an inverse design method [2] to optimize such couplers, allowing extensive exploration of design possibilities with minimal computational load. This method efficiently calculates the impact of design changes on coupling efficiency through forward and adjoint simulations.
Simultaneously, we addressed potential fabrication errors by co-optimizing multiple designs, enhancing robustness and reliability. Our couplers compatibility with existing fabrication processes for photonic components like waveguides and splitters reduces production time and cost, enabling wafer-scale testing before chip separation, benefiting manufacturers.

Results show a 63% efficiency at 1516nm with a 1dB bandwidth of 20nm for TM mode. A broadband design achieved 57% efficiency over a 165nm 1dB bandwidth. We also compared these methods with traditional light coupling techniques and discussed future research directions, including fabrication techniques [3] to enhance optical component integration.

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Magnetic Aerogels from FePt and $CoPt_3$ Directly from Organic Solution

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. Magnetic nanoparticles are applied in various different fields such as biomedicine, data storage, catalysis or hyperthermia.[1] To the present day mostly the non-connected magnetic nanoparticles are used for applications while combining the magnetic properties with the high surface area of aerogels[2] is beneficial.

In this work magnetic aerogels were synthesized and characterized and the influence of the gelation procedure on the magnetic properties was investigated. The gelation was induced without a previous phase transfer to aqueous medium and supercritical drying was used to obtain porous aerogels. TEM and SEM measurements were performed to analyze the structure and prove the formation of highly porous structures. SQUID measurements were performed to investigate the influence of the gelation procedure on the magnetic properties. The SQUID measurements revealed that magnetism is present even after the formation of the gel networks. In case of FePt the gelation even caused a change from nearly paramagnetic behavior before the gelation to superparamagnetic behavior afterwards at 300 K. This knowledge will help to develop and tailor new materials for various future applications, which combine their magnetic properties with the high surface area of gels.

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Photonic Integrated Scanning Microscopy

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Scanning Near-Field Optical Microscopy (SNOM) revolutionized imaging by offering high-resolution images surpassing the diffraction limit of traditional optical microscopy. However, its point-by-point scanning method limits its applicability for rapid imaging, particularly in dynamic biological systems. Here, we propose a novel approach utilizing Photonic Integrated Circuits (PICs) to enable parallel imaging, thereby addressing the trade-off between resolution and scanning speed. By integrating multiple waveguides onto a single chip, PICs facilitate simultaneous scanning of different areas of the sample, potentially reducing acquisition time. Leveraging advancements in plasmonic, one can enhance the resolution by depositing a thin layer of metal on top of the scanning waveguide tips, achieving the ultrahigh light confinement (in the orders of 10 nm) . Our configuration, multiple waveguides equipped with plasmonic structures, allows for a cost-effective solution for rapid, and high-resolution imaging. With applications spanning visible to mid-IR wavelengths, our approach promises transformative advancements in microscopy, offering high-speed imaging capabilities previously unattainable with conventional techniques.

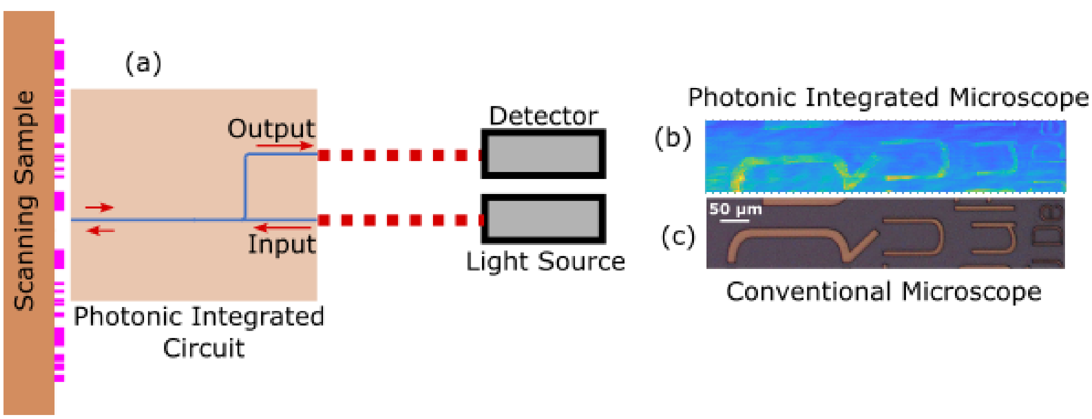

Figure 1. (a) Schematic of Photonic Integrated Microscope. Optical image of the scanning sample acquired using (b) Photonic Integrated Microsopce and (c) conventional microscope.

As a proof of principle, we demonstrate scanning capability facilitated by the single waveguide on the PIC (Figure 1a). Figure 1b shows the optical image acquired using our photonic integrated microscope. The resolution of this simple configuration is $\approx 2\,\mu m$, which can be further enhanced by using the plasmonic nanostructure. Acquired image using our microscope match very well with the image acquired using conventional microscope (Figure 2c). It's evident that the waveguide acts like a scanning tip and could be scaled up to reduce the acquisition time of the microscope.

Towards a high speed and low loss InP electro-optical phase modulator for heterogeneous integration with SiN photonics

Duarte Silva[1], Martijn Heck[1], Yuqing Jiao[1]

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SiN photonics is renowned for its ultra-low loss waveguides and non-linear optical properties. Such features, along with CMOS-compatibility, establish the platform as the preferred choice for many applications including classical and quantum computations, communications, metrology, sensing and imaging. Despite the superior passive component performance, the incorporation of phase modulators is essential and, while thermo-optic modulators allow for monolithic integration, high-speed operation is unattainable. For that reason, heterogeneous integration with TFLN and BTO have become an attractive approach due to their emerging wafer-scale processes. Despite promising early demonstrations, both materials lack the ability to generate and detect light. Integration with Si is the most compatible approach, but such devices are associated with high optical losses, which is an undesirable pairing with SiN for many applications. On the other hand, InP is an established material platform enabling the monolithic integration of gain sections and modulators. The development of the latter, however, has been dominated by the desire to achieve low power consumption and high-speed operation, while sacrificing low optical loss. In this work, we outline a design strategy for InP-based phase modulators towards an optimized balance between propagation losses and modulation efficiency. Furthermore, we present an analysis of the expected performance with respect to epitaxial growth tolerances, establishing the robustness of the design. The design of InP modulators is often associated with a high number of design variables, and together with the various electro-optical interactions and RF characteristics, we can be left with a sub-optimal design. This research offers insight on how to tame such a large optimization space, paving the way towards the development of low loss and high-speed modulators for future co-integration with SiN photonics.

Coherent multi-frequency photonic activation function

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After years of rapid scaling of model complexity, machine learning inference and training are close to reaching a bottleneck formed by the limitations of conventional Boolean logic processing hardware, especially with regard to power consumption, latency, and data movement. Photonics with their low latency, WDM potential and negligible energy per MAC cost are a promising platform for resolving these nascent issues. One of the current challenges in the development of photonic neural networks (NNs) is the activation function, which gives a NN its ability to perform arbitrary nonlinear transformation. Existing photonic activation functions often rely on opto-electronic conversion, which limits the bandwidth, increases latency and introduces optical losses. The search for a concept that would be free from these limitations is on. Other desired features that complicate the search are: (i) coherence (time-reversibility), which would facilitate the phase-reliant matrix multiplication schemes as well as advanced training techniques, and (ii) frequency selectivity, which accounts for resource-efficient frequency-multiplexed information encoding. In this work, we demonstrate an in-fibre nonlinear activation function, which is all-optical, coherent and frequency-selective [1]. Our design is based on stimulated Brillouin scattering [2] which can provide high-gain and low-noise amplification of coherent signals. It features an optically tunable activation function shape including Leaky ReLU, Sigmoid, and Quadratic. In addition, it offers a positive net gain as high as 20 dB, which is particularly helpful for deep neural network architectures.

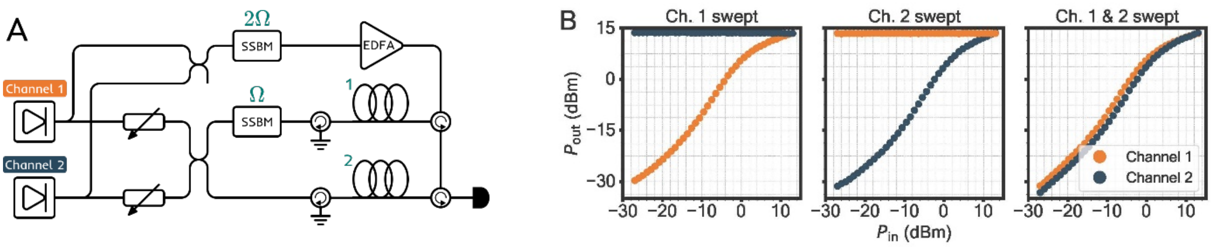

Figure 1. A Principal scheme of the setup. A single sideband modulator (SSBM) is used in each of the Brillouin amplifier stages to upshift the pump with respect to the probe by the Brillouin frequency Ω. B Demonstration of frequency-selective operation. The pump power is 34.5 dBm.

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Photoelectrochemical Investigation of Nanoparticle-Based Assemblies

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Gel-like networks based on semiconductor nanocrystals show the possibility of transferring the remarkable properties of their nanoscale building blocks to macroscopic structures. The resulting porous solvo- and aerogels consist of the nanoscopic building blocks linked via crystal-to-crystal contacts that allow enhanced delocalization of photogenerated charge carriers across the particle boundaries. The properties of the resulting gels depend on their composition as well as on the composition and morphology of the building blocks contained and the ligands used. Photoelectrochemical investigations provide information on the dynamics and kinetics of the charge carrier processes in the network, while photocatalytic measurements show the improved ability for photoactivated hydrogen production.

Polarization insensitive 40-channel 100 GHz spacing fold-back planar Echelle grating Mux/Demux for photonic integrated wavelength selective switches

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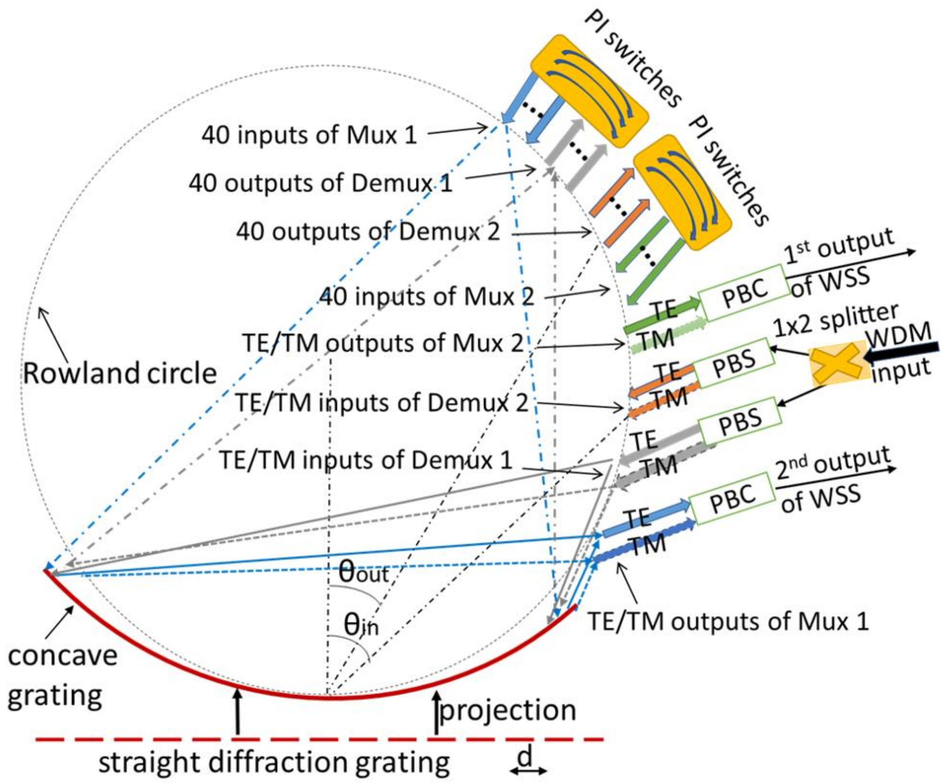
ECO Group, Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, The Netherlands

We numerically demonstrate a novel polarization insensitive (PI) 40-channel 100 GHz spacing fold-back planar Echelle grating (PEG) multiplexers/demultiplexers (Mux/Demux) to realize the compact 1×2 crossing-less photonic integrated wavelength selective switch (PIC-WSS). The PI operation is achieved by a polarization splitter to feed TE mode and TM mode into the PEG via two waveguides with different incidental angles so that the diffracted optical signals (two different modes) combine at the same PEG's output waveguides. Using different input/output angle combinations and sharing the same blazed angle, a single compact PI PEG with a fold-back configuration can simultaneously work as twice Demuxes and twice Muxes. The single fold-back PI PEG's footprint including input/output waveguides is only ~ 40 mm^2. The numerical results show that 40-channel 100 GHz spaced PI fold-back PEG owns < 2.4 dB insertion loss, <-60 dB cross-talk, zero polarization-dependent wavelength shift (PDWS), 0.3 dB polarization dependent loss (PDL), < 0.5 dB loss variation and < 0.01 nm wavelength shift between Mux and Demux.



Structure of PI fold-back PEG (twice Demuxes and twice Muxes) combining polarization beam splitter (PBS) and polarization beam combinier (PBC) for 1×2 crossing-less WSS.

Experimental setup for characterizing waveguide-integrated superconducting nanowire single-photon detectors at 1550nm.

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The astounding power of fundamental quantum physics, rf-electronics, and integrated photonics can be harnessed to reach the limit of measuring faint light on the single photon level, allowing to achieve breakthroughs in the fields of biological and medical sciences, quantum metrology, and quantum information and communication. Scalable sources and routing circuitry are their own pieces in the photonic integrated chip (PIC) puzzle, and another is single-photon detectors for the realization of information processing and computation applications. To realize the complex architectures needed for these applications the individual components need to be integrated on-chip and require low-loss interconnections and great stability against fluctuation of the environment conditions. Due to high efficiency, low noise, high count rate and reduced timing uncertainty, superconducting nanowire single photon detectors (SNSPDs) stand out between the present single-photon detection technologies as a viable solution [1,2]. This work presents an experimental setup to characterize NbN waveguide-integrated superconducting nanowire single-photon detectors at 1550 nm. Namely the procedure of cooling a chip with several SNSPDs below the critical temperature and aligning the on-chip focusing grating couplers with an external fiber array. The on-chip detection efficiency (OCDE) can be measured as a function of the bias current and the dead and reset time can be measured to determine optimal measurement conditions [1,3].

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Tuning Photonic Bandgaps in Porous Anodic Alumina Structures Via Liquid Crystals (LCs)

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Anodic aluminium oxide (AAO) porous structures exhibit photonic crystal functionalities, such as the emergence of photonic bandgaps (PBGs), while offering the advantages of a relatively cheap/quick bottom-up fabrication process. Here, we present a concept for tunable nanophotonics based on AAO structures infiltrated with liquid crystals (LCs). Our study is based on the numerical modelling of the LCs alignment in such AAO structures, followed by optical simulations. We show that by applying a voltage, it is possible to locally modify the LC alignment, thus leading to the tuning of the optical response of the system. We highlight the role of the nonhomogeneous LC realignment and the complexity of the permittivity tensor distribution on the tunability of the PBG spectral position. Dynamically changing the PBG of a photonic crystal structure can lead to interesting photonic devices, such as tunable Bragg reflectors. These and further aspects will be discussed in detail during the presentation.

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Optical systems for classical and quantum computing for machine learning in orbit

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Optical neural networks have been identified as a promising scheme for neuromorphic computer hardware, attributed to their inherent parallelism, fast processing speeds, and low energy consumption. In addition to its applications in classical machine learning, photonic is a promising platform to perform quantum logic operations and gates in quantum computing. In this contribution, we present the implementation of optical convolutional neural network with atomic nonlinearity [1] and optical matrix-vector multiplication schemes following the lines of Ref. [2]. Furthermore, we showcase our efforts towards a demonstrator featuring a payload controller for optical data processing on satellites (Fig.1) and discuss the link to quantum information processing.

(a) (b)

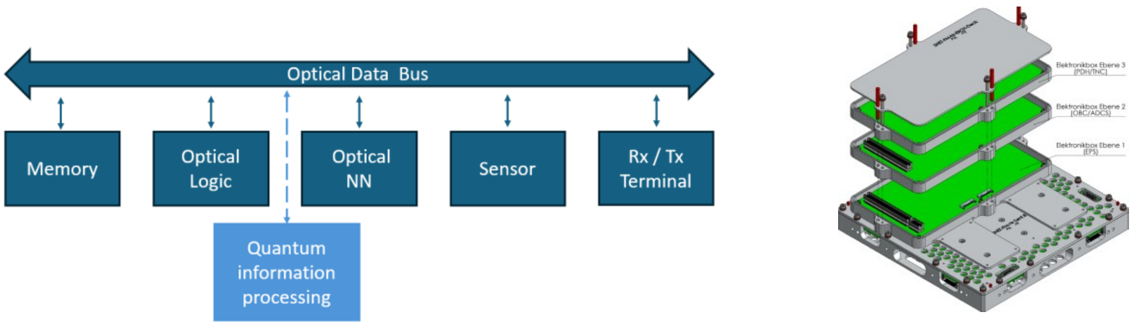

Fig. 1. (a) Hardware concept for optical data processing for optical computing on satellites. (b) Structure of the satellite bus boards including payload boards the missions SALSAT.

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Low-threshold lasing with a stationary inflection point in a three-coupled-waveguide structure

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The frozen mode regime is a unique slow-light scenario in periodic structures, where the flatbands (zero group velocity) are associated with the formation of high-order stationary points (aka exceptional points). The formation of exceptional points is accompanied by enhancement of various optical properties such as gain, Q-factor and absorption, which are key properties for the realization of wide variety of devices such as switches, modulators and lasers. Here I present a new integrated optical periodic structure consisting of three waveguides coupled via micro-cavities and directional coupler see Figure 1. I show that a proper choice of parameters yields a third order stationary inflection point (SIP). In addition, I analyzed the lasing frequencies and threshold level of finite structures (as a function of the number of unit-cells) and demonstrate that it outperforms conventional lasers utilizing regular band edge lasing (such as DFB lasers).

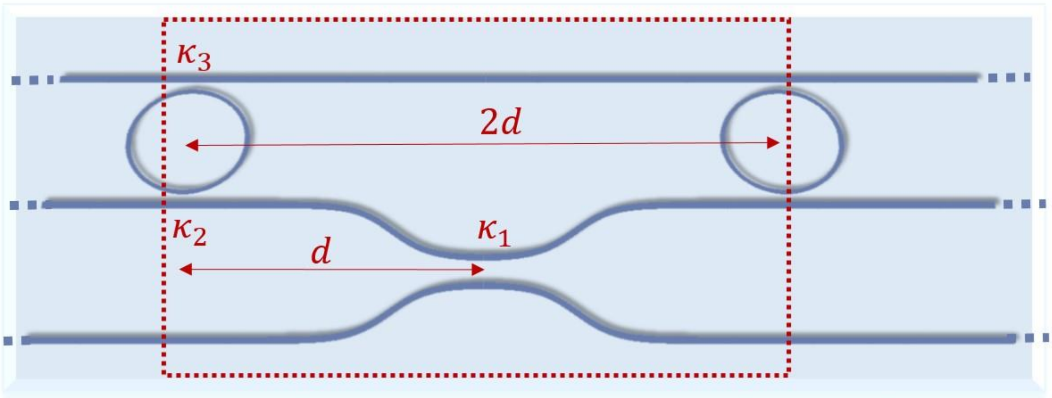

Figure 1 integrated optical periodic structure. One unit- cell is marked with the rectangular.

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Design of a Compact and Efficient Silicon-Based Integrated Optical Phased Array

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With the rapid development of photonic integrated circuits, optical phased array (OPA) technology has attracted much attention in recent years because it can turn quickly without mechanical structure, and has been widely studied in the fields of light detection and ranging (LiDAR). However, the two-dimensional optical phased array antenna is still limited by the antenna spacing, and it is difficult to expand the scanning range. We propose a two-dimensional silicon-based optical phased array (OPA) transceiver with high efficiency and a large field of view. The structure adjusts the phase of the two dimensions of the antenna through the external waveguide phase shifter of the antenna array and further scans the two dimensions of the far field. The 2N phase shifter outside the array used for beam control to reduce the complexity of the system, and then we optimized the structure of some functional devices in the array, such as Y-branch, curved waveguide routing, antenna, and so on. Then we take an 8 × 8 array as an example, reasonably design the array structure and optimize the performance of some functional devices. Finally, we can achieve a beam scanning range of 14.9°×11.2° by the antenna spacing of 6μm×8μm and the radiation aperture of 48μm×64μm. On this basis, by adding Mach-Zehnder optical switch, we can realize the function of a single-chip transceiver of the signal. This structure provides a feasible scheme for the integration of a two-dimensional OPA with high efficiency and a large field of view.

References

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