SQL 26

SENSING WITH QUANTUM LIGHT

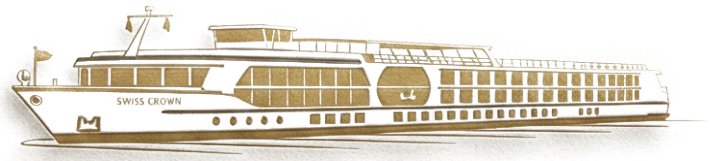
Programme

& Book of Abstracts

9 – 13 November 2026

On board MS Swiss Crown

Cologne · Dordrecht · Antwerp · Nijmegen · Cologne



Welcome to SQL26

Sensing with Quantum Light · 9–13 November 2026

„Sensing with Quantum Light“ was established in 2019 as a series of meetings to support the development of photonic quantum sensing. It brings together established scientists from leading research groups, junior researchers and graduate students. After several editions as a WE-Heraeus Seminar at the Physikzentrum Bad Honnef, SQL26 is the seventh meeting of the series – and, as in 2024, it takes place on board the river cruise ship MS Swiss Crown. This time we travel from Cologne through Germany, the Netherlands and Belgium and back: four nights on board and three full days of science.

Time to talk

SQL is deliberately not a conference of back-to-back talks. A small number of talks and long poster sessions leave most of the time for what often matters most: conversations. Over meals, at the posters, on shore and in the evenings, we encourage you to talk to people you do not know yet – across groups, countries and career stages, from PhD students to group leaders. The seating plan at lunch and a small game running all week are there to help with that. Ask questions, approach people, start discussions: this is what the week is made for.

What is shared on board stays on board

A small community working on closely related questions is the ideal setting to share work in progress – results that are not yet published, ideas that are not yet finished, problems that are not yet solved. This is how new insights and collaborations come about. To make it possible, everything presented and discussed at SQL26 is confidential by default:

- Please do not take photos or recordings of talks, slides or posters unless the presenter agrees.
- Please do not pass on or post unpublished results you see or hear on board without permission.
- If you are happy for your work to be shared – for example because it is already published – just say so.

We are looking forward to four days of inspiring science and good company on the river.

Sven Ramelow, Marthe Zeja and Frank Kühnemann

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Monday, 9 November · Cologne

13:00	Pre-booked lunch on board & luggage drop-off *(please arrive by 12:30)*
15:15	Pre-booked Cathedral tours *(starting at 15:15 and 15:30, meeting point: DOMFORUM)*
16:00	Boarding MS Swiss Crown *(16:00–18:00)*
18:00	Welcome reception
18:30	Dinner
19:00	MS Swiss Crown departs Cologne
20:00	Poster Wall Challenge & icebreaker games
21:30	Social evening

Tuesday, 10 November · Dordrecht

08:00	Breakfast
	Talk Session I *Quantum Imaging & Sensing with Entangled and Squeezed Light*
09:30	**Duncan England** INVITED · National Research Council Canada *Phase microscopy and 3D scene reconstruction with spatially entangled photons* p. 17
10:00	**Ady Arie** · Tel Aviv University *Quantum sensing of angular rotation and birefringence using structured quantum light* p. 18
10:20	Coffee break
11:00	**Da-Wei Wang** · Zhejiang University *Quantum squeezing enhanced photothermal imaging* p. 19
11:20	**Roman Schnabel** · Universität Hamburg *Quantum Radiometric Calibration* p. 20
11:45	Lunch on board
13:00	MS Swiss Crown arrives in Dordrecht · shore excursion *(until approx. 15:00)*
15:00	Poster pitches + **Poster Session I** with coffee and cake
18:00	Dinner
20:00	Short talks & discussion: **Research in the Age of AI**
21:00	Games & social evening
~03:00	MS Swiss Crown departs Dordrecht *(overnight)*

Wednesday, 11 November · Antwerp

08:00	Breakfast
	Talk Session II *Quantum Interferometry, Spectroscopy & Two-Photon Sensing*
09:30	**John Rarity** INVITED · University of Bristol *Quantum interference for near to far infrared sensing* p. 21
10:00	**Frank Schlawin** · MPI for the Structure and Dynamics of Matter / Universität Hamburg *Quantum Metrology in ultrafast spectroscopy* p. 22
10:20	Coffee break
11:00	**Paul Kwiat** · University of Illinois Urbana-Champaign *Quantum Enhanced Remote Interferometry* p. 23
11:20	**Avi Pe'er** · Bar-Ilan University *Generation and Detection of Hyperentangled Bell States at an Ultra-High Flux* p. 24
11:40	**Vira Besaga** · Friedrich Schiller University Jena *Two-Photon Quantum Polarimetry with Entanglement for Tissue-like Scattering Media* p. 25
12:00	MS Swiss Crown arrives in Antwerp
12:15	Lunch
13:30	Shore excursion Antwerp
16:00	Poster pitches + **Poster Session II** with coffee and cake
18:00	MS Swiss Crown departs Antwerp
19:00	Dinner
21:00	Games & social evening

Thursday, 12 November · Nijmegen

08:00	Breakfast
	Talk Session III *Quantum Imaging, Single-Photon Cameras & Telescopy*
09:30	**Ebrahim Karimi** INVITED · Chapman University *Bi-photon Quantum Imaging* p. 26
10:00	MS Swiss Crown arrives in Nijmegen
10:00	**Andrew White** · University of Queensland *Stretching telescopes using single photons* p. 27
10:20	Coffee break
10:50	**Radosław Łapkiewicz** INVITED · University of Warsaw *Quantum and time-resolved imaging with SPAD arrays* p. 28
11:20	**Edoardo Charbon** · EPFL *Quantum Imaging through SWIR Sensors* p. 29
11:40	**Dan Oron** · Weizmann Institute of Science *Image augmentation with photon correlations* p. 30
12:15	Lunch
13:30	Shore excursion Nijmegen
15:30	Poster pitches + **Poster Session III** with coffee and cake
16:00	MS Swiss Crown departs Nijmegen
18:30	Gala dinner
20:30	**Poster Award** & closing remarks
21:00	Social evening

Friday, 13 November · Cologne

08:00	Breakfast
09:30	MS Swiss Crown arrives in Cologne – end of conference *(disembarkation at Frankenwerft, pier 5)*

Practical information

GOOD TO KNOW BEFORE AND DURING SQL26

Boarding · Monday, 9 November

KD landing stage **„Bastei“**, Konrad-Adenauer-Ufer, north of the Hohenzollern Bridge (map) – a good kilometre (15–20 min on foot) from Cologne Cathedral and the main station. Check-in is from 16:00 to 18:00 – please be on board by **18:00**, dinner starts at 18:30.

Lunch on board (if booked): please arrive by 12:30.

Cathedral tours (if booked): the tours start at **15:15** and **15:30** – please meet us **in front of the DOMFORUM** opposite the main entrance (map) **10 minutes before your tour starts**. Only small bags are allowed in the Cathedral.

Disembarkation · Friday, 13 November

We arrive at **09:30** at KD landing stage no. 5, **Frankenwerft** (Old Town, map) – **a different pier than for boarding**. Please do not plan your onward train or flight too tightly: river traffic and waiting times at the locks can delay our arrival, and trains do not always run on time – at SQL24 some participants missed their flights because their train did not run.

Talks and posters

All talks and poster sessions take place in the lounge. Invited talks are 30 minutes, contributed talks 20 minutes, both including discussion. Each poster session starts with the **poster pitches**: one minute and one slide per poster, in the order of the poster numbers. Your poster number (e.g. P II-05) is printed at the top of your abstract page. The winners of the **Poster Award** will be announced on Thursday after dinner.

On board

Full board is included: breakfast, lunch, coffee and cake, and dinner. Water, juices, coffee, tea, house wine and beer are included throughout the day – just order at the bar or from the staff whenever you like.

Beyond talks and posters

MEETING PEOPLE, SHORE EXCURSIONS & EVENINGS ON BOARD

Seating at lunch

To mix people across groups and career stages, there is a fixed seating plan for lunch that changes every day. Your table number is printed on your name badge – please sit at your table. At breakfast and dinner you are free to sit wherever you like.

Shore excursions

Every afternoon we stop in a different city: Dordrecht (Tue), Antwerp (Wed) and Nijmegen (Thu). Suggestions for short walks, with routes in Google Maps, are at the end of this booklet: p. 105. The ship will not wait – please be back on board in time for the poster session: Dordrecht by **15:00**, Antwerp by **16:00**, Nijmegen by **15:30** (the ship leaves Nijmegen at 16:00).

Piers: Dordrecht – Buiten Walevest (map) · Antwerp – cruise pontoon at Het Steen, Scheldekaaien (map) · Nijmegen – on the River Waal, close to the old town; the exact pier will be announced on board.

Monday · Poster Wall Challenge & icebreaker

After the welcome reception we have dinner, and during dinner the ship leaves Cologne. At 20:00 everyone who likes can join the Poster Wall Challenge – setting up the poster walls in small mixed teams – and a round of icebreaker games. Both are optional: a relaxed way to get to know a few new people on the first evening.

Tuesday · Research in the Age of AI

At 20:00, after dinner, we meet in the lounge for a few short impulse contributions on how we actually use AI in our research – not for writing e-mails, but in the scientific work itself – followed by an open discussion. Join in if the topic interests you, and bring your experiences, good and bad. If you would rather keep chatting, the restaurant stays open.

Wednesday · games & social evening

After leaving Antwerp at 18:00 and dinner at 19:00, the evening is open for games and conversation. We bring a selection of games – if you have a favourite game from your country, feel free to bring it along.

Thursday · Gala dinner & Poster Award

Gala dinner at 18:30; afterwards the Poster Award and closing remarks – and one last social evening on the river before we return to Cologne.

All week · the Killer Game

A little game to get you talking to people you have not met yet. With your name badge you get a small card with the **name of another participant** and a **word**. Most important: **keep your card secret**. Your mission: get that person to **say the word** in a conversation. When they do, show them the card – they are out („killed“) and hand you **their** card, which gives you your next target. Only real conversations count (not talks, pitches or questions in the sessions), and no „please say…“. The game ends at the Gala Dinner on Thursday; whoever has collected the most cards wins a small prize. Not in the mood? Just ignore it – and let yourself be killed.

Whirlpool, sauna & steam bath

The ship has a whirlpool on the sun deck as well as a sauna and a steam bath. At SQL24 the whirlpool was popular every evening – so **bring your swimwear**. Sauna and steam bath have limited opening hours and need to be booked in advance at the reception.

Poster Session I

Tuesday, 10 Nov · 15:00 · poster pitches, coffee & cake

1	**Alexander Seeliger** · FSU Jena Pump shaping for improved spatial resolution in quantum imaging with undetected photons	p. 31
2	**Josué Ricardo León Torres** · Fraunhofer IOF Toward Practical Quantum Imaging with Undetected Light	p. 32
3	**Adrian Dannhauer** · Fraunhofer IOF Improved Detection in Multi-Modal Quantum Fluorescence Microscopy	p. 33
4	**Leif Albers** · Universität Hamburg Towards Tomographic Laser Sensing with Entangled Light	p. 34
5	**Rene Fabian Reichow** · Universität Hamburg Shifting optical squeezed states by MHz frequencies for sensing applications	p. 35
6	**Mikhail Korobko** · Universität Hamburg Hyperloss from coherent spatial-mode mixing in photonic quantum networks	p. 36
7	**Sophia Lorenz** · Universität Hamburg Distributed Fiber-Optic Sensing Using a Bidirectional Dual-Wavelength Mach-Zehnder Interferometer	p. 37
8	**Ian Bendix McKenzie** · DTU Data Processing and Noise Mitigation techniques for Heterodyne Rayleigh Microscopy.	p. 38
9	**Sandeep Singh** · DTU Heterodyne Rayleigh Scattering Microscopy: a platform for shot noise limited sensing of gold nanoparticles	p. 39
10	**Aaron Goldberg** · National Research Council of Canada Preasymptotic quantum metrology	p. 40
11	**Annameng Ma** · Heriot-Watt University Optimal referenceless parameter sensing through lossy complex environments	p. 41
12	**Xiao-Ye Xu** · USTC 3D imaging of the biphoton spatiotemporal wave packet	p. 42
13	**Hao-Shu Tian** · USTC Quantum phase estimation using photonic tensor network states	p. 43
14	**Ze-Shan He** · USTC Estimating amplifier gain using cascaded parametric down-conversion	p. 44

15	**Wen-Zhe Yan** · USTC Beating three-parameter precision trade-offs with entangling collective measurements	p. 45
16	**Byron Alexander** · Stellenbosch University Weighted graph states as a resource for quantum metrology	p. 46
17	**Ming Zhi Darren Koh** · CQT, National University of Singapore LIDAR with Optically Amplified Thermal Light	p. 47
18	**Bianca Nardi** · University of Innsbruck Quantum Rangefinding with Bragg-reflection waveguides	p. 48
19	**Federico Collé** · Politecnico di Torino / INRiM Quantum Target Ranging for LiDAR	p. 49
20	**Balázs Novák** · IFIC Valencia Quantum enhanced beam displacement estimation	p. 50
21	**Arpita Pal** · University of Innsbruck Selective Preparation of Collective States via SUPER Excitation: Toward Bio-inspired Energy Efficient Configuration	p. 51
22	**Matthias Gritzner** · University of Innsbruck The Marietta Blau Quantum Optical Ground Station: Measured Atmospheric Turbulence and Laboratory Emulation	p. 52
23	**Linda Sansoni** · ENEA Spectrally and time-resolved Quantum Ghost spectroscopy for threat detection	p. 53
24	**Marco Marangoni** · Politecnico di Milano Ultrafast holographic Fourier-Transform Infrared microscopy for cancer studies	p. 54
25	**Haim Suchowski** · Tel Aviv University High Frame-Rate Mid-Infrared SPAD Camera	p. 55

Poster Session II

Wednesday, 11 Nov · 16:00 · poster pitches, coffee & cake

1	**Felipe Lucas Gewers** · HU Berlin Industrial integration of non-destructive characterization of ceramics using mid-infrared optical coherence tomography with undetected photons	p. 56
2	**Daniel Gould** · HU Berlin Frequency domain undetected photon spectroscopy with an etalon in the signal arm	p. 57
3	**Anna Romanova** · HU Berlin Towards cavity-enhanced wide-field mid-IR spectral microscopy	p. 58
4	**Atta ur Rehman Sherwani** · HU Berlin Hyperspectral mid-infrared imaging of microplastics with undetected photons from a cavity-enhanced source	p. 59
5	**Marthe Zeja** · HU Berlin Between SU(1,1) and induced coherence: a family of nonlinear interferometers	p. 60
6	**Marlon Placke** · HU Berlin Spectrally bright sources for the mid-IR fingerprint region's blind spot	p. 61
7	**Patrick Hendra** · Fraunhofer IOF The Characterization of Mid-IR SNSPD Using Highly Non-Degenerate Photon-Pair Source	p. 62
8	**Rushikesh Burde** · BIAS Bremen Quantum Cavity Ring-down Spectroscopy (Q-CARDS)	p. 63
9	**Christian Vogt** · BIAS Bremen Cavity enhanced gas sensing based on differential absorption in nonlinear interferometers	p. 64
10	**Yu Mukai** · Kyoto University Quantum infrared spectroscopy in the long-wavelength fingerprint region	p. 65
11	**Farzad Ghafari** · Griffith University Single photon sources for mid-infrared sensing	p. 66
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13	**Alessandro Marcia** · ICFO On-chip Undetected photons for Mid-IR Absorption sensing	p. 68
14	**Dmitrii Akatev** · Max Planck Institute for the Science of Light Broad spiral bandwidth of thin-film spontaneous parametric down-conversion	p. 69

15	**Jonas Vasikonis** · Technical University of Darmstadt Vectorial field reconstruction without detecting the field	p. 70
16	**Sergei Kulkov** · Czech Technical University in Prague Massive spectral multiplexing for two-photon interference	p. 71
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18	**Cesar Bernardo** · ELI Beamlines Stimulated Raman with SPDC Source	p. 73
19	**Ohad Aridor** · Tel Aviv University Composite Directional Couplers for Narrowband Filtering in Integrated Quantum Photonics	p. 74
20	**Stefan Frick** · University of Innsbruck Optimized parametric down-conversion sources for photonic quantum technologies	p. 75
21	**Kirill Koshkin** · FSU Jena Temporally filtered photon subtraction for Cat-State generation	p. 76
22	**Sergio Alejandro Salazar Altamirano** · CINVESTAV Generation of Entangled States of Light in an Atomic Ensemble of Rubidium 85	p. 77
23	**Francesco Basso Basset** · Politecnico di Milano Tunable entangled-photon emitter based on a cavity-enhanced quantum dot on a micromachined piezoelectric actuator	p. 78
24	**Isa Ahmadalidokht** · University of Technology Sydney Multispectral Mid-Infrared Quantum Microscopy with Undetected Photons for Label-Free Biomedical Imaging	p. 79

Poster Session III

Thursday, 12 Nov · 15:30 · poster pitches, coffee & cake

1	**Ivan Zorin** · RECENDT Linz Fourier-and time-domain sensing with undetected photons: noise, sensitivity, and optimal measurement regimes	p. 80
2	**Michela Conti** · RECENDT Linz Sensing with undetected photons for applied non-destructive testing	p. 81
3	**Paul Gattinger** · RECENDT Linz Scanless quantum Fourier-Transform infrared microspectroscopy	p. 82
4	**Chiara Lindner** · Fraunhofer IPM Undetected Photons, Coherence, and Fourier-Transform Spectroscopy	p. 83
5	**Sanjukta Kundu** · University of Illinois Urbana-Champaign Skipper-CCD detection system for quantum infrared spectroscopy with visible light	p. 84
6	**Björn Kemper** · University of Münster SIM-QPIa: Mid-infrared spectroscopy with quantum light for detection of environmental microplastics in aqueous samples	p. 85
7	**Jürgen Schnekenburger** · University of Münster Transferring Quantum Photonics to real world applications	p. 86
8	**Emre Köse** · IFIC Valencia Quantum-Limited Mode-Parameter Estimation: Open-System Metrology and Applications to Optical Imaging	p. 87
9	**Michal Natan** · Bar-Ilan University Squeezing Enhanced Sagnac Sensing based on SU(1,1) Quantum Interference	p. 88
10	**Jonas Rittmeyer** · Universität Hamburg Path-Degenerate Quantum Interferometry for Quantum-Enhanced Sensing	p. 89
11	**Miroslav Kloz** · ELI Beamlines Polychromatic detection of entangled photon pairs with intensified CMOS camera	p. 90
12	**Carsten Pitsch** · Fraunhofer IOSB Asynchornous Quantum Ghost Imaging -Achieving real-time video processing and imaging with diffuse reflection	p. 91
13	**Shaurya Aarav** · INSP Paris Correlation-based Adaptive Optics	p. 92
14	**Raphael Guitter** · INSP Paris Certifying quantum entanglement with a time-stamping camera	p. 93

15	**Yanis Trouyet** · INSP Paris Non-local wavefront shaping using entangled photons	p. 94
16	**Xin Huang** · INSP Paris A Quantum Shield against Classical Light	p. 95
17	**Rosa Vaira** · Università di Bari Quantum imaging with entangled photons in the regime of many temporal modes per frame	p. 96
18	**Davide Giannella** · Università di Bari Correlation hyperspectral imaging with thermal light	p. 97
19	**Gianlorenzo Massaro** · Università di Bari Depth Imaging via Statistical Distinguishability of a True Thermal Source	p. 98
20	**Jakub Lewandowski** · University of Warsaw Towards structured illumination ghost imaging -beyond the correlation resolution limit	p. 99
21	**Maja Rynkiewicz** · University of Warsaw Measuring Momentum Anti-Correlations of SPDC Biphotons with Piccolo SPAD array	p. 100
22	**Sergei Bogdanov** · TU Wien Ghost Imaging with Free Electron-Photon Pairs	p. 101
23	**Alexander Preimesberger** · TU Wien Entanglement in Electron Microscopy – A First Demonstration	p. 102
24	**Philipp Haslinger** · TU Wien Entanglement in Electron Microscopy	p. 103

Phase Microscopy and 3D Scene Reconstruction With Spatially Entangled Photons

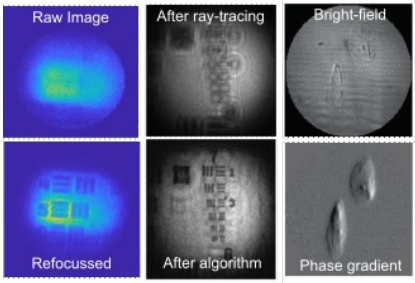
Duncan England[1], Yingwen Zhang[1,2], Ebrahim Karimi[2,3] ,and Ben Sussman[1,2]

[1] National Research Council, Ottawa, Canada. [2]University of Ottawa, Ottawa, Canada.
[3] Chapman University, Orange, California, USA

In this talk, I will present a progression across three experiments that exploit the position–momentum entanglement of photon pairs generated via spontaneous parametric down-conversion (SPDC), detected in coincidence with a time-stamping single-photon camera. The first experiment [1] demonstrates that measuring the position of one photon and the momentum of its entangled partner enables full reconstruction of the propagation trajectory of each photon pair, allowing a three-dimensional scene to be imaged with a single, stationary camera. This ray-tracing approach circumvents the need for microlens arrays, multiple perspectives, or moving parts inherent to classical light-field imaging techniques, while the intrinsically low photon flux makes it well suited to light-sensitive samples.

Building on this foundation, the second experiment [2] extends the ray-tracing concept into the microscopy regime by combining ray-optics-based digital refocusing with a Gerchberg–Saxton-type wave-optics reconstruction to recover diffraction-limited features from out-of-focus planes. The resulting system achieves a depth of field roughly 3–10× larger than conventional microlens-based light-field microscopes.

The third experiment [3] advances the platform toward quantitative phase imaging. By leveraging the momentum anti-correlation of entangled pairs as an intrinsic, reference-free wavefront sensor the technique directly retrieves phase gradients of transparent samples and incorporates a dynamic background-subtraction scheme that mitigates stray-light.



Left: Refocusing an out of focus target using ray-tracing [1].
Center: Algorithmic diffraction compensation for microscopic targets [2].
Right: Phase imaging [3].

[1] Zhang et al. Phys. Rev. A 105, L011701 (2022)
[2] Zhang et al. Phys. Rev. Applied 21, 024029, (2024)
[3] Zhang et al., Nature Com. 17, 3108, (2026)

Quantum sensing of angular rotation and birefringence using structure quantum light

Ady Arie[1]

[1] School of Electrical and Computer Engineering, Tel Aviv University, Tel Aviv, Israel

The spatial, spectral and polarization properties of entangled photons can be controlled in spontaneuous parametric down conversion (SPDC) process by pump shaping or by structured nonlinear crystals. I will discuss two sensing applications of these entangled photons for measuring (i) angular rotation and (ii) retardance of birefringent elements.

Specifically, we have developed a method for direct generation of path-entangled N00N states (with N=2) in an SPDC process, by using two crossed pump beams in a periodically poled KTP crystals. The N00N state is emitted out of the nonlinear crystal, without the need for any additional optical elements. This source was then used for mechanical rotation measurements. Super-resolution and high sensitivity were achieved by using two opposite spiral phase plates with different values of topological charge (1, 16 and 128). Further improvement in resolution was reached by detecting the higher order 4-photon states [1]. This system enables to measure the rotational Doppler shift of slowly rotating objects, with rotation rate as slow as $0.0083\ deg/sec$ [2]. Moreover, hanging a weight on the mechanical holder of one of the spiral phase plate converts it into a pendulum, thereby enabling to determine the gravity constant.

In a second set of experiments, we have used domain engineering to shape the joint spectral intensity in a type II SPDC process, so that it will exhibit only two dominant lobes along the energy conservation line of the signal-idler frequency plane. The location of two peaks were designed to be either symmetric, or anti-symmetric, when the signal and idler frequencies are swapped [3]. This crystal enables direct single-pass generation of a polarization entangled light, by separating the output beam after the nonlinear crystal using a spectral filter. The method was demonstrated both at telecom wavelengths (near 1550 nm) [3] and at shorter wavelengths, near 810 nm [4]. This source was used for nonlocal sensing of birefringence of waveplates, as well as to measure the wavelength-dependent optical activity of chiral molecules.

[1] G. Tshuva, O. Yesharim, H. S. Eisenberg and A. Arie, "512-Fold Rotational Super-Resolution via Four-Photon High-Dimensional Structured Light," *Lasers and Photonics Reviews* e020709 (2026)
[2] O. Yesharim, G. Tshuva and A. Arie, "Quantum Sensing of the Rotational Doppler Effect," *Optics Continuum* **5**, 3150-3156 (2026)
[3] A. Shukin, I. Hurvitz, L. Vidro, A. Arie and H. S. Eisenberg, "Direct Polarization-Entangled Photon Pair Generation Using Domain-Engineered Nonlinear Crystals," *Optica Quantum* **3**, 487-494 (2025)
[4] S. Izhak, I. Hurvitz, H. S. Eisenberg and A. Arie, "Compact polarization-entangled source near 810 nm and its application to nonlocal retardance measurement," *Optics Letters* **51**, 3421-3424 (2026)

Talk T03 · Tuesday, 10 November, 11:00

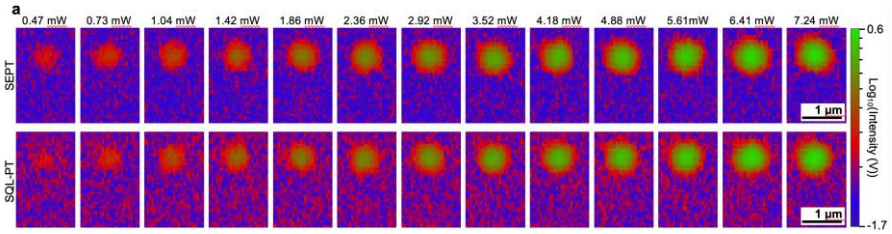
Quantum squeezing enhanced photothermal imaging

Pengcheng Fu, Xiao Liu, Siming Wang, Nan Li, Chenran Xu, Han Cai, Huizhu Hu, V. V. Yakovlev, Xu Liu, S.-Y. Zhu, Xingqi Xu, Delong Zhang, and Da-Wei Wang

[1] Zhejiang University, Hangzhou 310027, China

Photon shot noise constrains the sensitivity, illumination dose and acquisition speed of optical microscopy. Squeezed light enables enhanced chemical and mechanical imaging [1,2], but its practical use depends on source compatibility and optical loss. Here, we present squeezing-enhanced photothermal (SEPT) imaging [3], which separates classical excitation from quantum detection. A 532-nm pump induces absorption-dependent thermal changes, while continuous-wave quantum-correlated twin beams generated by four-wave mixing in rubidium provide balanced readout at 795 nm.

We retain 3.5 ± 0.3 dB of intensity-difference squeezing after the microscope. Relative to balanced coherent photothermal detection under matched conditions, SEPT achieves a 2.3 ± 0.3-fold increase in imaging throughput or a 32 ± 4% reduction in pump power at comparable image quality (figure). We distinguish gold nanoparticle populations with nominal diameters of 13 and 15 nm through photothermal amplitude statistics and reveal cytochrome-c-associated absorption contrast in fixed HEK293T cells. Combining an independently selected classical pump with a fixed-wavelength quantum probe provides a framework for extending quantum-enhanced absorption imaging to additional spectral bands without requiring a tunable squeezed-light source.



[1] C. A. Casacio et al., "Quantum-enhanced nonlinear microscopy," Nature 594, 201-206 (2021).
[2] T. Li et al., "Harnessing quantum light for microscopic biomechanical imaging of cells and tissues," Proc. Natl. Acad. Sci. USA 121, e2413938121 (2024).
[3] P. Fu et al., “Quantum Squeezing Enhanced Photothermal Microscopy”, arXiv: 2601.20632.

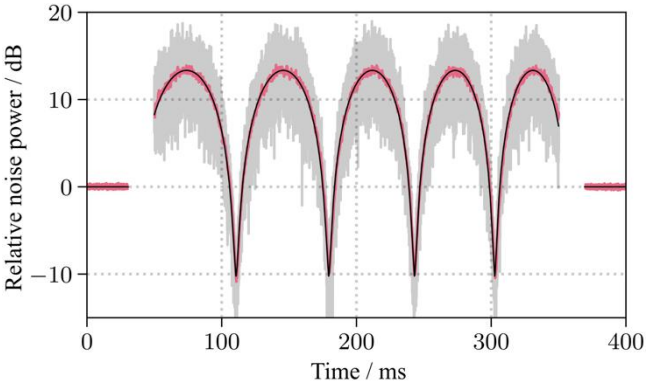
Quantum Radiometric Calibration

Roman Schnabel[1], Leif Albers[1], Jan-Malte Michaelsen[1],

[1] Institut für Quantenphysik, Universität Hamburg, Hamburg, Germany

Optical quantum computing, as well as sensing technology based on quantum correlations are in preparation. These require photodiodes with close to perfect quantum efficiency for the detection of about 10^{16} to 10^{18} photons per second. Already the radiometric calibration is a challenge. Here, I present the proof of concept of the quantum radiometric calibration (QRC) method [1], which is based on Heisenberg's uncertainty principle, derive the formula for its precision, and exclude the potential sources of systematic error. As an example, we calibrate a pair of the most efficient commercial photodiode at 1550 nm to the previously unknown system detection efficiency of (97.20 ± 0.37) % using 10-dB-squeezed vacuum states. This value is unexpectedly low, too low for planned gravitational wave detectors and for continuous-variable optical quantum computing. With further improved precision, our work opens up the second true end-user application of the advantage provided by quantum correlations.

The figure shows the measured quantum noise variances that form the basis of QRC. The ground-state (vacuum state) variance is normalized to 0 dB. The lowest and highest values represent the squeezed and anti-squeezed variances, respectively. Due to photon loss, their product is significantly above the minimum of Heisenberg's uncertainty relation. Additional measurements quantify the contribution from the imperfect photodiode quantum efficiency providing the calibrated value for its detection efficiency. The precision of the calibration method increases with the number of quantum-correlated photons in the squeezed state and the measurement time.



[1] Leif Albers, Jan-Malte Michaelsen, Roman Schnabel, submitted, arXiv: 2512.14947.

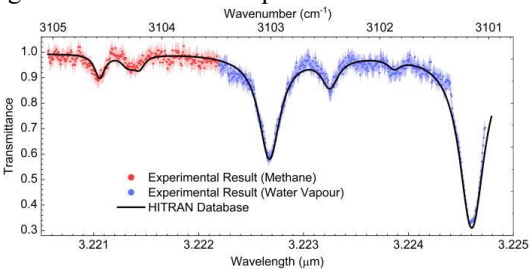
Invited talk T05 · Wednesday, 11 November, 09:30

Quantum interference for near to far infrared sensing.

John G. Rarity[1], Jinghan Dong,[1], Jingrui Zhang[1], Alex Clark[1]

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After discovering two-photon interference in the 1980's various curious interference effects were discovered including the suppression and enhancement of spontaneous emission of photon pairs in a two photon Michelson interferometer [1] and induced coherence interferometry [2]. These first experiments in non-linear interferometry (NLI) were largely forgotten for two decades until the Zeilinger team demonstrated their application to imaging without detection [3] and the realisation that asymmetric pairs meant remote spectral regions could be probed. Both schemes feature in other talks at this conference. Here I will report on our progress in using NLI for spectroscopic gas detection with an idler beam in the mid-to far infrared wavelength region focussing on detection of Methane and SF_6, both potent greenhouse gasses. A signal beam in the NIR enables the use of high sensitivity silicon based detectors. For methane detection we have built a Michelson non-linear interferometer adapted now to highly asymmetric photon pair wavelengths. Using a narrowband stimulating laser for the idler we can scan through narrow mid-IR absorption lines with detection sensitivity capable of seeing background levels of methane in the laboratory (see figure and [4]). The absorption is measured solely using the signal photon fringe visibility measured in a single shot using spatial fringes imaged on a CMOS camera. We have recently extended this method using a $BaGa_2GeSe_6$ crystal allowing generation of asymmetric phase matched photon pairs with idler wavelengths extending over 8-20 μm and NIR signal photons detected in a cooled CMOS detector. We have also recently demonstrated the non-linear interferometry principle on a silicon photonic chip showing phase shifts and attenuation in a 3um wavelength channel. Here the phase stability allows the induced coherence arrangement to be used. The aim is to make future chip-scale methane sensors and I will discuss potential future circuits that would allow on-chip evanescent or off-chip remote sensing.



[1] TM Herzog, J.G. Rarity, H. Weinfureter and A.Zeilinger, Frustrated two-photon creation via interference, PRL. 72, 629–632 (1994).

[2] X. Y. Zou, L.J. Wang and L.Mandel, Induced coherence and indistinguishability in optical interference, PRL. 67, 318 (1991).

[3] G. B. Lemos V. Borish, G. D. Cole, S. Ramelow, R. Lapkiewicz, and A.Zeilinger, Quantum imaging with undetected photons, Nature 512, 409–412 (2014).

[4] J Dong, A.C Cardoso, H. Zhou, W. Nie, A.c. Clark and J.G. Rarity, Open-path methane sensing via backscattered light in a nonlinear interferometer APL Photonics 10, 116106 (2025).

Talk T06 · Wednesday, 11 November, 10:00

Quantum Metrology in Ultrafast Spectroscopy

Giacomo Sorelli[1], Manuel Gessner[2, 3], and Frank Schlawin[4,5,6]

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[2] Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València
[3] Departament de Física Teòrica, UV, Avinguda Vicent Andrés Estellés, 19, E-46100 Burjassot (València), Spain
[4] Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany
[5] University of Hamburg, Luruper Chaussee 149, Hamburg, Germany
[6] The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, Hamburg D-22761, Germany

There is growing interest in using quantum light for nonlinear spectroscopy and imaging. With this growing interest and first proof-of-concept demonstrations, we have also seen increasing scrutiny regarding the 'true' quantum advantage attainable in realistic settings [1].

We present a quantum metrological approach to this question and explain how it enables the systematic optimization of spectroscopic measurement protocols with quantum light. We will then discuss applications in two-photon absorption [2], and Raman spectroscopy and imaging [3,4].

[1] T. Landes, B. J. Smith, and M. G. Raymer, Phys. Rev. A **110**, 033708 (2024).
[2] S. Panahiyan, C. S. Muñoz, M. V. Chekhova, and F. Schlawin, Phys. Rev. Lett. **130**, 2030604 (2023).
[3] F. Schlawin and M. Gessner, Qu. Sci. Tech. **11**, 02LT01 (2026).
[4] G. Sorelli, M. Gessner, and F. Schlawin, Optica Quantum **4**, 366-373 (2026).

Talk T07 · Wednesday, 11 November, 11:00

Quantum Enhanced Remote Interferometry

Paul Kwiat
University of Illinois Urbana-Champaign

The abstract had not been submitted when this booklet was published.

Talk T08 · Wednesday, 11 November, 11:20

Generation and Detection of Hyperentangled Bell States at an Ultra-High Flux

Avi Pe'er

Bar-Ilan University

The abstract had not been submitted when this booklet was published.

Two-Photon Quantum Polarimetry with Entanglement for Tissue-like Scattering Media

Jinliang Ren[1], Vira R. Besaga[2], Ivan V. Lopushenko[3], Jinyong Ma[1,4], Alexander Bykov[3], Igor Meglinski[5], Frank Setzpfandt[2,6], Andrey A. Sukhorukov[1]

[1] ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS), Department of Electronic Materials Engineering, Research School of Physics, The Australian National University, Canberra, Australia
[2] Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, Jena, Germany
[3] Opto-Electronics and Measurement Techniques, Advanced Electronics Centre, Faculty of Information Technology and Electrical Engineering, University of Oulu, Oulu, Finland
[4] Institute of Quantum Precision Measurement, State Key Laboratory of Radio Frequency Heterogeneous Integration, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, P. R. China
[5] College of Engineering and Physical Sciences, Aston University, Birmingham, UK
[4] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena, Germany

We present a fundamentally new quantum polarimetric sensing modality in which both photons of a polarization-entangled pair interact with a sample [1]. In contrast to conventional quantum polarimetry [2,3], where one photon probes the sample while the other serves as a reference, our approach uses higher-order polarization correlations to investigate how the sample modifies the joint two-photon state. We demonstrate this technique experimentally using tissue-like samples with controlled scattering properties and compare its performance with quantum one-photon probing polarimetry. The experimental results show that two-photon probing offers enhanced sensitivity to depolarization-induced changes in the probing state, particularly relevant for optically thin samples. Moreover, our theoretical analysis shows that the proposed approach enables complete sample Mueller matrix to be reconstructed from measured two-photon state using only two probing states. When the sample's dominant response is known, the approach allows the Mueller matrix to be reconstructed in a single shot.

By exploiting the joint polarization evolution of entangled photons, two-photon quantum polarimetry establishes a new measurement principle for characterizing complex scattering media, with the potential to reduce measurement complexity and acquisition time, and thereby advance quantum photonic sensing and the characterization of real-world samples.

[1] J. Ren *et al*, "Quadratic Quantum Polarimetry with Entangled Photon Pairs," arXiv 2604.09257 (2026).
[2] Y.D. Zhang *et al*, "Quantum imaging of biological organisms through spatial and polarization entanglement," Sci. Adv. 10, eadk1495 (2024).
[3] V. R. Besaga *et al*, "Bridging Classical and Quantum Approaches for Quantitative Sensing of Turbid Media with Polarization-Entangled Photons," Laser Photonics Rev. 20, e01172 (2026).

Invited talk T10 · Thursday, 12 November, 09:30

Bi-photon Quantum Imaging

Ebrahim Karimi[1,2]

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[2] Nexus for Quantum Technologies, University of Ottawa, Ottawa, Ontario K1N 5N6, Canada

Spontaneous parametric down-conversion (SPDC) has been at the heart of quantum optics for decades, providing entangled photon pairs for experiments ranging from fundamental tests of quantum mechanics to quantum communication and imaging. Yet, despite its widespread use, the quantum states generated through this seemingly simple process are far richer than we often assume. Their complex spatial structure, high-dimensional correlations, and sensitivity to experimental conditions present both challenges and opportunities.

In this talk, I will discuss how we can turn these challenges into new possibilities for quantum imaging. I will begin with our recent advances in characterising the amplitude and phase of biphoton wavefunctions using digital holography [1], interferometry, and phase retrieval [2]. These techniques allow us to explore high-dimensional entanglement and uncover unexpected features of SPDC-generated states, challenging some of the approximations commonly used to describe photon pairs [3]. I will present our experiments in super-resolution imaging [4,5], quantum ghost microscopy [6,7], and correlation-based light-field imaging [8], where the joint spatial information carried by entangled photons provides new ways to resolve fine structures, recover phase information, and extend the depth of field. I will also discuss how quantum correlations can improve imaging performance through a scatter material, where every detected photon matters [9].

[1] D Zia, N Dehghan, A D'Errico, F Sciarrino, E Karimi, *Nature Photonics* **17**, 1009 (2023).
[2] N Dehghan, A D'Errico, F Di Colandrea, E Karimi, *Optica* **11**, 1115 (2024).
[3] C Howard, R Ghobadi, N Dehghan, A D'Errico, E Karimi, *Optics Express* **34**, 22452 (2026).
[4] F Grenapin, D Paneru, A D'Errico, V Grillo, G Leuchs, E Karimi, *Physical Review Applied* **20,** 024077 (2023).
[5] D. Paneru, A. D'Errico, E Karimi, *Physical Review A* **113**, L011702 *(*2026).
[6] N Dehghan, A D'Errico, Y Zhang, B. Sussman, , E Karimi, *APL Photonics* **11**, 066116 (2026).
[7] Y Zhang, PA Moreau, D England, E Karimi, B Sussman, *Nature Communications* **17**, 3108 (2026).
[8] Y. Zhang, D. England, A Orth, E. K. and B. Sussman, *Physical Review Applied* **21**, 024029 (2024).
[9] A D'Errico, J Hubble, R Abolhassani, N Dehghan, Y Klein, Y Zhang, E Karimi, arXiv:2605.28998.

Talk T11 · Thursday, 12 November, 10:00

Stretching telescopes using single photons

Andrew White
University of Queensland

The abstract had not been submitted when this booklet was published.

Invited talk T12 · Thursday, 12 November, 10:50

Quantum and time-resolved imaging with SPAD arrays

R. Lapkiewicz[1,2]

[1] Quantum Imaging Lab, Faculty of Physics, University of Warsaw, Poland
[2] Center for Hybrid Quantum-Classical Information Technologies QLAB, University of Warsaw, Poland

Single-photon avalanche diode (SPAD) arrays combine single-photon sensitivity with picosecond timing in every pixel. I will present three applications developed in the Quantum Imaging Lab by Maja Rynkiewicz, Jakub Lewandowski, Bernard Gorzkowski, Rounak Chatterjee, Aleksander Macioch, Paweł Szczypkowski, and Amalesh Kumar, in collaboration with Paul Mos, Claudio Bruschini, and Edoardo Charbon (AQUA Lab, EPFL).

First, using Piccolo [1], a 32 × 32 SPAD array with 130 ps time-tagging accuracy, we measure momentum anti-correlations of photon pairs generated in spontaneous parametric down-conversion (SPDC). Replacing a Gaussian pump with a striped one splits the single peak of the sum-coordinate coincidence distribution into two, showing that the transverse structure of the pump laser is imprinted on the biphoton correlations [2].

Second, we exploit this transfer to propose structured illumination microscopy (SIM) for ghost imaging with biphotons. The resolution of ghost imaging is limited by the width of the spatial correlations, which is set by the crystal length: thinner crystals give narrower correlations but lower brightness [3]. Shaping the pump beam and applying SIM reconstruction can overcome this trade-off. Our simulations support the approach, and the experiment is under construction.

Third, we perform widefield fluorescence lifetime imaging microscopy (FLIM) using temporal focusing. In temporally focused two-photon excitation, a diffraction grating spreads the spectral components of a femtosecond pulse, so the pulse is short, and two-photon excitation is efficient only near the image plane of the grating [4]. This gives optical sectioning over the whole field of view without raster scanning. We combine it with SwissSPAD2, a time-gated 512 × 512 SPAD array [5], and obtain widefield lifetime images of biological samples such as stained mouse neurons. Axial sectioning of a few micrometres opens the way to fast 3D lifetime imaging of volumetric samples.

[1] Zhang et al., Sensors, 18(11), 4016 (2018).
[2] Boucher et al., Opt. Lett. 46, 4200–4203 (2021).
[3] E. Brambilla et al., Phys. Rev. A 69, 023802 (2004).
[4] D. Oron et al., Opt. Express 13, 1468 (2005).
[5] A. C. Ulku et al., IEEE J. Sel. Top. Quantum Electron. 25, 6801212 (2019).

Quantum Imaging through SWIR Sensors

Edoardo Charbon
EPFL

The abstract had not been submitted when this booklet was published.

Talk T14 · Thursday, 12 November, 11:40

Image augmentation with photon correlations

Shay Elmalem[1], Shaurya Aarav[2], Allard Hubler[3], Hugo Defienne[2], Dan Oron[1]

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[2] Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP,Paris, France
[3] Georg-August-Universität, 37073 Göttingen, Germany

Widefield fluorescence microscopy is an essential biological imaging tool, yet its penetration depth is fundamentally restricted by tissue-induced aberrations. Correcting these requires precise characterization of the point spread function (PSF), but existing wavefront sensing techniques rely either on often-unavailable guide stars, or on computationally heavy indirect phase retrieval methods, that could struggle in low-contrast regions. Here, we show that the PSF can be mapped directly and non-invasively by exploiting quantum correlations between photons.

Standard fluorophores inherently exhibit photon antibunching, effectively acting as sources of "missing" photon pairs. By capturing the correlation statistics across a wide field of view using a single-photon avalanche diode (SPAD) array imager, we extract the local PSF autocorrelation directly from the fluorescence emission itself with no restrictions on the imaged object in terms of sparsity or frequency content [1]. Further, this approach bypasses the limitations of classical intensity measurements, requiring no iterative or complex numerical optimization. We demonstrate widefield direct PSF retrieval in a second or less, paving the way for real-time operation. By translating quantum optical concepts to conventional fluorescent probes, this technique provides a robust, direct pathway to deep-tissue adaptive optics in life sciences.

[1] S. Elmalem et al., "Aberration sensing in fluorescence microscopy using quantum correlations", arXiv 2609.19806 (2026).

Pump shaping for improved spatial resolution in quantum imaging with undetected photons

Alexander Seeliger[1] and René Sondenheimer[1,2]

[1] Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-Universität Jena
[2] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena

Quantum imaging with undetected photons enables imaging at wavelengths where direct detection is challenging by probing an object with one photon while detecting only its correlated partner [1]. In momentum-correlated implementations, the spatial structure of the pump beam shapes the transverse photon correlations and thereby influences image resolution [2].

We theoretically compare Gaussian pumps, individual radial Laguerre–Gaussian modes, and tailored coherent superpositions of these modes [3]. For a fair comparison, we match the spatial variance of their intensity distributions. Imaging performance is evaluated through the width of the point-spread function, the minimum resolvable distance of two point objects, and the edge response.

Individual Laguerre–Gaussian modes can narrow the central point-spread-function peak and reduce the minimum resolvable distance compared with Gaussian pumping. However, their side lobes affect image formation, and these gains do not necessarily translate into a corresponding improvement in edge resolution. To assess this behavior, we examine the edge-spread function and its derivative, the line-spread function, using the full width at half maximum of its central peak as an additional resolution measure.

Coherent pump superpositions provide further improvements in point-object resolution. However, superpositions optimized for the point-spread-function width can perform worse in edge imaging. Optimizing for the line-spread-function width instead improves edge resolution while generally also narrowing the point-spread function. Nevertheless, the improvement in point resolution is typically smaller than with superpositions optimized for point-spread function alone.

These results identify pump shaping as a route to improved spatial resolution in quantum imaging with undetected photons and highlight the need to consider point and edge responses together when designing structured pumps.

[1] Lemos et al., Nature 512, 409–412 (2014).
[2] Fuenzalida et al., Quantum 6, 646 (2022).
[3] Seeliger and Sondenheimer, in preparation.

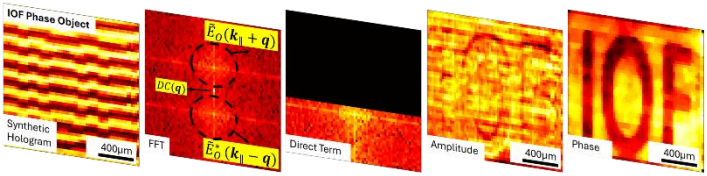
Toward Practical Quantum Imaging with Undetected Light

Josué R. León-Torres[1,2,3], Patrick Hendra[1], Byron Caiza[1], Sebastian Töpfer[4], Frank Setzpfandt[3], Markus Gräfe[1,4], Valerio Gili[1]

[1] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, 07745 Jena, Germany
[2] Cluster of Excellence Balance of the Microverse, Friedrich Schiller University Jena, Jena, Germany
[3] Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Straße 6, 07745 Jena, Germany
[4] Institute for Applied Physics, Technical University of Darmstadt, Otto-Berndt-Straße 6, 64287 Darmstadt, Germany

Quantum imaging with undetected light (QIUL) enables the retrieval of spatial information about an object without directly detecting the photons interacting with it, opening new possibilities for imaging at wavelengths where conventional detection technologies are limited or unpractical. However, translating QIUL from proof-of-concept demonstrations toward practical applications requires overcoming challenges related to acquisition speed, spatial resolution, phase sensitivity, and experimental complexity.

Here, we review and compare the evolution of phase-imaging techniques within QIUL, from digital phase-shifting holography (DPSH) [1] to off-axis holography (OAH) [2, 3], wide-field synthetic holography [4], and scanning synthetic holography [5, 6]. We highlight the underlying principles, advantages, and limitations of each approach, particularly regarding the number of required measurements, dependence on spatial correlations, noise resilience, and imaging performance. By examining the trade-offs between these complementary techniques, we discuss how recent developments are addressing key experimental limitations and paving the way toward robust, efficient, and practical quantum imaging systems.



[1] S. Töpfer et al., Sci. Adv. 8, eabl4301 (2022)

[2] León-Torres et al., Opt. Express 32, 35449–35461 (2024)

[3] León-Torres et al., Adv. Quantum Technol. 9(7), e70355 (2026)

[4] Töpfer et al, Optica Quantum 3, 129–136 (2025)

[5] León-Torres et al., Laser Photonics Rev. 20(9), e02356 (2026)

[6] León-Torres et al., arXiv:2607.16176 (2026)

Improved Detection in Multi-Modal Quantum Fluorescence Microscopy

Adrian Dannhauer[1], Tobias Gäbler[1,2], Valerio Gili[1]

[1] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena, Germany
[2] Abbe Center of Photonics, Friedrich Schiller University, Jena, Germany

The experimental realization of fluorescence imaging with entangled light remains an ongoing research topic, as only a few successful demonstrations have been reported to date. A critical challenge in this field is optimizing the optical imaging design, which often hinders the investigation of different fluorescence imaging methods. To address this issue, we developed a multi-modal design approach that enables straightforward investigation under different conditions.

To demonstrate the utility of this multi-modal design approach, we apply it to a particularly demanding fluorescence imaging modality: fluorescence lifetime imaging (FLIM), which provides quantitative contrast based on the nanosecond-scale decay dynamics of fluorophores. Established lifetime measurements require illuminating the probe with pulsed or amplitude-modulated light. Additionally, conventional FLIM is fundamentally limited by the need for many detected photons to estimate a lifetime precisely, which prolongs acquisition and increases photobleaching and phototoxicity, consequently restricting in-vivo applications. [1] Here, we present a comparison of the classical and the quantum-enhanced approach to FLIM that exploits the strong time-frequency correlation of entangled photons generated by a continuous-wave source. Exploiting the frequency anti-correlation of the photon pairs, the signal and idler photons are spectrally separated by a dichroic element. The idler photon is detected directly and serves as a heralding timing reference, while the signal photon excites the sample (Fig. 1). Lifetimes are reconstructed from arrival-time-difference histograms via TCSPC.

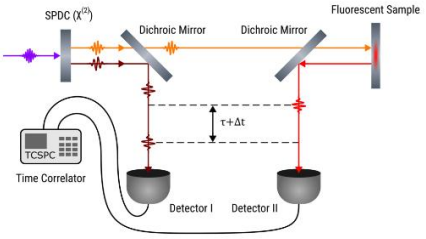


Fig. 1: Schematic of the quantum-enhanced FLIM setup.

This illumination method aims to improve lifetime estimation per detected photon and per unit excitation dose.

[1] Gäbler, T. B. et al. Benchmarking of fluorescence lifetime measurements using time-frequency correlated photons. *Methods in Microscopy* **2**,133–145 (2025).

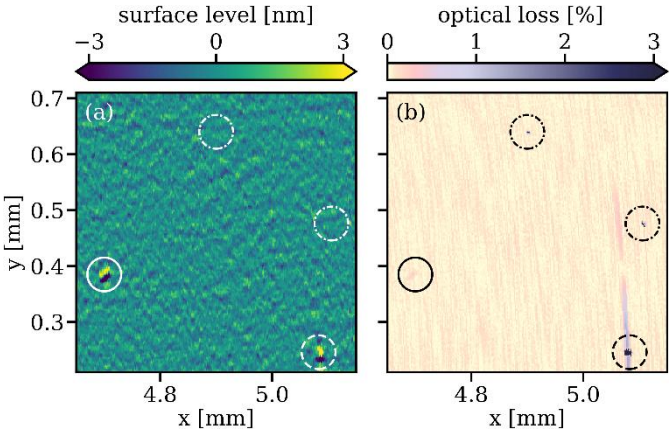
Towards Tomographic Laser Sensing with Entangled Light

Leif Albers[1], Roman Schnabel[1]

[1] Institut für Quantenphysik, Universität Hamburg, Hamburg, Germany

We present a spiral laser scanning microscopy method that reconstructs tomographic phase and loss images of optical surfaces and samples. A focused probe beam scans the sample along a spiral trajectory, achieving diffraction-limited spatial resolution while minimizing acquisition time. Combined with a Mach-Zehnder-based read-out we reach a phase sensitivity of up to 3.1 fm/√Hz, limited largely by photon shot-noise. We use this to computationally reconstruct phase maps of the sample surface. A subsequent intensity-based measurement yields a spatially co-registered optical loss map. We apply this approach to investigate point absorbers in mirror coatings and their correlation with surface roughness. [1]

We further aim to implement simultaneous read-out of both phase and amplitude quadrature in a single measurement to enable mapping moving samples. By injecting entangled states of light, the sensitivity can be pushed beyond the shot-noise limit for both quadratures, enabling phase space tomography of sensitive samples with reduced laser power.



[1] Leif Albers, Malte Hagemann, Roman Schnabel. Laser Scanning Microscopy for Tomographic Imaging of Roughness and Point Absorbers in Optical Surfaces. Adv Devices Instrum. 2024;5:0064. DOI:10.34133/adi.0064

Shifting optical squeezed states by MHz frequencies for sensing applications

Rene Reichow[1], Mikhail Korobko[1], Roman Schnabel[1]

[1] Institut für Quantenphysik, Universität Hamburg, Hamburg, Germany

Squeezed states of light reduce quantum noise below the shot-noise limit. This improves the sensitivity of optical measurements without increasing the light power. Squeezed light is usually generated by degenerate parametric down-conversion, so its carrier frequency is set by the pump laser and the squeezing resonator. This makes fast and precise tuning of the squeezed carrier technically demanding. A low-loss shift of the carrier by MHz to GHz frequencies would therefore bring quantum-enhanced sensitivity to a wider range of physical phenomena while also enabling new schemes that rely on a fixed frequency offset.

One possible application is in third-generation gravitational-wave detectors such as the Einstein Telescope and Cosmic Explorer. These detectors plan to use long, costly filter cavities to make the squeezing frequency-dependent. Applying a radio-frequency shift between two passes through the same filter cavity could reduce the number of cavities needed, provided the frequency shift can be made sufficiently low-loss. Unlike EPR-based schemes [1,2], this approach avoids a 3 dB sensitivity penalty.

In a proof-of-principle experiment, we use an acousto-optic modulator (AOM) with 88 % single-pass efficiency to shift 7 dB squeezed vacuum at 1064 nm by 80 MHz and subsequently measure 4.5 dB of squeezing in the shifted field. This is a significantly higher squeezing value than in the first experiment of this kind, which used an interferometric approach [3]. Using constructive self-interference, efficiencies close to 100 % appear achievable [3]. We also discuss current limitations and sketch how the proposed filter-cavity scheme could be realized.

[1] J. Südbeck, S. Steinlechner, M. Korobko, R. Schnabel, “Demonstration of interferometer enhancement through EPR entanglement,” Nat. Photonics 14, 240–244 (2020).

[2] M. J. Yap et al., “Generation and control of frequency-dependent squeezing via Einstein–Podolsky–Rosen entanglement,” Nat. Photonics 14, 19–23 (2020).

[3] Q. Deng, W. Li, X. Guo, and X. Li, “Frequency tuning of a squeezed vacuum state using interferometric enhanced acousto-optic effect,” Opt. Express 32, 39632–39642 (2024).

Hyperloss from coherent spatial-mode mixing in photonic quantum networks

Stephan Grebien[1], Julian Gurs[1], Roman Schnabel[1], Mikhail Korobko[1]

[1] Institut für Quantenphysik and Zentrum für Optische Quantentechnologien, Universität Hamburg, Hamburg, Germany

Squeezed light is becoming a key resource for precision interferometry, quantum sensing, communication, and photonic information processing. As these systems develop into larger multimode optical networks, their performance increasingly depends on preserving fragile quantum correlations through imperfect optical interfaces. Spatial-mode mismatch is usually entered into loss budgets as an incoherent loss. This approximation can fail when light couples coherently into higher-order spatial modes at several nodes. Differential phases between the modes then determine how the scattered field returns to the detected fundamental mode. For some phases, anti-squeezing is mixed into the measured squeezed quadrature so strongly that the apparent loss exceeds 100% of the initial squeezing. We call this regime hyperloss. The same coherence also creates a recovery regime in which correlations scattered out of the measured mode interfere constructively on return.

We demonstrated both regimes in a two-cavity quantum network [1]. A squeezed field in the LG_{00} mode was reflected from two overcoupled cavities with an intentionally introduced 8% coupling into LG_{01} between them. Tuning the differential spatial-mode phase converted 5.8 dB of observed squeezing into an effectively thermal state with about 1.5 dB noise above shot noise. All quantum correlations were lost.

Tuning the phase between the modes allowed to enter the recovery regime, where up to 5.2 dB of the initial 5.8 dB squeezing reappeared: approximately 15% geometrical mismatch produced only about 2.8% effective loss. A phase-insensitive loss model predicts neither limit.

Our results establish differential spatial-mode phase as a control resource for the next generation of squeezed-light systems. Phase-engineered Gouy propagation, tunable cavity responses, and adaptive wavefront control could recover otherwise hidden correlations, helping future interferometers, quantum links, and photonic processors preserve their quantum advantage as they scale.

[1] Grebien, S., Gurs, J., Schnabel, R., & Korobko, M. (2026). Hyperloss from coherent spatial-mode mixing in quantum-correlated networks. Nature Communications, 17(1), 7270. https://doi.org/10.1038/s41467-026-75899-5

Distributed Fiber-Optic Sensing Using a Bidirectional Dual-Wavelength Mach-Zehnder Interferometer

Sophia Lorenz[1,2], Leif Albers[1,2], Roman Schnabel[1]

[1] Institute of Quantum Physics, University of Hamburg, Hamburg, Germany
[2] FiberGuard, Hamburg, Germany

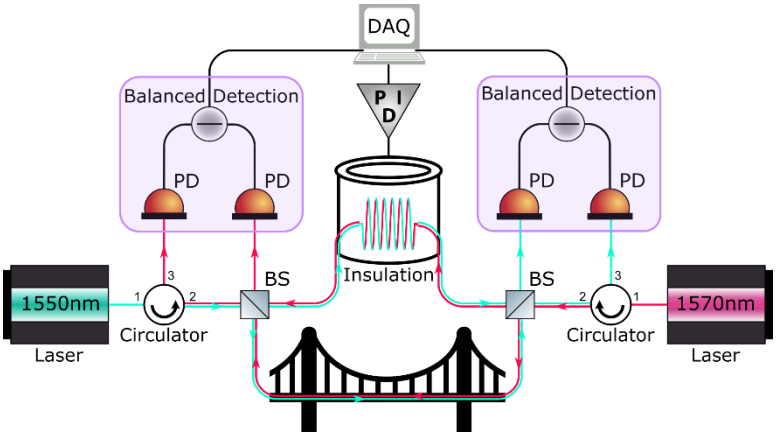
Distributed fiber-optic sensing provides a promising route toward continuous monitoring of large-scale infrastructure, but combining interferometric sensitivity with spatial information remains challenging.

We are developing a bidirectional, dual-wavelength fiber Mach-Zehnder interferometer for spatially resolved vibration sensing along extended fiber paths. Two optical wavelengths propagate through the sensing fiber in opposite directions. By correlating the resulting signals in both propagation directions, the position of a disturbance along the fiber can be reconstructed while retaining the high phase sensitivity of an interferometric measurement.

The system is actively stabilized for long-term operation and is designed around two optical modes, making it compatible with squeezed-light measurements and future investigations of quantum-enhanced distributed sensing [1].

Following laboratory validation, the next step is to operate the system under real environmental conditions. A field test is planned on infrastructure at the Port of Hamburg.

[1] R. Schnabel, Device for fiber-optical measurement and transport of measurement signals, European Patent EP4202374A1 (2023), granted as EP4202374B1 (2026).



Data Processing and Noise Mitigation techniques for Heterodyne Rayleigh Microscopy.

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Over the past decade, several studies have demonstrated single-molecule sensitivity by imaging the interference between scattering from the object of interest and a reference field. This approach has enabled mass photometry of single biomolecules owing to the linear scaling of image contrast with molecular polarizability [1, 2]. So far, most implementations are based upon a single path interferometer and thus cannot separate and independently tune the reference and scattered field [2]. Here, we demonstrate an extension to this approach using a split-path geometry similar to a Mach-Zehnder interferometer. By coherently up-shifting the reference light and employing balanced heterodyne detection, we record both quadratures of the scattered field, while moving detection away from near-DC electronic noise. Using a raster scan method, single-pixel detection introduces imaging artifacts such as row-banding noise and interferometric drift between the arms. Here we show how to cancel these effects, without loss of particle signal, by normalizing each image to the in-situ coverslip reflection and a per-line gain and phase drift estimate. We further identify a static offset in the I/Q demodulation as the dominant source of row banding in raster-scanned images and correct it. We demonstrate the platform and post-processing by imaging gold nanoparticles down to 5 nm in diameter.

[1 Ginsberg, N.S., Hsieh, CL., Kukura, P. *et al.* Interferometric scattering microscopy. *Nat Rev*
[2] Thiele, J.C., Pfitzner, E. & Kukura, P. Single-protein optical holography. *Nat. Photon.*

Heterodyne Rayleigh Scattering Microscopy: a platform for shot noise limited sensing of gold nanoparticles

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Label-free detection of single biomolecules is of wide interest in microscopy, as it avoids the perturbation introduced by scattering labels in the imaging [1]. However, the field scattered by a single biomolecule is extraordinarily weaker than the illumination field, and under coherent illumination and amidst the low-frequency noises it becomes comparable to the technical noise present in the overall measurement process. Simply increasing the coherent optical power to overcome the technical noise is not viable, since the biomolecules would be damaged long before the signal-to-noise ratio (SNR) becomes adequate. The challenge is therefore to extract the maximum information from every available photon in the illumination beam [2].

Conventional common-path interferometric scattering (iSCAT) microscopy derives its reference from the sample coverslip reflection, which acts as a fixed background against the scattered field and cannot be adjusted independently of the sample, an inherent constraint on optimizing the interference visibility thus SNR. We address this by building a heterodyne Rayleigh microscope at 532 nm in a Mach–Zehnder configuration with a separate external local oscillator (LO), allowing the reference strength to be freely controlled. We shift the illumination thus. probe by 5 MHz to keep the signal away from low-frequency technical noise and used balanced detection with I/Q demodulation to retrieve both quadratures of the scattered field. This architecture accepts a modest shot-noise penalty owing to heterodyne detection and requires raster scanning to image the full sample, but in exchange provides independent LO control and access to the full complex scattered field.We initially benchmarked this microscope using standard gold nanoparticles.

Reference: -

1] Taylor, Michael A. et al. Nature Photonics volume 7, 229–233 (2013)
[2] Casacio, Catxere A. et al. Nature volume 594, 201–206 (2021)

Preasymptotic quantum metrology

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Quantum theory promises advantages in precision measurement, but only in the asymptotic limit of infinite measurements, governed by the quantum Cramér-Rao bound (CRB). We show how to find optimal advantages before the CRB becomes relevant, including their mathematical and geometrical properties.

True experiments only have finite data. As well, for continuous measurements, there are classical drifts and noise that lead to tomorrow's measurement being different from today's. We seek a theory for how to find quantum metrological advantages with limited data.

To do so, we rederive the CRB while including higher order correction terms, which typically vanish as the number of measurements becomes large. We inspect each of these corrections, interrogating how they scale with different estimators, different probe states, and different measurement procedures that would otherwise be deemed identical. We identify optima for each of these in the context of rotation measurements and speculate on their generalization to arbitrary measurement contexts.

[1] Beyond the Quantum Cramér-Rao Bound, J. R. Hervas, A. Z. Goldberg, A. S. Sanz, Z. Hradil, J. Řeháček, and L. L. Sánchez-Soto. *Phys. Rev. Lett.* **134**, 010804 (2025).
[2] Higher-order corrections to the quantum Cramér-Rao bound, J. R. Hervas, A. Z. Goldberg, A. S. Sanz, Z. Hradil, J. Řeháček, and L. L. Sánchez-Soto. *Phys. Rev. A* **112**, 022426 (2025).

Optimal referenceless parameter sensing through lossy complex environments

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The abstract had not been submitted when this booklet was published.

3D imaging of the biphoton spatiotemporal wave packet

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Photons are among the most important carriers of quantum information owing to their rich degrees of freedom, including various spatiotemporal structures. The ability to characterize these degrees of freedom, as well as the hidden correlations among them, directly determines their capabilities for quantum sensing [1, 2]. While various methods have been developed for measuring the spatiotemporal structure of classical light fields, owing to the technical challenges posed by weak photon flux, there have so far been no reports of observing such structures in their quantum counterparts, except for a few studies limited to correlations within individual degrees of freedom [3, 4].

We propose and experimentally demonstrate a self-referenced, high-efficiency, and all-optical method, termed three-dimensional imaging of photonic wave packets, for comprehensive characterization of the spatiotemporal structure of a quantum light field, namely, the biphoton spatiotemporal wave packet [5]. Benefiting from this developed method, we successfully observe the spatial-spatial, spectral-spectral, and spatiotemporal correlations of biphotons generated via spontaneous parametric down-conversion, revealing rich local and nonlocal spatiotemporal structure in quantum light fields. Our approach provides a foundation for developing quantum sensing schemes that harness the rich spatiotemporal correlations of biphotons.

[1] Brooks, R. M. J., Maggio, L., Jaeken, T., Ho, J., Gauger, E. M., Tamma, V., & Fedrizzi, A. (2026). Optical Sensing near the Quantum Limit with Enhanced Dynamic Range by Resolving the Spectra of Interfering Photons. Physical Review Letters, 136(6), 060803. https://doi.org/10.1103/6xy6-c2yd
[2] Defienne, H., Ndagano, B., Lyons, A., & Faccio, D. (2021). Polarization entanglement-enabled quantum holography. Nature Physics, 17(5), 591-597. https://doi.org/10.1038/s41567-020-01156-1
[3] Thekkadath, G. S., Bell, B. A., Patel, R. B., Kim, M. S., & Walmsley, I. A. (2022). Measuring the Joint Spectral Mode of Photon Pairs Using Intensity Interferometry. Physical Review Letters, 128(2), 023601. https://doi.org/10.1103/PhysRevLett.128.023601
[4] Schneeloch, J., Tison, C. C., Fanto, M. L., Alsing, P. M., & Howland, G. A. (2019). Quantifying entanglement in a 68-billion-dimensional quantum state space. Nature Communications, 10(1), 2785. https://doi.org/10.1038/s41467-019-10810-z
[5] Xue, Y., He, Z. S., Tian, H. S., Wang, Q. Q., Yin, B. T., Zhong, J., ... & Guo, G. C. (2026). 3D imaging of the biphoton spatiotemporal wave packet. arXiv preprint arXiv:2601.21250. https://arxiv.org/abs/2601.21250

Quantum phase estimation using photonic tensor network states

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Quantum-enhanced metrology exploits nonclassical correlations to surpass the shot-noise limit (SNL), offering promising advantages for precision sensing. However, demonstrating such quantum advantages with scalable many-photon states remains a major challenge. Here, we demonstrate quantum-enhanced sensing using scalable photonic many-body states generated in a programmable optical platform. By integrating these entangled photonic states into a phase interferometer, we achieve a measurement precision, as quantified by the per-photon classical Fisher information, 5.04±0.23 dB above the SNL. Our results demonstrate the potential of scalable entangled photonic states for practical quantum sensing applications and provide a route toward implementing quantum-enhanced metrology with large-scale photonic systems [1].

[1] Z.-S. He*, **H.-S. Tian***, Q.-Q. Wang*, Y. Xue*, et al., Quantum metrology using photonic tensor network states, manuscript in preparation. * Equal contribution

Estimating amplifier gain using cascaded parametric down-conversion

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Accurate estimation of optical amplifier gain is important for characterizing parametric amplification and developing photonic sensing protocols [1]. Conventional strategies typically rely on independent amplification events, whereas coherent cascades allow correlations to develop across successive interactions. Here, we experimentally demonstrate enhanced local estimation of power gain using a synchronously pumped optical parametric amplifier network. The network generates photonic tensor-network states across time-bin modes [2], providing a scalable setting for studying gain estimation with coherent cascaded amplification. We measure joint photon-number outcomes directly using pseudo-photon-number-resolving detection and obtain their empirical probabilities from raw counts. These measured gain-dependent distributions determine the classical Fisher information and the corresponding single-trial Cramér–Rao bound for locally unbiased estimation. By tuning the delay between pump pulses and the circulating signal field, we switch the same platform between coherent cascaded amplification and a configuration of independent amplifiers. This reconfiguration permits a direct comparison of the two protocols under matched conditions. In the four-mode configuration, the coherent cascaded protocol yields a (2.12 ± 0.17) -fold enhancement in classical Fisher information over the independent-amplifier protocol.

[1] R. Nair, G. Y. Tham, and M. Gu, Optimal gain sensing of quantum-limited phase-insensitive amplifiers, Phys. Rev. Lett. 128, 180506 (2022).
[2] I. Dhand et al., Proposal for quantum simulation via all-optically-generated tensor network states, Phys. Rev. Lett. 120, 130501 (2018).

Beating three-parameter precision trade-offs with entangling collective measurements

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Quantum-mechanical incompatibility, which precludes the simultaneous precise measurement of non-commuting observables, imposes fundamental limits on the rate at which classical information can be extracted. While the potential to surpass these limits using entangling collective measurements has been explored for two parameters, the regime of three or more parameters remains largely unexplored despite its fundamental and technological importance. Here, we investigate the three-parameter trade-off relations for estimating the Bloch vector components of a qubit, comparing conventional individual measurements with entangling collective measurements. We theoretically derive optimal collective measurements on two identical qubits and experimentally implement the measurements on two-qubit states encoded in four path modes of a single photon using a programmable photonic circuit as a proof-of-principle demonstration. Our experimental results demonstrate a clear violation of the entanglement-free trade-off relation, achieving a tomography precision beyond the reach of any individual measurement scheme. This work directly confirms that optimal collective measurements can surpass the fundamental quantum limits of individual schemes in a three-parameter setting—thereby deepening our understanding of quantum uncertainty relations beyond the two-parameter regime and providing a clear strategy to overcome the precision trade-offs imposed by quantum incompatibility.

Weighted graph states as a resource for quantum metrology

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Quantum metrology exploits quantum mechanical effects to increase the precision of measurements of physical quantities. A wide variety of applications are currently being developed for scientific and technological purposes; however, most research relies on highly entangled resource states that are challenging to generate and control in a given physical system. Here, we study weighted graph states as more accessible resources for quantum metrology, yielding favourable precision beyond the classical limit and approaching the Heisenberg limit. We find notable robustness to variations in the weights and less challenging weight requirements compared with standard graph states, which require a maximal weight at all edges. Both aspects reduce the practical demands on a physical setup, with the latter implying that significantly less entanglement is required to gain a quantum advantage in metrology. We study the quantum Fisher information and optimized estimator variance of two identified subclasses of weighted graph states for an arbitrary number of N qubits, providing analytical forms and investigating their scaling. Our work opens opportunities for using weakly entangled states in quantum-enhanced metrology.

LIDAR with Optically Amplified Thermal Light

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Thermal light, such as blackbody radiation or spontaneous emission from an ensemble of atoms, can be described as a superposition of electric fields with no fixed phase between them [1]. This gives rise to intensity fluctuations, on a timescale corresponding to its coherence time τ_c. Thermal light has been utilized as a source of entropy for applications such as quantum random number generation. The associated intensity correlation also on the same timescale, often referred to as photon bunching, is desirable for light detection and ranging (LIDAR) illumination as it does not require additional modulation and is resistant to turbulence. Previous LIDAR experiments with thermal light have demonstrated centimeter depth resolution at long distances and spatial resolution beyond the diffraction limit [2, 3].

Thermal light sources often have a broad frequency spectrum result in short coherence time of femtoseconds as $\tau_c \propto 1/\Delta\lambda$, where $\Delta\lambda$ is the bandwidth of the light. This makes the intensity fluctuation unresolvable. As such, spectral filtering is often done to increase the coherence time at the cost of brightness. This reduces thermal light usefulness, especially in applications with high return losses such as in LIDAR, where previous experiments were limited to table top experiments, in optical fibers, or with retroreflective targets [2, 3, 5].

In this poster, we show that thermal light [6] when amplified through stimulated emission, has its intensity fluctuations and correlation preserved. This is done by measuring and comparing its second order coherence function $g^{(2)}(\tau)$ before and after amplification. With a higher power level accessible using amplification, we then demonstrate a LIDAR raster scan of a building at 1.3 km, utilizing only the diffuse reflection off the building, achieving a depth resolution of 2 cm.

[1] R. Loudon, The Quantum Theory of Light, 2nd ed. (Clarendon Press, Oxford, 1983).
[2] P. K. Tan, X. J. Yeo, A. Z. W. Leow, L. Shen, and C. Kurtsiefer, Practical range sensing with thermal light, Physical Review Applied 20, 014060 (2023).
[3] L.-C. Liu, C. Wu, W. Li, Y.-A. Chen, X.-P. Shao, F. Wilczek, F. Xu, Q. Zhang, and J.-W. Pan, Active optical intensity interferometry, Physical Review Letters 134, 180201 (2025).
[4] P. K. Tan, G. H. Yeo, H. S. Poh, A. H. Chan, and C. Kurtsiefer, Measuring temporal photon bunching in blackbody radiation, The Astrophysical Journal Letters 789, L10 (2014).
[5] J. Zhu, X. Chen, P. Huang, and G. Zeng, Thermal-light-based ranging using second-order coherence, Applied optics 51, 4885 (2012).
[6] X. J. Yeo, D. M. Z. Koh, J. Y. X. Peh, C. Kurtsiefer, and P. K. Tan, Near-lossless method for generating thermal photon-bunched light (2026), arXiv:2602.00633 [quant-ph].

Quantum Rangefinding with Bragg-reflection waveguides

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Quantum LiDARs promise improvements to the state-of-the-art classical LiDARs in terms of range accuracy and signal-to-noise ratio (SNR) at low power regimes, by using nonclassical properties of light. In this context, Quantum Rangefinding [1] aims to perform time-of-flight (TOF) measurements by sending light that camouflages within the background across all degrees of freedom. This guarantees a fundamental covertness that classical LiDARs are unable to provide. Inspired by quantum illumination, we use an SPDC source to exploit correlations between signal photons, detected locally, and the idler photons, sent to the target before detection. The target distance is calculated from the relative delay between signal and idler detection. Each half of a SPDC biphoton state manifests the same thermal statistics [2] as the background, for a single-mode field. Therefore, from the target point of view, a quantum rangefinder is indistinguishable from the background radiation.

Due to their high $\chi^{(2)}$-nonlinearity, AlGaAs Bragg-reflection Waveguides (BRW) are reliable bright photon-pair sources [3]. For our structures, the characteristic SPDC emission lies within a ~200 nm-broad telecom band. This wavelength is resilient to atmospheric turbulence, and the SPDC emission spreading across several spectral modes ensures that the bright rangefinder doesn't exceed the background average photon number per spectral mode [4].

In this work, we present an implementation of a BRW quantum rangefinder showing its performance with targets of different reflectivity, at different background levels, and with different losses. Additionally, we use a collimator to collect the light sent from the BRW quantum rangefinder and test its operation from the target point of view, challenging its performance by artificially injecting uncorrelated noise.

[1] Frick, S., et al., (2020). Quantum rangefinding. Optics Express, 28(25), 37118-37128.

[2] Blauensteiner, B., et al., (2009). Photon bunching in parametric down-conversion with continuous-wave excitation. Physical Review A—Atomic, Molecular, and Optical Physics, 79(6), 063846.

[3] Thiel, H., et al., (2023). Fabrication of low-loss III-V Bragg-reflection waveguides for parametric down-conversion. Optical Materials Express, 13(5), 1278-1289.

[4] Nardi, B., et al., (2025). Bragg-reflection waveguides as practical photon-pair sources for quantum rangefinding. Journal of Lightwave Technology, 2025.

Quantum Target Ranging for LiDAR

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We investigate Quantum Target Ranging (QTR) as a multi-hypothesis testing problem in real- world LiDAR systems. Our work experimentally studies the performance of quantum ranging using phase-insensitive measurements, which are commonly used in conventional LiDAR systems. Using entangled photonic probes combined with photon-counting measurements , we demonstrate a significant improvement in target sensing performance compared with classical coherent probes.

We further investigate a more interesting and practically relevant covert sensing scenario, where the target must be ranged while minimizing the probability of being detected by an adversary. In this regime, we experimentally demonstrate that covertness can be maintained using low-brightness quantum probes, whereas classical probes cannot achieve the same level of covert operation. Our experimental results validate the proposed QTR protocol [1] as well as the covert sensing applicability [2] and demonstrate its behavior under realistic operating conditions.

Our findings could open a new perspective in optical quantum sensing and provide a strong motivation for the development of quantum LiDAR.

References

[1] Ortolano, G., & Ruo-Berchera, I. (2025). Quantum target ranging for LiDAR. *Physical Review Research*, *7*(2). https://doi.org/10.1103/physrevresearch.7.l022059

[2] Ortolano, G., Ruo-Berchera, I., & Banchi, L. (2025). Chernoff Information bottleneck for covert quantum target sensing. *Physical Review Letters*, *136*(6), 060801. https://doi.org/10.1103/my2s-wypw

Quantum enhanced beam displacement estimation

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Transverse spatial beam displacement sensing is crucial in many applications of quantum optics, including surface topography, beam alignment, tracking and stabilization, as well as superresolution imaging [1-3]. A theory for mode parameter estimation was recently developed, providing insight into when and how quantum enhancement is possible when a parameter is encoded in the mode structure of the light [4]. We apply this framework to calculate the precision bounds and optimal probe states for the estimation of two-mode lossless beam displacement, comparing the Hermite-Gauss and Laguerre-Gauss mode bases.

We consider and contrast two types of probe states with different resource constraints. For states with fixed total photon number we calculate the ultimate precision bound, find the initial state that saturates it and show that a rotated NOON state is asymptotically optimal. Conversely, we also consider pure Gaussian states with fixed average photon number and show that a single mode (in a suitably rotated basis) squeezed vacuum state is asymptotically optimal and analyse the corresponding sensitivity. We use the quantum Fisher information as the figure of merit and show that in both scenarios it exhibits the quantum enhanced scaling beyond the standard quantum limit, with the Gaussian probe being approximately a factor of 2 better compared to the NOON state. Finally, we propose measurement schemes using the method of moments that capture the quantum enhanced sensitivities in the absence of noise. In particular, we propose the balanced twin-Fock state is a reasonable alternative to the NOON state with similar sensitivity.

[1] P. Boucher, C. Fabre, G. Labroille, and N. Treps, Spatial optical mode demultiplexing as a practical tool for optimal transverse distance estimation, Optica 7, 1621 (2020).
[2] K. Patel, M. O'Toole, K. Newell, R. Venkat, and H. Tomey, Fiber bundle-based beam tracking approach for free space optical communications link optimization, Optical Engineering 63, 041212 (2024).
[3] A. von Schmidsfeld, T. Nörenberg, M. Temmen, and M. Reichling, Understanding interferometry for micro- cantilever displacement detection, Beilstein Journal of Nanotechnology 7, 841 (2016).
[4] M. Gessner, N. Treps, and C. Fabre, Estimation of a parameter encoded in the modal structure of a light beam: a quantum theory, Optica 10, 996 (2023)

Selective Preparation of Collective States via SUPER Excitation: Toward Bio-inspired Energy Efficient Configuration

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Here, we theoretically demonstrate selective and efficient preparation of super and subradiant states of two dipole-coupled quantum emitters [1] and of a deep-subwavelength triangular trimer [2] using the Swing-UP of quantum EmitteR population (SUPER) excitation scheme [3]. The SUPER scheme enables near-unity population transfer into a chosen collective state and reasonably isolates the 'pure layer of electromagnetic interaction' from environmental decoherence [1, 2]. This opens a direct route toward observing signature radiative features of superradiance and subradiance in quantum dots and molecules amid some dissipation. Furthermore, our study attempts to justify using the Markovian master equation approach in the evolving landscape of bio-inspired, energy-efficient configurations [4], which is, of course, a much simpler model than reality.

[1] J. Kerber et al., Phys. Rev. Res. **8**, 013179 (2026).
[2] T. Nunner et al., arXiv:2607.12665 (2026).
[3] T. K. Bracht et al., PRX Quantum **2**, 040354 (2021).
[4] A. Pal et al., New J. Phys. **27**, 094101 (2025).

The Marietta Blau Quantum Optical Ground Station: Measured Atmospheric Turbulence and Laboratory Emulation

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The “Marietta Blau” quantum optical ground station at Hafelekar (2283 m) operates a 1 m Ritchey-Chrétien reflector telescope for future satellite and mountain-to-mountain quantum links. In the laboratory, we prepare the quantum hardware for the station: a Sagnac source of polarization-entangled photon pairs at 785 nm and 835 nm (type-0 SPDC, ppKTP crystal) with a brightness of 2×10^4 pairs/s/mW and a fidelity of 0.957, and a compact APD-based six-state polarization analyzer with in-house developed electronics. Here we focus on the atmospheric channel this hardware will face. Using a 1 kHz InGaAs camera, we recorded angle-of-arrival jitter of 30 stars at elevations from 20° to 79°, yielding power spectral densities with an integrated single-axis RMS jitter of 0.27-0.44 µrad. We emulate the site-specific turbulence in the laboratory by generating disturbances matched to the measured spectra on a tip-tilt mirror. We show the reduction of the RMS jitter by a factor of 6, with disturbance rejection up to 60 Hz with a feedback loop based on a fast-steering mirror and the InGaAs camera. [1] This approach lets us test the hardware under realistic channel conditions before deployment at the ground station.

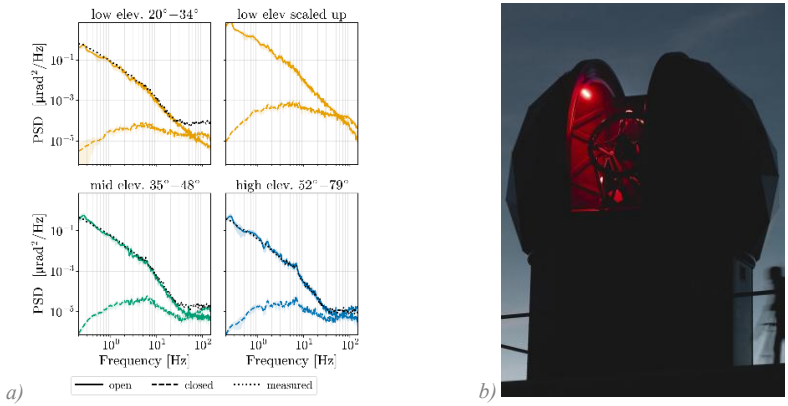


Fig. 1: (a) AoA power spectral densities measured at three different elevation tertiles and a scaled-up scenario, compared with the emulated signal in the laboratory in open-and closed loop (b) The quantum optical ground station (Photo: Christoph Johann, © Innsbrucker Nordkettenbahnen Betriebs Gmbh)

[1] M. Gritzner, S. Frick, G. Weihs, “Embedded Tip-Tilt Control with Turbulence-Matched Validation for Free-Space Quantum Links,” presented at the International Conference on Space Optics (ICSO 2026), to be published in *Proc. SPIE*.

Spectrally and time-resolved Quantum Ghost spectroscopy for threat detection

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Quantum ghost spectroscopy (QGS) is a technique where pairs of non-degenerated, spectrally correlated photons are exploited to reveal spectral features in the near IR wavelengths while using detectors for the visible region [1] (Fig. 1 left).
To this aim, a broadband source of correlated pairs based on chirped apodized poling of KTP crystals has been developed and characterized [2]. Bandwidths larger than 100 nm with a flat spectral distribution have been measured and employed for the QGS experiment where the absorption spectrum of a target in the telecom band has been retrieved by means of spectral measurements on the correlated visible photons. High coincidence to accidental ratio (CAR) over a large span of pump powers has been observed (Fig. 1 right), allowing spectral identification of the target regardless of the amount of colored noise present in the source [3].
The spectral analysis which is now based on spatial separation of the different wavelengths, requiring the adoption of a multi-pixel detector, will be converted into time-resolved measurements, where the different wavelengths will experience different delays in highly dispersive media and be measured in time with a single pixel detector.

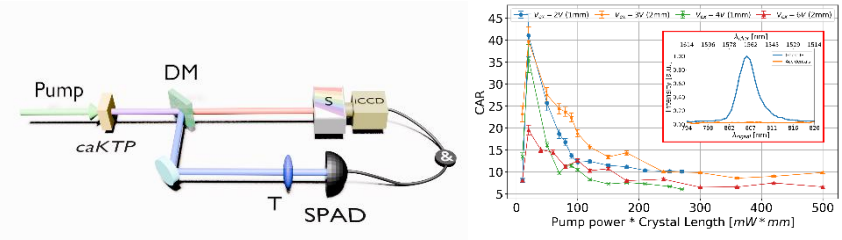


Figure 1: (Left) setup: The IR photon goes through a target sample (T) and is then detected by a single pixel SPAD; the VIS photon is spectrally analyzed by means of a spectrograph (S) and an intensified CCD camera (iCCD). Coincidences between the detector and the camera are recorded (&). (Right) CAR of a QGS measurement as a function of pump power per crystal length - Inset: quantum ghost spectroscopical measurement of an interference filter

[1] A. Chiuri et al. Eu. Phys. J. Plus 140, 186 (2025)
[2] L. Sansoni et al. arXiv:2610.10217 (2026)
[3] L. Sansoni et al. Quantum Sci. Tech. 10, 045020 (2025)

Ultrafast holographic Fourier-Transform Infrared microscopy for cancer studies

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The abstract had not been submitted when this booklet was published.

High Frame-Rate Mid-Infrared SPAD Camera

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Imaging at the mid-infrared spectral regime (2-5 μm) offers unique opportunities in chemical in thermal science[1], chemical sensing[2], astronomy and medical diagnostics[3]. However, photon-counting and high frame rate imaging in this spectral range remain challenging. Silicon single-photon avalanche diode (SPAD) arrays have revolutionized visible-light imaging by enabling high frame rates, photon counting, and time-resolved detection, but their spectral sensitivity does not extend to the mid-IR. Conventional mid-IR imaging relies primarily on HgCdTe detectors, which often require cryogenic cooling, offer limited temporal resolution and lack the combination of high spatial resolution, ultrahigh frame rates, and photon-counting functionality available in silicon SPAD technology.

Here we demonstrate the first broadband mid-infrared imaging system with single-photon imaging capabilities and nanosecond resolution. Using an adiabatically poled nonlinear crystal[4,5], we upconvert light from the 2-5 μm spectral range to the visible. The upconverted visible light is then imaged by a SPAD array comprising 512x512 pixels. We demonstrated room-temperature broadband mid-IR imaging at frame rates of up to 60,000 frames per second and exploit the system's temporal and spatial resolution to capture nanosecond scale laser-induced heating and cooling dynamics via mid-IR thermal emission. Our results establish a new approach to mid-infrared imaging, combining broadband frequency conversion with high-speed silicon SPAD detection. This platform opens new opportunities for studying transient thermal phenomena and ultrafast light-matter interactions in the mid-infrared spectral region, even at the single-photon level.

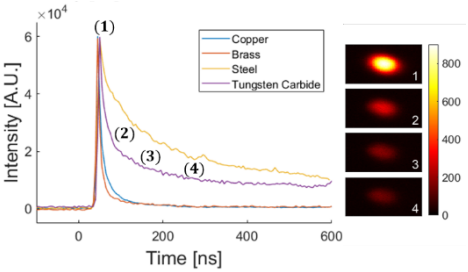


Fig. 1: Nanosecond-scale mid-IR imaging and temporal analysis of cooling dynamics in various metals.

[1] Vollmer, M. & Möllmann, K.-P. Infrared Thermal Imaging: Fundamentals, Research and Applications. (John Wiley & Sons, 2018).
[2] Gabrieli, F., Dooley, K. A., Facini, M. & Delaney, J. K. Near-UV to mid-IR reflectance imaging spectroscopy of paintings on the macroscale. Sci. Adv. 5, eaaw7794 (2019).
[3] Fernandez, D. C., Bhargava, R., Hewitt, S. M. & Levin, I. W. Infrared spectroscopic imaging for histopathologic recognition. Nat. Biotechnol. 23, 469–474 (2005).
[4] Suchowski, H., Porat, G. & Arie, A. Adiabatic processes in frequency conversion. Laser and Photonics Reviews vol. 8 333–367 https://doi.org/10.1002/lpor.201300107 (2014).
[5] Abelson, Z. et al. High Frame-Rate Mid-Infrared SPAD Camera. arXiv:2605.04276 (2026).

Industrial integration of non-destructive characterization of ceramics using mid-infrared optical coherence tomography with undetected photons

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The optical characterization of highly scattering ceramic micro-components via optical coherence tomography (OCT) is challenging. While mid-infrared (mid-IR) OCT can reduce scattering, conventional systems are costly and noisy. Here, we present an OCT system using undetected photons to overcome these limitations [1]. Using a 660 nm continuous-wave laser to generate photon pairs by spontaneous parametric down-conversion, we probe a sample in the mid-IR (3.3 – 4.3 µm) and detect interference with a standard silicon grating spectrometer (780 – 825 nm). The system is miniaturized in an 80 × 60 mm^2 module (Figure 1a), including the pump laser, and integrated into an industrial characterization machine [2]. This approach offers a cost-effective and intrinsically low-noise alternative to conventional mid-IR OCT methods. We validate the system by characterizing zirconium dioxide samples, resolving subsurface interfaces (Figure 1b) and achieving accurate measurements of thickness and group refractive index. These results highlight the technique's potential for visualizing microstructures in three dimensions and for quality control of high-precision ceramic components.

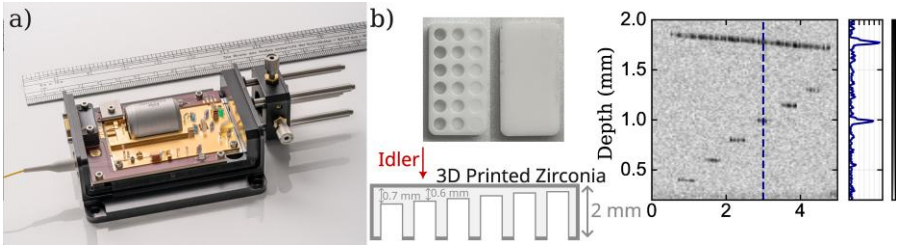


Figure 1: (a) Experimental module. (b) Resolved subsurfaces of 3D-printed zirconia.

[1] A. Vanselow et al., "Frequency-domain optical coherence tomography with undetected mid-infrared photons," Optica 7, 1729-1736 (2020).
[2] G. Blume et al., "Long wavelength, small quantum interferometer module," Proc. SPIE 13392, 118 (2025).

Frequency domain undetected photon spectroscopy with an etalon in the signal arm

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Frequency-domain undetected-photon spectroscopy brings established frequency-domain optical coherence tomography techniques to spectroscopy at mid-infrared wavelengths [1–3]. This technique now has known signal-to-noise ratio advantages over its scanning time-domain alternative [3]. However, it has a very clear limit. Spectroscopic information measured with this technique is encoding onto a sinusoidal signal, measured across the spectrometer's pixels array. There is thus a fundamental trade-off between spectral resolution and signal strength, set by the finite spectral resolution of the grating spectrometer. In increasing the frequency of the sampling sinusoid, the signal strength undergoes a characteristic roll off. This motivates our guiding question: can the signal to noise roll off be improved without changing the grating spectrometer?

By introducing an over-coupled etalon into the nonlinear interferometer's signal arm, we encode a periodic 2π phase shift onto the signal photons. This in turn causes the interference patten at the output of the nonlinear interferometer to become a periodic Lorentzian-like signal. This signal has two tunable parameters: its linewidth, set by the finesse of the signal-arm cavity, and its period, set by the length of the signal-arm etalon. This work presents an exploration of this system and a final negative result, whereby the higher harmonic components of the Lorentzian-like signal, which also contain spectroscopic information, worsen the roll-off in signal strength.

[1] Kaufmann, P. et al. Mid-IR spectroscopy with NIR grating spectrometers. Opt. Express, OE 30, 5926–5936 (2022).
[2]Sherwani, A. U. R. et al. "Polymer identification via undetected photons using a low footprint nonlinear interferometer". Opt. Express, OE 34, 21000–21016 (2026).
[3]Gattinger, P. et al. "Scanless quantum Fourier-transform mid-infrared spectroscopy for rapid high-sensitivity hyperspectral mapping". Preprint https://doi.org/10.48550/arXiv.2607.17964 (2026).

Towards cavity-enhanced wide-field mid-IR spectral microscopy

Anna Romanova
HU Berlin

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Hyperspectral mid-infrared imaging of microplastics with undetected photons from a cavity-enhanced source

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Identifying microplastics and lipids requires their mid-infrared (MIR) vibrational signature, but MIR detectors are costly, noisy and often need cryogenic cooling. We report fast raster-scanned imaging while spectrally resolving undetected MIR photons. The MIR idler probes the sample in the C–H stretch region, and its absorption is read from the interference of the partner near-infrared photons on a room-temperature silicon grating spectrometer [1,2]. Obtaining the spectral information requires no scanning, unlike in classical FTIR. Because the photon pairs generated via SPDC are broadband [3], a single spectrometer exposure records the interference across the whole band, giving the complete absorbance spectrum of each sample point with a resolution better than 8 cm^{-1}; only the sample position is raster scanned to form the hyperspectral image.

Our SPDC source is made ultra-bright by resonantly enhancing the pump in a monolithic nonlinear cavity. The high photon flux allows spectral acquisition at kHz rates with high signal-to-noise ratio, so that each image point needs only a short exposure.

We show hyperspectral images of microplastic particles and lipid samples that reveal their characteristic C–H absorption, and discuss the potential of this approach for robust bio-environmental sensing.

[1] A. U. R. Sherwani et al., “Polymer identification via undetected photons using a low footprint nonlinear interferometer,” Opt. Express 34, 21000 (2026).
[2] P. Kaufmann, H. M. Chrzanowski, A. Vanselow, and S. Ramelow, “Mid-IR spectroscopy with NIR grating spectrometers,” Opt. Express 30, 5926 (2022).
[3] A. Vanselow, P. Kaufmann, H. M. Chrzanowski, and S. Ramelow, “Ultra-broadband SPDC for spectrally far separated photon pairs,” Opt. Lett. 44, 4638 (2019).

Between SU(1,1) and induced coherence: a family of nonlinear interferometers

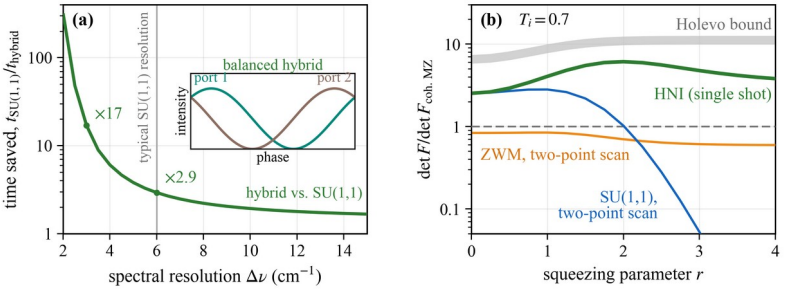
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SU(1,1) and induced-coherence (Zou–Wang–Mandel, ZWM) interferometers are usually treated as two separate classes. We show that hybridizing the two gives rise to a whole family of new nonlinear interferometers, with SU(1,1) and ZWM as its limiting cases. Each member has its own fringe pattern, and with it its own way of reading a sample in the undetected idler arm with transmission T_i and phase φ_i. What can the new members in between do? We pick out two: one of practical interest, because it does what neither SU(1,1) nor ZWM can, and one of fundamental interest, because at high gain it outperforms both.

The practical one first: the hybrids allow single-shot spectroscopy of transmission and phase. SU(1,1) and ZWM cannot do this, because T_i and φ_i change their detected signal in the same way, and one working point cannot tell the two apart. The usual way out is to record the signal on a spectrometer: a path difference writes carrier fringes across the spectrum, and a Hilbert transform recovers both. But the finite spectrometer resolution washes the fringes out, and that costs visibility, signal-to-noise ratio and in the end measurement time. In the balanced hybrid the two output ports oscillate in quadrature (inset of Fig. a), and one recording of both ports gives transmission and phase at once. For an interferometer at low gain with visibility 0.6 (no sample, zero delay), this saves a factor 2.9 in measurement time at 6 cm^{-1} resolution and a factor of 17 at 3 cm^{-1} (Fig. a).

The fundamental one matches SU(1,1) at low gain, but in a single shot: it carries the same information as an SU(1,1) interferometer with an optimal two-point scan, because it is the same measurement, multiplexed in space instead of in time. With finite gain, however, the hybrid pulls ahead of SU(1,1) and ZWM, for the joint estimate (Fig. b, $T_i = 0.7$) as well as for the phase alone.



Spectrally bright sources for the mid-IR fingerprint region's blind spot

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Quantum sensing with nondegenerate and undetected photons has now been studied for over a decade and has continuously been refined to offer improved utility for real-world applications [1, 2]. In this discipline, mid-IR idler probes have been particularly highlighted as a tool to interrogate samples in a label-free, non-destructive, and overall mild manner [3]. In this spectral region, the sharp, characteristic resonances of molecular vibrations enable streamlined chemical composition analyses. But typical workhorse media for the generation of entagled signal and idler photons such as lithium niobate or potassium titanyl phosphate remain limited to a fraction of the full mid-IR spectral range and, thereby, also remain limited to particular functional groups of molecular matter.

Here, we present a novel source concept that can illuminate the entire mid-IR range with spectrally bright idler radiation while producing signal photons that are compatible with high performance CMOS detector technology. The concept was developed with sensing with undetected photons techniques in mind to guide the source design parameters and yield state-of-the-art performance metrics.

[1] Lemos, Gabriela Barreto, et al. "Quantum imaging with undetected photons." *Nature* 512.7515 (2014): 409-412.

[2] Lemos, Gabriela Barreto, et al. "Quantum imaging and metrology with undetected photons: tutorial." *Journal of the Optical Society of America B* 39.8 (2022): 2200-2228.

[3] Kviatkovsky, Inna, et al. "Microscopy with undetected photons in the mid-infrared." *Science Advances* 6.42 (2020): eabd0264.

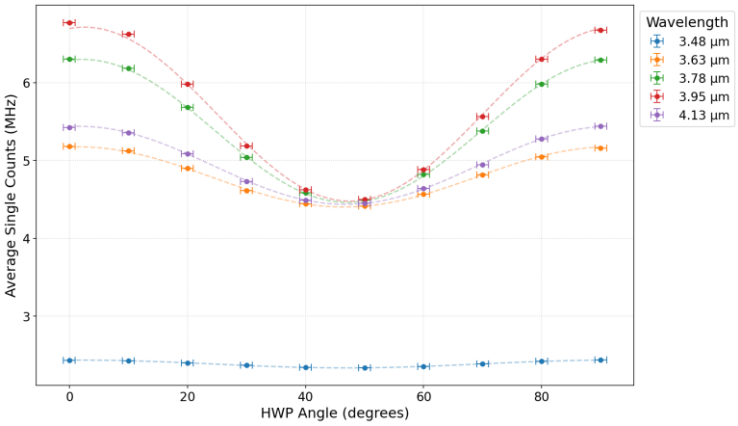
The Characterization of Mid-IR SNSPD Using Highly Non-Degenerate Photon-Pair Source

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Efficient photon detection in the mid-infrared (MIR) is a key enabler for photonic sensing systems, as the MIR spectral region hosts strong, highly specific molecular absorption fingerprints. This potential has sparked various schemes utilizing highly non-degenerate spontaneous parametric down-conversion (SPDC), such as in quantum imaging [1] and Fourier-transform infrared spectroscopy [2]. However, due to the lack of commercially available superconducting nanowire single-photon detectors (SNSPDs) in the deeper MIR spectral region, previous works characterizing entangled visible-MIR sources were either limited to approximately 1.9 µm [3] or relied on inferring MIR properties through detected partner photons in the near-infrared [4].

In this work, a state-of-the-art SNSPD operating in the MIR (3–4 µm) is characterized using a highly non-degenerate photon-pair source. Building on this characterization, a pseudo-sample was employed to estimate the minimum transmittance required to maintain reliable coincidence detection.



[1] J. R. León-Torres et al., Laser Photonics Rev. 20, e02356 (2026)
[2] K. Hashimoto et al., Commun. Phys. 7, 217 (2024)
[3] M. Kumar et al., Appl. Phys. Lett. 119, 244001 (2021)
[4] F. Krajinić et al., Appl. Phys. B 132, 48 (2026)

Quantum Cavity Ring-down Spectroscopy (Q-CARDS)

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Climate change, driven primarily by rising greenhouse gas emissions, remains one of the most critical challenges of our time. Achieving 'Net Zero' requires an accurate balance between emitted and removed greenhouse gases, which in turn demands precise measurement of atmospheric carbon dioxide (CO_2), the primary driver of the greenhouse effect.

Here we present an advanced optical gas sensing concept based on Cavity Ring-Down Spectroscopy (CARDS), a highly sensitive technique that traps light between high-finesse mirrors to create an effective multi-kilometre absorption path length. By measuring the decay rate of light at the 2336 cm^{-1} absorption frequency, CARDS enables detection of even minute fluctuations in atmospheric CO_2, making it a powerful tool monitoring and verifying carbon efforts. However, the most relevant absorption region for CO_2 spans 2336 cm^{-1} to 2350 cm^{-1}, equivalent to 4.25 µm to 4.28 µm, which falls within the mid-infrared spectral range[1]. Working in this region is technically demanding and comes with considerably high instrumentation costs[2].

To overcome these limitations, we introduce Quantum Cavity Ring-Down Spectroscopy (Q-CARDS). By exploiting optical parametric amplification (OPA) via stimulated parametric down-conversion in a nonlinear crystal, the process is actively driven by the mid-infrared idler circulating within the cavity. Drawing inspiration from the concept of sensing with undetected photons[3], the mid-infrared absorption dynamics inside the cavity are mapped directly onto the generated visible-wavelength signal beam. This effectively transfers the mid-infrared spectral measurement into the visible domain, bypassing the need for mid-infrared photodetectors and enabling the use of accessible, low-cost silicon sensors. Q-CARDS offers a practical, highly sensitive, and cost-effective platform for atmospheric CO_2 monitoring with direct applications in global climate policy verification.

[1] Kalashnikov, D., Paterova, A., Kulik, S. *et al.* Infrared spectroscopy with visible light. *Nature Photon* **10**, 98–101 (2016).
[2] Razeghi, M., Nguyen, B. Advances in mid-infrared detection and imaging: a key issues review, *Reports on Progress in Physics* **77**, 082401 (2014).
[3] Lemos, G., Borish, V., Cole, G. *et al.* Quantum imaging with undetected photons. *Nature* **512**, 409–412 (2014).

Cavity enhanced gas sensing based on differential absorption in nonlinear interferometers

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Cavity ring-down spectroscopy (CRDS) [1] is a well-established technique for the highly sensitive detection and quantification of trace gases. In CRDS, laser light is coupled into a high-finesse optical cavity, where the circulating optical power builds up through multiple reflections between highly reflective mirrors. Upon abruptly switching off the incident laser, the stored optical energy decays exponentially, with a decay rate determined by the intrinsic cavity losses and absorption by the intracavity medium. Owing to the exceptionally long effective optical interaction length, CRDS enables highly sensitive absorption measurements, with detection limits reaching the parts-per-trillion (ppt) range under optimized conditions. Many gas-phase molecules exhibit characteristic rovibrational absorption transitions in the infrared spectral region, making it particularly attractive for selective molecular detection.

Spectroscopy with undetected photons enables the investigation of infrared optical properties without requiring direct detection at infrared wavelengths. Here, we propose a cavity-enhanced (CRDS inspired) sensing scheme based on induced coherence [2], in which two nominally identical optical cavities are incorporated into the idler paths of a nonlinear interferometer, while a variable optical delay is introduced in the signal path. Differential absorption within the cavities modifies the coherence and interference visibility of the detected signal photons, providing a means to infer the absorption coefficient and, consequently, the concentration of gaseous species confined within the cavities. Unlike conventional cavity ring-down spectroscopy, which relies on monitoring the exponential decay of stored optical intensity, the proposed approach operates at the single-photon level, where the temporal response is governed by the evolution of quantum probability amplitudes and their mutual coherence. We theoretically investigate the influence of photon coherence length, optical delay, cavity decay dynamics, and intracavity absorption on the resulting interference signal. This approach establishes a framework for combining cavity-enhanced light–matter interactions with quantum interferometric detection, potentially enabling highly sensitive infrared gas spectroscopy using detectors operating at visible or near-infrared wavelengths.

[1] M. Mazurenka et al. Annu. Rep. Prog. Chem., Sect. C: Phys. Chem. (2005) 101: 100–142

[2] L. J. Wang, X. Y. Zou, and L. Mandel, Phys. Rev. A **44**, 4614 (1991)

Quantum infrared spectroscopy in the long-wavelength fingerprint region

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Quantum infrared spectroscopy (QIRS), which exploits nonlinear quantum interference between photon-pair generation processes, enables infrared (IR) spectroscopy with only visible/near-infrared (VNIR) sources and detectors. Since the pioneering demonstration of IR spectroscopy with visible light [1], efforts have been made to broaden its spectral coverage [2–5] and to apply it to a variety of measurement modalities [6,7]. However, the long-wavelength half of the molecular fingerprint region, 10–20 μm, has remained out of reach because the nonlinear crystals employed so far, such as $AgGaS_2$, become opaque beyond ~13 μm; QIRS has thus been limited to below ~10.5 μm in the fingerprint region [5]. Recently, photon-pair emission beyond 20 μm has been inferred from signal emission spectra [8], but its application to spectroscopy has yet to be realized.

Here we report broadband QIRS extending beyond 10 μm. Using a wavelength-tunable, highly nondegenerate photon-pair source based on a gallium selenide (GaSe) crystal, which is transparent up to ~20 μm, together with a Michelson-type nonlinear quantum interferometer, we observed nonlinear quantum interference with idler wavelengths extending to 20 μm and performed quantum Fourier-transform IR spectroscopy of a polymer film over the 8.6–20 μm range. Together with previous results, this demonstrates that QIRS can now cover the entire molecular fingerprint region. In the poster, we will present the design and characterization of the GaSe photon-pair source, the quantum interferograms and their Fourier spectra, and the measured transmittance spectra in comparison with conventional FTIR.

[1] D. A. Kalashnikov, A. V. Paterova, S. P. Kulik, and L. A. Krivitsky, Nat. Photonics **10**, 98 (2016).
[2] A. V. Paterova, Z. S. D. Toa, H. Yang, and L. A. Krivitsky, ACS Photonics **9**, 2151 (2022).
[3] C. Lindner, S. Wolf, J. Kiessling, and F. Kühnemann, Opt. Express **28**, 4426 (2020).
[4] P. Kaufmann, H. M. Chrzanowski, A. Vanselow, and S. Ramelow, Opt. Express **30**, 5926 (2022).
[5] Y. Mukai *et al.*, Opt. Express **30**, 22624 (2022); T. Tashima *et al.*, Optica **11**, 81 (2024).
[6] M. Placke, C. Lindner, F. Mann, I. Kviatkovsky, H. M. Chrzanowski *et al.*, Optica **13**, 328 (2026).
[7] J. Dong, W. Nie, A. C. Cardoso, H. Zhou, J. Zhang, J. G. Rarity, and A. S. Clark, APL Photon. **10**, 116106 (2025).
[8] E. S. Zatsepin *et al.*, Laser Phys. Lett. **23**, 015201 (2026); Adv. Photon. Res. **7**, 2500267 (2026).
[9] J. Dong, J. Zhang, H. Zhou, W. Nie, J. G. Rarity, and A. S. Clark, arXiv:2610.11582 (2026).

Single photon sources for mid-infrared sensing

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Accurate, field-deployable sensing of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) is essential for meeting decarbonisation and climate-reporting obligations. Conventional mid-infrared spectroscopy faces fundamental noise limits that restrict sensitivity at trace concentrations. This project is developing a quantum photon-pair source based on spontaneous parametric down-conversion (SPDC) to overcome these limits and enable quantum-enhanced sensing in the mid-infrared molecular fingerprint region.

The core technical approach employs a non-degenerate free-space SPDC configuration in which a near-infrared pump (~0.70–1.31 µm) generates signal photon at 800-1550 nm and a mid-infrared idler photon in the 7.2–8.5 µm range — directly targeting the strong N_2O absorption band near 7.8 µm and CH_4 features in adjacent windows. A systematic analysis of five nonlinear crystal platforms (AGS, AGSe, BGS, BGGSe, HGS) has identified silver gallium sulphide (AGS [1,2]) as the near-term material of choice for reaching this spectral window, with orientation-patterned gallium phosphide (Op-GaP [3]) under investigation as an advanced platform offering broader transparency, a larger nonlinear coefficient, and mature quasi-phase-matching capability. The telecom-band signal photon is compatible with superconducting nanowire single-photon detectors and fibre-optic distribution, supporting future distributed sensing architectures relevant to carbon-capture and storage site monitoring.

[1] Kato, K., Okamoto, T., Grechin, S., & Umemura, N. (2019). New Sellmeier and thermo-optic dispersion formulas for AgGaS2. Crystals, 9(3), 129.
[2] Zatsepin, E. S., Sabanin, A. S., Badikov, D. V., Kulik, S. P., & Paterova, A. V. (2026). Dispersion Analysis of Silver Thiogallate in a Broad Mid-Infrared Range. Advanced Photonics Research, 7(1), e202500267.

[3] Schunemann, P. G., Johnson, K., Farrell, C., Maidment, L., Shi, Y., Rutkauskas, M., & Reid, D. T. (2021). Continuous wavelength tuning from 3.9–12 µm from an optical parametric oscillator based on orientation-patterned GaP grown on GaAs. Optical Materials Express, 11(3), 654-663.

Designing Broadband Sources for Imaging-based Quantum FTIR

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[1] Los Alamos National Laboratory, Los Alamos, NM, USA

For induced coherence to be used for mid-infrared (MIR) spectroscopy, ultra-broadband sources of entangled light are required. Previously, the 2-5 µm spectral range was covered using chirped poling in a long nonlinear crystal[1] (Fig. 1, top left). With a chirped crystal design, different regions of the crystal generate portions of the broad down-converted spectrum. However, this solution is not compatible with near-field imaging where position correlations between signal and photons are used to achieve high-resolution imaging for microscopy. The chipred design is only compatible with far-field imaging because each band is generated at different axial locations within the crystal.

A fan-out poling design can be used to generate ultra-broadband entangled light for near-field imaging (Fig. 1, top right). Fan-out poling generates the various bands across the transverse direction of the crystal instead of the along the *z*-axis. Therefore, shorter crystals compatible with near-field imaging can be used. We report on the development of an ultra-broadband entangled source for near-field imaging for induced coherence.

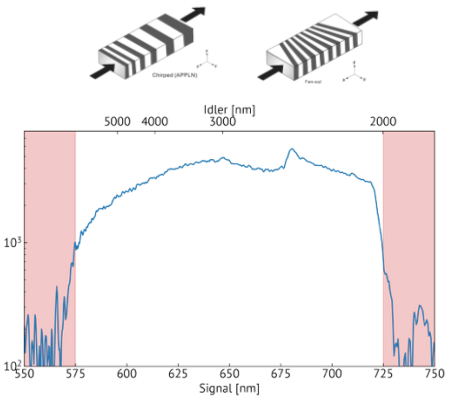


Figure 1: Chirped poling (top left) and fan-out poling (top right) can generate ultra-broadband entangled light. Using four fan-out crystals, the 2-5 µm spectral range can be covered.

Using a pair of galvo mirror to scan/descan the length of a fan-out crystal, we generate entangled photons for imaging with induced coherence, covering 2-5 µm. The scanning itself does not impact the interferometry for induced coherence. However, we also report that such ultra-broadband sources require dispersion compensation due to other optical elements common to all induced coherence layouts[2].

[1] Tashima, T.; Mukai, Y.; Arahata, M.; Oda, N.; Hisamitsu, M.; Tokuda, K.; Okamoto, R.; Takeuchi, S. Ultra-Broadband Quantum Infrared Spectroscopy. Optica, OPTICA 2024, 11 (1), 81–87. https://doi.org/10.1364/OPTICA.504450

[2] Kumar, M.; Dupish, D.; Kumar, P.; Zhang, L.; Lung, S.; Besaga, V.; Pertsch, T.; Setzpfandt, F. Controlling Visibility in Nonlinear Interferometry for Spectroscopy with Undetected Photons. APL Photonics 2025, 10 (10), 106121. https://doi.org/10.1063/5.0297837

On-chip Undetected photons for Mid-IR Absorption sensing

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Infrared light provides access to absorption features that reveal the composition of gases, liquids and solids, supporting applications from environmental monitoring to material characterization, but infrared sources and detectors are often costly and complex. Sensing with undetected photons, based on induced coherence in a nonlinear interferometer [1], separates the probing wavelength from the detection wavelength: the infrared transmission of a sample is retrieved by detecting only partner photons at shorter wavelengths, where mature detectors exist. Bringing this approach onto a photonic chip reduces footprint and alignment requirements, improves interferometric stability and provides reconfigurable optical control, opening a route toward compact, portable sensors. Undetected-photon phase measurement has recently been demonstrated on a silicon chip [2]; here we target absorption.

We present the design, fabrication and initial characterization of a silicon photonic circuit for on-chip absorption sensing with undetected photons. Pumped in the telecom band (1561 nm), two straight-waveguide sources employ intermodal spontaneous four-wave mixing [3] to generate signal and idler photons around 1300 nm and 2000 nm, respectively. The idler propagates from the first source to the second through an integrated Mach–Zehnder interferometer, whose tunable transmission emulates an absorbing object. The signal outputs are recombined off-chip, and the sensing readout relies exclusively on detection at 1300 nm.

Initial measurements show quadratic scaling of the signal and idler count rates with pump power, as expected for spontaneous four-wave mixing. The idler-path interferometer reaches an extinction ratio of approximately 11 dB at 2000nm, allowing the emulated object transmission to be tuned over more than an order of magnitude. Interference measurements between the two sources are under way to validate the sensing scheme. We will also discuss designs on other material platforms, including silicon nitride, and alternative source and object geometries, such as silicon ring resonators.

[1] G. B. Lemos *et al.*, “Quantum imaging with undetected photons,” Nature 512, 409–412 (2014).

[2] C. Michelini, S. Signorini, L. Pavesi, V. Pruneri, “Quantum undetected photon phase measurement on a silicon chip,” APL Photonics 10, 101301 (2025).

[3] S. Signorini *et al.*, “A silicon source of heralded single photons at 2 µm,” APL Photonics 6, 126103 (2021).

Broad spiral bandwidth of thin-film spontaneous parametric down-conversion

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Thin-film spontaneous parametric down-conversion (SPDC), enabled by strongly relaxed longitudinal phase-matching conditions, generates photon pairs with exceptionally broad spectral and angular bandwidths [1] and strong entanglement in both time--frequency and position--momentum degrees of freedom. The broad angular emission provides access to a large spatial-mode space, particularly to orbital-angular-momentum (OAM) modes, making thin-film SPDC a promising platform for high-dimensional quantum-state generation and quantum sensing, where the achievable spatial resolution can scale with the order of the employed OAM mode [2].

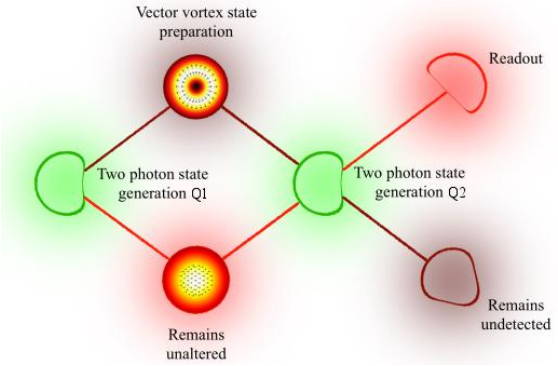
In this work, we exploit a 7 μm-thick lithium niobate film to generate a broadband OAM spectrum of photon pairs. We directly compare its spiral spectrum with that generated in a 500 μm-thick lithium niobate crystal and demonstrate an almost ninefold enhancement of the spiral bandwidth in the thin-film source. In addition, we show that the spatial-mode content of thin-film SPDC remains independent of frequency, in contrast to bulk-crystal SPDC, where the OAM distribution varies across the emission spectrum.

[1] C. Okoth et al., Phys. Rev. Lett. 123, 263602 (2019).
[2] M. Hiekkamäki et al., Phys. Rev. Lett. 127, 263601 (2021).

Vectorial field reconstruction without detecting the field

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Vector beams, whose polarization varies across the transverse profile, are a central resource in structured-light optics and quantum photonics, but their characterization is challenging in spectral regions lacking efficient spatially resolving detectors. Here we demonstrate spatially resolved reconstruction of an undetected vector beam using induced coherence [1] in a nonlinear interferometer, where indistinguishability between two down-conversion pathways lets information in an undetected field be read out via interference of its detected partner. A telecom idler field acquires a spatially varying polarization transformation but is never detected; its local polarization is inferred from single-photon interference of the visible signal field, enabled by photon-pair momentum correlations. Using phase-shifting [2] and off-axis quantum holography [3] with two polarization projections, we reconstruct the horizontal and vertical amplitudes and their relative phase across the beam profile, recovering the full vectorial structure of the field. We experimentally retrieve the polarization texture of an m = 2 vector beam and compare multi-shot and single-shot reconstruction. Our results extend imaging with undetected light from scalar objects to vectorial fields, opening a route to polarization-sensitive sensing in hard-to-access spectral regions [4].

[1] X. Y. Zou, L. J. Wang, L. Mandel, Phys. Rev. Lett. 67, 318 (1991).
[2] S. Töpfer et al., Sci. Adv. 8, 2 (2022).
[3] J. R. León-Torres et al., Opt. Express 32, 35449 (2024).
[4] J. Vasikonis et al., arXiv:2605.13483 (2026).

Massive spectral multiplexing for two-photon interference

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Massive spectral multiplexing for two-photon interference is becoming a reality thanks to advances in single-photon avalanche diodes (SPADs). We demonstrate a fast single-photon spectrometer based on a linear array of 512 SPADs, with resolutions of 48 ps and 48 pm (both rms) [1]. Aiming to apply this technology to quantum telescopes and entanglement-swapping schemes, we project an increase in the signal-to-noise ratio for stellar astrometry [2] by a factor of 10-20, and a 20x faster swap rate [1].

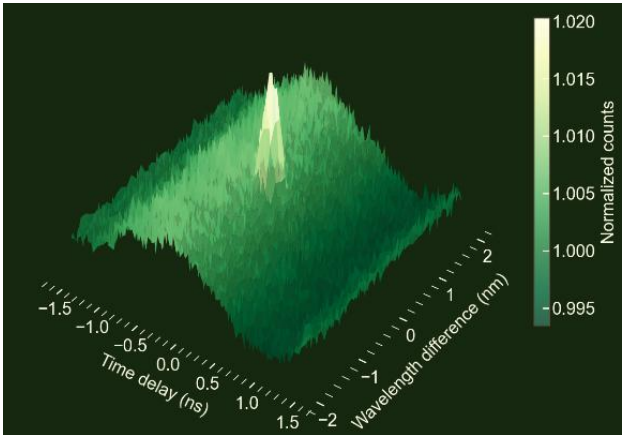


Figure: Second-order correlation function $g^{(2)}(\Delta t, \Delta\lambda)$ as a function of the time delay Δt and the wavelength difference $\Delta\lambda$ between detected photon pairs. Since both the arrival time and the wavelength of each photon are recorded, correlations can be resolved simultaneously in the time and spectral domains.

[1] Kulkov, S. et al. Hanbury Brown–Twiss interference with massively parallel spectral multiplexing for broadband light. Advanced Photonics Nexus 5, 1–13 (2026).

[2] Stankus, P., Nomerotski, A., Slosar, A. & Vintskevich, S. Two-photon amplitude interferometry for precision astrometry. The Open Journal of Astrophysics 5 (2022).

Towards experimental observation of the extended Hong-Ou-Mandel effect

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The Hong-Ou-Mandel effect is a foundationnal quantum effect[1]; two indistinguishable photons interfering on a beam splitter will never come out through different output ports. This has also been demonstrated in interferences between single photons and weak coherent states. Curiously, this kind of quantum interference persists and scales, even for coherent states with high mean photon numbers, as illustrated in figure 1. This property is ultimately what allows for homodyne detection.

In fact, there is broader a class of interferences between quantum states and many-photon states such as coherent, squeezed, thermal, photon-added that can be refered to as the „extended Hong-Ou-Mandel effect“[2]. Those interferences induce measurable quantum correlations in photon number distributions.

We are in the process of assembling a setup to observe photon number correlations in the ouput arms of a beam splitter interfering a single photon and a coherent state, using photon number resolving detectors. We also plan extensions to the setup to explore various phenomena related to the extended Hong-Ou-Mandel effect.

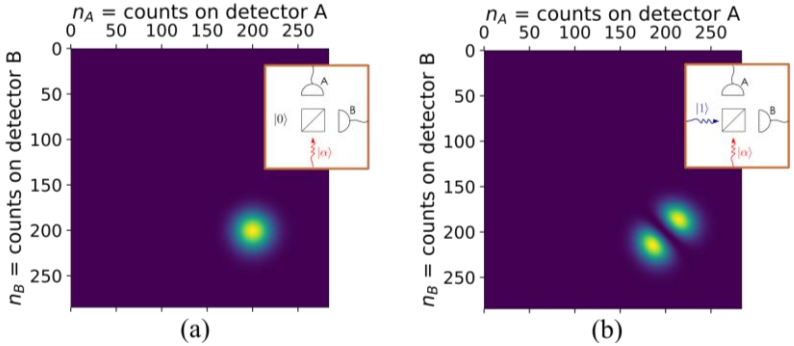


Figure 1: Joint probability distributions of measuring given numbers of photons on the output of a beam splitter, in the case of **(a)** only a coherent state on the input and **(b)** a coherent state interfering with a single photon on the input. In both cases the coherent state amplitude is such that $|\alpha|^2 = 400$. The color scale is in arbitrary units.

[1] Hong, C., Ou, Z., & Mandel, L. (1987). Measurement of subpicosecond time intervals between two photons by interference. Phys. Rev. Lett., 59, 2044–2046.

[2] Alsing, P., Birrittella, R., Gerry, C., Mimih, J., & Knight, P. (2022). Extending the Hong-Ou-Mandel effect: The power of nonclassicality. Phys. Rev. A, 105, 013712.

Stimulated Raman with SPDC Source

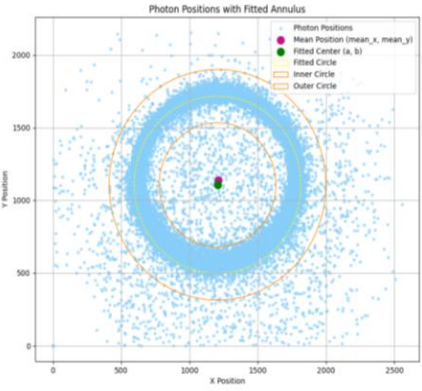
Cesar R. Bernardo[1,2], Beáta Plaskurová[3], Pavel Malý[3],Miroslav Kloz[1,2]

1. Extreme Light Infrastructure ERIC, Za Radnicí 835, 252 41 Dolní Břežany, Czech Republic; 2. ELI Beamlines, Za Radnicí 835, 252 41 Dolní Břežany, Czech Republic; ; 3. Charles University, Faculty of Mathematics and PhysicsKe Karlovu 3, 121 16 Praha 2, Czech Republic

In recent decades, quantum entanglement has gained prominence both for probing fundamental physics and on real applications such as quantum imaging, metrology, sensing and computing. Nonlinear spectroscopy stands to benefit significantly from quantum light, which enables low-light probing of delicate biological samples, improved signal-to-noise ratio and control of excitation pathways in matter.

Here we present an investigation towards an ultrafast, frequency-resolved stimulated Raman technique that uses entangled photons to probe both electronic and vibrational coherences. The approach builds on an analogy between stimulated Raman scattering and spontaneous parametric down-conversion (SPDC): both generate photon pairs whose frequencies sum to a narrow value. An SPDC probe tuned to the degenerate frequency of the central Raman wavelength is therefore well suited, since Stokes gain and anti-Stokes loss both unbalance the photon statistics and reduce the pair correlation. As a first step, we built a pulsed entangled-photon source in the visible range, where electronic transitions of molecular systems such as rhodopsins lie. Photon pairs at 687 and 515 nm were generated by type-I SPDC in BBO, pumped by the third and fourth harmonics of a 1030 nm Yb:YAG femtosecond laser, and detected with an intensified sCMOS camera.

We observed correlations between quadrants of the SPDC cone, with the radial correlation peak agreeing with simulations. Also, it as possible to confirm spatio-spectral correlations using a home-built spectrograph. Optimising the photon rate and selecting the degenerate part of the SPDC cone markedly improved the measurements. But better pump-beam shaping, walk-off compensation and higher detection efficiency seems needed to strengthen these correlations, and enable their implementation in stimulated Raman spectroscopy.



Composite Directional Couplers for Narrowband Filtering in Integrated Quantum Photonics

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Precise spectral control of light is fundamental to quantum technologies. Conventional integrated narrowband filters, such as ring resonators, Bragg gratings and long directional couplers, trade off footprint, bandwidth, thermal sensitivity and fabrication tolerance, and often need active stabilization.

Here, we map the composite-pulse formalism of quantum control [1, 2] onto coupled integrated waveguides. A narrowband composite pulse sequence for selective population inversion becomes a cascade of directional-coupler segments: the detuning Δ maps to the phase mismatch $\Delta\beta$, set by the waveguide width difference, and the Rabi frequency Ω to the coupling κ, set by the gap. Engineering $\Delta\beta(z)$ and $\kappa(z)$ yields a single, non-resonant narrow transfer band in a fully passive device.

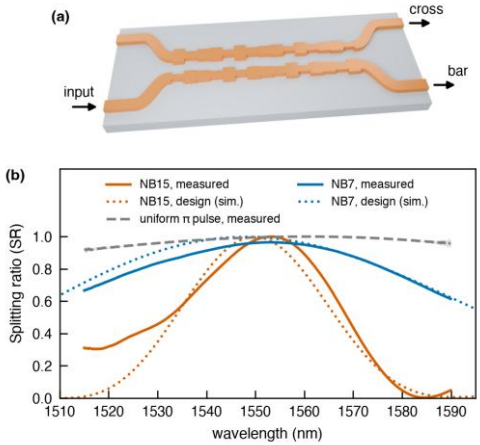


Fig. 1. (a) Schematic of the 15-segment composite coupler with its input, cross and bar ports; Splitting ratio (SR) is the fraction of power transferred to the cross port. (b) Measured splitting ratio (SR) of 15-segment coupler (NB15) and of a 7-segment coupler (NB7), with their design simulations, and of a uniform coupler.

We fabricated the couplers on a 220 nm silicon-on-insulator foundry platform and measured them with a robust four-port splitting-ratio method [3] (Fig. 1). NB15 reaches a peak SR of 0.999 within 3.2 nm of its 1550 nm design wavelength, with a 3-dB bandwidth of 37 nm, much narrower than a uniform coupler, which keeps SR > 0.91 over the whole 1515–1590 nm window. These results establish composite directional couplers as a new class of compact, passive spectral components for scalable quantum photonics, enabling narrowband filtering of single photons for quantum light sensing.

[1] H. Gevorgyan, Optics Express 33, 23095-23109 (2025)
[2] E. Kyoseva, H. Greener, H. Suchowski, Physical Review A 100, 032333 (2019)
[3] J. Piasetzky et al., arXiv:2412.11670 (2024)

Optimized parametric down-conversion sources for photonic quantum technologies

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We report a telecom-wavelength (1550 nm) type-II SPDC source based on potassium titanyl phosphate (KTP) that jointly engineers the nonlinear domain structure and the pump spectrum to suppress spectral correlations without sacrificing heralding efficiency [1]. The source uses apodized crystals with a Gaussian nonlinearity profile, combined with Gaussian pump spectral shaping implemented by a programmable spatial light modulator, to realize a Gaussian-like joint spectral amplitude (JSA) whose symmetry approaches the ideal circular form [2]. The design targets high purity while maintaining brightness, leveraging a crystal length L and a normalized nonlinear width chosen as r/L = 1/6.04.

Simulations predict a spectral purity as high as 99.99% for the optimally shaped joint spectrum. Experimentally, time-of-flight spectrometry (TOFS) reconstruction of the JSA yields a purity of 99.90% with an upper bound of 99.9272(6)% in the unfiltered case [3], consistent with the simulations and representing the highest reported upper bound for SPDC sources. Time-resolved two-photon interference [4] between photons from independent sources shows a visibility of 98.5% ± 0.8% without spectral filtering, surpassing prior results under similar conditions and highlighting improved indistinguishability.

Key design choices include using a 30 mm crystal length and a pump spectral width around 0.308–0.321 nm, with a measured pump pulse duration near 1.21 ps (slightly above the transform-limited 1.17 ps). Minor purity reductions arise from Poissonian noise and residual spectral-phase effects not fully captured by TOFS. The work demonstrates a practical route to bright, nearly pure, telecom-photon sources suitable for scalable quantum photonics and heralded single-photon applications.

[1] T. Faleo et al., Appl. Phys. Lett. 128, 204004 (2026)
[2] N. Quesada et al., Phys. Rev. A 98, 043813 (2018)
[3] M. Avenhaus et al., Opt. Lett. 34, 2873-2875 (2009)
[4] C. K. Hong et al., Phys. Rev. Lett. 59, 2044 (1987)
[5] A. Monmayrantet al., J. Phys. B: At. Mol. Opt. Phys. 43, 103001 (2010)

Temporally filtered photon subtraction for Cat-State generation

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Schrödinger cat states are promising non-Gaussian resource states for quantum information science, particularly for fault-tolerant bosonic quantum computation [1]. Advanced experiments such as optical state breeding [2], which can generate cat states with larger amplitudes or approximate Gottesman–Kitaev–Preskill (GKP) states, require small-amplitude cat states as a core resource.

A well-established method for generating small-amplitude cat states is photon subtraction from squeezed vacuum. Spectral filtering of the subtracted photons requires particular attention, as it affects the purity and temporal mode of the heralded state [3]. Implementing a source of such non-Gaussian resource states remains an experimentally challenging task.

We built an experimental platform capable of generating the desired small-amplitude cat states. The temporal mode of the resulting conditional state was characterized using a balanced homodyne detector (BHD) and principal component analysis (PCA). The characterization of the system provides a foundation for projects involving optical cat states in advanced protocols.

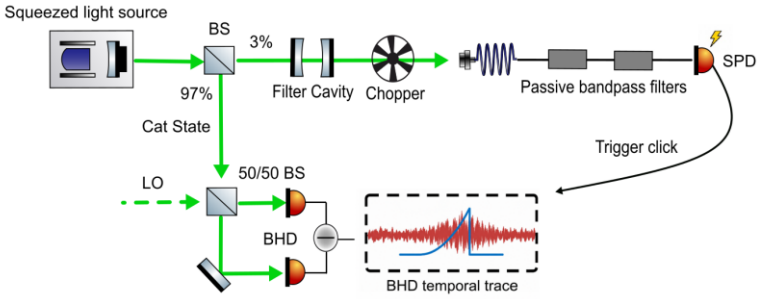


Figure 1. A simplified overview of the experimental setup. Subtracted photons are transmitted through a sequence of spectral filters to be detected by a single photon detector.

[1] A. P. Lund et al., "Fault-Tolerant Linear Optical Quantum Computing with Small-Amplitude Coherent States," Physical Review Letters 100, 030503 (2008).
[2] D. V. Sychev et al., "Enlargement of optical Schrödinger's cat states," Nature Photonics 11, 379–382 (2017).
[3] J.-i. Yoshikawa et al., "Purification of photon subtraction from continuous squeezed light by filtering," Physical Review A 96, 052304 (2017).

Generation of Entangled States of Light in an Atomic Ensemble of Rubidium 85

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Quantum entanglement and squeezing [1,2] are essential quantum resources for fundamental research in areas of quantum information and quantum technology, specifically in quantum computing, quantum communication, and quantum metrology. The last one, quantum metrology, is able to harness quantum features of light or matter in estimation of unknown parameters achieving precision beyond that a classical system could reach. Among its various applications like quantum cryptography, quantum imaging, spectroscopy and quantum-enhanced sensors, optical phase estimation has attracted considerable attention in metrology area because its measurement is relevant for other experiments and applications [3]. The approach for quantum-enhanced phase sensing is a nonlinear interferometer, to be more precise a SU(1,1) interferometer where nonlinear amplifiers replace the beamsplitters in classic Mach-Zehnder interferometer [4].

Entanglement can be exhibited by squeezed light, the squeezing is obtained by means of nonlinear parametric processes, for this work this process is Four-Wave Mixing [5] in a double-Λ scheme over the D1 transition of Rubidium 85, in a hot vapor cell. Multimodal entanglement is attained with a double process in the same vapor cell happening side by side. The entangled states will be sent through a multimodal optical fiber to analyze the correlation maintenance before their implementation in the interferometer. Simultaneously, a theoretical work is underway since an analytical calculation of other specific input states for this system are being studied, this is carried out with a Python program which is able to generalize input states and transformations involved in the whole system. The potential of this program is expected to be broad in the quantum optics area and not only for this application.

[1] Einstein, A., Podolsky, B., y Rosen, N. (1935a). Can quantum-mechanical description of physical reality be considered complete? Physical Review, 47, 777. doi: 10.1103/PhysRev.47.777

[2] Slusher R, Hollberg L, Yurke B, Mertz J and Valley J 1985 Phys. Rev. Lett. 55 2409

[3] Caves, C. M. (1981). Quantum-mechanical noise in an interferometer. Physical Review D, 23(8), 1693–1708. https://doi.org/10.1103/PhysRevD.23.1693

[4] Bernard Yurke, Samuel L McCall, and John R Klauder. Su (2) and su (1, 1) interferometers. Physical Review A, 33(6):4033, 1986. DOI: https://doi.org/10.1103/PhysRevA.33.4033.

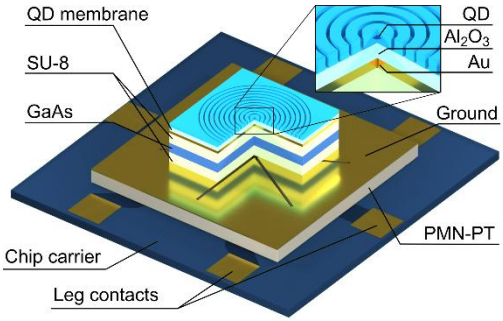
[4] C. F. McCormick, V. Boyer, E. Arimondo, and P. D. Lett, "Strong relative intensity squeezing by four-wave mixing in rubidium vapor," Opt. Lett. 32, 178-180 (2007) https://doi.org/10.1364/OL.32.000178

Tunable entangled-photon emitter based on a cavity-enhanced quantum dot on a micromachined piezoelectric actuator

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[2]Department of Physics, Sapienza University of Rome, Rome, Italy
[3]Institute of Semiconductor and Solid State Physics, JKU Linz, Linz, Austria
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[5]Department of Optics, Palacký University, Olomouc, Czech Republic
[6]Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, Campinas, Brazil
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[8]Forschungszentrum Mikrotechnik, FH Vorarlberg, Dornbirn, Austria
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Semiconductor quantum dots are emerging as one of the most promising sources of single and entangled photons, thanks to their capability to generate photons on demand and to tune their emission via strain engineering [1]. Yet, their full potential has been hindered by limitations such as low extraction efficiency caused by refractive index mismatch and entanglement degradation linked to intrinsic anisotropies. A major step forward has been achieved with circular Bragg resonators, which address many of these challenges by enhancing photon extraction [2]. Building on this concept, we have developed a device that integrates circular Bragg resonators with a micromachined piezoelectric actuator [3], enabling active strain control. I will present the state-of-the-art performance of this device in terms of low multiphoton probability, fast emission enabled by the Purcell effect, high indistinguishability, and simultaneous optimization of brightness and entanglement. Already proven useful in entanglement-based quantum communication protocols [4], this deterministic and tunable entangled photon emitter constitutes a versatile platform with potential applications across all areas of quantum photonics, including quantum sensing.



[1] R. Trotta, et al., *Physical Review Letters* **114**(15), 150502 (2015).
[2] J. Liu, et al., *Nature Nanotechnology* **14**(6), 586 (2019).
[3] M. B. Rota, T. M. Krieger, et al. *eLight* **4**, 13 (2024).
[4] A. Laneve, et al., *Nature Communications* **16**, 10028 (2025).

Multispectral Mid-Infrared Quantum Microscopy with Undetected Photons for Label-Free Biomedical Imaging

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Mid-infrared (mid-IR) microscopy provides access to molecular vibrational signatures and offers a powerful approach for label-free characterization of biological samples. We are developing a quantum microscopy platform based on imaging with undetected photons, where mid-IR idler photons interact with the sample while correlated near-infrared signal photons are detected. The current system generates idler photons spanning 3.4 – 4.3 µm and achieves a ~1 mm field of view with ~31 µm spatial resolution. Wavelength-selective imaging is implemented in the signal arm using an angle-tuned bandpass filter centered at 808 nm with a 3 nm bandwidth. Using this approach, we have acquired multispectral images of biological spheroids across multiple wavelength channels.

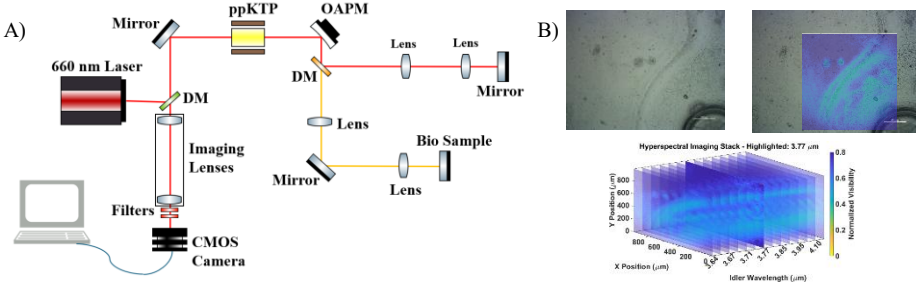


Figure 1: A) Experimental schematic for wavelength-selective mid-infrared microscopy with undetected photons. B) Multispectral image stack of spheroid acquired at selected mid-infrared wavelength channels.

Multispectral imaging was performed on spheroids formed from MDA-MB-231 triple-negative breast cancer cells. The cells were cultured in ultra-low-attachment plates for seven days to form three-dimensional spheroids, which provide a model for studying cellular interactions within the tumour microenvironment. The same spheroid region was then imaged at selected wavelength channels corresponding to different regions of the correlated mid-infrared spectrum. The resulting image stack reveals wavelength-dependent variations in image contrast and provides a basis for investigating spatially resolved spectral responses within the sample.

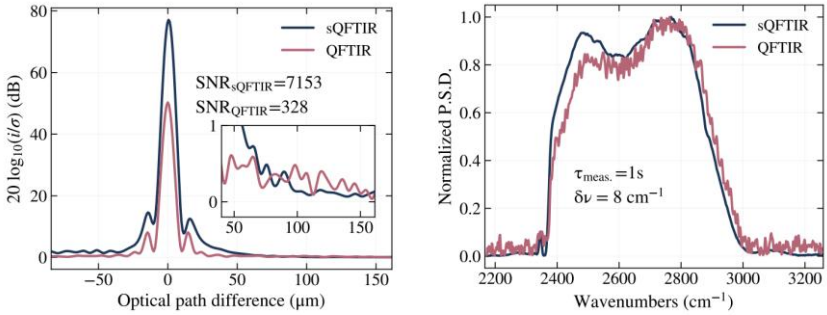
[1] M. Placke et al., Optica, 2026, 13, 328–335. DOI: 10.1364/OPTICA.573220.
[2] I. Kviatkovsky et al., Sci. Adv., 2020, 6, eabd0264. DOI: 10.1126/sciadv.abd0264.
[3] G. B. Lemos et al., Nature, 2014, 512, 409–412. DOI: 10.1038/nature13586.

Fourier- and time-domain sensing with undetected photons: noise, sensitivity, and optimal measurement regimes

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In this contribution, a detailed analysis and comparison of Fourier- and time-domain detection schemes in nonlinear interferometry (NLI) are presented, with particular emphasis on noise, sensitivity, and associated trade-offs. It is demonstrated that Fellgett's advantage well-known in classical mid-IR sensing, turns to become a disadvantage in shot-noise-limited operational regimes of NLI. The intrinsic sensitivity advantage of spectral-domain measurements associated with multipixel detection and coherent averaging is derived theoretically and verified experimentally using the same NLI system [1]. The results lead to a counterintuitive conclusion: a sensitivity advantage can be achieved even under shot-noise-limited detection conditions by appropriately engineering the acquisition scheme. These findings can be used to enhance QFTIR performance [2] and provide a justification for complex envelope extraction methods [3].



(a) TD comparison of sQFTIR and QFTIR (b) FD comparison of sQFTIR and QFTIR

Figure 1: Demonstration of sensitivity advantage: signal-to-noise ratios in the time (QFTIR[1]) and Fourier (sQFTIR[2]) domains for a measurement time of 1 s obtained in the same nonlinear interferometer. Sensitivity advantage by factor of 21.8 (26.8 dB) is demonstrated.

[1] P. Gattinger, B. Heise, A. W. Schell, K. Duswald, M. Brandstetter, and I. Zorin, "Scanless quantum Fourier-transform mid-infrared spectroscopy for rapid high-sensitivity hyperspectral mapping," Jul. 2026, Available: http://arxiv.org/abs/2607.17964.

[2] P. Gattinger, A. W. Schell, S. Ramelow, M. Brandstetter, and I. Zorin, "Quantum Fourier Transform Infrared Spectroscopy: Evaluation, Benchmarking, and Prospects," *Appl. Spectrosc.*, May 2025, doi: 10.1177/00037028251340945.

[3] P. Kaufmann, H. M. Chrzanowski, A. Vanselow, and S. Ramelow, "Mid-IR spectroscopy with NIR grating spectrometers," *Opt. Express*, vol. 30, no. 4, p. 5926, Feb. 2022, doi: 10.1364/OE.442411.

Sensing with undetected photons for applied non-destructive testing

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In this contribution, cost-effective and promising approaches to applied non-destructive testing based on metrology with undetected photons are demonstrated. Thus, polarimetric measurements of polypropylene performed using scanless quantum Fourier transform IR spectroscopy (sQFTIR) [1] are presented. Based on the linear dichroism of vibrational modes [2], the molecular orientation parameter of the polymer thin film is extracted. Furthermore, we showcase the feasibility of a robust co-propagating system based on chirped crystals. In this configuration, interference is set by the group delay accumulated within the nonlinear crystal itself. The broad bandwidth, low-cost and robustness make this architecture attractive for low-cost gas sensing applications. Besides, we propose integration of a pump-resonant monolithic cavity based on optical bonding for optical coherence tomography to enhance sensitivity [3].

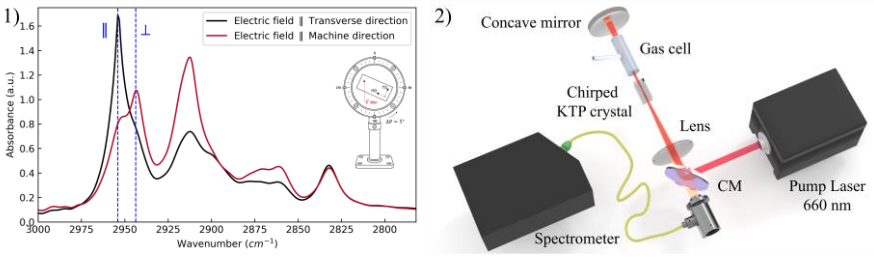


Figure 1: Polarization dependent absorbance spectra of a polypropylene thin film measured with sQFTIR. The two orthogonal input polarizations reveal opposite dichroic behavior in selected absorption bands (blue dashed lines), which is used to determine the molecular orientation parameter.
Figure 2: Scheme of the co-propagating nonlinear interferometer.

[1] P. Gattinger, B. Heise, A. W. Schell, K. Duswald, M. Brandstetter, and I. Zorin, "Scanless quantum Fourier-transform mid-infrared spectroscopy for rapid high-sensitivity hyperspectral mapping," Jul. 2026, Available: http://arxiv.org/abs/2607.17964.

[2] Hiroyuki Tadokoro, Masamichi Kobayashi, Minoru Ukita, Katsutoshi Yasufuku, Shunsuke Murahashi and Tatsuo Torii, "Normal Vibrations of the Polymer Molecules of Helical Conformation. V. Isotactic Polypropylene and Its Deuteroderivatives", *J. Chem. Phys*, vol. 42, no. 4, p. 1432, Feb. 1965, https://doi.org/10.1063/1.1696134.

[3] Ivan Zorin, Dominik Brouczek, Sebastian Geier, Serkan Nohut, Julia Eichelseder, Guillaume Huss, Martin Schwentenwein, Bettina Heise, "Mid-infrared optical coherence tomography as a method for inspection and quality assurance in ceramics additive manufacturing", *Open Ceramics*, vol.12, no. 100311, Sept. 2022, https://doi.org/10.1016/j.oceram.2022.100311

Scanless quantum Fourier-Transform infrared microspectroscopy

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We present a reconstruction protocol for scanless quantum Fourier-transform infrared spectroscopy (sQFTIR) [1,2]. This method measures signal photon interference in a nonlinear Michelson-type interferometer in the spectral domain and combines well established reconstruction algorithms from optical coherence tomography and FTIR spectroscopy. It allows us to perform QFTIR-like spectroscopy without scanning the reference arm of the nonlinear interferometer [3]. Furthermore, it introduces a sensitivity advantage due to multiplexing. We exploit this multiplex advantage and apply an sQFTIR system to perform rapid chemical (hyperspectral) mapping of various samples such as a polymer multilayer foil, dried pharmaceuticals and biological samples.

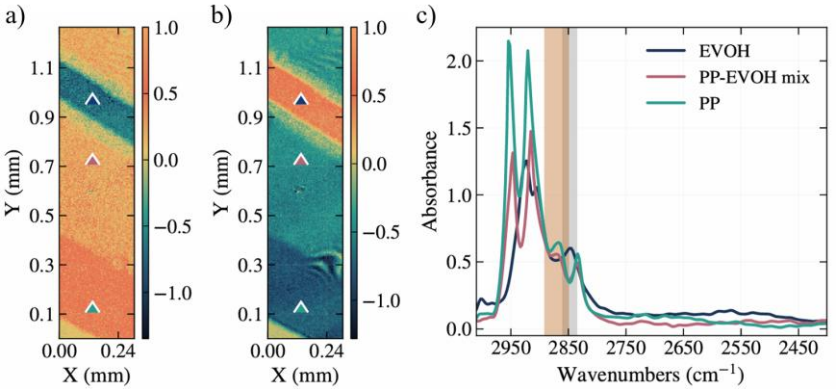


Figure 1: Chemical mapping of a polymer multilayer foil. (a),(b) Chemical image integrated over the spectral bands 2850-2890 cm^{-1} and 2836-2860 cm^{-1}, respectively; (c) single spectra extracted from the hyperspectral data-cube with and integration time of 10 ms per spectrum.

[1] P. Kaufmann, H. M. Chrzanowski, A. Vanselow, and S. Ramelow, "Mid-IR spectroscopy with NIR grating spectrometers," *Opt. Express*, vol. 30, no. 4, p. 5926, Feb. 2022, doi: 10.1364/OE.442411.

[2] P. Gattinger, B. Heise, A. W. Schell, K. Duswald, M. Brandstetter, and I. Zorin, "Scanless quantum Fourier-transform mid-infrared spectroscopy for rapid high-sensitivity hyperspectral mapping," Jul. 2026, Available: http://arxiv.org/abs/2607.17964.

[3] P. Gattinger, A. W. Schell, S. Ramelow, M. Brandstetter, and I. Zorin, "Quantum Fourier Transform Infrared Spectroscopy: Evaluation, Benchmarking, and Prospects," *Appl. Spectrosc.*, May 2025, doi: 10.1177/00037028251340945.

Undetected Photons, Coherence, and Fourier-Transform Spectroscopy

Chiara Lindner
Fraunhofer IPM

The abstract had not been submitted when this booklet was published.

Skipper-CCD detection system for quantum infrared spectroscopy with visible light

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Absorption spectroscopy at very low light levels is needed for light-sensitive samples, lossy paths, weak absorbers, and compact or space-borne instruments without high-power IR sources or cooled IR detectors. In our Quantum-entangled SPectrometer using Infra-Red Interference Technology (Q-SPIRIT), IR absorption is measured without detecting IR light. A 532-nm pump generates photon pairs (~810nm/~1550nm) in a nonlinear interferometer; the 1550-nm photon passes through the sample, but the absorption appears in the interference fringes of its 810nm partner, detected with a silicon sensor [1,2]. The setup eliminates the need for an infrared detector, but because only a few 810-nm photons reach the sensor in each spectrum, the performance of the visible detector is critical. Readout noise limits the sensitivity, as does interference visibility, optical loss, background, and phase stability.

Here we present results using a Skipper CCD [3] as this detector. We measure each pixel's charge repeatedly and non-destructively. Averaging N samples lowers the readout noise as $1/\sqrt{N}$. We are using a back-illuminated sensor (10.5-um pixels); the measured system has a quantum efficiency near 100% at 810nm [4,5], and the readout noise is below 0.14 e^- with N=300 [3,6], contrasted with a conventional CCD with readout noise on the order of a few electrons.

As a preliminary measurement, we reconstruct the transmission of a 1550-nm bandpass filter (~7nm Δ_{FWHM}) from the associated visible spectra: the filter's transmission window appears at the correct wavelength, with a peak transmission of ~0.7 limited by the ~15% interference visibility. For our low-level signal, the limit is detector-readout noise rather than the photon statistics; we simulate that, using the Skipper CCD, the reconstruction error (normalized L1-norm) falls from around 0.8 at 10^2 e^- counts to around 0.05 at 10^4 e^- counts per measured spectrum. Our simulation accommodates photon count Poissonian noise, background light, and interferometric drift similar to that observed in our experiment. We discuss where this matters (i.e., below about 10^4 e^- per spectrum), and what is needed to exploit it (higher interference visibility and Poisson-statistics fitting).

[1] G. B. Lemos et al., Nature 512, 409 (2014).
[2] I. Kviatkovsky et al., Sci. Adv. 6, eabd0264 (2020).
[3] J. Tiffenberg et al., Phys. Rev. Lett. 119, 131802 (2017);
[4] E. Villalpando et al., 2024 PASP, 136 045001.
[5] S. Holland, Astron. Nachr. 344, e20230072 (2023).
[6] C. Chavez et al., Sensors 22, 4308 (2022).

SIM-QPla: Mid-infrared spectroscopy with quantum light for detection of environmental microplastics in aqueous samples

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[2] Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany
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[5] pacemaker Solutions GmbH, Muenster, Germany

Plastic waste, especially microplastics (MP), represents a growing environmental challenge. Mid-infrared (MIR) spectroscopy is a key methodology for label-free identification and assessment of MP contaminations. However, current MIR instrumentation is cost-intensive, not designed for mobile analytics or in-situ monitoring and measurements are time consuming. To addresses this topic the German project SIM-QPla combines quantum sensing, microfluidics and machine learning for microplastics detection in aqueous samples. A compact entangled photon-based MIR spectroscopy module, a MIR compatible microfluidics unit and ML-based identification of MP in quantum optical MIR spectra are presented.

Transferring Quantum Photonics to real world applications

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[2] Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany
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[5] pacemaker Solutions GmbH, Muenster, Germany

The German BMFTR project SIM-QPla uses entangled photons for the detection of microplastics in environmental samples. The transfer of quantum photonics lab concepts to real world applications has several critical steps and unforeseen hurdles. The generation and use of entangled photons is determined by the nonlinear crystal and the pump laser wavelength. The selected combination of 720 nm pump laser and periodically-poled KTP crystals results in mid-infrared (MIR) spectra from 3.2 – 3.6 µm which fit perfectly the MIR fingerprint area of plastic materials. The particle detection can use simpler optics and detectors in the near infrared range.

For a successful microplastic detection the system needs a constant and strong quantum light emission. The project developed several pump lasers and quantum light modules in small boxes, which were improved for laser stability and photon loss. Another source of system instability are environmental conditions. Especially temperature control inside and outside of the system is crucial for the temperature sensitive nonlinear crystals. A suitable cooling system for the compact modules is required for higher laser power. Another challenge is the perfect adjustment of optical components and fibers for optimal transmission of invisible light. This is of high importance for prototype development and a robust system use on site.

Finally, the project goal is the measurement of microplastics in aqueous media in a microfluidic channel. Since water has a broad peak partially overlapping with the systems MIR range, state of the art FT-IR systems only measure purified and dried samples. For the detection of microplastics in water, the amount of water has to be reduced by extremely flat channels combined with microfluidic chip materials with optimized MIR optical properties.

With newly developed software, algorithms and user interfaces for system control and data analysis, the project gets closer to end-user defined applicability.

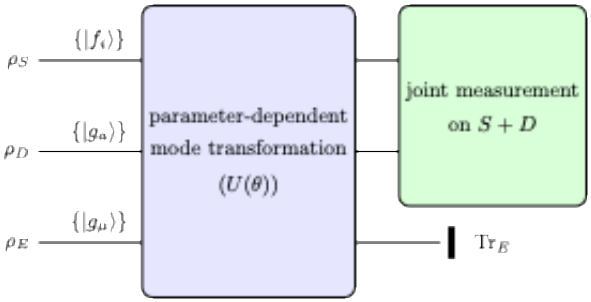
Quantum-Limited Mode-Parameter Estimation: Open-System Metrology and Applications to Optical Imaging

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[1] Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València and Departament de Física Teòrica, UV, Avinguda Vicent Andrés Estellés, 19, E-46100 Burjassot (València), Spain

We show how parameter-dependent deformations of optical modes can be converted into metrological gain under passive optical transformations, including in the presence of diffraction and loss. When all modes are accessible, the quantum Fisher information (QFI) separates into coherent mixing within the prepared mode subspace and geometric coupling to orthogonal mode directions [1]. This separation identifies conditions for Heisenberg scaling and clarifies how unmonitored attenuation at regular fixed working points restricts the asymptotic advantage to shot-noise scaling. For partial measurement access, we retain accessible derivative modes and trace out inaccessible modes, obtaining the exact reduced-state symmetric logarithmic derivative QFI at arbitrary local working points. A self-consistent variational formulation then identifies optimized Fock and Gaussian probes for reduced-state estimation, which we benchmark against channel-extension upper bounds. We demonstrate the framework with Zernike mode rotation sensing and two-source imaging for real and phase-structured Gaussian point-spread functions. Linear and cubic phases reveal distinct photon-number and mode-mixing mechanisms for quantum enhancement beyond the standard quantum limit. Finally, we construct a physical four-mode imaging model with prepared, finite-width fundamental and derivative-shaped source modes that encode the unknown separation through a common propagation kernel. Optimization over Fock and Gaussian probe states reveals quantum-enhanced separation sensitivity near the Rayleigh limit, even in the presence of diffraction and optical loss.

[1] M. Gessner, N. Treps, and C. Fabre, Estimation of a parameter encoded in the modal structure of a light beam: a quantum theory, Optica 10, 996 (2023).



Squeezing Enhanced Sagnac Sensing based on SU(1,1) Quantum Interference

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We present a simple and robust design for a squeezing-enhanced Sagnac interferometer [1] that combines the principles of SU(1,1) quantum interference with conventional Sagnac rotation sensing. By incorporating a single optical parametric amplifier (OPA) inside the Sagnac loop (Fig. 1), both counter-propagating beams are squeezed, enabling enhanced sensitivity to small rotation-induced phase shifts beyond the shot-noise limit (SNL). The proposed configuration retains the conventional Sagnac geometry while exploiting the quantum advantages of squeezed light, with inherent phase stability arising from the co-propagation of the pump and seed through the loop.

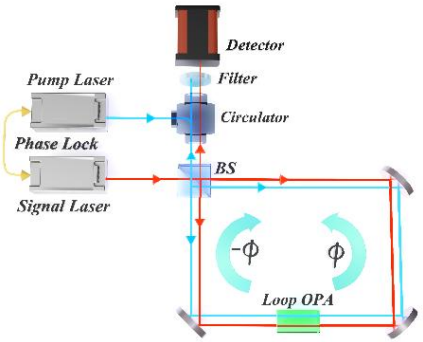


Figure 1 ***Proposed squeezing-enhanced Sagnac sensor****. The setup incorporates a single intra-loop OPA that squeezes the counter-propagating beams. The interference at the BS produces an intensity-squeezed output at the dark port, allowing sub-shot-noise sensitivity via* ***Direct Detection****. To overcome detector inefficiency, this setup can be extended to* ***Parametric Homodyne Detection*** *by adding a second OPA at the dark output to amplify the squeezed quadrature before detection.*

To extract the phase information, we consider two detection strategies: **direct detection**, which measures the output intensity at the Sagnac dark port and offers a simple implementation but requires high-efficiency photodetectors; and **parametric homodyne detection**, which introduces an additional OPA to amplify the squeezed quadrature before photodetection, reducing sensitivity to detector inefficiency at the cost of increased optical complexity. Both approaches provide a route toward quantum-enhanced rotation sensing while preserving the simplicity and stability of the Sagnac interferometer.

References

[1] M. Natan, S. Levin, and A. Pe'er, "Squeezing enhanced Sagnac sensing based on SU(1,1) quantum interference," *Optica Quantum* **4**, 311–320 (2026).

Path-Degenerate Quantum Interferometry for Quantum-Enhanced Sensing

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[3] Faculty of Physics, M V Lomonosov Moscow State University, Moscow, Russia

Quantum enhanced interferometers like gravitational wave (GW) detectors utilise squeezed vacuum states of light to reduce quantum noise relative to the signal. There optimised squeeze angles quantum-correlate photon shot noise and quantum back-action noise. In this way, sensitivity in the quantum non-demolition (QND) regime is achievable. However, the decoherence caused by loss of photons partially destroys the quantum correlations, which is a challenge even in future, highly optimised GW detectors such as the Einstein Telescope. With higher loss resilience, the QND performance could be enhanced even further by the `variational output' technique, which optimizes the measured field quadrature for every signal frequency. So far, the level of loss and experimental complexity prevented it for being considered for future GW detectors.

Here we propose and partially experimentally demonstrate the path-degenerate quantum interferometry scheme that promises lower photon loss due to fewer optical components, mitigates the decoherence effect caused by loss in the output channel, reduces the impact of spatial mismatches between different optical modes and automatically integrates a variational output scheme without additional components. Our proposal delivers a further improved signal-to-quantum-noise ratio and has the potential to enhance the sensitivity of both GW detectors and other high precision quantum sensors.

The proposed scheme is equivalent to a folded, degenerate SU(1,1) interferometer and provides loss resilient quantum advantage at single, highly optimizable wavelength by combining the advantages of squeezing with those of output amplification.

Rittmeyer, Böttner, Khalili, Korobko, Schnabel - „ Path-Degenerate Quantum Interferometry for Loss Resilience in Gravitational-Wave Detectors “- http://arxiv.org/abs/2609.12204

Polychromatic detection of entangled photon pairs with intensified CMOS camera

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Most quantum optics experiments are experimentally realized through coincidence counting using pairs of single-photon detectors. This approach is well established and carries many advantages. However, it is not particularly suitable for applications where a large number of entangled photon pairs are generated simultaneously. Additionally, it is not suitable for studying number states, as typical single-photon detectors cannot distinguish between single-photon and multiphoton events. Intensified cameras can, in principle, detect and resolve large quantities of single photons, but at a high cost. These costs include the relatively low quantum efficiency of even the best single-photon intensifiers and the need for advanced image processing to extract single-photon events, which appear as highly variable peak structures in the intensified camera.

We conducted several studies with an intensified CMOS camera to evaluate its potential to directly image the wavelengths and momentum of entangled photons generated by an SPDC source. This work serves as preparation for experiments where entanglement between Stokes and anti-Stokes Raman-scattered photons will be investigated[1].

[1] Chizhov, A.V. Stokes-anti-Stokes entanglement in stimulated Raman scattering. Phys. Part. Nuclei Lett. 6, 494–497 (2009)

Asynchornous Quantum Ghost Imaging - Achieving real-time video processing and imaging with diffuse reflection

Carsten Pitsch[1], Henri Haka[2], Davide Moschella[2], Dominik Walter[1], Alberto Tosi[2], Federica Villa[2]

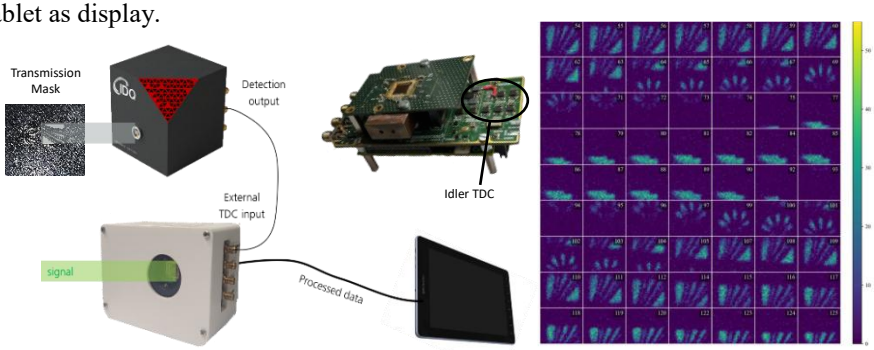
[1] Fraunhofer IOSB, Ettlingen, Germany
[2] Politecnico di Milano, Milan, Italy

Asynchronous Quantum Ghost Imaging is a correlation imaging technique, that separates the coincidence detection from the layout of the optical setup. Since it is time-tagging based, coincidence detection directly allows 3D measurements and efficient remote sensing scenarios, including the use of diffuse reflection.

Current implementations are limited in efficiency due to the need to establish a common timebase, leading to time-consuming synchronization and data corrections. Moreover, data transfer constraints of the time-tagging camera interface limit both resolution and duty cycle of the camera systems.

Here we present two new cameras based on Single Photon Avalanche Diode (SPAD) imagers, which both integrate an additional Time-to-Digital Converter (TDC) either in a dedicated chip inside the camera (shown below) or in the SPAD imager itself. This TDC is connected to an SMA input of the camera, allowing time-tagging of the external idler detector by the camera and inherently achieving temporal synchronization. This enabled real-time coincidence image processing at up to 60 fps with a coincidence peak width of up to 700 ps (FWHM).

Since the data stream of the camera already used the entire bandwidth of the USB3.0 interface, we further investigated direct processing of the acquired data on the FPGA board of the camera. This implementation was tested experimentally with the same setup and yielded exactly the same results with the added benefit of not requiring a processing unit. It could be shown to run efficiently with a common tablet as display.



Left to right: Acquisition scheme of the new camera system; camera stack with idler TDC implemented on the FPGA board; real-time coincidence image stream obtained on the tablet display (26 fps)

Correlation-based Adaptive Optics

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[2] Imagine Optic SA (France)
[3] Institut des Sciences Moléculaires d'Orsay, Univ. Paris-Saclay, CNRS (France)
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Adaptive optics (AO) is central to modern microscopy, enabling high-resolution imaging in the presence of aberrations [1]. These aberrations could be introduced by inhomogeneity in the samples or non-ideal optical components. Existing AO approaches are typically tailored to specific imaging modalities, such as fluorescence or label-free microscopy, and rely either on guide stars, additional hardware, or object-dependent image metrics. As a result, their performance depends on prior knowledge of the sample and may require specialized instrumentation.

Here we introduce a general, correlation-based adaptive optics framework that exploits the high-dimensional information contained in photon correlations, which is largely unused in conventional AO. Using a unified quantum-optical description, we show that measurements of second-order correlations provide direct access to the aberrated point-spread function, independent of whether the correlations originate from classical fluctuations, sample dynamics, or quantum illumination, thereby substantially expanding our previous work based on entangled light [2]. Crucially, the resulting correction is object-independent and requires no additional hardware beyond a standard camera.

We experimentally demonstrate this approach in three distinct imaging scenarios: correlations engineered through structured illumination of a fluorescent sample, correlations generated by blinking emitters, and correlations arising from a quantum two-photon beam. In all cases, correlation-based AO recovers sharp images without prior knowledge of the sample. These results establish photon correlations as a universal resource for adaptive optics, providing a unified strategy applicable across classical and quantum microscopy platforms.

[1]: Zhang, Q., Hu, Q. I., Berlage, C., Kner, P., Judkewitz, B., Booth, M., & Ji, N. (2023). Adaptive optics for optical microscopy. Biomedical Optics Express, 14(4), 1732-1756.

[2]: Cameron, P., Courme, B., Vernière, C., Pandya, R., Faccio, D., & Defienne, H. (2024). Adaptive optical imaging with entangled photons. Science, 383(6687), 1142-1148.

Certifying quantum entanglement with a time-stamping camera

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High-dimensional entangled states, such as spatially entangled photon pairs produced by Spontaneous Parametric Down-Conversion, are a key resource for quantum technologies [1][2]. In recent years, camera-based coincidence counting approaches have considerably improved the ability to characterize them in terms of speed and dimensionality, using Einstein-Podolsky-Rosen (EPR) [3] criterion to certify entanglement between photons. However, these methods have limitations, namely the necessity to subtract accidental coincidences or the need for exact implementation of the measurement basis [4][5]. We present here experimental results showing that high dimensional entanglement certification can be obtained without accidentals subtraction for a single-photon avalanche diode (SPAD) array and an intensified time-stamping (Tpx3Cam) camera [6]. We also show preliminary results on using Fractional Fourier Optics to certify entanglement in cases where the usual position-momentum EPR criterion fails.

[1] H. Bechmann-Pasquinucci et W. Tittel. “Quantum cryptography using larger alphabets”, Phys. Rev. A 61 (2000), p. 062308.
[2] Sebastian Ecker et al. “Overcoming Noise in Entanglement Distribution”, Phys. Rev. X 9 (4 nov. 2019), p. 041042

[3] M. D. Reid, P. D. Drummond, et al.,"Colloquium : The Einstein-Podolsky-Rosen paradox : From concepts to applications", Rev. Mod. Phys. 81, (2009

[4] J.C. Howell, R.S. Bennink et al."Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion", Phys. Rev. Lett. 92, 210403 (2004).

[5] M.P. Edgar, D.S. Tasca et al.,"Imaging high-dimensional spatial entanglement with a camera" Nat Commun 3, 984 (2012)

[6] Raphael Guitter et al., "Accidental coincidences in camera-based high-dimensional entanglement certification," Opt. Lett. **50**, 7532-7535 (2025)

Non-local wavefront shaping using entangled photons

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Wavefront shaping is a crucial technique in optics, traditionally used to correct aberrations and scattering that an optical beam may encounter along its propagation path [1,2]. In a conventional wavefront shaping architecture, the optical signal passes through the complex medium, and an aberration correction device - typically a spatial light modulator (SLM) - is positioned along the same optical path. One challenge of this approach is to properly integrate the SLM into the optical system to efficiently correct aberrations by developing suitable algorithms. To overcome this challenge, and also explore a new avenue in optical wavefront control, we developed a non-local wavefront shaping approach using entangled photons. This approach decouples the wavefront shaping from the system containing the aberrations, enabling the development of new correction algorithms that may surpass existing methods and opening up new possibilities for applications in communication and imaging.

In our experiment, the photon pairs are produced by Spontaneous Parametric Down Conversion, therefore exhibiting strong spatial correlations. One of the photon of the pair is sent through a scattering medium, while its twin propagates through a SLM. By shaping the photon that hasn't interacted with the medium to mimic the scattering effects experienced by its pair, we demonstrate the restoration of strong correlations and entanglement between the pairs.

[1] Rotter, S. and Gigan, S. Light fields in complex media: Mesoscopic scattering meets wave control. Rev. Mod. Phys. 89, 015005 (2017)
[2] Cao, H., Mosk, A.P. and Rotter, S. Shaping the propagation of light in complex media. Nat. Phys. 18, 994–1007 (2022)

A Quantum Shield against Classical Light

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Discriminating quantum signals from classical light is crucial for secure communication and high-dimensional sensing [1]. Conventional filtering fails when classical and quantum states share identical spectral, temporal, and spatial profiles [2]. Here, we propose an active "Quantum Shield" that renders a channel opaque to separable light while remaining transparent to spatial entanglement.

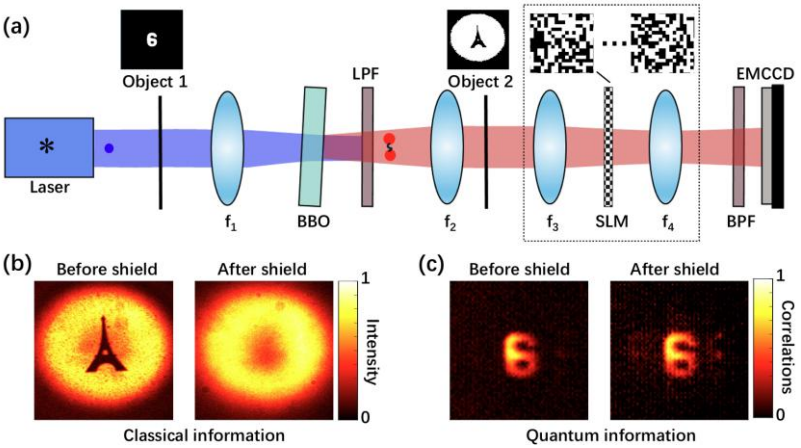


Fig. 1. (a) Experimental setup. (b) Classical information (Object 2) and (c) entanglement-encoded quantum information (Object 1) before and after the quantum shield.

In our setup (Fig. 1a), the shield comprises a spatial light modulator (SLM) between two lenses driven by dynamic, random binary (0–π) phase patterns. For separable states (coherent, incoherent, or classically correlated light), the resulting speckle point-spread function irreversibly scrambles spatial features. Conversely, SPDC photon pairs traverse the SLM at identical positions, accumulating twice the local phase and thus remaining immune to 0 and π modulations. In a dual-target experiment—featuring Object 1 (digit "6", entanglement-encoded [3]) and Object 2 (Eiffel Tower, incoherent illumination)—averaging over 200 random masks obliterates classical contrast (Fig. 1b), whereas the quantum image tunnels through the disorder with high fidelity via coincidence imaging (Fig. 1c).

[1] Lloyd, Seth. "Enhanced sensitivity of photodetection via quantum illumination." *Science* 321.5895 (2008): 1463-1465.

[2] Tan, Si-Hui, et al. "Quantum illumination with Gaussian states." *Physical review letters* 101.25 (2008): 253601.

[3] Vernière, Chloé, and Hugo Defienne. "Hiding images in quantum correlations." *Physical Review Letters* 133.9 (2024): 093601.

Quantum imaging with entangled photons in the regime of many temporal modes per frame

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Correlations in light beams have been shown to enable overcoming many limitations in the field of imaging. Within the context, Ghost Imaging (GI) and Correlation Plenoptic Imaging (CPI) [1] enable image reconstruction and scanning-free high resolution volumetric imaging by exploiting correlations. Here, we implement a quantum imaging setup using SPDC-generated entangled photons and investigate the information provided by the second-order correlation function $G^{(2)}$ while operating in the regime where many temporal modes are detected in each frame.

In this framework we implement data analysis strategies to achieve GI and 3D images reconstruction with high SNR. We demonstrate the need to introduce a signal filtering procedure in order to recover correlations [Figure 1], working around experimental non-idealities and also aiming at optimizing the SNR.

[Figure 1]

[1] Francesco V Pepe, Francesco Di Lena, et al. Correlation plenoptic imaging with entangled photons. Technologies, 4:17, 2016.

Correlation hyperspectral imaging with thermal light

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Hyperspectral imaging (HSI) is a technique that merges conventional imaging with spectroscopy, enabling the simultaneous capture of both spatial information and the full broadband spectral distribution of light emitted from an object (the so-called *hyperspectral cube*). The ability to resolve a large number of spectral bands across a wide spectral range makes HSI a highly powerful and versatile analytical tool, capable of identifying subtle spectral fingerprints arising from various physical processes such as reflection, diffusion, and emission. Despite these advantages, HSI is inherently constrained by a fundamental trade-off among spatial resolution, spectral resolution, and acquisition speed, which stems directly from its underlying acquisition methodologies based on spatial or spectral scanning or on sharing spatial and spectral information on the same sensor.

In recent years, a novel method named correlation plenoptic imaging (CPI) has demonstrated, theoretically and experimentally [1], how the second-order correlation function measured from thermal light (statistically characterized by intrinsic intensity fluctuations) acquired by two spatially resolved detectors, encodes rich information enabling the extraction of three-dimensional information about a sample. Well-grounded in the work to develop CPI, we now present a novel approach known as correlation hyperspectral imaging (CHI) [2] in which the second-order correlation function from thermal light, measured, now, from the intensity impinging on a spatially resolved detector and a spectrometer, encodes the hyperspectral cube of the sample, overcoming the limitations of HSI by achieving high spatial and spectral resolution simultaneously.

Here, we present the theoretical framework underpinning CHI and support it with simulations illustrating its working principle and key capabilities, including the enhanced optical performance inherited from the coherent nature of the correlation measurement [3] and the capability of the protocol to act as an intrinsic tunable spectral filter, naturally suppressing background contributions broader than the spectral lines of interest, due to the strong dependence of the measured correlation function on the detector exposure time.

[1] G. Massaro, *et al.*, "Light-field microscopy with correlated beams for high-resolution volumetric imaging", Sci. Rep., **12**, nº. 1, 16823 (2022).
[2] G. Massaro, F. V. Pepe and M. D'Angelo, Correlation hyperspectral imaging, Phys. Rev. Lett. **133**, 183802, 2024.
[3] G. Massaro, B. Barile, G. Scarcelli, F. V. Pepe, G. P. Nicchia, M. D'Angelo, "Direct 3D Imaging through Spatial Coherence of Light'', Laser Photonics Rev, **18**, 2301155 (2024).

Depth Imaging via Statistical Distinguishability of a True Thermal Source

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We propose an optical depth ranging technique based on the coherence properties of light. Our approach is based on two well-established methods, namely, optical coherence tomography (OCT), which relies on first-order interference between the reference and sample fields [1], and Quantum OCT, which relies instead on two-photon correlations between entangled photon pairs [2]. However, the former requires interferometric phase stability, and the latter requires a non-classical source. In this work, it is shown that depth information is also encoded in the photon-number statistics of a true thermal source, a light-emitting diode coupled to a single-mode fiber, and that it can be retrieved without entanglement and is robust to sample vibration and dephasing.

A discrete temporal-mode model of a Michelson interferometer illuminated by thermal light is developed. We predict, and validate experimentally, that when the arm-length mismatch exceeds the coherence length, the two arms deliver statistically independent thermal modes to the detector, and the photon-number distribution remains that of a thermal state. When the interferometer is balanced, the source interferes with itself, and the photon-number distribution is modified. The balanced and unbalanced configurations thus exhibit different photon-number statistics, and the two are shown to be distinguishable even though the mean number of detected photons is the same. The difference extends to the full count distribution and to all its higher-order moments, which relate directly to the higher-order correlation functions of the field.

Balanced and unbalanced configurations can therefore be discriminated from the statistics of a time-tagged photon stream alone, without entanglement, fringe scanning or phase stabilization. The model is compared with experimental photon-counting measurements, by using a time-tagging SPAD array as a photon-number resolving detector. Because the statistical contrast can potentially be evaluated independently for each pixel of a photon-counting detector array, this approach lays the foundation for wide-field depth imaging with classical thermal light.

[1] D. Huang et al., "Optical coherence tomography," Science 254, 1178 (1991)/
[2] A. F. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, M. C. Teich, "Quantum-optical coherence tomography with dispersion cancellation," Phys. Rev. A 65, 053817 (2002)/

Towards structured illumination ghost imaging - beyond the correlation resolution limit

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The quality of ghost imaging using spatially entangled biphotons from spontaneous parametric down-conversion (SPDC) strongly depends on crystal length. Thinner crystals exhibit narrower spatial correlations, enabling higher resolution or a larger field of view (FOV), depending on whether position correlations or momentum anticorrelations are used, respectively [1]. This improvement comes at the cost of reduced photon-pair generation rates (brightness), which can compromise the signal-to-noise ratio when imaging complex samples [2]. This trade-off is illustrated in Fig. 1 for the case where position correlations are used.

By exploiting the transfer of the pump beam's transverse structure to the biphoton wavefunction, we propose structured illumination microscopy (SIM) with biphotons to overcome the resolution limit imposed by crystal length while maintaining high brightness. Theoretical simulations have been performed, and an experimental setup is currently being developed to verify the results.

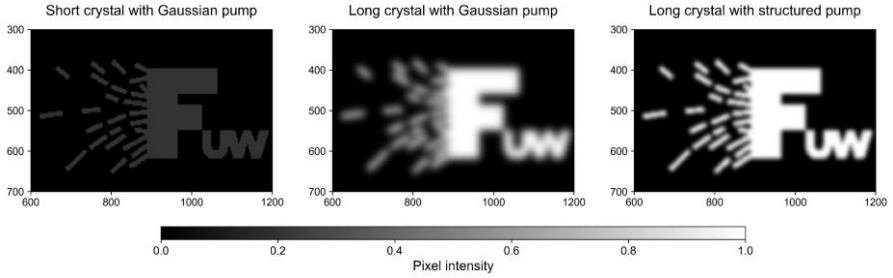


Figure 1: Schematic representation of ghost imaging using position correlations from an SPDC source. A short crystal provides high spatial resolution but low brightness, while a longer crystal increases brightness at the cost of resolution. By shaping the pump beam and applying structured illumination microscopy (SIM) reconstruction, both high brightness and high spatial resolution can be achieved.

[1] E. Brambilla et al., Phys. Rev. A 69, 023802 (2004).

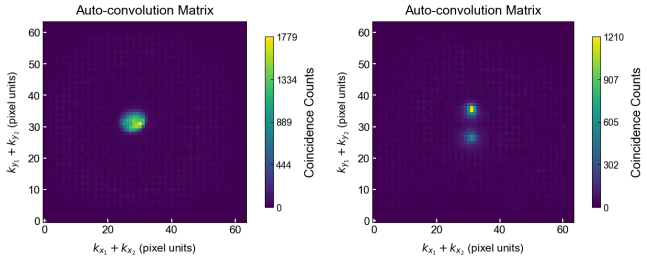
[2] M. Hojo and K. Tanaka, Sci. Rep. 11, 17986 (2021).

Measuring Momentum Anti-Correlations of SPDC Biphotons with Piccolo SPAD array

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[3] Advanced Quantum Architecture Laboratory (AQUA), École polytechnique fédérale de Lausanne (EPFL), Switzerland

We demonstrate the use of Piccolo [1], a 32 x 32 SPAD array with spatially resolved single-photon detection and 130 ps time-tagging accuracy, to measure momentum anti-correlations of photon pairs generated via spontaneous parametric down-conversion (SPDC). Coincidences between photon pairs are calculated from their arrival times, enabling the reconstruction of spatial correlations across the detector array. Building on this characterization, we investigate how modifying the spatial pump beam profile affects the observed biphoton correlation structure, mainly by using a striped pump in comparison to a Gaussian pump beam. The correlation pattern is determined by the pump beam shape, as well as the phase matching condition of the nonlinear crystal [2]. While the Gaussian pump produces a single dominant peak in the sum-coordinate coincidence distribution, the striped pump profile gives rise to two distinct peaks, as can be seen in figure 1. Our measurements therefore demonstrate the potential of pump beam shaping to modify spatial correlations in SPDC processes and the suitability of Piccolo for their spatially resolved characterization.



(a) (b)

Figure 1: Sum-coordinate coincidence distributions of SPDC photon pairs generated using (a) a Gaussian pump beam and (b) a striped pump beam. The Gaussian pump produces a single dominant peak, whereas the striped beam produces two distinct peaks.

[1] Zhang et al., Sensors, 18(11), 4016 (2018). https://doi.org/10.3390/s18114016
[2] Boucher et al., Opt. Lett. 46, 4200–4203 (2021). https://doi.org/10.1364/OL.425372

Ghost Imaging with Free Electron-Photon Pairs

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Coincidence imaging, also known as ghost imaging, is a technique that exploits correlations between two particles to reconstruct information about a specimen. The particle that relays the spatial information about the object remains completely non-interacting, while the particle used to probe the object is not spatially resolved. While ghost imaging has been primarily implemented on photonic platforms [1], it becomes particularly intriguing when applied to particles with fundamentally different properties, such as massive, charged electrons and massless, neutral photons, especially considering the role of both particles as cornerstones of highly advanced microscopic platforms. Utilizing a custom-built free-space cathodoluminescence setup integrated within a transmission electron microscope (see Fig. 1), we demonstrate electron–photon ghost imaging of complex patterns with a spatial resolution down to 2 µm [2]. These advances have also enabled the first experimental demonstrations of entanglement between photons and free space electrons [3], [4].

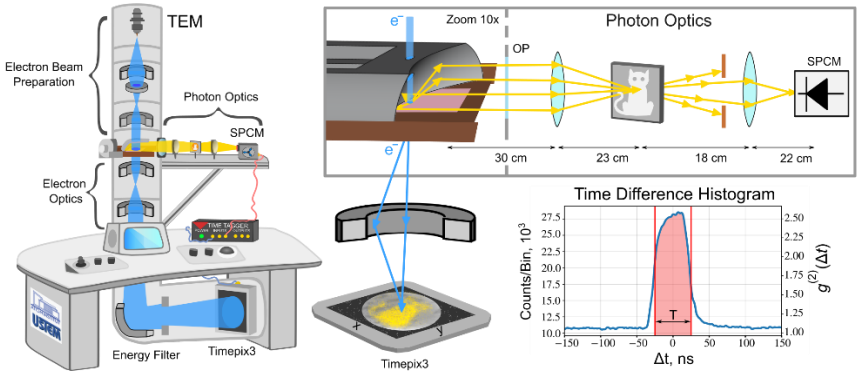


Fig. 1: Experimental setup for electron-photon pair coincidence (ghost) imaging [2].

[1] D'Angelo, et al., Physical Review Letters 92, 23 (2004).

[2] S. Bogdanov, A. Preimesberger, et al., Phys. Rev. Research 8, 033120 (2025).

[3] A. Preimesberger, S. Bogdanov, et al., arXiv:2504.13163, (2025).

[4] J.-W. Henke, H. Jeng, M. Sivis, C. Ropers, arXiv:2504.13047 (2025).

Entanglement in Electron Microscopy – A First Demonstration

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Entanglement is a central resource in quantum technologies, yet it has only recently become accessible in free-electron optics. In my contribution, I will present our recent experimental demonstration of quantum correlations between free electrons and cathodoluminescence photons generated inside a transmission electron microscope [1].

Using 200 keV electrons passing through a thin silicon membrane, we produce correlated electron-photon pairs via transition radiation. A time-resolved single-photon detector and a Timepix3-based direct electron detector allow us to identify coincident pairs and measure their transverse position and momentum correlations. By adapting ghost-imaging techniques [2] and an entanglement witness from photonic quantum optics, we quantify these correlations and show a violation of the MGVT separability bound [3], providing evidence for continuous-variable electron-photon entanglement.

We hope that these results will help to make entanglement available as a resource for electron microscopy, enabling novel measurement schemes inspired by photonic quantum optics.

[1] A. Preimesberger, S. Bogdanov, I.C. Bicket, P. Rembold, P. Haslinger, accepted in Nature Physics, doi:10.1038/s41567-026-03506-x (2026)
[2] M. J. Padgett and R. W. Boyd, Philos. Trans. R. Soc. A 375, 20160233, (2017).
[3] S. Mancini, V. Giovannetti, D. Vitali, P. Tombesi, Phys. Rev. Lett. 88, 120401 (2002).

Entanglement in Electron Microscopy

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Over the past decades, experimental quantum physics has developed rapidly in the realm of photonics, establishing a mature experimental toolbox that exploits quantum effects across a broad range of demonstrations and technologies. Representative examples include Bell tests, entanglement swapping, quantum teleportation, ghost imaging, imaging with undetected photons, NOON-state interferometric measurements, and squeezed-state metrology [1-7].

In contrast, (scanning) transmission electron microscopy ((S)TEMs) remains detached from this broader quantum toolbox. Although (S)TEMs operate intrinsically with quantum particles, they typically do not exploit quantum correlations for imaging, sensing, or measurement enhancement. Recent advances, including the experimental certification of electron-photon entanglement [8, 9] and the demonstration of ghost imaging with electron photon pairs [10], suggest a viable route toward adapting quantum schemes, and in particular, quantum photonics schemes into electron microscopy.

In this work, we present a comprehensive overview and conceptual generalization of established quantum photonic protocols to the emerging framework of electron-photon entanglement. We discuss how concepts developed in quantum optics may be translated to free-electron systems and integrated within the (S)TEM architecture. Finally, we analyze the potential opportunities offered by incorporating quantum protocols into (S)TEMs, including novel imaging modalities, quantum ghost imaging schemes, and quantum-enabled measurement strategies.

[1] S. J. Freedman and J. F. Clauser, Experimental Test of Local Hidden-Variable Theories, PRL (1972)
[2] J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, Experimental Entanglement Swapping: Entangling Photons That Never Interacted, Phys. Rev. Lett. (1998)
[3] D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Experimental Quantum Teleportation, Nature (1997)
[4] T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, Optical Imaging by Means of Two-Photon Quantum Entanglement, Phys. Rev. A (1995)
[5] G. B. Lemos, et al., Quantum Imaging with Undetected Photons, Nature (2014)
[6] M. W. Mitchell, J. S. Lundeen, and A. M. Steinberg, Super-Resolving Phase Measurements with a Multiphoton Entangled State, Nature (2004)
[7] J. Aasi et al., Enhanced Sensitivity of the LIGO Gravitational Wave Detector by Using Squeezed States of Light, Nat. Photonics (2013)
[8] A. Preimesberger, S. Bogdanov, P. Rembold, I. C. Bicket, and P. Haslinger, Experimental Demonstration of Electron--Photon Entanglement, arXiv:2504.13163
[9] J.-W. Henke, H. Jeng, M. Sivis, and C. Ropers, Observation of Quantum Entanglement Between Free Electrons and Photons, arXiv:2504.13047
[10] S. Bogdanov et al., Ghost Imaging with Free Electron--Photon Pairs, arXiv:2509.14950

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Dordrecht

Tuesday, 10 November · shore time approx. 13:00–15:00

back on board by 15:00 (Poster Session I)

Dordrecht, the oldest city in Holland, sits where three rivers meet. We moor at **Buiten Walevest** (map), a short walk from the old town.

Suggested walk – 3.0 km, about 40 min on foot plus stops · route in Google Maps
Groothoofdspoort – the 17th-century city gate at the confluence of Merwede, Noord and Oude Maas → the historic harbours **Wolwevershaven** and **Kuipershaven** → **Voorstraat**, the main street lined with gabled merchants' houses → **Groenmarkt** → town hall above the Voorstraathaven → **Grote Kerk** with its massive leaning tower (outside only) → back along the **Nieuwe Haven**.

Sweet break: freshly made *poffertjes* (tiny Dutch pancakes) at **Visser's Poffertjes**, Groenmarkt 9 – a local institution since 1932, open from 12:00.

If it rains: the **Dordrechts Museum** (Museumstraat 40, Tue–Sun 11:00–17:00, €17, students €6) shows Dutch painting from the Golden Age to today.

Good to know: on Tuesdays in November the Grote Kerk, Huis Van Gijn and Hof van Nederland are closed.

Antwerp

Wednesday, 11 November · shore time approx. 13:30–16:00

back on board by 16:00 (Poster Session II)

We dock at the cruise pontoon on the Scheldt, right next to **Het Steen** (map), Antwerp's medieval riverside castle – today a visitor centre with a free rooftop terrace. **11 November is a public holiday in Belgium** (Armistice Day), so some shops may keep shorter hours.

> **Suggested walk** – 3.1 km, about 40 min on foot plus stops (allow 30–40 min for the Cathedral) · route in Google Maps
> **Het Steen** → **Grote Markt** with its Renaissance town hall and Brabo fountain (5 min) → **Cathedral of Our Lady** with four masterpieces by Rubens (open daily, €12) → via Groenplaats into the **Korte Gasthuisstraat** → **The Chocolate Line** in the Palace on the Meir → back via Hoogstraat to the ship.

Chocolate & souvenirs: The Chocolate Line by star chocolatier Dominique Persoone, Meir 50 (open seven days a week, about 15 min walk). In the **Korte Gasthuisstraat** (10 min) you find several chocolatiers and **Philip's Biscuits** with the local *Antwerpse handjes*, hand-shaped biscuits recalling the city's founding legend.

Prefer a view? The rooftop of the **MAS** museum (15 min walk) is free and open until 22:00; the museum halls are open until 17:00 (last entry 16:00).

Good to know: on Wednesdays the **DIVA** diamond museum and the **Rubens House** are closed, and the **Plantin-Moretus Museum** is closed for renovation until December. **Chocolate Nation** is open but next to the central station, about 30 min on foot each way.

Nijmegen

Thursday, 12 November · shore time approx. 13:30–15:30

back on board by 15:30 – the ship leaves at 16:00

Nijmegen, founded by the Romans more than 2,000 years ago, claims to be the oldest city in the Netherlands. We moor on the River Waal, close to the old town; the riverside promenade there is called the **Waalkade**.

Suggested walk – 2.4 km, about 35 min on foot (some steps uphill) plus stops · route in Google Maps
Up the steps to the **Valkhof Park** – site of a Roman fortress and later an imperial palace of Charlemagne and Barbarossa, with views across the Waal → **Valkhof Museum** or its café → **Grote Markt** with the 17th-century weigh house and the Stevenskerk → **Lange Hezelstraat**, said to be the oldest shopping street in the Netherlands → back down to the river.

Museum: the newly reopened **Valkhof Museum** (Kelfkensbos 59, Tue–Fri 11:00–17:00) tells stories of borders across 40,000 years; its café is open without a ticket.

Local treat: *Marikenbrood*, a sweet local bread, in the Lange Hezelstraat.

If it rains: the **Velorama** National Bicycle Museum is right on the Waalkade by the river.

Good to know: the Stevenskerk is closed inside during our visit.

SQL 26

„Sensing with Quantum Light“ SQL26 is organised by
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A letter from AQLS.

CO-ORGANISER & SPONSOR OF SQL26

Dear colleagues,

It is our great pleasure to co-organise *Sensing with Quantum Light* for the second time and to support this meeting as a sponsor.

SQL brings together outstanding science, close exchange and an exceptional setting aboard the MS Swiss Crown. With time to discuss unfinished ideas, share experimental challenges and get to know one another, it builds collaborations that go beyond the usual conference encounters.

At AQLS, we bring quantum optics from the laboratory into practical applications. Quantum sensing is one of the fields we build for. Together with international research groups, we develop photonic quantum hardware that serves both research and emerging applications.

We look forward to hearing about your research, learning what your experiments need and exploring joint projects. Whether you have a concrete challenge in mind or an idea to exchange, please come and talk to us.

We wish you an inspiring week of science, conversation and good company on the river.

Warm regards,
Janik Wolters, Leon Meßner and Daniel Vajner
on behalf of the AQLS team

AQLS

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