Sensing with Quantum Light

790. WE-Heraeus-Seminar

05 - 07 June 2023

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 790. WE-Heraeus-Seminar:

In the last two decades, the ability to prepare and manipulate quantum states at the individual level has led to a wide range of scientific activities. It is expected that the laws of quantum mechanics with phenomena such as quantum entanglement and quantum superposition will revolutionize a wide range of fields, now frequently coined the so-called "second generation" quantum technologies.

The area of quantum sensing is considered to be one which most likely is going to deliver real-world applications and products soon. Sensing with light in the form of imaging, microscopy, spectroscopy or other interferometric methods has always played an enormous role. As an example, quantum imaging aims at utilizing the properties of quantum optical states to overcome the limits of classical imaging.

This seminar will cover theoretical and experimental aspects of sensing with quantum light. Topics will include modalities like sensing with undetected photons via nonlinear interferometers, sensing with squeezed light, induced, spectroscopy with entangled light, the generation of highly non-degenerate photon, high-dimensionally entangled light and their application potential for sensing tasks.

By bringing together established scientists from leading research groups in the field, junior scientists and graduate students, participants from fundamental and applied physics and industry the seminar aims at providing a vibrant forum for the exchange of ideas and discussion.

Scientific Organizers:

PD Dr. Frank Kühnemann	Fraunhofer-Institut für Physikalische Messtechnik IPM, Freiburg, Germany E-mail: Frank.Kuehnemann@ipm.fraunhofer.de
Dr. Sven Ramelow	Humboldt-Universität zu Berlin Institut für Physik, Germany E-mail: sven.ramelow@physik.hu-berlin.de

Introduction

Administrative Organization:

Dr. Stefan Jorda
Marion Reisinger

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-18
Fax +49 6181 92325-15
E-mail reisinger@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

Marion Reisinger (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (16:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 04 June 2023

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

Monday, 05 June 2023

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome and Infos**
09:05 – 09:40	Jeff Ou	**Interference by direct amplitude addition**
09:40– 10 :15	John Rarity	**Quantum remote sensing**
10:15 – 10:50	Roman Schnabel	**Quantum dense sensing of trajectories**
10:50 – 11:20	*COFFEE BREAK*	
11:20 – 11:55	Ulrik Andersen	**Quantum sensing with squeezed light**
11:55 – 12:30	Nicolas Treps	**Separation estimation of incoherent optical sources reaching the Cramér-Rao bound**
12:30 – 12:40	*CONFERENCE PHOTO*	
12:40 – 14:00	*LUNCH*	

Program

Monday, 05 June 2023

14:00 – 14:35	Rob Thew	**Entangled two photon absorption**
14:35 – 15:10	Dan Oron	**Studying multicarrier interactions in semiconductor nanocrystals using heralded spectroscopy**
15:10 - 15:30	Zhedong Zhang	**Monitoring electronic coherence of molecules by quantum-light spectroscopy**
15:30 – 15:40	***Announcement SQL24: 27.-31.10.2024***	
15:40 – 16:15	*COFFEE BREAK*	
16:15 – 17:15	***Poster Flash 1***	
17:15 – 18:45	***Poster Session 1***	
18:45	*DINNER*	
19:30 – 22.00	*Discussions*	

Program

Tuesday, 06 June 2023

08:00	*BREAKFAST*	
09 :00 – 09 :35	Frank Schlawin	**Quantum-enhanced spectroscopy in nonlinear interferometers**
09:35 – 10:10	Kazuki Hashimoto	**Quantum light sources and nonlinear interferometers for molecular spectroscopy**
10:10 – 10:45	Anna Paterova	**Broadband quantum spectroscopy at the mid-infrared region**
10:45 – 11:20	*COFFEE BREAK*	
11 :20 – 11 :55	Edoardo Charbon	**Large-format single-photon image sensors for quantum imaging**
11:55 – 12:30	Federica Villa	**24×24-pixels SPAD camera for quantum imaging at low optical power**
12:30 – 14:00	*LUNCH*	
14:00 – 14:35	Milena D’Angelo	**Fast and high resolution 3D imaging through correlated photons**
14:35 – 15:10	Marta Gilaberte Basset	**Image resolution of quantum imaging with undetected photons via position correlations**
15:10 – 15:45	Daniele Faccio	**Hong Ou Mandel microscopy and fluorescence lifetime quantum imaging**
15:45 – 16:15	*COFFEE BREAK*	
16:15 – 17:15	**Poster Flash 2**	
17:15 – 18:45	**Poster Session 2**	
18:45	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 07 June 2023

08:00	*BREAKFAST*	
09:00	**Awarding Poster Prizes**	
09:10 – 09:45	William Plick	**Versatile super-sensitive metrology using induced coherence**
09:45 – 10:20	Amr Helmy	**Enhancement in LiDAR SNR using non-classical light**
10:20 – 10:55	Robert Fickler	**Spatial Mode N00N States and the Quantum Gouy Phase**
10:55 – 11:25	*COFFEE BREAK*	
11:25 – 12:00	Zheshen Zhang	**Entanglement-enhanced sensing and data processing**
12:00- 12:35	Paul David Lett	**Creation of large-scale entangled states for exploring sensing networks**
12:35- 12:40	**Closing remarks**	
12:40 – 14:00	*LUNCH*	

End of the seminar and departure

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

Posters

Posters

Omid Abed	**Toward experimental realization of sub-diffraction quantum imaging with undetected photons**
Denis Abramović	**Non-classical holography with heralded single- photon source**
Konstantin Albert	**CMOS SPADs for quantum applications and time-of-flight imaging**
Foroud Bemani	**Generating squeezing with coherent feedback in cavity optomechanics**
Emma Brambila	**Theoretical study of spatial coherence for quantum enhanced imaging**
Patrick Cameron	**Quantum-assisted adaptive optics for label-free microscopy**
Arthur Cardoso	**Sensing without detection on silicon photonic chips: Highly sensitive methane detection and beyond**
Johanna Conrad	**Spectral purity characterization of telecom wavelength photons generated in aperiodically poled KTP**
Baptiste Courme	**Manipulation and certification of high-dimensional spatial entanglement in scattering media**
Jinghan Dong	**Enhancing methane sensors by sensing without detection**
Dupish Dupish	**Quantum ghost imaging using 2-D SPAD array**
Stefan Frick	**Quantum and nonlinear integrated photonics with algaas**
Jorge Fuenzalida	**Quantum state tomography of undetected photons**
Tobias Gäbler	**Fluorescence excitation of quantum dotsby entangled two-photon absorption**

Posters

Paul Gattinger	**Infrared spectroscopy and hyperspectral imaging driven by supercontinuum light and spatial light modulation**
Bohnishikha Ghosh	**Towards demonstrating quantum optical backflow**
Valerio Flavio Gili	**Near-infrared hyper-spectral scanning quantum imaging of HEK 293T Cells**
Patrick Hendra	**Photon-pair recombination via sum-frequency generation by chirped, aperiodically poled linb waveguide**
Thomas Arne Hensel	**Precision estimation of adaptive localization strategies**
Marcin Jastrzębski	**Fractional fourier transform of Hermite - Gaussian modes in quantum memory**
Mikhail Korobko	**Mitigating quantum decoherence in cavity-enhanced force sensors by internal squeezing**
Valeriia Kosheleva	**Two photon ionization of atoms by broadband squeezed states of light**
Aleksa Krstić	**High-gain quantum spectroscopy with undetected photons**
Sanjukta Kundu	**Adaptively gated single-photon camera for high-dimensional quantum correlation measurements**
Jachin Kunz	**Mid-infrared spectroscopy with nonlinear interferometers using pump-enhanced SPDC**
Stanisław Kurzyna	**Experimental implementation of Fractional Fourier transform for spectro-temporal cat state**
Mirco Kutas	**Towards Terahertz imaging with visible photons**

Posters

Changhyoup Lee	**Optimal quantum metrology of two-photon absorption parameter**
Josué Ricardo León Torres	**Mid-IR quantum scanning microscopy with visible light**
Hui Min Leung	**Exploring quantum mimicry via classically entangled light for enhanced bioimaging**
Chen-Ting Liao	**Towards quantum light beyond visible and infrared spectra**
Gur Lubin	**Heralded Spectroscopy - a new probe for quantum light emitters**
Felix Mann	**A frequency-domain two-photon interferometer**
Yu Mukai	**Quantum infrared spectroscopy in the fingerprint region**
Weijie Nie	**Quantum-inspired frequency-agile optical source for covert rangefinding**
Mayerlin Nunez Portela	**Classical and entangled two-photon absorption in atoms and molecules**
Shahram Panahiyan	**Quantum-enhanced stimulated Raman scattering with squeezed states of light**
Carsten Pitsch	**3D quantum ghost imaging**
Marlon Placke	**Mid-IR hyperspectral imaging with undetected photons**
René Pollmann	**Integrated bright broadband PDC source for quantum metrology**
Éva Rácz	**Efficient OPA tomography**

Posters

Christian Rodriguez-Camargo	**The role of vibrational molecular structure in entangled two photon absorption: Perturbation theory limits**
Franz Roeder	**Bi-photon correlation time measurements with a two-colour broadband SU(1,1) interferometer**
Axel Schönbeck	**The "squeeze laser" and its applications**
Atta ur Rehman Sherwani	**Enhanced microplastic and biosample analysis using mid-ir spectroscopy with undetected photons in the 2900 cm-1 window**
René Sondenheimer	**On the validity of the Gaussian approximation of SPDC bi-photon states for quantum imaging based on position correlations**
Rajshree Swarnkar	**Mid-infrared frequency-domain optical coherence tomography with undetected photons**
Sebastian Toepfer	**Image distillation in quantum holography with undetected light**
Chloé Vernière	**Encoding images in quantum correlations of photons**
Zhengjun Wang	**Quantum-inspired multidimensional spectroscopy**
Till Weickhardt	**Entangled two-photon absorption in 2D semiconductors**
Xiao-Ye Xu	**Precise sensing via quantum weak measurement**
Marthe Zeja	**A student-lab setup for sensing with undetected photons**
Jingrui Zhang	**Nonlinear interferometers for imaging without detection**

Abstracts of Talks

(in alphabetical order)

Quantum Sensing with Squeezed Light

Jens A. H. Nielsen, Rayssa B. de Andrade, Jonas S. Neergaard-Nielsen, Tobias Gehring and Ulrik L. Andersen

Center for Macroscopic Quantum States (bigQ), Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kongens Lyngby, Denmark

Quantum sensing with squeezed light has emerged as a powerful technique for achieving high-precision measurements beyond the limits of classical methods. In this talk, we present our recent works on utilizing squeezed light for quantum microscopy and improving the sensitivity even beyond the NOON state limit.

First, we demonstrate the application of squeezed light to achieve sub-shot-noise limited imaging in a quantum microscope. Our experiment utilizes a squeezed vacuum state generated via parametric downconversion to improve the signal-to-noise ratio of the measurement. By combining the squeezed light with an optimized measurement scheme, we achieve a precision that exceeds the shot-noise limit.

In addition, we present our fundamental studies on improving the sensitivity beyond the NOON state limit. The NOON state, a highly entangled state of two photons, has been used to achieve the ultimate limit of precision in quantum metrology. However, the NOON state is highly sensitive to phase noise, limiting its practical use. Here, we explore alternative entangled states and measurement strategies to overcome this limitation and achieve even higher sensitivities [1].

Our results demonstrate the potential of squeezed light for advancing the field of quantum sensing and metrology.

References

[1] Jens A. H. Nielsen et al, Phys. Rev. Lett. 130, 123603 (2023)

Single-photon Cameras for Quantum Imaging Applications

Abstract— In this talk, we will review the evolution of solid-state photon counting sensors from avalanche photodiodes (APDs) to silicon photomultipliers (SiPMs) to single-photon avalanche diodes (SPADs). The impact of these sensors on time-resolved imaging, such as fluorescence lifetime imaging microscopy (FLIM), positron-emission tomography (PET) and light detection and ranging (LiDAR) has been remarkable. However, more innovations are to come with the continuous advance of integrated SPADs and the introduction of powerful quantum imaging techniques, such as ghost imaging, quantum distillation, and quantum LiDAR, to name a few. New technologies, such as 3D-stacking, which was originally introduced for consumer cameras, and ultra-fast SPADs, which reach 7.5ps FWHM timing resolution, are accelerating the adoption of SPAD cameras, so as to be embedded in the sensors, while enabling new sensing functionalities, such as phasors and $g^{(2)}$ processing, at pixel level. These new techniques, in combination with hyperspectral and multispectral optics, could open up new and interesting avenues in quantum imaging for scientific and consumer applications alike. We will conclude the talk with a perspective on how all these technologies could come together in low-cost, computational-intensive single-photon image sensors, for affordable, yet powerful novel applications.

Biography
Edoardo Charbon

Edoardo **Charbon** (SM’00 F’17) received the Diploma from ETH Zurich, the M.S. from the University of California at San Diego, and the Ph.D. from the University of California at Berkeley in 1988, 1991, and 1995, respectively, all in electrical engineering and EECS. He has consulted with numerous organizations, including Bosch, X-Fab, Texas Instruments, Maxim, Sony, Agilent, and the Carlyle Group. He was with Cadence Design Systems from 1995 to 2000, where he was the Architect of the company's initiative on information hiding for intellectual property protection. In 2000, he joined Canesta Inc., as the Chief Architect, where he led the development of wireless 3-D CMOS image sensors. Since 2002 he has been a member of the faculty of EPFL, where is a full professor. From 2008 to 2016 he was with Delft University of Technology’s as Chair of VLSI design. Dr. Charbon has been the driving force behind the creation of deep-submicron CMOS SPAD technology, which is mass-produced since 2015 and is present in telemeters, proximity sensors, and medical diagnostics tools. His interests span from 3-D vision, LiDAR, FLIM, FCS, NIROT to super-resolution microscopy, time-resolved Raman spectroscopy, and cryo-CMOS circuits and systems for quantum computing. He has authored or co-authored over 400 papers and two books, and he holds 24 patents. Dr. Charbon is a distinguished visiting scholar of the W. M. Keck Institute for Space at Caltech, a fellow of the Kavli Institute of Nanoscience Delft, a distinguished lecturer of the IEEE Photonics Society, and a fellow of the IEEE.

Fast and high resolution 3D imaging through correlated photons

C.Abbattista[1], L. Amoruso[1], S. Burri[2], E. Charbon[2], S. De Gioia[3,4], D. Diacono[3,4], F. Di Lena[3], D. Giannella[3,4], Z. Hradil[5], M. Iacobellis[1], G. Massaro[3,4], A. Monaco[3,4], P. Mos[2], L. Motka[5], M. Paúr[5], F. V. Pepe[3,4], M. Peterek[5], I. Petrelli[1], J. Rehácek[5], F. Santoro[1], F. Scattarella[3,4], A. Torrisi[3,4], A. Ulku[2], S. Vasiukov[3], M. Wayne[2], C. Bruschini[2], B. Stoklasa[5], and M. D'Angelo[3,4]

[1] Planetek Hellas E.P.E., Marousi, Greece
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland
[3] INFN, Sezione di Bari, Bari, Italy
[4] Dipartimento Interateneo di Fisica, Università degli Studi di Bari, Bari, Italy
[5] Department of Optics, Palacký University, Olomouc, Czech Republic

We present a new generation of 3D imaging devices based on the working principle of Correlation Plenoptic Imaging (CPI) [1]. Both spatio-temporal and photon-number correlations are exploited to provide scanning-free 3D imaging at diffraction-limited volumetric resolution, with an unprecedented combination of resolution and depth of focus. In particular, we will present the results obtained while addressing the challenge of the typically long acquisition times of quantum imaging devices (from minutes to tens of hours): the exploitation of the classical correlations of chaotic light, combined with novel ultra-fast cameras (512 x 512 SPAD-arrays working at 100,000 fps), has enable acquisition of 10 volumetric images per second.

Dedicated statistical algorithms, ranging from quantum tomography to compressive sensing and deep learning, have also been developed to further increase the acquisition speed by 2 orders of magnitude, thus enabling video rate acquisition of volumetric images based on photon correlations. Further research is being performed in terms of low-level programming of ultra-fast electronics [2], with the aim of speeding up the elaboration time toward real time 3D imaging.

The potential of CPI in terms of super-resolution will also be discussed based on recent developments based on quantum Fisher information [3].

The potential applications of the presented technology in different fields of research, from 3D microscopy to space imaging, shall also be discussed.

References

[1] Pepe, F.V., et al. Phys. Rev. Lett. **119**, 243602 (2017).
[2] Ulku, A.C.et al., IEEE J. Sel. Top. Quantum Electron. **25**, 6801212 (2019)
[3] Rehácek, J., et al, Phys. Rev. Lett. **123**, 193601 (2019)

Hong Ou Mandel Microscopy and Fluorescence Lifetime Quantum Imaging

Ashley Lyons, Vytautas Zickus, Raul Mendoza, Daniele Faccio
[1]*School of Physics & Astronomy, University of Glasgow, UK*

Hong-Ou-Mandel or two-photon interference is a widely used effect in quantum optics with applications including sensing path length changes all the way down to the nanometre scale, filtering of quantum states and teleportation and also forms the basis of quantum computing based on Boson sampling.

We will report on recent work in which we have extended the use of HOM sensing to the imaging domain for microscopy applications [1] and will briefly overview some of the main constraints such as the biphoton mode-matching conditions between the quantum light and the camera pixels that need to be considered. We will then present a development (ongoing work) in which we use HOM interference applied to the case of fluorescence lifetime imaging, a widespread microscopy technique. This FLHOM technique provides access to very short fluorescence lifetimes, i.e. lifetime resolution in the picosecond range that is therefore 100x better that what can be achieved with standard TCSPC approaches. We demonstrate the advantage of this for the case of viscosity measurements in which we measure the fluorescence lifetime of “rotor” molecules, thus providing a new approach to nanorheology with applications for intracellular in-vivo measurements that are not currently otherwise possible.

References

[1] *Quantum microscopy based on Hong-Ou-Mandel interference*, B.Ndagano, H. Defienne, D. Branford, Y.D. Shah, E.M. Gauger, D. Faccio, Nat. Photonics **16**, 384 (2022)

Spatial Mode N00N States and the Quantum Gouy Phase

M. Hiekkamäki[1], R. F. Barros[1], M. Ornigotti[1], R. Fickler[1]
[1]Tampere University, Photonics Laboratory, Tampere, Finland

Photonic N00N states, i.e., states of light where N photons are in an extremal superposition between two orthogonal states $1/\sqrt{2}\,(|N,0\rangle + |0,N\rangle)$ have an increased phase-sensitivity in comparison to classical light fields. When N00N states are implemented using transverse spatial modes of photons, novel super-sensitive measurement schemes become possible [1].

In the presented work, I will focus on the investigation of the so-called Gouy phase in combination with spatial mode N00N states. The Gouy phase is a fundamental wave phenomenon that describes the anomalous phase delay of transversely confined waves when propagating through a focus. We find that similar to the phase accumulated by photon number states upon free space propagation, the Gouy phase experiences a phase speed-up scaling with the number of photons. To show this effect experimentally, we implement a spatial mode N00N state using two radial modes of different mode orders and investigate their propagation through a focus (see Fig.1) [2].

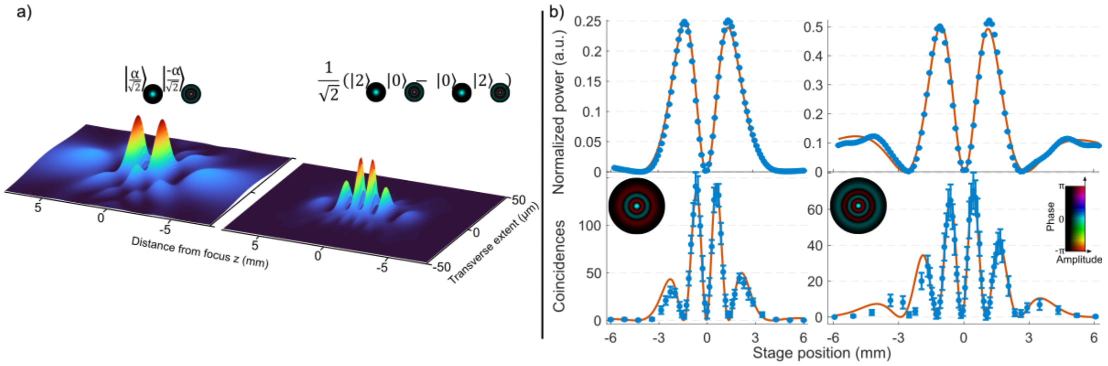


Fig.1: a) Calculated intensity distribution of a classical radial mode superposition and the two-photon probability distribution for a N00N state. b) Experimental data of the interference between two radial modes due to the classical Gouy phase (top row) and the quantum Gouy phase for two-photon N00N states (bottom row) between the same pairs of modes.

Our results further support the proposition of Feng and Winful's on the origin of the Gouy phase [3] by linking the speeding up of the quantum Gouy phase to an increasing spread in the transverse momentum of the state. In addition, we were able to demonstrate that our results open up the possibility for supersensitive measurements of longitudinal displacement and also highlight that the so-called photonic de Broglie wavelength is not sufficient for describing the behavior of photon number states.

References

[1] M. Hiekkamäki, F. Bouchard, R. Fickler, Phys. Rev. Lett. **127**, 263601 (2021)
[2] M. Hiekkamäki, R. F. Barros, M. Ornigotti, R. Fickler, Nat. Phot. **16**, 828 (2022)
[3] S. Feng, H. G. Winful, Opt. Lett. **26**, 485 (2001)

Image resolution of quantum imaging with undetected photons via position correlations

M. Gilaberte Basset[1,2] , **R. Sonderheimer**[1,3], **J. Fuenzalida**[4], **A. Vega**[2],
S. Töpfer[4], **E. Santos**[2], **F. Setzpfandt**[2], **F. Steinlechner**[1,2], **M. Gräfe**[1,2,4]

[1]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745, Jena, Germany
[2]Friedrich-Schiller-University Jena, Institue of Applied Physics, Abbe Center of Photonics, Albert-Einstein-Str. 6, 07745, Jena, Germany
[3]Friedrich-Schiller-University Jena, Institute of Condensed Matter Theory and Optics, Max-Wien-Platz 1, 07743 Jena, Germany
[4]Institute of Applied Physics, Technical University of Darmstadt, Schloßgartenstraße 7, 64289 Darmstadt, Germany

Resolution is one of the main parameters defining the quality of any image. In quantum imaging, resolution is governed by the spatial correlations that exist between the two photons of the pairs created by the spontaneous parametric down-conversion (SPDC) process in a nonlinear crystal. In this talk, I will focus on quantum imaging with undetected light (QIUL), which has the unique advantage of creating the image of an object with light that did not illuminate it. Several works have exploited the momentum anti-correlations that dominate when imaging at the far-field of the nonlinear crystal with QIUL [1-2]. However, only one used the near-field configuration to demonstrate the viability of using the position correlations instead [3].

The effect on the resolution of other source parameters such as the pump waist, crystal length, and wavelengths involved in the process has been analyzed for both cases; momentum [4] and position [5,6] correlations. Nevertheless, the experimental demonstration in the near-field is missing. In this talk, I will present that we were able to experimentally demonstrate the dependency of the image resolution on various parameters.

References

[1] G. Lemos, V. Borish, G. Cole, S. Ramelow, R. Lapkiewicz, “Quantum imaging with undetected photons,” Phys. Nature **512**(7515), 409-412(2014).

[2] S. Töpfer, M. Gilaberte Basset, J. Fuenzalida, F. Steinlechner, J. P. Torres, M. Gräfe, “Quantum holography with undetected light,” Sci. Adv. **8**, 2 (2022).

[3] I. Kviatkovsky, H. M. Chrzanowski, S. Ramelow, “Mid-infrared microscopy via position correlations of undetected photons,” Optics Express **30**(4), 5916-5925(2022).

[4] J. Fuenzalida, A. Hochrainer, G. B. Lemos, E. Ortega, R. Lapkiewicz, M. Lahiri, A. Zeilinger, “Resolution of quantum imaging with undetected photons,” Quantum **6**, (2022).

[5] B. Viswanathan, G. B. Lemos, M. Lahiri, “Resolution limit in quantum imaging with undetected photons using position correlations,” Optics Express **29**(23), (2021).

[6] A. Vega et al, “Fundamental resolution limit of quantum imaging with undetected photons,” Phys. Rev. Research **4**, (2022).

Quantum light sources and nonlinear interferometers for molecular spectroscopy

Kazuki Hashimoto[1], **Dmitri Horoshko**[2] **and Maria Chekhova**[1,3]

[1]Max Planck Institute for the Science of Light, 91058 Erlangen, German
[2] Univ. Lille, CNRS, UMR 8523 - PhLAM - F-59000 Lille, France
[3]Friedrich-Alexander Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Infrared and Raman spectroscopy are used in various fields as tools for analyzing samples in a label-free manner via molecular vibrations. Improving the measurement sensitivity of vibrational spectra is essential for increasing the spectral acquisition rate and efficiently detecting weak molecular vibrations.

Quantum light sources and nonlinear interferometers[1] increase the measurement sensitivity of vibrational spectroscopy. For instance, nonlinear interferometers based on nondegenerate optical parametric amplifiers enable sensitive infrared spectroscopy with undetected photons[2]. Also, amplitude-squeezed light sources enable coherent Raman spectroscopy with a sub-shot-noise signal-to-noise ratio (SNR)[3]. Those measurements are often demonstrated in a continuous-wave pumping regime.

In this study, we develop quantum light sources based on parametric amplification strongly pumped by picosecond pulses to demonstrate quantum-enhanced vibrational spectroscopy. Fig. 1a shows an SU(1,1) interferometer with broadband bright twin beams generated from an aperiodically-poled lithium niobate crystal. Using the interferometer, we demonstrate broadband upconversion spectroscopy with ~ 20-THz spectral bandwidth. We also develop a source of amplitude-squeezed pulses towards sub-shot-noise stimulated Raman scattering (SRS) microscopy (Fig. 1b).

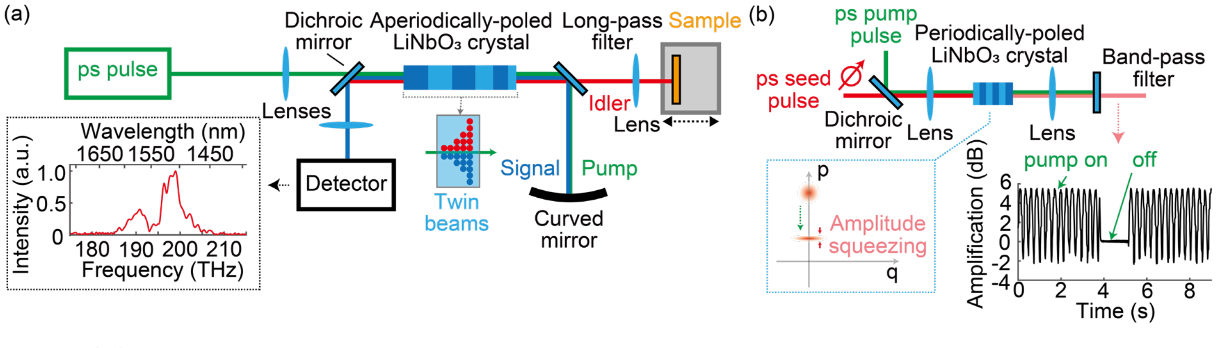


Fig.1 (a) Broadband spectroscopy with undetected photons with strong parametric amplification. (b) Source of amplitude-squeezed pulses for quantum-enhanced SRS microscopy.

References

[1] M. V. Chekhova and Z. Y. Ou, Adv. Opt. Photonics **8**, 104-155 (2016).
[2] C. Lindner *et al.*, Opt. Express **28**, 4426-4432 (2020).
[3] R. B. de Andrade *et al.*, Optica **7**, 470-475 (2020).

Enhancement in LiDAR SNR using non-Classical Light

Amr S. Helmy

Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, Ontario, Canada M5S 3G4

a.helmy@utoronto.ca

Sensing modalities and instrumentation for target detection and raging applications have received tremendous attention over the past decade. This has been driven in no small part by the unsatiable demand for cheaper, more compact and significantly improved Light Detection and Ranging (LiDAR), which is essential for autonomous navigation.

The detection of objects in the presence of significant background noise is a problem of fundamental interest in sensing. In this talk I aim to demonstrate theoretically and experimentally how one can exploit non-classical light generated in monolithic semiconductor light sources in conjunction with non-local effects to enhance the performance of optical target detection and model LiDAR system.

Our protocols utilize quantum time-correlation which are obtained from a spontaneous parametric down-conversion sources. The protocols only requires time-resolved photon-counting detection, which is phase-insensitive and therefore suitable for practical target detection. As a representative comparison to such a detection protocol, we also consider a classical phase-insensitive target detection protocol based on intensity detection. Unlike classical target detection and ranging protocols, the probe photons in our detection protocol are completely indistinguishable from the background noise and therefore useful for covert ranging applications.

Non-local effects also have the potential to radically move forward quantum enhanced LiDAR to provide an advantage over classical LiDAR not only in laboratory environments but practical implementation. In this talk, we demonstrate over 40dB higher signal-to-noise ratio using time-frequency entanglement compared with a classical phase-insensitive LiDAR system. Our system can tolerate more than 3 orders of magnitude higher noise than classical single- photon counting LiDAR systems before detector saturation. To achieve these advantages, we use non-local cancellation of dispersion to take advantage of the strong temporal correlations in photon pairs in spite of the orders of magnitude larger detector temporal uncertainty. By conducting the measurement in a rotated basis between time and frequency—the Fractional Fourier domain—we can magnify the probe- reference temporal uncertainty while maintaining the same degree of correlation. We also incorporate this scheme with purpose-built scanning collection optics to image non-reflecting targets in an environment with noise. Finally, our technological platform is highly scalable and tunable and thus amenable to large scale integration necessary for practical applications.

The experimental results agree very well with the theoretical prediction. In particular, we find that in a high-level environment noise and loss, our detection protocol can achieve performance comparable to that of the classical protocol that is practical in the optical regime.

References

[1] P. Abolghasem, M. Hendrych, X. Shi, J. P. Torres, and A. S. Helmy, Bandwidth control of paired photons generated in monolithic bragg reflection waveguides, Optics letters 34, 2000 (2009).

[2] D. Kang, A. Anirban, and A. S. Helmy, Monolithic semi- conductor chips as a source for broadband wavelength-multiplexed polarization entangled photons, Optics express 24, 15160 (2016).

[3] H. Liu, D. Giovannini, H. He, D. England, B. J. Sussman, B. Balaji, and A. S. Helmy, Enhancing lidar performance metrics using continuous-wave photon-pair sources, Optica 6, 1349 (2019).

[4] H. Liu, B. Balaji, and A. S. Helmy, Target detection aided by quantum temporal correlations: Theoretical analysis and experimental validation, IEEE Transactions on Aerospace and Electronic Systems 56, 3529 (2020).

[5] H. He, D. Giovannini, H. Liu, E. Chen, Z. Yan, and A. S. Helmy, Non-classical semiconductor photon sources enhancing the performance of classical target detection systems, Journal of Lightwave Technology 38, 4540 (2020).

[6] H. Liu, and A.S. Helmy, Joint measurement of time–frequency entanglement via sum frequency generation, NPJ Quantum Information, No 6: 66, (2020).

[7] P. Blakey, H. Liu, and A.S. Helmy, et al. , Quantum and Non- local Effects Offer over 40dB Noise Resilience Advantage Towards Quantum Lidar, Nature communications, 13(1):1–8, 2022..

Creation of large-scale entangled states for exploring sensing networks

Zhifan Zhou[1], Luis de Araujo[2], Matt DiMario[1], Jing Su[1], Jie Zhao[1], Kevin Jones[3], B. Anderson[4], Paul Lett[1,5]

1 Joint Quantum Institute, National Institute of Standards and Technology

and the University of Maryland, College Park, Maryland 20742, USA

2 Institute of Physics "Gleb Wataghin," University of Campinas (UNICAMP), 13083-859 Campinas, Sao Paulo, Brazil

3 Department of Physics, Williams College, Williamstown, Massachusetts 01267, USA

4 Department of Physics, American University, Washington, DC 20016 USA

5 Quantum Measurement Division, National Institute of Standards and Technology, Gaithersburg, MD 20899 USA

Large-scale entangled states can be used to investigate measurement-based computing and entangled quantum sensing applications. Using our established 4WM techniques in Rb vapor for generating 2-mode squeezing [1], we can further entangle these states to generate multi-dimensional graph states. Instead of using the multiple spatial modes that this system offers, we use the frequency spectrum. Following the suggestion of Zhu et al. [2], we then mix frequency modes of the generated 2-mode squeezed states using electro-optical modulators to construct multi-dimensional graph states that are transformable, with Gaussian local unitary operations, into cluster states. While this structure is not necessarily important for networked sensors, it is important for quantum computing. While the frequency spectrum accessible in 4WM in Rb vapor is relatively small, this limitation also allows us to straightforwardly digitize the entire spectrum and to process the digitized signals off-line in software, as suggested in [3].

We also investigate the nonlocal phase modulation of continuous-variable entangled twin beams. We modulate the phase of entangled beams of light, with a pair of electrooptical phase modulators driven at the same frequency. While a single phase modulator in either one of the twin beams reduces the two-mode squeezing signal, we find that the pair of modulators interfere nonlocally, depending on the relative phase of the modulation, to modify the two-mode beam correlations. The modulators act cumulatively to determine the effective modulation depth.

References

[1] 1. C. McCormick, et al. Opt. Lett. 32,178 (2007)

[2] 2. X. Zhu, et al. Optica 8, 281 (2021)

[3] 3. G. Ferrini, et al. Phys. Rev. A 94, 062332 (2016)

Studying multicarrier interactions in semiconductor nanocrystals using heralded spectroscopy

D. Amgar, G. Lubin, N. Frenkel, M. Kazes, D. Oron

Weizmann Institute, Rehovot, Israel

The advent of SPAD-array based parallelized detection of time-stamped single photons opens a pathway for extracting previously inaccessible spectroscopic information from dim sources of quantum light. In particular, it enables to multiplex detection both in time and in additional dimensions such as space, frequency or spatial frequency. We use this to study the interactions between pairs of excitons in doubly excited colloidal semiconductor nanocrystals, revealing weak multielectron effects at room temperature against a strong temperature broadened background.

We present heralded spectroscopy [1], the unique identification and post-selection of pair emission events from single nanocrystals while performing a spectral measurement (using a line SPAD array [1]) or a defocused imaging measurement (using a 2D SPAD array [2]). Using this method we can characterize subtle differences between the first emitted photon (representing emission from the doubly excited state) and the second emitted photon (representing the singly excited state). Several examples for this will be given, including interaction effects on emission anisotropy from semiconductor nanorods [2] (see Fig. 1) and identification of multiexcitonic states in quantum dot molecules [3]. The utility of our method for study of higher excited states via three-photon correlation will also be discussed.

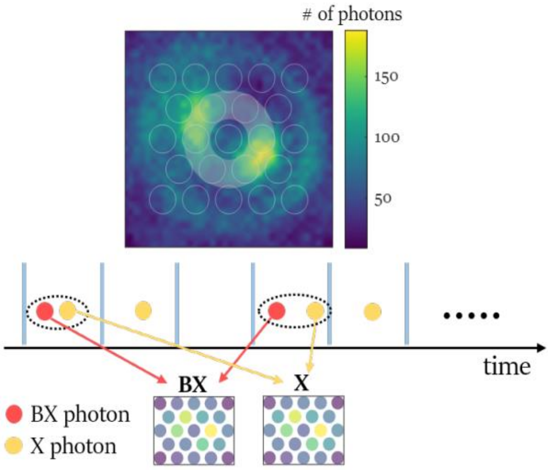


Fig. 1: Heralded defocused imaging of multiexciton emission can reveal subtle differences in the transition dipole moment anisotropy between the doubly excited state and the singly excited state of a single emitting colloidal semiconductor nanocrystal.

References

[1] G. Lubin et al., Nano Lett. 21, 6756 (2021)

[2] D. Amgar et al., arXiv: 2301.07211 (2023)

[3] N. Frenkel et al., in preparation.

Interference by Direct Amplitude Addition

Z. Y. Jeff Ou

City University of Hong Kong, Kowloon, Hong Kong
jeffou@cityu.edu.hk

Interference effects are usually observed by intensity measurement. Path indistinguishability by quantum complementarity principle requires projection of the interfering fields into a common mode before detection. On the other hand, the essence of quantum interference is the addition of amplitudes of the interfering fields. Therefore, if amplitudes can be directly measured and added, interference can occur even though the interfering fields are in well-distinguishable modes. Here, we make a comprehensive study in both theory and experiment of a technique by homodyne measurement of field amplitudes to reveal interference. This works for both classical and quantum fields even though there exists distinguishability in the interfering paths of the fields. This technique is particularly useful for recovering interference in unbalanced interferometers with path-imbalance beyond coherence length of the input field and can be applied to remote sensing to extend applicable range. This approach leads to a new paradigm to study coherence between optical fields, even for nonlocally separated case.

Broadband quantum spectroscopy at the mid-infrared region

Anna V. Paterova[1,*], **Zi S.D. Toa**[1], **Hongzhi Yang**[1], **Leonid A. Krivitsky**[1]

*[1] Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis #08-03, Singapore 138634, Republic of Singapore*

The infrared (IR) range of the optical spectrum is very attractive in terms of fingerprint properties of materials. Unique properties of the media can be obtained by performing IR spectral measurements. This finds application in material characterization and sensing. Even though IR range is very promising, existing IR metrology methods remain costly and having inferior performance, compared to visible range techniques.

It is possible to address to these challenges by exploiting features of quantum and nonlinear optics. Here we propose a method of IR metrology, which allows to perform broadband IR spectroscopy using only visible optics and detectors. We use the interference of spontaneous parametric down conversion (SPDC) photon pairs produced in two nonlinear crystals [1-3]. Correlation between photons of the pairs allows studying IR properties of media by detecting visible light. This method was realized in earlier works [3,4]. However, in these works the optical path of the IR light through the medium under study is limited, which decreases the sensitivity of those schemes. Here, we build the configuration of a common path quantum interferometry scheme for a spectroscopy in a broad mid-IR range. The optical path of the IR light through the medium in our scheme is extended up to 200 mm [5]. The interferometer consists of parabolic mirror, which allows compensating for the transverse phase shifts acquired by light travelling through the interferometer. Therefore, the interference pattern is observed across wider range in the spectrum of the SPDC light.

This work was supported by National Research Foundation Singapore and A*STAR under Project #NRF2021-QEP2-03-P08 and by Agency for Science, Technology and Research (A*STAR) via AME YIRG 2021 grant funding no. A2084c0178.

References

[1] X. Y. Zou et al, Phys. Rev. Lett. 67, 318–321 (1991)
[2] G. B. Lemos et al, Nature **512**, 409-412 (2014)
[3] D. A. Kalashnikov et al, Nat. Photonics **10**, 98-101 (2016)

[4] C. Lindner et al, Opt. Exp. **29**(3), (2021)
[5] A. V. Paterova et al, ACS Photonics **9**, 2151−2159 (2022)

Versatile super-sensitive metrology using induced coherence

Ashe (Nathaniel R.) Miller[1], Sven Ramelow[2], and William N. Plick

[1]Louisiana State University, Baton Rouge, USA
[2] Humboldt University, Berlin, Berlin, Germany

We theoretically analyze the phase sensitivity of the Induced-Coherence (Mandel-Type) Interferometer, including the case where the sensitivity is “boosted” into the bright input regime with coherent-light seeding. We find scaling which reaches below the shot noise limit, even when seeding the spatial mode which does not interact with the sample – or when seeding the undetected mode. It is a hybrid of a linear and a non-linear (Yurke-Type) interferometer, and aside from the supersensitivity, is distinguished from other systems by “preferring” an imbalance in the gains of the two non-linearities (with the second gain being optimal at low values), and non-monotonic behavior of the sensitivity as a function of the gain of the second non-linearity. Furthermore, the setup allows use of subtracted intensity measurements, instead of direct (additive) or homodyne measurements – a significant practical advantage. Bright, super-sensitive phase estimation of an object with different light fields for interaction and detection is possible, with various potential applications, especially in cases where the sample may be sensitive to light, or is most interesting in frequency domains outside of what is easily detected, or when desiring bright-light phase estimation with sensitive/delicate detectors. We use an analysis in terms of general squeezing and discover that super-sensitivity occurs only in this case – that is, the effect is not present with the spontaneous-parametric-downconversion approximation, which many previous analyses and experiments have focused on.

Quantum Remote Sensing

A. C. Cardoso, H. Zhou, J. Dong, W. Nie, P. Zhang and J. G. Rarity

Quantum Engineering Technology Labs,
Department of Electrical & Electronic Engineering and H. H. Wills Physics Laboratory
University of Bristol, Bristol BS8 1FD, UK

There have been great claims for the benefits of quantum illumination in sensing and rangefinding and in this talk I will illustrate where quantum can help. Primarily the use of photon counting detectors has allowed a dramatic improvement of sensitivity in low power (quasi-CW) LIDAR both for rangefinding [1] and in gas sensing applications [2, 3]. The addition of a quantum illumination in the form of a pair photon source can provide further advantage although with limited brightness [4]. Here I will present two new remote sensing technologies. The first is a novel quantum inspired spread spectrum source for low-light rangefinding and the second a novel gas sensing method using stimulated non-linear interferometry to sense methane down to background levels [5].

References

1. G.S. Buller et al, Review of scientific instruments 76, 083112 (2005)
2. M. Quatrevalet et al, IEEE JSTQE, 23, 5300311 (2017)
3. See https://qlmtec.com/
4. S. Frick et al, Optics Express 28, 37118 (2020)
5. A.C. Cardoso, H. Zhou, S.K. Joshi, J. G. Rarity, arXiv:2209.15289 (2020)

Quantum-enhanced spectroscopy in nonlinear interferometers

S. Panahiyan[1,2,3], C.S. Muñoz[4], M. V. Chekhova[5,6], and F. Schlawin[1,2,3]

[1]Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany
[2]Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, Hamburg D-22761, Germany
[3]University of Hamburg, Luruper Chaussee 149, Hamburg, Germany
[4]Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, Madrid, Spain
[5]Max-Planck Institute for the Science of Light, Staudtstr. 2, Erlangen D-91058, Germany
[6]University of Erlangen-Nuremberg, Staudtstr. 7/B2, Erlangen D-91058, Germany

In this talk, we will discuss optimal quantum-enhanced measurements of multiphoton absorption. We will discuss optimal quantum states of light to carry out these measurements and investigate experimental setups which can make optimal use of these states. In particular, we find that a seeded nonlinear interferometer can reduce the uncertainty of m-photon absorption $\Delta\epsilon_m$ substantially. For measurements with coherent states of light, this uncertainty decreases as $\Delta\epsilon_m \sim n^{-(2m-1)/2}$, where n is the mean photon number. Using nonlinear interferometers, this scaling behaviour can be improved to $\sim n^{-m}$. At large photon numbers, this can provide a tremendous quantum enhancement of the resolution and reduce the necessary light intensity to carry out such measurements [1].

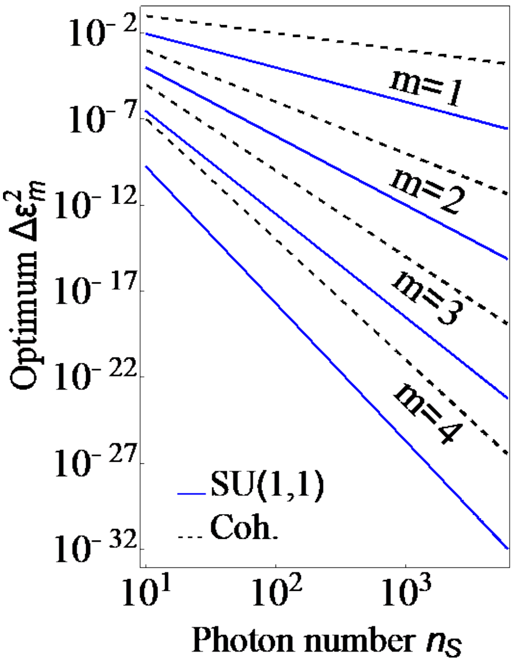


Figure 1: Optimised uncertainty $\Delta\epsilon_m^2$ for the measurement to m-photon absorption with coherent light and in a nonlinear interferometer.

References

[1] S. Panahiyan, C. S. Muñoz, M. V. Chekhova, and F. Schlawin, arXiv: 2209.02697

Quantum Dense Sensing of Trajectories

R. Schnabel[1] **and J. Zander**[1]

[1]*Institut für Laserphysik, Luruper Chausse 149, Universität Hamburg,*
22761 Hamburg, Germany

The phase space trajectory of an ensemble quantum state can be fully monitored through *simultaneous* measurements of the two non-commuting phase space observables $\hat{X}$ and $\hat{Y}$. Since every measurement is performed on a fresh ensemble member, quantum back action is not an issue. However, the Heisenberg uncertainty principle is an issue. It sets a limit to the accuracy of simultaneous measurements of non-commutative phase space observables, but not(!) if the measurement uses Einstein-Podolsky-Rosen entangled states.

Here we demonstrate 'quantum dense sensing'. It provides pairs of values (X_i, Y_i) from simultaneous measurements on ensemble member no 'i' with an imprecision of up to 10 dB below the Heisenberg uncertainty limit. We succeed in monitoring the phase space dynamics of an ensemble with the same sub-Heisenberg precision [1].

Quantum Dense Sensing is useful in laser interferometric measurements, even when the signal usually appears in only a single observable. Gravitational wave detectors are just one example [2].

References

[1] J. Zander and R. Schnabel, NPJ Quantum Information **7**, 148 (2021).

[2] M. Ast, S. Steinlechner, and R. Schnabel, Phys. Rev. Lett. **117**, 180801 (2016).

Entangled Two Photon Absorption

R. Thew

Department of Applied Physics, University of Geneva, Switzerland

.

We will show some of our work on trying to experimentally demonstrate and understand entangled two photon absorption (ETPA). We present some of the techniques and challenges, as well as discussing some of the open questions that remain, especially concerning the underlying mechanisms that are involved – if we are feeling bold this will include discussing what we think we know, known unknowns and possibly drift into speculation about unknown unknowns. This work will focus on both the degree of freedom of the entanglement and temporal characteristics [1] as well at looking at the spatial properties [2].

References

[1] D. Tabakaev *et al*., *Physical Review A, **103**, 033701 (2021)*

[2] D. Tabakaev *et al*., *Physical Review Letters*, **129**, 183601 (2022)

Separation estimation of incoherent optical sources reaching the Cramér-Rao bound

C. Rouvière[1], D. Barral[1], A. Grateau[1], G. Sorelli[2], I. Karuseichyk[1], M. Walschaers[1] and N. Treps[1]

[1]*Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université,*
Collège de France, 24 Rue Lhomond, 75005, Paris, France
[2] *Fraunhofer IOSB, Ettlingen, Fraunhofer Institute of Optronics, System Technologies*
and Image Exploitation, Gutleuthausstr. 1, 76275 Ettlingen, Germany

In the optical scenario, would it be in imaging, remote sensing or interferometric measurement, a parameter to be estimated can be encoded on the quantum state of the probe light, but also in its spatio-temporal distribution. Optimal quantum parameter estimation is thus at the crossroads between quantum information theory and optical mode manipulation, where only by taking into account both classical and quantum optimization one can derive efficient and practical estimators.

We study the model problem of resolving light sources below the diffraction limit. It was shown that the separation between two point sources can be estimated at the quantum limit using intensity measurements after spatial-mode demultiplexing. We implement this technique and provide an optimal estimator based on a linear combination of demultiplexed intensity measurements [1-3]. Our experimental setup allows for the generation of the images of two sources, with tunable mutual coherence, as well as for spatial mode demultiplexing to estimate their separation [4].

We are able to estimate the separation between two incoherent sources in two regimes, at high photon flux (100μW) with a relative sensitivity of 3.10^{-5}, and at low photon flux (5fW), and are able to saturate the Cramér-Rao bound in both cases.

References

[1] G. Sorelli *et al.,* Phys. Rev. Lett. 127, 123604 (2021).
[2] G. Sorelli *et al,* Phys. Rev. A 104, 033515 (2021).
[3] M. Gessner *et al.*, Phys. Rev. Lett. 125, 100501 (2020).
[4] P. Boucher *et al.*, Optica 7, 11 1621 (2020).

24×24-pixels SPAD camera for Quantum Imaging at low optical power

F. Villa[1], F. Severini[1], I. Cusini[1], F. Madonini[1], R. Camphausen[2], Á. Cuevas[2]

[1]*Dipartimento di Elettronica, Informazione e Bioingegneria – Politecnico di Milano, Milano, 20133 Italy*
[2] *Institut de Ciències Fotòniques, Barcelona, 08860 Spain*

Temporal correlations among photons is a useful information for quantum imaging applications [1]. Single Photon Avalanche Diodes (SPADs) are solid state detectors with single photon sensitivity and high temporal resolution typically employed in quantum setups. Photon coincidences are usually detected by post-processing their timestamps measured by means of Time-to-Digital Converters (TDCs), through a time and power consuming procedure, which impairs the overall system performance. Here, we propose an innovative 24 × 24 SPAD imager (micrograph in Figure 1-left), able to detect photon coincidences directly on chip and provide the spatial position of the photon pair through an event-driven readout (330 ns readout time per photon pair). The architecture is modular, so easily scalable to higher pixel number [2].The detector enabled quantum imaging at extremely low, microwatt-level, optical pump powers, four order of magnitude lower than previous experiments with similar optical setups. An example of far field transverse entanglement experiment is shown in Figure 1-right, where the ring shape of the counts and the spot in the coincidence projection in the sum-coordinates prove the momentum conservation of the entangled photon pair and the correct functionality of the detector.

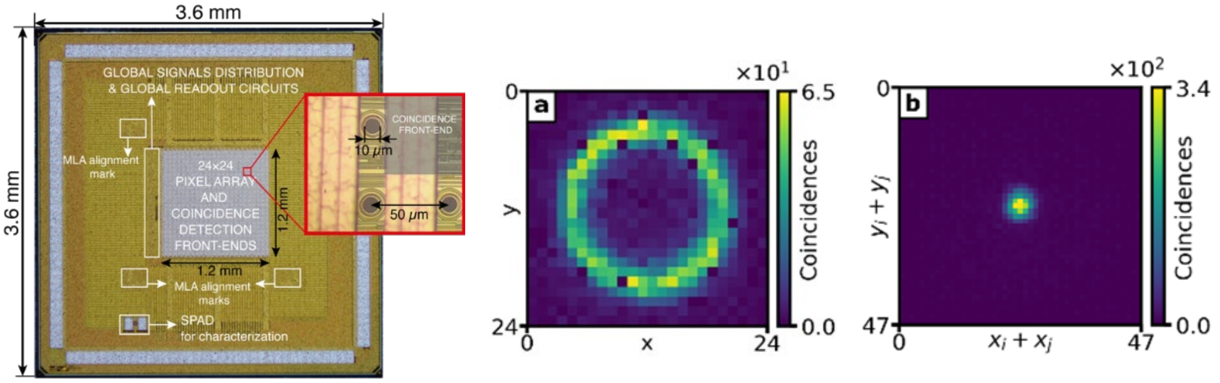


Figure 1: Micrograph of the SPAD array (left). Far field transverse entanglement experiment: photon counts (a) and coincidence projection in sum-coordinates (b) (right).

References

[1] F. Madonini, F. Severini, F. Zappa, F. Villa, Advanced Quantum Technologies **2100005**, 1-26 (2021)

[2] F. Severini, et al., Journal of Solid State Circuits, **early access**, 1-10 (2023)

Entanglement-Enhanced Sensing and Data Processing

Zheshen Zhang[1]

[1]Department of Electrical and Computer Engineering
University of Michigan, Ann Arbor, MI 48109, USA

The 20th century has witnessed the rise of quantum mechanics and its fueled scientific and technological revolution. The humankind is now on the verge of a second quantum revolution sparked by quantum information science and engineering (QISE). Entanglement as a quintessential quantum resource lies at the heart of QISE, giving rise to a plethora of quantum-enabled or enhanced capabilities that shift the landscape of communication, sensing, and computing. In this talk, I will present our recent experimental advances in entanglement-enhanced sensing and data processing. I will first describe entangled sensor networks for precise radiofrequency [1] and optomechanical [2] sensing beyond the standard quantum limit. Building on entangled sensors, I will introduce quantum-enhanced machine learning for data classification at a physical layer [3]. Next, I will discuss a major endeavor to foster the transition from basic quantum research to near-term, widely impactful real-world quantum technologies: the construction of a quantum-network testbed as a distributed infrastructure to advance convergent QISE research and education.

References

[1] Y. Xia *et al.*, Demonstration of a Reconfigurable Entangled Radio-Frequency Photonic Sensor Network, Phys. Rev. Lett. **124**, 150502 (2020).
[2] Y. Xia, A. R. Agrawal, C. M. Pluchar, A. J. Brady, Z. Liu, Q. Zhuang, D. J. Wilson, and Z. Zhang, Entanglement-Enhanced Optomechanical Sensing, arXiv:2210.16180.
[3] Y. Xia, W. Li, Q. Zhuang, and Z. Zhang, Quantum-enhanced data classification with a variational entangled sensor network, Phys. Rev. X **11**, 021047 (2021).

Monitoring Electronic Coherence of Molecules by Quantum-Light Spectroscopy

Zhedong Zhang[1]

[1]*Department of Physics, City University of Hong Kong, Hong Kong SAR*

Quantum states of the light, e.g., single photons, entanglement and squeezing, open up a new avenue for spectroscopy by utilizing the parameters of quantum optical fields as novel control knobs and through the variation of photon statistics. With the advancements of cavity quantum electrodynamics and light source technology, imaging and controlling the electron and vibrational motions of molecules can be achieved, towards unprecedented resolution and precision, not accessible by the classical light pulses. Two key issues emerge at nanoscale: quantum states of photons and strong matter-light interaction. The underlying physics is still an open issue for molecules and spectroscopy.

In this talk, I will present an overview of our recent work on multidimensional spectroscopic probes for nonequilibrium dynamics of complex molecules. Several spectroscopic signals will be covered: multidimensional coherent probe, photon-coincidence counting, and Raman spectra with entangled photons [1,2]. Microscopic models for molecular polaritons using density matrix and Heisenberg-Langevin approach will be incorporated for a unified understanding of the spectroscopic signals [3].

References

[1] Z. D. Zhang, *et al*., Physical Review Letters **130**, 103001 (2023)
[2] Z. D. Zhang, *et al*., Light: Science & Applications **11**, 274 (2022)
[3] Z. D. Zhang, *et al*., Physical Review B **106**, L220306 (2022)

Abstracts of Posters

(in alphabetical order)

Toward experimental realization of sub-diffraction quantum imaging with undetected photons

Omid Abed[1], Frank Setzpfandt[1,2], Thomas Pertsch[1,2], and Sina Saravi[1]

[1] Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
[2] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany

The resolution of conventional quantum imaging with undetected photons schemes is limited by the diffraction limit [1]. However, Recently, a new scheme based on the near-field interaction of an object with an SPDC source has been proposed that can surpass the resolution of previous methods [2]. In my poster, I will describe the initial results of my PhD project, towards an experimental realization of the scheme for sub-diffraction quantum imaging with undetected photons. To test the theory, as our sample, we use a nonlinear substrate with subdiffraction-sized nanoparticles spread over it. Then, we use a setup comprised of a pulsed laser with tunable power, wavelength, and polarization to excite the SPDC process. We shine the pump light on the sample and collect the scattered/generated light from the substrate, and guide it to sensitive cameras and spectrometers. According to the theory, SPDC production is enhanced at the wavelength that nanoparticles have high absorption in one of the channels of the produced photon pairs. Hence, by detecting the enhancement of the signal wavelength, one can obtain the spatial information of the absorption in the corresponding idler wavelength with sub-diffraction resolution. The preliminary results show a few peaks in the spectra of the generated photons that could be associated with this nonlinear quantum process. However, more investigations are required to properly verify the origin of the signals as a near-field quantum imaging signature.

References

[1] Vega, A., Santos, E. A., Fuenzalida, J., Basset, M. G., Pertsch, T., Gräfe, M., ... & Setzpfandt, F. (2022). Fundamental resolution limit of quantum imaging with undetected photons. Physical Review Research, 4(3), 033252.

[2] Santos, E. A., Pertsch, T., Setzpfandt, F., & Saravi, S. (2022). Subdiffraction Quantum Imaging with Undetected Photons. Physical Review Letters, 128(17), 173601.

Non-classical holography with heralded single-photon source

D. Abramović[1,2] **and H. Skenderović**[1,2]

[1]*Institute of Physics, Bijenicka 46, 10000 Zagreb, Croatia*
[2] *Centre of Excellence for Advanced Materials and Sensing Devices, Photonics and Quantum Optics Unit, Rudjer Boskovic Institute, Bijenicka 54, 10000 Zagreb, Croatia*

Various sources of noise, covert imaging (low photon flux), intrusion of illumination light (high photon flux) onto imaged object can ruin the amplitude and phase information related to intrinsic properties of imaged object. I will present our work [1] in low-light holography with heralded single-photon source and off-axis image-plane Twyman-Green interferometer. Essentially, we have three messages about our results: single-photon states are suitable for recording interferograms (holograms) from which amplitude and phase information can be obtained, it is possible to show advantages over classical non-heralded holography, and third it is possible to record interferograms with continuous characterization of the nature of the light source. In comparison to other works in low-light holography [2-7], some advantages and disadvantages of our setup will be highlighted. The implications of the observed experimental results are interesting because they shed light about the relation between classical and quantum holography from a perspective of single photons and experimentally tackle the problem of the indeterminate phase of a single photon [8] with continuously monitored photon statistics that is characteristic of single-photon states.

References

[1] D. Abramović, N. Demoli, M. Stipčević, and H. Skenderović, doi:10.48550/arXiv:2209.00431 (2022).
[2] M. Yamamoto, H. Yamamoto, and Y. Hayasaki, Opt. Lett. **34**, 1081 (2009)
[3] N. Demoli, H. Skenderović, and M. Stipčević, Opt. Lett. **39**, 5010 (2014).
[4] R. Chrapkiewicz, M. Jachura, K. Banaszek, and W. Wasilewski, Nat. Photonics **10**, 576 (2016).
[5] H. Defienne, B. Ndagano, A. Lyons, and D. Faccio, Nat. Phys. **17**, 591 (2021).
[6] W. Szadowiak, S. Kundu, J. Szuniewicz, and R. Lapkiewicz, Quantum **5**, 516 (2021).
[7] S. Töpfer, M. Gilaberte Basset, J. Fuenzalida, F. Steinlechner, J. P. Torres, and M. Gräfe, Sci. Adv. **8**, eabl4301 (2022).
[8] A. I. Lvovsky, H. Hansen, T. Aichele, O. Benson, J. Mlynek, and S. Schiller, Phys. Rev. Lett. **87**, 050402 (2001).

CMOS SPADs for Quantum Applications and Time-of-Flight Imaging

K. Albert[1]**, S. Grosse**[1] **and M. Ligges**[1]

[1]*Fraunhofer Institute for Microelectronic Circuits and Systems, Duisburg, Germany*

Quantum applications using single photons rely on highly efficient, low-noise and time resolving single-photon detectors. Single-Photon Avalanche Diodes (SPADs) can offer excellent performance for quantum applications like Ghost Imaging, Quantum Communication, Quantum Random Number Generation, Readout in Ion-Trap Quantum Computing, Photonic Quantum Computing and more. The SPAD technology is also commonly used when it comes to Time-of-Flight measurements of short laser pulses as in Light Detection And Ranging (LiDAR) applications. The ability to detect ultra-low light intensities makes it even suitable for Non-Line-of-Sight (NLOS) systems where multi-scattered photons are detected to reconstruct hidden scenes. The performance in single photon detection is limited by the dark count rate of the SPADs which is excellent [1,2] at the Fraunhofer SPAD technology. The integration of SPADs into the CMOS process enables a high amount of flexibility in developing application specific sensor devices. Additional post-processing allows performance increases and the combination of CMOS technologies for higher integration and further design options. We present the potential and performance characteristics of novel SPAD devices of the Fraunhofer IMS inhouse technology and the ongoing technological advances as well as an outlook into future developments.

References

[1] C. Accarino et al., IEEE Sensors Journal **19**, 7319-7327 (2019)

[2] D. Bronzi et al., Proceedings of the European Solid-State Device Research Conference (ESSDERC), 230-233 (2012)

Generating squeezing with coherent feedback in cavity optomechanics

F. Bemani, O. Černotík and R. Filip

Department of Optics, Palacký University, 17. listopadu 1192/12, 77146 Olomouc, Czechia

We can use coherent feedback to steer a quantum system toward a specific state [1]. In this technique, we perform definite operations on the relevant subsystems of the system while retaining quantum information throughout the control loop. Additionally, coherent feedback does not rely on measurements, which can bypass problems like measurement backaction, decoherence, noise, latency, and dispersion.

The quantum mechanical nature of squeezed states makes them a powerful platform in quantum technologies, particularly communications and measurement. Optical squeezing results from coherent photon-phonon interaction in optomechanical systems [2]. Squeezing may have applications in quantum communication, quantum information with continuous variables, and sensing and metrology capabilities. Optically coherent feedback loops have been studied for their potential to enhance key processes, including cooling [3-5], steady-state squeezing [6], entanglement [4-7], enhancing optomechanical nonlinearity [8], and optical-to-mechanical state transfer [6].

Here we discuss the enhancement of squeezing assisted by coherent feedback in optomechanical systems in the unresolved sideband regime. Our scheme requires adjustments of the optical path without needing additional optical cavities or interactions with other quantum systems. The system with feedback can generate optical and conditional mechanical squeezing using state-of-the-art optomechanical setups.

References

[1] J. Zhang, Y. xi Liu, R.-B. Wu, K. Jacobs, and F. Nori, Phys. Rep. **679**, 1 (2017).

[2] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, Reviews of Modern Physics **86**, 1391 (2014).

[3] G.-L. Schmid, C. T. Ngai, M. Ernzer, M. B. Aguilera, T. M. Karg, and P. Treutlein, Phys. Rev. X **12**, 011020 (2022).

[4] J. Guo and S. Gröblacher, Quantum 6, 848 (2022)

[5] M. Ernzer, M. B. Aguilera, M. Brunelli, G.-L. Schmid, C. Bruder, P. P. Potts, and P. Treutlein, arXiv:2210.07674 (2022).

[6] A. Harwood, M. Brunelli, and A. Serafini, Phys. Rev. A **103**, 023509 (2021).

[7] J. Li, G. Li, S. Zippilli, D. Vitali, and T. Zhang, Phys. Rev. A **95**, 043819 (2017).

[8] Z. Wang and A. H. Safavi-Naeini, Nat. Commun. **8**, 15886 (2017).

Theoretical study of spatial coherence for quantum enhanced imaging

J. León[1,2], A. Vega[2], R. Sondenheimer[1,2] and E. Brambila[1,2]

[1] *Fraunhofer IOF, Jena, Germany*
[2] *University of Jena, Jena, Germany*

The nonlinear process of spontaneous parametric down conversion (SPDC) is nowadays used as a usual quantum source of photon pairs [1]. Therefore, it is relevant to study the properties of the generated quantum states depending on different parameters to exploit the full potential for various quantum technologies.

The motivation of studying the effect of partial spatial coherence with photon pairs comes from a classical beam property. It is well-known that partial spatial coherent classical beams are more robust under turbulence conditions, compared to fully coherent beams [2]. There are already a couple of works which studied the properties of SPDC under different spatial pump coherence cases [3]. In this work, I will present a calculation of the output image from a nonlinear interferometer by varying this parameter.

Nonlinear interferometers are novel setups used for a range of quantum sensing applications [4,5]. The approach of imaging with undetected photons remarks their use in life-science applications due to the photon pair two-wavelength advantage [6]. This allows to illuminate the sample with one photon, having a specific wavelength optimized for the sample, and detect its partner with different wavelength optimized for the detection scheme.

The study of the spatial pump coherence is relevant to understand better a key component for enhanced images towards more complex applications of the technique of imaging with undetected photons under turbulence conditions.

References

[1] F. Steinlechner, M. Gilaberte, *et al.*, J. Opt. Soc. Am. B **9**, 2068 (2014).
[2] G. Gbur and E. Wolf, J. Opt. Soc. Am. A **19**, 1592 (2002).
[3] A. K. Jha and R. W. Boyd, Phys. Rev. A **81**, 013828 (2010).
[4] M. V. Chekhova and Z. Y. Ou, Adv. in Opt. and Phot. **1**, 104 (2016).
[5] P. Vergyris, C. Babin, *et al.,* Appl. Phys. Lett. **117**, 024001 (2020).
[6] A. V. Paterova, H. Yang, et al. Quantum Sci. Technol. **3**, 025008 (2018).

Quantum-assisted adaptive optics for label-free microscopy

P. Cameron[1] , **D. Faccio**[1], **and H.Defienne**[2]

[1]School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK [2]Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris, France

The use of adaptive optics (AO) in microscopy has revolutionized the field by correcting aberrations caused by the imaging system and the specimen, resulting in improved image resolution and contrast. In label-free linear microscopy, however, conventional AO methods are limited by the absence of guidestar and the need to select an optimization metric specific to the type of microscope being used. Here, we propose a quantum-assisted AO approach that exploit correlations between entangled photons to directly access and correct the point spread function (PSF) of the imaging system. This is a guidestar-free, robust and reliable metric, independent on the physical structure of the object being imaged and the imaging modality. We demonstrate our approach on a wide-field imaging configuration to image biological samples in transmission with spatially-entangled photon pairs. We show that it exhibits better performance than conventional AO in correcting certain types of aberrations, particularly in cases involving significant defocus. Furthermore, our results indicate that the approach enables, in principle, to correct for high-order aberrations. Our work improves AO for label-free microscopy, and could play a major role in the development of quantum microscopes, in which optical aberrations and scattering can counteract the advantages of using entangled photons and undermine their practical use.

Sensing Without Detection on Silicon Photonic Chips: Highly Sensitive Methane Detection and Beyond

Haichen Zhou[1] **and** **Arthur Cardoso**[1]

[1]*University of Bristol, Bristol, UK*

Silicon optical chips are optoelectronic devices based on silicon-based materials and are an important part of optical technology. They have become one of the mainstream technologies in the fields of optical communication, optical computing and optical sensing with their high integration, fast response time, good immunity to interference, environmental characteristics and high compatibility with semiconductor technology. It has a broad application prospect and market potential. One area where they could have a significant impact is the detection of methane, a potent greenhouse gas that has a major impact on climate change. Highly sensitive means of detecting methane gas can help us to better monitor and manage methane emissions and thus reduce its environmental impact. Traditional direct optical gas sensing methods use a laser with a wavelength around 1.65um, a wavelength band that balances the absorption of methane gas with reasonable photon detection efficiency. To be fair, however, neither is satisfactory. The most discernible and visible absorption peak for methane gas is near 3.3um, but photon detectors for this wavelength are expensive and poorly efficient. In order to balance the efficiency of the detector with the efficient methane absorption peak, the sensing without detection technique was invented. The core idea is to use four-wave mixing to generate signal-idler photon pairs at 1.5um and 3.3um respectively from the pump photons, and when the idler photons are indistinguishable, the signal photons will produce clearly visible interference fringes between them. And when there are idler photons absorbed by methane, it will affect the interference fringe between signal photons. Information about the methane gas concentration can be learned by measuring the interference visibility between signal photons. This method combines the advantages of high detection efficiency of the signal light and the strong methane absorption peak of the idler light, making it a highly sensitive method for methane detection. However, the bulk optics device still has the disadvantages of being difficult to install and commission, and of being less stable. For this reason we plan to transfer this experiment to silicon optical chips in order to combine the advantages of fast response time, high process accuracy, and ease of electrical control of silicon optical chips. Wavelength conversion based on the FWM principle on silicon optical chips has already been achieved, and signal photon output around 1.5um has been observed with an input of 2um pump light. It is planned to test the gas detection capability of the idler photon and to perform sensing without detection experiments.

References

Spectral purity characterization of telecom wavelength photons generated in aperiodically poled KTP

Johanna Conrad[1,2], Rodrigo Gómez[1,2], Markus Leipe[1,2], Meritxell Cabrejo Ponce[1], Gregor Sauer[1,2] and Fabian Steinlechner[1,2]

[1]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745 Jena, Germany
[2]Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Straße 6, 07745 Jena
E-mail: johanna.conrad@iof.fraunhofer.de

The production of spectrally pure single photon states is a fundamental requirement for numerous quantum protocols and applications, such as entanglement swapping for quantum networks [1] and quantum sensing using multi-photon states of light [2]. Quantum light sources based on spontaneous parametric down conversion (SPDC) commonly use periodically poled titanyl phosphate (ppKTP) non-linear crystals for such process, but periodic poling limits the achievable spectral purity due to the sinc function behavior of the phase matching function. Combined with a quasi-gaussian pump envelop function, this results in spectral correlations and therefore reduces the photon indistinguishability. Purity in ppKTP can be improved by narrow filters, which introduce losses and lower photon heralding. New approaches using aperiodically poled KTP (apKTP) can improve the achievable spectral indistinguishability of the SPDC photons due to better engineering of the phase matching function [3], approximating the phase matching function to a gaussian shaped function, so that no filtering is necessary. In this work we report the experimental characterization of the performance of ppKTP and apKTP crystals in SPDC quantum light sources. We characterize and compare the crystals' performance in terms of their spectral purity, brightness, and visibility in two photon Hong-Ou-Mandel experiments. We discuss the expected performance of our quantum light sources in future applications to generate non-gaussian states and entangled four-photon sources.

References

[1] R. Kaltenbaek, R. Prevedel, M. Aspelmeyer, and A. Zeilinger, Phys. Rev. Lett. **79**, 040302 (2009)

[2] Q. Ke, X. Zhan, M. Li, and X. Xu, arXiv:2210.02537v1 [quant-ph] (2022)

[3] F. Graffitti, P. Barrow, M. Proietti, D. Kundys, and A. Fedrizzi, Optica **5**, 514-517 (2018)

Manipulation and certification of high-dimensional spatial entanglement in scattering media

Baptiste Courme[1,3] **Patrick Cameron**[2] **Daniele Faccio**[2] **Sylvain Gigan** [, 1] **and Hugo Defienne**[2,3,*]

[1]Laboratoire Kastler Brossel, École normale supérieure (ENS) – Université Paris Sciences & Lettres (PSL), CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, Paris 75005, [2]School of Physics and Astronomy, University of Glasgow, G12 8QQ Glasgow, United Kingdom

[3]Sorbonne Université, CNRS, Institut des NanoSciences de Paris (INSP), Paris F-75005, France

High-dimensional entangled quantum states improve the performance of quantum technologies compared to qubit-based approaches. In particular, they enable quantum communications with higher information capacities or enhanced imaging protocols. However, the presence of optical disorder such as atmospheric turbulence or biological tissue perturbs quantum state propagation and hinders their practical use. Here, we demonstrate a wavefront shaping approach to transmit high-dimensional spatially entangled photon pairs through scattering media. Using a transmission matrix approach, we perform wave-front correction in the classical domain using an intense classical beam as a beacon to compensate for the disturbances suffered by a copropagating beam of entangled photons. Through violation of an Einstein-Podolski-Rosen criterion, we show the presence of entanglement after the medium. Furthermore, we certify an entanglement dimensionality of 17. This work paves the way toward manipulation and transport of entanglement through scattering media, with potential applications in quantum microscopy and quantum key distribution.

References

[1]: Popoff, S.M et al. Measuring the transmission matrix in optics an approach to the study of light propagation in disordered media.

[2]: Ndagano, B., Defienne, H., Lyons, A. et al. Imaging and certifying high-dimensional entanglement with a single-photon avalanche diode camera.

[3]: Bavaresco, J., Herrera Valencia, N., Klöckl, C. et al. Measurements in two bases are sufficient for certifying high-dimensional entanglement.

Enhancing methane sensors by sensing without detection

Arthur.C.Cardoso[1] and Jinghan Dong[2]

[1]University of Bristol, Bristol, United Kingdom
[2] University of Bristol, Bristol, United Kingdom

Accurately detecting greenhouse gas is critical in understanding their impact on the environment and developing effective strategies to mitigate their effects [1]. The methane sensor we report on in this study is based on three-wave mixing, a technique that takes advantage of methane's strong absorption characteristics in the mid-infrared region. However, traditional mid-infrared detectors are inefficient and expensive, making them unsuitable for widespread deployment. To overcome this limit, we developed a sensing without detection method that relies on detecting idler photons in the near-infrared region, rather than detecting signal photons that interact with the gas. In our experimental demonstration, we were able to measure small methane concentrations inside a gas cell with high precision using this technique and the whole absorption spectrum of methane is measured. The sensitivity of our method to detect methane concentrations in the high-gain region was found to be higher than that of the state-of-the-art direct detection method, as demonstrated by the correlation calculation of the signal-to-noise ratio. Furthermore, it can be used to make spectral analysis of the absorption lines of the gas sample. A potentially more compact design of this experiment can detect low concentrations of methane at a range of 100 meters and this design can be extended to accurately detect other harmful gases. Overall, our findings present a promising avenue for developing cost-effective methane sensors with high precision at the high gain regime.

References

[1] D. Shindell, J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. 244 Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. 245 Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. Kim Oanh, G. Milly, M. Williams, V. Demkine, D. Fowler, 246 “Simultaneously mitigating near-term climate change and improving human health and food security,” Science 335, 247 6065 183–189 (2012).

Quantum Ghost Imaging using 2-D SPAD array

V. F. Gili [1,2], D. Dupish [1], A. Vega [1], M. Gandola [3], E. Manuzzato [3], M. Perenzoni [3,4],
L. Gasparini [3], T. Pertsch [1,2], F. Setzpfandt [1,2]
1 Friedrich-Schiller-Universität Jena, Institute of Applied Physics,
Abbe Center of Photonics, 07745 Jena, Germany
2 Fraunhofer Institute for Applied Optics and Precision Engineering, 07745 Jena, Germany
3 Fondazione Bruno Kessler, 38123 Trento, Italy
4 Current address: Sony Europe Technology Development Centre, 38123 Trento, Italy

Quantum Ghost Imaging (QGI) is a powerful imaging technique that takes advantage of the spatial correlations of photon pairs [1] generated using Spontaneous Parametric Down conversion (SPDC). In QGI, only one of the spatially correlated photons interacts with the object but does not carry any information about the structural features. The image is surprisingly reconstructed by correlating the two photons [2]. We present a QGI scheme which utilizes a 2D Single-Photon Avalanche Diode (SPAD) array in the spatially resolving arm while allowing investigation of the object with near-infrared photons. This innovative approach enables us to capture images across the field of view in under a minute, without scanning, while removing the need for cumbersome image-preserving delay lines inherent to QGI with Intensified Charge-Coupled Device (ICCD) cameras [3]. We demonstrate the effectiveness of our scheme by using pairs of non-degenerate spatially correlated photons, generated at a wavelength difference of 800 nm by a Beta-Barium Borate (BBO) crystal, which allows us to investigate samples at infrared wavelengths without a spatially resolving camera sensitive to infrared wavelengths. Our results demonstrate the potential of this scheme to provide efficient imaging capabilities with the possibility of investigating samples at wavelengths rendered inaccessible due to the unavailability of suitable cameras.

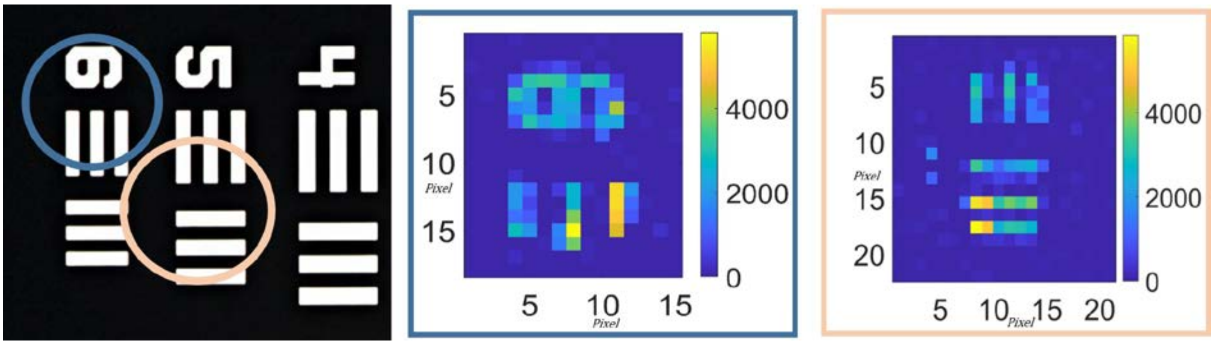


Fig. 1: Ghost images of resolution target using the presented scheme. USAF resolution target with highlighted zones (Left) and corresponding ghost images (Right). Accumulation time ~ 20 min

References

[1] T. B. Pittman et al., Phys. Rev. A 52, R3429–R3430 (1995).
[2] D. V. Strekalov et al., Phys. Rev. Lett. 74, 073032 (1995).
[3] R. S. Aspden et al., N. J. Phys. 15, 073032 (2013).

Quantum and Nonlinear Integrated Photonics with AlGaAs

Stefan Frick[1], **Alexander Schlager**[1], **Hannah Thiel**[1], **Johannes Loitzl**[1], **Bianca Nardi**[1], **and G. Weihs**[1]

[1]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria*

Aluminium gallium arsenide waveguides constitute a promising platform for integrated nonlinear and quantum photonics.

The III-V semiconductor material offers a direct band gap at aluminium concentrations of less than 40 %, which enables a wider range of potential integration of active components.

We present recent results on the fabrication of Bragg-reflection waveguides in AlGaAs [1] and demonstrate the generation of difference-frequency generation in a waveguide with an on-chip quantum dot laser [2].

Time-bin entanglement of photons is achieved by using a hybrid integrated waveguide source, which is pumped off-chip but filtered and routed on a polymer platform

References

[1] H. Thiel, Optical Materials Express **13**, 1278 (2023)
[2] A. Schlager, Journal of Optics **23**, 085802 (2021)

Quantum state tomography of undetected photons

J. Fuenzalida,[1,2,3] **J. Kysela,**[1,2] **K. Dovzhik,**[1,2]
G.B. Lemos,[4] **A. Hochrainer,**[1,2] **M. Lahiri,**[5] **and A. Zeiliger**[1,2]

[1]*Institute for Quantum Optics and Quantum Information,*
Austrian Academy of Sciences, Boltzmanngasse 3, Vienna A-1090, Austria.
[2]*Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics,*
Boltzmanngasse 5, University of Vienna, Vienna A-1090, Austria.
[3] *Institute of Applied Physics, Technical University of Darmstadt,*
Schloßgartenstraße 7, 64289 Darmstadt, Germany.
[4]*Instituto de Física, Universidade Federal do Rio de Janeiro,*
Av. Athos da Silveira Ramos 149, Rio de Janeiro, CP: 68528, Brazil.
[5]*Department of Physics, Oklahoma State University,*
Stillwater 74078, Oklahoma, USA.

In the last year, there has been a growing interest in techniques based on the induced coherence effect [1]. By using quantum interference of two photons, these techniques allow extracting information about the system of one of the photons without detecting it. Instead, the undetected photon's information is extracted in the form of coherence by detecting its partner photon [2]. Today, most of these techniques have been limited to the area of quantum metrology, ranging from imaging, microscopy, sensing, spectroscopy, holography, and optical coherence tomography [3]. However, considering the many degrees of freedom carried by photons, there are still plenty of unexplored possibilities offered by induced coherence.

In this work, we bring the induced coherence effect to the area of quantum information science by introducing, for the first time, a polarization quantum state tomography of undetected single photons [4]. We experimentally proved our technique for linear and circular pure states, obtaining mean fidelities of 0.97 and 0.92, respectively. We also introduce a general theory for both mixed and pure states. We hope our experiment opens up a new avenue within the important field of quantum state measurement and estimation.

References

[1] X. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991).

[2] A. Hochrainer, M. Lahiri, M. Erhard, M. Krenn, and A. Zeilinger, Rev. Mod. Phys. **94**, 025007 (2022).

[3] G. B. Lemos, M. Lahiri, S. Ramelow, R. Lapkiewicz, and W. Plick, "Quantum imaging and metrology with undetected photons: tutorial," J. Opt. Soc. Am. B **39**, 2200–2228 (2022).

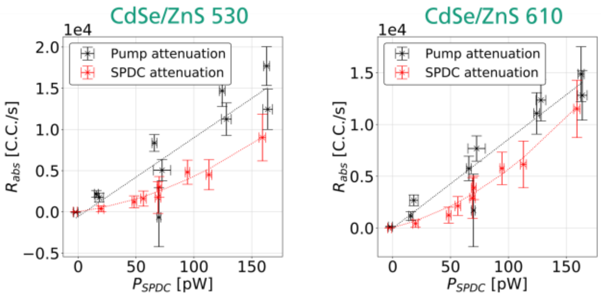
[4] J. Fuenzalida, J. Kysela, K. Dovzhik, G.B. Lemos, A. Hochrainer, M. Lahiri, and A. Zeiliger, arXiv:2211.10304 (2022).

Fluorescence Excitation of Quantum Dots by Entangled Two-Photon Absorption

T.B. Gäbler[1,2], P. Hendra[1,2], N. Jain[1], E. Prenzel[1] and M. Gräfe[1,3]

[1]Fraunhofer Institute of Applied Optics and Precision Engineering IOF,
Jena, Germany
[2] Friedrich-Schiller-Universität Jena, Abbe Center of Photonics, Jena, Germany
[3]Technische Universität Darmstadt, Institute of Applied Physics, Darmstadt, Germany
E-mail: tobias.bernd.gaebler@iof.fraunhofer.de

Fluorescence excited by absorption of entangled light becomes a prominent candidate to tackle the challenges in the state-of-the-art two-photon imaging techniques, such as the requirement of bright excitation light and fast photobleaching. The main advantage of entangled two-photon absorption (eTPA) is the linear increasing of absorption rate on the incoming photon flux. In contrast, absorption rate increases quadratically for common classical two-photon absorption (cTPA) [1].
However, due to the low brightness of entangled photon pair sources used in most studies, fluorescence measurements were not feasible. To overcome this issue, an ultra bright entangled photon pair source are desirable to based on nonlinear waveguides are promising candidates to enable fluorescence excitation by entangled photons. Our work addresses this issue by development of a source consisting of a periodically poled lithium niobate waveguide and analysis of its key characteristics. several experimental parts. Initially, a setup of an efficient entangled photon pair source based on nonlinear waveguides was assembled. To demonstrate its suitability as key component for imaging experiments, the entangled two-photon absorption behavior of CdSe/ZnS quantum dot solutions was experimentally investigated.



Our measurements of two-photon absorption rates demonstrate that obstacles like disruptive single-photon effects or insufficient photon pair rates can be handled. These results represent the next step towards an experimental realization of entangled light fluorescence microscopy [2].

References

[1] F. Lissandrin et al., Phys. Rev. B **69**, 165317 (2004).
[2] T. Gaebler et al., arXiv:2303.16584 (2023)

Infrared Spectroscopy and Hyperspectral Imaging Driven by Supercontinuum Light and Spatial Light Modulation

<u>P. Gattinger</u>[1], I. Zorin[1], A. Ebner[1] C. Rankl[1] and M. Brandstetter[1]

[1]RECENDT - Research Center for Non-Destructive Testing, Altenberger Strasse 69, 4040 Linz, Austria

Supercontinuum laser (SCL) sources have been a driving force in mid-infrared (MIR) spectroscopy in the last decade [1]. In our contribution we demonstrate various application scenarios that exploit the unique properties of SCLs (high spatial coherence and broad bandwidth in the MIR spectral region). By its combination with a digital micromirror device (DMD), a freely programmable optical mask, several powerful sensing modalities can be realized. The DMD can be used to either modulate the light in the spatial or in the spectral domain. This allows us to do single-pixel hyperspectral imaging as well as single-pixel spectroscopy, also known as spectral-coding spectroscopy. In both cases the signal-to-noise ratio benefits from a scalable multiplex advantage. Moreover, expensive infrared array detectors can be avoided.

We demonstrate an SCL-based hyperspectral diffraction-limited single-pixel microscope as well as an SCL-based standoff single-pixel spectrometer [2,3]. We show measurement results of different samples, such as gas, blood and plastics.

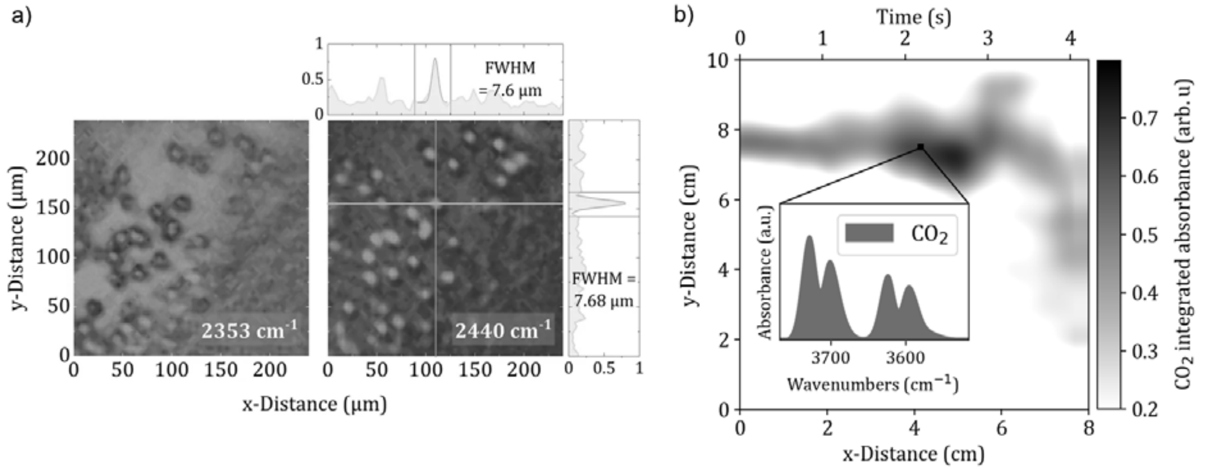


Fig.1: a) diffraction limited measurements of blood samples with the SCL-based single-pixel hyperspectral imaging setup; b) integrated absorbance of a CO_2 gas-plume acquired by the spectral-coding spectrometer via a scanning approach.

References

[1] I. Zorin et al., Opt. Express **30**, 1-34 (2022)
[2] A. Ebner et al., Sci. Reports **13**, 1-10 (2023)
[3] P. Gattinger et al., Opt. Express **30**, 6440-6449 (2022)

Towards demonstrating quantum optical backflow

B. Ghosh[1]*, **A. Daniel**[1], **B. Gorzkowski**[1], **R. Lapkiewicz**[1]

[1]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Ludwika Pasteura 5, 02-093 Warsaw
**b.ghosh@uw.edu.pl*

A quantum particle prepared as a superposition of positive momentum states can have a negative probability current during local instances of time [1]. The phenomenon of probability flow in the ‘wrong’ direction is referred to as ‘backflow’ and is a manifestation of wave interference. Superoscillations refer to situations where the local oscillation of a superposition is faster than its fastest Fourier component [2]. M.V. Berry’s work [3] highlighted the correspondence between backflow in quantum mechanics and superoscillations in waves. This correspondence has been used to demonstrate backflow in transverse linear momentum for optical waves [4,5]. In the present work, we examine the interference of classical light carrying only negative orbital angular momentum (OAM) and observe in the dark fringes of such an interference pattern, positive local OAM [6]. We refer to this as *azimuthal backflow*. Our finding may be useful where strong phase gradients over small spatial extents are needed, for instance, to enhance chiral light-matter interactions [7], or for detecting photons in regions of low light intensity [8]. From the fundamental point of view, an interesting open question is to which extent a study of the transverse two-dimensional spatial degree of freedom of a single photon can emulate the more robust two-dimensional quantum backflow analyzed in [9]. The current work is a step towards observing quantum optical backflow [10].

References

[1] A. J. Bracken and G. F. Melloy, J. Phys. A: Math. Gen. **27**, 2197 (1994).
[2] M. V. Berry and S. Popescu, J. Phys. A: Math. Gen. **39**, 6965 (2006).
[3] M. V. Berry, J. Phys. A: Math. Theor. **43**, 415302 (2010).
[4] Y. Eliezer, T. Zacharias, and A. Bahabad, Optica **7**, 72 (2020).
[5] A. Daniel, B. Ghosh, B. Gorzkowski, and R. Lapkiewicz, New. J. Phys. **24**, 123011 (2022).
[6] B. Ghosh, A. Daniel, B. Gorzkowski, and R. Lapkiewicz, arXiv:2304.13124 (2023).
[7] Y. Tang and A. E. Cohen, Science **332**, 333 (2011).
[8] V. Klimov, D. Bloch, M. Ducloy, and J. R. R. Leite, Opt. Express **17**, 9718 (2009).
[9] M. Barbier, A. Goussev and S. C. L. Srivastava, Phys. Rev. A **107**, 032204 (2023).
[10] A realization of the experiment with single photons is underway.

Near-infrared Hyper-spectral Scanning Quantum Imaging of HEK 293T Cells

Masoud Safari Arabi[1], Valerio Flavio Gili[1,2], Philipp Rühl[3], Thomas Pertsch[1,2], Frank Setzpfandt[1,2]

[1]Friedrich-Schiller-Universität Jena, Institute of Applied Physics, Abbe Center of Photonics, 07745 Jena, Germany
[2] Fraunhofer Institute for Applied Optics and Precision Engineering, 07745 Jena, Germany
[3]Friedrich-Schiller-Universität Jena, Department of Biophysics, Center for Molecular Biomedicine, 07745 Jena, Germany

Quantum correlation of photon pairs in time and space has been widely employed for quantum enhanced measurements and specially in the field of quantum imaging. We recently proposed one quantum imaging approach based on illumination scanning, which exploits the time correlation of photon pairs. A PPLN waveguide is illuminated by a pump beam to generate correlated photon pairs in the near-infrared range (NIR) through a non-degenerate SPDC process [1]. After splitting the photon pairs by a dichroic beam splitter (DBS), the signal photon is detected directly by a Single-photon Detector (SPD), while the idler photon is coupled to a galvo-galvo scanning microscope. Then, the reflected beam, after separating from the incident one with a circulator, is sent to a SPD to reconstruct the quantum image of the sample exploiting the time correlations of photon pairs [2]. By tuning the pump wavelength, we were able to scan the wavelength of signal and idler photons in the NIR range (1200 nm - 2000 nm) due to the broadband phase matching condition allowed in our waveguide, enabling us to carry out hyperspectral quantum imaging in the full SPDC wavelength range. Taking the quantum image of a sample consisting of HEK 293T cells at different wavelengths by tuning the pump wavelength, allows us to estimate the absorption spectrum of the sample in the 1200 nm - 2000 nm wavelength range. Distinct areas in the acquired quantum images resulted in different absorption spectral behavior, where individual peaks can be attributed to specific molecular motions. A further extension of this technique towards the mid-infrared range would allow to access the fingerprint region, and fully exploit the potential of quantum imaging and spectroscopy for applications in biology and material characterization [3].

References

[1] A. S. Solntsev, P. Kumar, T. Pertsch, A. A. Sukhorukov, and F. Setzpfandt, APL Photonics **3**, 021301 (2018).

[2] V. F. Gili, C. Piccinini, M. Safari Arabi, P. Kumar, V. Besaga, E. Brambila, M. Gräfe, T. Pertsch, and F. Setzpfandt, Appl. Phys. Lett. **121**, 104002 (2022).

[3] K. B. Be´c, J. Grabska, and C. W. Huck, Molecules **25**, 2948 (2020).

Photon-Pair Recombination via Sum-Frequency Generation by Chirped, Aperiodically Poled LiNb Waveguide

Patrick Hendra[1,2], **Josué Ricardo León-Torres**[1,2], **Markus Gräfe**[1,2,3]
1. *Fraunhofer Institute of Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, 07745 Jena, Germany*
2. *Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Straße 6, 07745 Jena, Germany*
3. *Institute of Applied Physics, Technical University of Darmstadt, Schloßgartenstraße 7, 64289 Darmstadt, Germany*
E-Mail: patrick.hendra@iof-student.fraunhofer.de

In the past couple of decades, the use of quantum states of light has been gaining interest in different disciplines from telecommunications to imaging and sensing due to its non-classical features that allow to exceed classical limitations. A quantum enhancement in fluorescence microscopy has been explored in a recent study, whereby, time-frequency-entangled photon pairs generated through spontaneous parametric down conversion (SPDC) process were used to demonstrate linear absorption rates in standard fluorophores by the virtue of entangled two-photon absorption (ETPA) [1]. Meanwhile, a prior study on sum-frequency generation (SFG) with down-converted photon pairs has demonstrated that the rate of photon pair recombination is linearly proportional to the down-converted bandwidth [2]. In other words, as the bandwidth of the down-converted photon pairs increases, it reduces the temporal separation between the photons, which in turn, increases the probability for up-conversion via SFG.

This work presents a novel approach in the photon-pair recombination experiment by incorporating chirped, aperiodically poled Lithium Niobate waveguide to generate high-brightness and broad-bandwidth correlated photon pairs. An illustrative diagram of the chirped, aperiodically poled waveguide is depicted in Fig. 1(a). As each poling period segment is linearly increased from one end to the other, the total number of biphoton is distributed over broader spectrum [3]. The spectrum of resulting SPDC photons from both experimental measurement and theoretical simulation is shown in Fig. 1(b), which has bandwidth of around 140 nm full width at half maximum. Furthermore, a schematic diagram of the photon pair SFG experiment is given by Fig. 1(c).

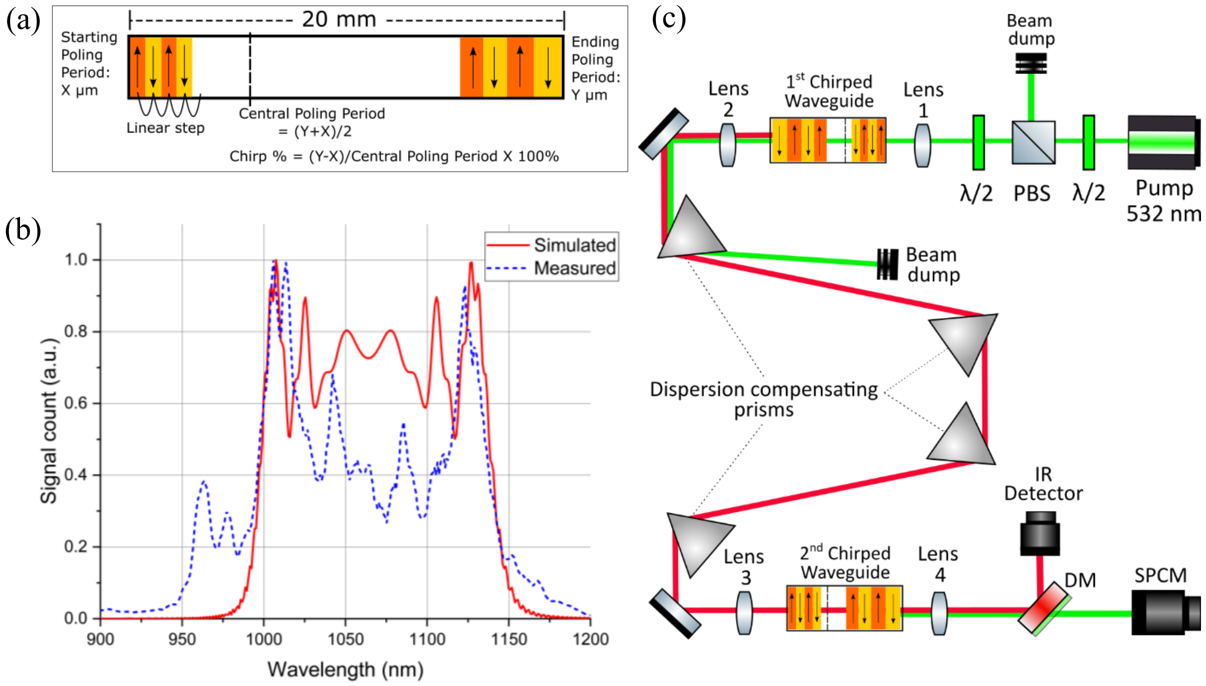


Fig. 1 (a) The characteristic properties of chirped aperiodically poled Lithium Niobate waveguide. (b) Experimental (blue) and theoretical (red) results of SPDC spectrum characterization. (c) SFG experimental setup diagram.

[1] T. Gäbler, N. Jain, J. León Torres, P. Hendra, and M. Gräfe, "Entangled Two-Photon Absorption in Commercial Fluorophores," in Conference on Lasers and Electro-Optics, J. Kang, S. Tomasulo, I. Ilev, D. Müller, N. Litchinitser, S. Polyakov, V. Podolskiy, J. Nunn, C. Dorrer, T. Fortier, Q. Gan, and C. Saraceno, eds., OSA Technical Digest (Optica Publishing Group, 2021), paper SW3D.3.
[2] B. Dayan, A. Pe'er, A.A. Friesem, and Y. Silberberg, "Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons," Phys. Rev. Lett. **94**, 043602 (2005).
[3] M.B. Nasr, S. Carrasco, B.E.A. Saleh, A.V. Sergienko, M.C. Teich, J.P. Torres, L. Torner, D.S. Hum, and M.M. Fejer, "Ultrabroadband Biphotons Generated via Chirped Quasi-Phase-Matched Optical Parametric Down-Conversion," Phys. Rev. Lett. **100**, 183601 (2008).

Precision estimation of adaptive localization strategies

T. A. Hensel[1], S.W. Hell[1]

[1]*Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany*

Optical far-field superresolution fluorescence microscopy has significantly advanced biological research by enabling the visualization of close features[1–3] . However, the finite photon budget of fluorophores remains a fundamental challenge, limiting image resolution. In this study, we explore new estimators for the localization precision of single molecules using the MINFLUX concept, which is a well-established approach for photon-efficient single-emitter localization in nanoscopy and single-molecule tracking applications[4]. By utilizing tailored excitation light distributions with displaced intensity minima, MINFLUX reduces the number of required photons for precise localization. Adaptive localization strategies enhance the field of view and localization capabilities[5,6]. Our findings contribute to the development of new estimators for single-molecule localization techniques based on the established MINFLUX concept, addressing limitations related to localization precision in the presence of a finite photon budget.

References

1. Hell, S. W. & Wichmann, J. *Opt. Lett., OL* **19**, 780–782 (1994).
2. Rust, M. J., Bates, M. & Zhuang, X. *Nat Methods* **3**, 793–795 (2006).
3. Gustafsson, M. G. L. *PNAS* **102**, 13081–13086 (2005).
4. Balzarotti, F. *et al. Science* (2017).
5. Pape, J. (2020) doi:10.53846/goediss-8248.
6. Gwosch, K. C. , PhD Thesis(2017).

Fractional Fourier transform of Hermite - Gaussian modes in quantum memory

Marcin Jastrzębski[1,2], **Bartosz Niewelt**[1,2], **Stanislaw Kurzyna**[1,2], **Jan Nowosielski**[1,2], **Wojciech Wasilewski**[1,2], **Mateusz Mazelanik**[1,2] **and Michał Parniak**[1,3]
[1] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*
[2] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[3] *Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen*

In this work[1], we present the experimental implementation of optical Fractional Fourier Transform. The protocol is realised in gradient echo memory. Hermite-Gaussian modes of light are encoded in rubidium atoms with the coupling impulse linearly chirped in frequency - this corresponds to the temporal lens [2]. Then the ac-Stark beam is applied to the atoms which leads to them acquiring the spectral phase corresponding to the propagation through a spectral lens. This operation results in the rotation of the Wigner function of the input state [3] and is exactly the Fractional Fourier Transform (FrFT) of the input function. The Hermite-Gaussian modes of light are the eigenfunctions of FrFT.

$$\widehat{\mathrm{FrFT}}^{(\varphi)}\left[H_n^G(x)\right] = H_n^G(x)e^{-in\varphi} \tag{1}$$

The figure below presents the fidelity of measured hermite-gaussian modes for FrFT angles $\frac{\pi}{4}$ and $\frac{2\pi}{3}$ with colormap representing the phase as well as Wigner functions of the measured impulse.

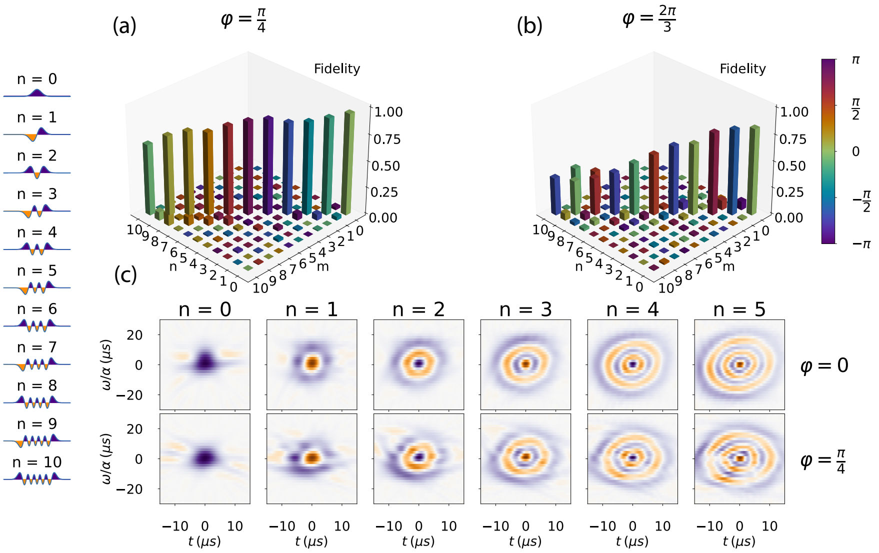


Figure 1: (a) Histogram of the fidelity for measured Hermite-Gaussian modes (m) projected onto modes (n) for $\varphi = \frac{\pi}{4}$. The colormap represents the angle of the overlap. (b) Histogram of the fidelity for measured Hermite-Gaussian modes (m) projected onto modes (n) for $\varphi = \frac{2\pi}{3}$. The colormap represents the angle of the overlap. (c) Wigner functions of measured subsequent Hermite-Gaussian modes for $n \in [0, 10] \cap \mathbb{N}$. The upper row represents $\varphi = 0$ and the lower $\varphi = \frac{\pi}{4}$.

References

[1] Bartosz Niewelt, Marcin Jastrzębski, Stanisław Kurzyna, Jan Nowosielski, Wojciech Wasilewski, Mateusz Mazelanik, and Michał Parniak. Experimental implementation of the optical fractional Fourier transform in the time-frequency domain. March 2023. arXiv:2303.13305.

[2] B. Jalali, D. R. Solli, and S. Gupta. Silicon's time lens. *Nature Photonics*, 3(1):8–10, January 2009.

[3] Adolf W. Lohmann. Image rotation, wigner rotation, and the fractional fourier transform. *J. Opt. Soc. Am. A*, 10(10):2181–2186, Oct 1993.

Mitigating quantum decoherence in cavity-enhanced force sensors by internal squeezing

M.Korobko[1], J.Südbeck[1], S.Steinlechner[2] and R.Schnabel[1]

[1]*Institut für Laserphysik, Universität Hamburg, Hamburg, Germany*
[2] *Maastricht University, Maastricht, Netherlands*

The most efficient approach to laser interferometric force sensing to date uses monochromatic carrier light with its signal sideband spectrum in a squeezed vacuum state. Quantum decoherence, i.e., mixing with an ordinary vacuum state due to optical losses, is the main sensitivity limit. In this work [1], we present both theoretical and experimental evidence that quantum decoherence in high-precision laser interferometers enhanced with optical cavities and squeezed light injection can be mitigated by a quantum squeeze operation inside the sensor's cavity.

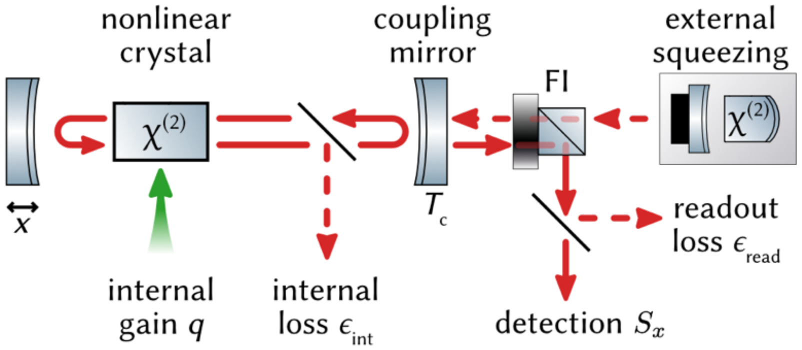


Figure 1: Conceptual representation of a cavity-enhanced sensor with internal and external squeezing. The detector cavity is used to measure the displacement x of the movable end mirror.

Our experiment shows an enhanced measurement sensitivity that is independent of the optical readout loss in a wide range. Our results pave the way for quantum improvements in scenarios where high decoherence previously precluded the use of squeezed light. Our results hold significant potential for advancing the field of quantum metrology and enabling new experimental approaches in wide range of quantum sensors, from table-top to large-scale, such as gravitational-wave detectors[2,3].

References

[1] Korobko, M., Südbeck, J., Steinlechner, S., & Schnabel, R. (2023). Fundamental quantum limit achieved by internal squeezing in cavity-enhanced interferometric measurements. *arXiv preprint arXiv:2303.09983*.

[2] Korobko, M., Ma, Y., Chen, Y., & Schnabel, R. *Quantum expander for gravitational-wave observatories*. Light: Science & Applications, ***8***(1), 1-8 (2019).

[3] Korobko, M, *Taming the quantum noise: How quantum metrology can expand the reach of gravitational-wave observatories.* PhD Thesis, 2020

Two photon ionization of atoms by broadband squeezed states of light

V. P. Kosheleva[1] , S. Panahiyan[1,2,3], A. Rubio[1,4,5], and F. Schlawin[1,2,3]

[1]*Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany*
[2] *The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany*
[3] *University of Hamburg, Hamburg, Germany*
[4]*Center for Computational Quantum Physics (CCQ), The Flatiron Institute, New York, USA*
[5]*Universidad del País Vasco, San Sebastian, Spain*

The two-photon ionization (TPI) is a crucial nonlinear phenomenon in the interaction between light and matter, where an atom absorbs two photons and emits a photoelectron. Over the years, numerous investigations have been carried out on the dependence of the angular distribution of photoelectrons on incoming radiation [1–3]. Recently, bright squeezed vacuum states have become available, which enable the exploration of nonlinear processes with nonclassical light [4]. In this study, we utilize a fully-relativistic Scattering S-matrix formalism to investigate TPI of alkali-like atoms using broadband squeezed states of light. Our results contribute to the understanding and potential manipulation of TPI using non-classical light sources.

References

[1] G. De Ninno, et al., Nature Photonics **14**, 554–558 (2020)
[2] V. P. Kosheleva, et al., Phys. Rev. A **102**, 063115 (2020)
[3] F. Jin, et al., Optics express **29**, 7 (2021)
[4] K. Yu. Spasibko, et al., Phys. Rev. Lett. **119**, 223603 (2017)

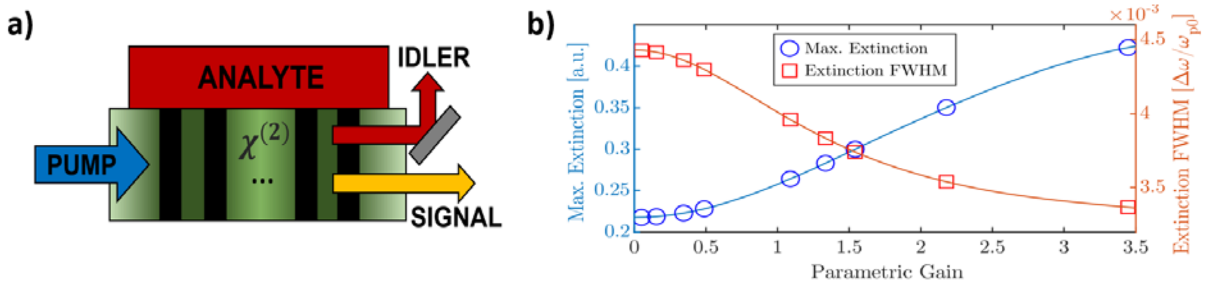
High-gain quantum spectroscopy with undetected photons

A. Krstić[1], **F. Setzpfandt**[1,2] **and S. Saravi**[1]

[1] *Institute of Applied Physics, Abbe Center of Photonics, Jena, Germany*
[2] *Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany*

In recent years, the use of nonclassical light in imaging and spectroscopic applications has attracted much attention. A notable example of "quantum advantage" in spectroscopy is the use of frequency-entangled, non-degenerate photon pairs, where only one of the entangled photons (called *idler*) interacts with the measured sample, but the effects of the sample's dispersion and/or absorption can be studied by detecting the other photon (called *signal*). This method, called quantum spectroscopy with undetected photons (QSUP), can overcome the limited availability of high-sensitivity detectors in certain frequency regions of probe fields interacting with material of interest [1].

Commonly, QSUP relies on distinct entangled photon pairs, obtained, e.g., using spontaneous parametric down-conversion (SPDC) sources operated in the low-gain regime. However, it was recently shown that using sources operating in the high-gain regime, where more than one pair is produced at the same time, can be beneficial in certain quantum-spectroscopic applications [2]. In this work, we investigate the effects of using high-gain SPDC sources in QSUP.



We consider an integrated nonlinear waveguide SPDC source in contact with an analyte whose absorption spectrum is within the frequency range of the idler photons produced in the waveguide, schematically shown in Fig. a). We study the signal photon spectra at the output of the waveguide at different values of parametric gain and observe that the shape of the spectral dip and the corresponding signal photon extinction, caused by the analyte loss, changes with increasing gain, an effect not predicted by low-gain investigations of the same structure [3]. In particular, the maximum extinction *increases* as gain is increased, while its full-width-at-half-maximum (FWHM) *decreases*, as shown in Fig. b). Additionally, both effects show signs of saturation at very high levels of gain.

References

[1] S. K. Lee, et al, Opt. Express **27**, 14853-14870 (2019)
[2] P. Cutipa and Maria V. Chekhova, Opt. Lett. **47**, 465-468 (2022)
[3] P. Kumar, et al, Phys. Rev. A **101**, 053860 (2020)

Adaptively gated single-photon camera for high-dimensional quantum correlation measurements

Sanjukta Kundu, Jerzy Szuniewicz, Grzegorz Firlik, Alexander Krupinski-Ptaszek and Radek Lapkiewicz

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Poland

We present a hybrid intensified camera that combines a high spatial resolution sensor and a high temporal resolution detector with an adaptively-gated image intensifier. This configuration enables control over the number of photons detected within each frame, facilitating spatially resolved single-photon counting measurements at an enhanced data acquisition rates. Our camera effectively measures momentum correlations of photon pairs generated in type-I spontaneous parametric down-conversion (SPDC).

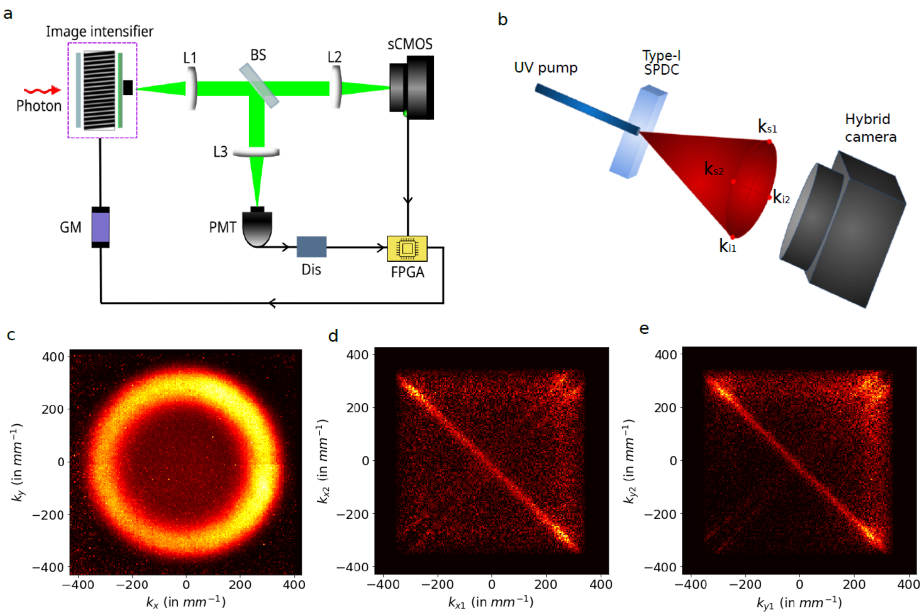


Fig. 1: (a) Schematic of the hybrid camera; (b) Setup for SPDC type - I photon pairs momentum correlation; (c) Intensity distribution of the SPDC-I light in far field configuration; (d) and (e) represent measured two-photon momentum correlations along kx and ky – the subscripts 1, 2 represent signal and idler generated in SPDC.

Mid-infrared spectroscopy with nonlinear interferometers using pump-enhanced SPDC

Jachin Kunz, Chiara Lindner, Simon J. Herr, Sebastian Wolf, Jens Kiessling, Frank Kühnemann

Fraunhofer IPM, Georges-Koehler-Allee 301, 79110 Freiburg Germany

Nonlinear interferometers allow mid infrared spectroscopy with silicon detectors. They are based on light sources that produce correlated photon pairs via spontaneous parametric down conversion (SPDC).

The signal-to-noise ratio with this type of measurements is limited by the amount of SPDC light. For spectroscopic applications we want to increase the SPDC power while staying in the low gain regime, to keep the linear response to light absorption. This can be achieved by enhancing the pump power with an optical cavity, which is only resonant for the pump light [1]. Here, we employ a pump enhanced SPDC source inside of a nonlinear interferometer to perform spectral analysis of a multi-gas sample, with a measurement concept that is analogue to classical Fourier-transform infrared (FTIR) spectrometers.

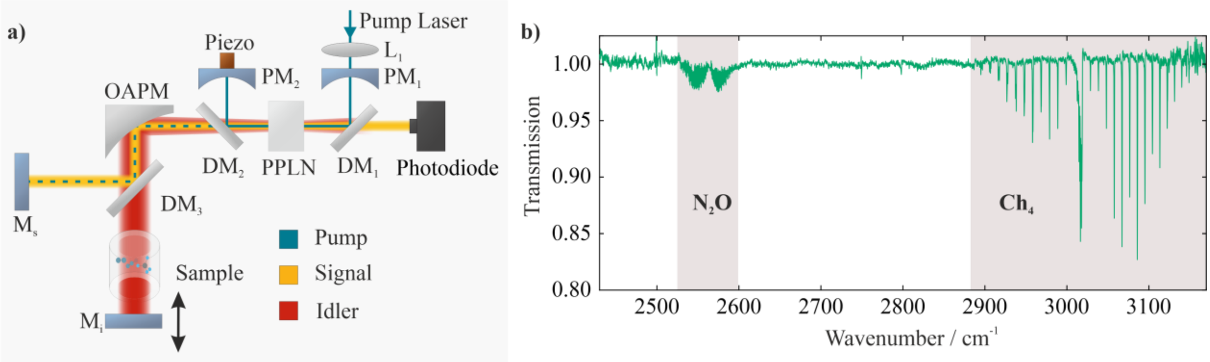


Fig. 1: a) Schematic setup of the nonlinear interferometer with the cavity confined by the two parabolic mirrors $PM_{1/2}$. **b)** Transmission spectrum of the measured gas sample (0.9% N_2O and 0.3% CH_4 in nitrogen).

The correlated photon pairs in the near (signal) and mid infrared (idler) are generated by SPDC in a nonlinear crystal that is placed inside of a cavity, resonant for the 775 nm pump laser (Figure 1a). Signal and idler light are unaffected by the cavity and pass through the dichroic mirror DM_2. The interferometer itself is set up in a Michelson-geometry, with the sample gas cell placed in the idler arm.

In our contribution we will present the improvement of signal-to-noise ratio due to pump enhancement and how this translates to spectroscopic measurements with nonlinear interferometers. High spectral resolution and low noise level show what is possible with this measurement technique.

References

[1] Chiara Lindner et al., High-sensitivity quantum sensing with pump-enhanced spontaneous parametric down-conversion. APL Photonics 1 May 2023; 8 (5): 051301.

Experimental implementation of Fractional Fourier transform for spectro-temporal cat state

Stanisław Kurzyna[1,2], **Bartosz Niewelt**[1,2], **Marcin Jastrzebski**[1,2], **Jan Nowosielski**[1,2], **Wojciech Wasilewski**[2], **Mateusz Mazelanik**[2], **Michał Parniak**[2,3]
1. Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland
2. Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
3. Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark

Fractional Fourier transform (FrFT) is an important tool used in signal processing. It is usually utilized to filter the noise in acoustic signals and it is generalization of Fourier transform. In recent years it was also presented that it has a crucial role in optics, especially mode sorting. One of the important interpretations of FrFT is rotation of the Wigner distribution in time-frequency domain called chronocyclic Wigner function. We have shown that it is possible to perform rotation of arbitrary angle φ coresponding to angle of FrFT. Despite its usefulness, it is still very difficult to perform FrFT in the time-frequency domain. Our experiment is based on the gradient echo memory built around cloud of ultracold rubidium 87 atoms trapped in the magneto-optical trap. The memory protocol uses two-photon Raman transition to store signal pulses in atomic coherence. By applying spatial lens with ac-Stark modulation and imposing two temporal lenses in specific order [1]. We have experimentally performed FrFT in spectro-temporal domain for the cat state [2].

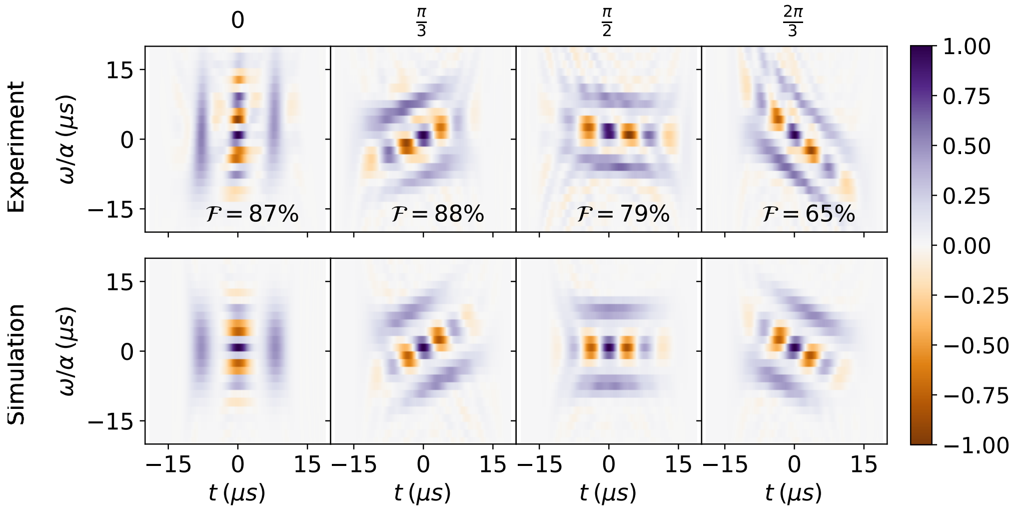


Fig. 1 Wigner functions of two-pulse state rotated by angles $\varphi \in \{0, \frac{\pi}{3}, \frac{\pi}{2}, \frac{2\pi}{3}\}$. The upper row presents the experimental data. The lower row presents the results obtained from numerical simulations, taking into account the atoms' absorption bandwidth and the coupling laser pulse finite duration.

References

[1] Mateusz Mazelanik, Adam Leszczyński, Michał Lipka, Michał Parniak, and Wojciech Wasilewski. Temporal imaging for ultra-narrowband few-photon states of light. *Optica*, 7(3):203–208, Mar 2020.

[2] Bartosz Niewelt, Marcin Jastrzebski, Stanisław Kurzyna, Jan Nowosielski, Wojciech Wasilewski, Mateusz Mazelanik, and Michał Parniak. Experimental implementation of the optical fractional fourier transform in the time-frequency domain. *arxiv*, 2303.13305.

Towards Terahertz Imaging with Visible Photons

M. Kutas[1,2], B. Haase[1,2], F. Riexinger[1,2], J. Klier[1],
G. von Freymann[1,2], and D. Molter[1]

[1] *Department of Materials Characterization and Testing, Fraunhofer ITWM, Kaiserslautern, Germany*
[2] *Department of Physics and Research-Center OPTIMAS, University of Kaiserslautern-Landau, Kaiserslautern, Germany*

We all have become familiar with being able to quickly take a photo with our smartphones. Unfortunately, image capture in other spectral ranges is not as easy as in the visible range. Especially in long-wavelength spectral ranges with low photon energies, for example in the terahertz frequency range, a great effort must be expended to take an image or sometimes only to gain the information of a single pixel. Often, these detectors must be either heavily cooled or are built from expensive and complex laser systems. However, it is this detector problem that has preoccupied many researchers for decades. One possible solution to this problem is a recently evolved quantum-optical imaging method that allows information to be transferred between spectral regions [1]. This principle called “quantum imaging with undetected light” is based on nonlinear interferometers in which pairs of correlated photons, called signal and idler, are created by pumping nonlinear crystals [2]. When signal and idler photons are processed in an appropriate manner, interference between the signal and idler photons from different sources can be observed. The interference of any part of the spectrum depends not only on itself but also on the other parts. Therefore, a change in the optical properties in one of the spectral regions directly affects the interference in the other spectral region. This transfer allows for the usage of sophisticated detectors from the visible range for measurement while using hard-to-detect radiation to study the sample.

We report on our progress towards imaging in the terahertz spectral range using this novel detection principle. Starting from the observation of the nonlinearly generated signal with corresponding idler photons in the terahertz frequency range [3], further developed to the realization of quantum sensing [4] and spectroscopy [5], to our most recent imaging attempts.

References

[1] M. Kutas *et al.*, Adv. Quantum Technol. **5**, 2100164 (2022)
[2] G. Lemos *et al.*, Nature **512**, 409-412 (2014)
[3] B. Haase *et al.*, Opt. Express **27**, 7458-7468 (2019)
[4] M. Kutas *et al.*, Sci. Adv. **6**, eaaz8065 (2020)
[5] M. Kutas *et al.*, Optica **8**, 438-441 (2021)

Optimal quantum metrology of two-photon absorption parameter

A. Karsa[1], R. Nair[2,3], A. Chia[4], K.-G. Lee[5], and C. Lee[1]

[1]Korea Research Institute of Standards and Science, Daejeon, Korea
[2] School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore
[3] Complexity Institute, Nanyang Technological University, Singapore
[4] Centre for Quantum Technologies, National University of Singapore, Singapore
[5] Department of Physics, Hanyang University, Seoul, Korea

Two-photon absorption (TPA) is a crucial nonlinear optical process with significant applications. Despite its importance, precisely measuring and characterizing TPA parameters is challenging due to the weak nature of the process and the discrete nature of light. In this work, we study the use of quantum light to enhance TPA parameter estimation precision. Quantum Fisher information (QFI) is employed to quantify the information about the parameter, leading to a fundamental precision bound through the quantum Cramer-Rao inequality. We optimize discrete variable (DV) quantum states to maximize QFI for given losses, revealing a quantum advantage compared to classical benchmarks. It is shown that the Fock state is optimal for large TPA losses, while a superposition of vacuum and a particular Fock state is optimal for small losses. This differs from single-photon absorption, where the Fock state is optimal across all parameters. For practical relevance, we also investigate the performance of a single-mode squeezed vacuum state. In comparison with the coherent state, the squeezed state outperforms for small TPA losses but underperforms in the intermediate regime and becomes comparable in the large loss limit. These behaviors can be understood by the difference between even and odd number Fock states, which are also analyzed. Interestingly, the QFI for even number states diverges in both large and small loss limits, while that for odd number states diverges only in the small loss limit. We also examine the photon number counting scheme as a practical measurement setup, demonstrating that it offers nearly optimal performance compared to the QFI bound for the studied states in a wide range of TPA losses. This work provides valuable insights into quantum-enhanced TPA parameter estimation, and paves the way for its potential application in TPA imaging techniques.

Mid-IR Quantum Scanning Microscopy with Visible Light

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

[1]*Fraunhofer Institute of Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, D-07745 Jena, Germany*
[2]*Friedrich-Schiller-Universität Jena, Abbe Center of Photonics, Max-Wien-Platz 1, D-07745 Jena, Germany*
[3]*Institute of Applied Physics, Technische Universität Darmstadt, Schloßgartenstraße 6, D-64289 Darmstadt, Germany*
E-Mail: josue.ricardo.leon.torres@iof.fraunhofer.de

Laser scanning microscopy (LSM) is known to be the workhorse for modern life-science, it allows to get new insights into a variety of biological processes. LSM together with illumination in the mid infrared region (Mid-IR) permits to map the chemical composition of samples to a space frame. However, low-light observations in the Mid-IR spectrum are still challenging and a limiting factor for a faster development. A label-free quantum imaging system is presented here, capable of performing the detection in the visible regime, while illuminating the sample with undetected light in the Mid-IR region. Our quantum imaging with undetected light implementation aims to retrieve amplitude and phase images of biological samples containing a variety of functional groups that are present in the Mid-IR region. The point-by-point raster scanning will allow to achieve a better spatial resolution in comparison to the wide-field implementations of quantum imaging with undetected photons [1, 2]. Due to phenomenon of induced coherence without induced emission [3] the illumination can take place in the Mid-IR spectrum and the detection can be carried out with silicon-based technology in the VIS spectrum.

References

[1] M. G. Basset, A. Hochrainer, S. Töpfer, F. Riexinger, P. Bickert, J. R. León-Torres, F. Steinlechner, M. Gräfe, “Video-Rate Imaging with Undetected Photons,” Laser Photonics Rev. **15** 202000327 (2021).
[2] S. Töpfer, M. G. Basset, J. Fuenzalida, F. Steinlechner, J. P. Torres, M. Gräfe, “Quantum holography with undetected light,” Sci. Adv. **8**, eabl4301 (2022)
[4] X. Y. Zou, L. J. Wang, L. Mandel, “Induced coherence and indistinguishability in optical interference, ” Phys. Rev. Lett., **67,** 318 (1991).

Exploring quantum mimicry via classically entangled light for enhanced bioimaging

Hui Min Leung[1] **and Chen-Ting Liao**[1]

[1]*JILA, University of Colorado and NIST, Boulder, Colorado, USA*

There has been growing evidence that quantum illumination via entangled photon pairs can enhance the performance of metrology and imaging (e.g., better resolution, lower the noise floor).[1,2] However, the lack of bright, decoherence-immune quantum illumination severely limits their practical use in many bioimaging and biosensing applications. Our research aims to test the use of classical light to perform quantum mimicry to overcome some of the inherent limitations of quantum imaging. Through the creation of new methods of realizing quantum-inspired classical entanglement, we aim to develop robust, bright quantum-like imaging protocols that could potentially bring quantum advantages to real-world imaging applications. More specifically, our work aims to utilize advance forms of light pulses that possesses properties such as orbital angular momentum (OAM), spin angular momentum, time-varying, and spatio-temporal OAM[3,4], in an interferometric configuration to improve the performance of depth-resolved optical coherence tomography (OCT). The cross-sectional imaging capabilities of OCT has found important usage in the biomedical field, healthcare and non-destructive 3D examination of specimens.[5,6] However, large scattering and absorption remain as fundamental obstacles that limit the amount of information that OCT could extract. Enabling quantum advantages with classical light sources could therefore bring about widespread benefits to the field of optical bioimaging and sensing.

References

1. Magaña-Loaiza, O. S. & Boyd, R. W. Quantum imaging and information. *Reports Prog. Phys.* **82**, 124401 (2019).
2. Okano, M. *et al.* 0.54 μm resolution two-photon interference with dispersion cancellation for quantum optical coherence tomography. *Sci. Rep.* **5**, 18042 (2015).
3. Gui, G. *et al.* Single-Frame Characterization of Ultrafast Pulses with Spatiotemporal Orbital Angular Momentum. *ACS Photonics* **9**, 2802–2808 (2022).
4. Gui, G., Brooks, N. J., Kapteyn, H. C., Murnane, M. M. & Liao, C. T. Second-harmonic generation and the conservation of spatiotemporal orbital angular momentum of light. *Nat. Photonics* **15**, 608–613 (2021).
5. Leung, H. M. *et al.* Intranasal micro-optical coherence tomography imaging for cystic fibrosis studies. *Sci. Transl. Med.* **11**, eaav3505 (2019).
6. Leung, H. M. *et al.* Imaging intracellular motion with dynamic micro-optical coherence tomography. *Biomed. Opt. Express* **11**, 2768–2778 (2020).

Towards Quantum Light Beyond Visible and Infrared Spectra

Chen-Ting Liao

JILA, University of Colorado and NIST, Boulder, Colorado, USA

Advancements in the preparation and control of quantum states have enabled a broad scientific endeavor. There is an anticipation that the principles of quantum entanglement and superposition of light will significantly transform numerous fields with tangible real-world applications such as quantum sensing. Using light for sensing through imaging, microscopy, spectroscopy, and interferometry has been crucial. Quantum imaging, for instance, seeks to leverage the quantum advantage of quantum optical states to surpass the shot-noise limit of conventional imaging. This so-called quantum advantage has been successfully demonstrated in visible and infrared light, imaging cells with a signal-to-noise ratio beyond the classical limit associated with the illumination power. However, practical means for creating quantum light in shorter wavelengths (<100nm) are nearly nonexistent.

Using short-wavelength vacuum-UV (VUV), extreme-UV (EUV), and soft x-ray light, researchers can map out static and out-of-equilibrium band structures of materials, investigate the magnetic and oxidation states with element specificity, penetrate thick samples, and capture ultrafast charge and energy flow across molecular sites and buried interfaces. While most research directions are pursuing ever brighter VUV, EUV, and x-ray light from tabletop or facility setups, those light sources are not conducive to probing many classes of materials, such as dose-sensitive soft matter and live biospecimen. Overcoming this problem requires inventing novel ways to make every photon count—to use the quantum states of light. My current research aims to tackle this challenge by exploring novel approaches to generating nonclassical VUV and EUV light, potentially extending the technologies into the soft x-ray regime in the future.

References

1. A. Rana[†], C. -T. Liao[†] *et al.,* "Three-dimensional topological magnetic monopoles and their interactions in a ferromagnetic meta-lattice," Nature Nanotechnology 18, 227 (2023)
2. X. Shi, C.-T. Liao *et al.,* “Attosecond light science and its applications for probing quantum materials.” Journal of Physics B: Atomic, Molecular and Optical Physics 53 184008 (2020)

Heralded Spectroscopy
a new probe for quantum light emitters

G. Lubin[1] and D. Oron[1]

[1]*Weizmann Institute of Science, Rehovot, Israel*

Emitters of quantum light are at the heart of quantum optic science and a key resource for emerging quantum technologies. Yet, tools to study all but single-photon sources are limited, specifically temporally and spectrally in parallel. A prominent example is multiply-excited semiconductor quantum dots - an intriguing multi-photon quantum system that features rich physics and technological potential but remains elusive to direct observation by existing techniques.

Heralded Spectroscopy is a new type of spectroscopy, tailored to address this challenge. The technique harnesses photon correlations, a resource that has played a seminal role in quantum optics, including this year's Nobel Prize in physics, and is now seeing renewed potential with the maturation of distributed single-photon detection technologies. Specifically, using single-photon avalanche diode array technology allows realizing the first sub-ns, single-photon correlation spectrometer. Combining this groundbreaking capability with a novel temporal-spectral photon correlation analysis allows uncovering hitherto hidden physics of multiple-photon quantum emitters.

Heralded Spectroscopy is applied as the first direct probe of multiply-excited nanocrystals. The method unambiguously determines exciton–exciton interactions revealing correlations with quantum confinement and previously inaccessible dynamical fluctuations. The technique's reach is further demonstrated through expansions to resolve prevalent controversies in perovskite nanocrystals, uncover multiple multi-excitonic species in quantum dot molecules and polarization of multiexcitonic transitions, thus highlighting the outlook for a broad impact on quantum optic science.

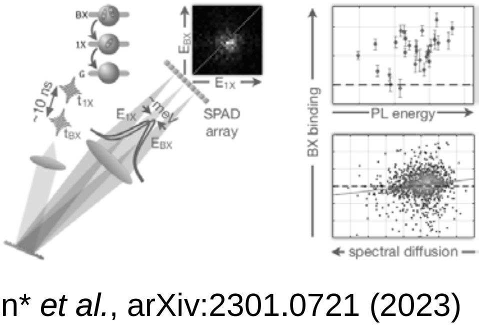


Figure 1: Sketch of the Heralded Spectroscopy setup and examples of extracted insights when applied to emission from quantum dots. Figure reprinted from ref. [4]. *(BX- biexciton, 1X- exciton, GS- ground state, SPAD- single-photon avalanche diode, PL - photoluminescence)*

References

[1] D. Amgar*, G. Lubin* *et al.*, arXiv:2301.0721 (2023)
[2] G. Lubin *et al.*, ACS Photonics **9 (9)**, 2891–2904 (2022)
[3] G. Lubin *et al.*, ACS Nano **15 (12)**, 19581-19587 (2021)
[4] G. Lubin *et al.*, Nano Letters **21 (16)**, 6756–6763 (2021)
[5] G. Lubin *et al.*, Optics Express **27 (23)**, 32863-32882 (2019)

A frequency-domain two-photon interferometer

Felix Mann[1], Marlon Placke[1], Helen M. Chrzanowski[1], Sven Ramelow[1,2]

[1] *Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany*

[2] *IRIS Adlershof, Humboldt-Universität zu Berlin, Berlin, Germany*

Utilizing quantum frequency converters as frequency-domain beamsplitters, several fundamental quantum optical experiments have been carried over into the frequency-domain recently. This includes frequency-domain Hong-Ou-Mandel interference with a single photon and a pulse [1], two single photons [2] or also - using two frequency-domain beamsplitters - Ramsey interference with single photons [3].

Here we present the concept of a frequency-domain two-photon interferometer. The two-photon interferometer in the spatial domain with semi-transparent mirrors as beamsplitters was first performed by [4].

Our experiment consists of a photon-pair source pumped by a blue CW-laser creating pairs at red and telecom and two quantum frequency converters which are used in succession. The converters are set to 50% conversion efficiency defining the splitting ratio of the frequency-domain beamsplitters.

The first beamsplitter creates a bichromatic two-photon NOON state which accumulates a variable phase before entering the second beamsplitter. Behind the second beamsplitter coincidences are measured between red and telecom. A sinusoidal fringe pattern with increased phase-sensitivity is expected.

References

[1] Kobayashi, Toshiki, et al. "Frequency-domain Hong–Ou–Mandel interference." *Nature Photonics* 10.7 (2016): 441-444.

[2] Joshi, Chaitali, et al. "Frequency-domain quantum interference with correlated photons from an integrated microresonator." *Physical Review Letters* 124.14 (2020): 143601.

[3] Clemmen, Stéphane, et al. "Ramsey interference with single photons." *Physical Review Letters* 117.22 (2016): 223601.

[4] Ou, Z. Y., et al. "Experiment on nonclassical fourth-order interference." *Physical Review A* 42.5 (1990): 2957

Quantum infrared spectroscopy in the fingerprint region

Y. Mukai[1], R. Okamoto[1,2], and S. Takeuchi[1]

[1]Department of Electronic Science and Engineering, Kyoto University,
Kyotodaigakukatsura, Nishikyo-ku, Kyoto 615-8510, Japan
[2]Japan Science and Technology Agency, PRESTO, Gobancho, Chiyoda-ku,
Tokyo102-0076, Japan

Quantum infrared spectroscopy (QIRS) based on quantum nonlinear interferometers enables the determination of infrared optical properties only using visible light sources and detectors [1]. The interference of the visible-infrared photon-pair generation processes plays a key role to harness the correlation between the photons with different energies. Thus far, the QIRS measurements have been demonstrated at wavelengths below 5 μm [2] or in the terahertz region [3]. However, QIRS in the fingerprint region, which is considered an important spectral region for IR spectroscopy (approximately 6.6 to 20 μm), has not been realized.

In this study, we developed a QIRS system that utilizes $AgGaS_2$ crystal for highly nondegenerate photon-pair generation and operates in the fingerprint region. As an experimental demonstration, we measured the complex transmittance spectrum of a fluoropolymer sheet, polytetrafluoroethylene (PTFE), by applying the quantum Fourier-transform infrared spectroscopy (QFTIR) method [4] over a wide FIR range of 8 to 10.5 μm. As shown in Fig. 1, we observed characteristic absorption dips of the PTFE sheet due to C-F bond stretching modes [5]. In the presentation, we will discuss the details of the experimental result including the phase information obtained by QFTIR analysis.

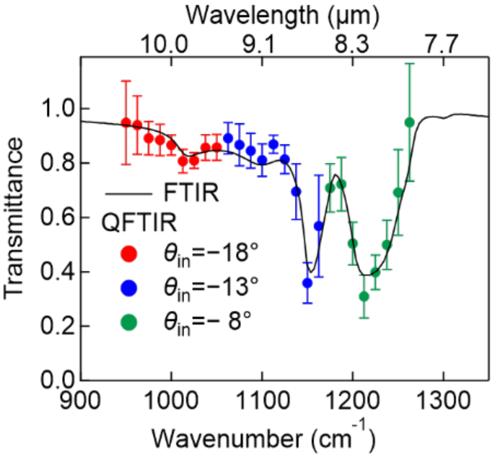


Figure 1 Transmittance spectrum of PTFE film measured by QFTIR (circle) and conventional FTIR method (line)

This work is supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067634, Cabinet Office, Government of Japan, Public/Private R&D Investment Strategic Expansion Program (PRISM), JSPS KAKENHI Grant Number 21H04444, and JST-PRESTO (JPMJPR15P4).

References

[1] D. A. Kalashnikov, A. V. Paterova, S. P. Kulik, and L. A. Krivitsky, Nat. Photonics **10**, 98 (2016) [2] C. Lindner, S. Wolf, J. Kiessling, and F. Kühnemann, Opt. Express **28**, 4426 (2020) [3] M. Kutas, B. Haase, P. Bickert, F. Riexinger, D. Molter, and G. von Freymann, Sci. Adv. **6**, eaaz8065 (2020) [4] Y. Mukai, M. Arahata, T. Tashima, R. Okamoto, and S. Takeuchi, Phys. Rev. Appl. **15**, 034019 (2021) [5] Y. Mukai, R. Okamoto, and S. Takeuchi, Opt. Express **30**, 22624 (2022)

Quantum-inspired frequency-agile optical source for covert rangefinding

W. Nie[1], P. Zhang[1], A. McMillan[1], and J.G. Rarity[1]

[1]*Quantum Engineering Technology (QET) Laboratories,*
Department of Electrical and Electronic Engineering, University of Bristol,
Woodland Road, Bristol BS8 1US, United Kingdom

Rangefinding for distance measurements has been widely applied in the fields of security, military, navigation, civil engineering and construction. In existing applications, the classical bright pulsed laser is widely employed as an optical source in rangefinder platforms for measuring the distance by detecting weak pulses of light reflected from the target. In recent years the advantages of detecting single photon returns have been realized for low light rangefinding and sensing. However, the high-brightness pulses of narrow-bandwidth laser light is easily distinguished from the thermal solar background. In contrast, quantum rangefinding has been proposed where a pair photon source is used to create broad band heralded single photons indistinguishable from a thermal, low-brightness background [1], essentially covert and replacing the classical source with quantum illumination. The signal-to-noise ratio can be enhanced in high background scenarios by heralding single photon time and frequency exploiting the strong correlations of time and energy within the entangled photon pair [2]. However, even when exploiting multiple frequency channels, the source brightness is much lower than typical laser sources, limiting the operating range in real-world application.

Inspired by this quantum rangefinding, we are developing a frequency agile pseudo-random coded light source mimicking the broad wavelength band of thermal light in order to improve the brightness whilst retaining other advantages. We will show results from a proof-of-principle, spread-spectrum rangefinder by dispersing the broad band optical pulse in time and carving out three wavelength channels using an electro-optic modulator with suitably delayed drive pulses. The resulting temporally encoded wavelength pulses are re-compressed into a single pulse. We have incorporated this source into a rangefinder and are testing the system by illuminating a Lambertian target at various ranges to demonstrate the feasibility of this covert rangefinding scheme. The brightness is orders of magnitude brighter than the quantum source while lower than the solar background, leading to longer-distance covert measurements.

References

[1] S. Frick, A. McMillan, and J. G. Rarity, Opt. Express **28**, 37118 (2020)
[2] S. Lloyd, Science **321**, 1463-1465 (2008)

Classical and Entangled Two-Photon Absorption in Atoms and Molecules

Michael Stiven Caracas Núñez, Miguel Ángel González Jaimes, Ana Maria Torres Nova, Alejandra Valencia, Mayerlin Nuñez Portela

[1]Laboratorio de Óptica Cuántica, Universidad de los Andes, A.A. 4976, Bogotá, D.C., Colombia.
Email: m.nunez@uniandes.edu.co

The Two-photon absorption processes (TPA) is currently of great interest due to its variety of technical applications. Two-photon transitions can be excited using light with different properties such as laser light, pseudo-thermal light and entangled photons pairs (ETPA). In particular the ETPA process has promising applications in different fields due to its linear dependence with the photon flux. However, results of different ETPA experiments have many questions regarding the difficulty to distinguish an ETPA signal from single photon losses when measuring in organic molecules. In order to understand the characteristics of the TPA process with different light sources, the classical TPA cross section must be measured.

In this work we present experimental values of the classical TPA cross section for cesium atoms. These are compared with theoretical ones obtained by means of second order perturbation theory. These values are the starting point for experiments of ETPA in cesium atoms. Additionally, measurements of the ETPA cross section in Rhodamine B using a coincidence detection scheme are presented. The ETPA cross section is quantified considering the effects of single photon losses in the experiment and considering parameters that are linear-loss independent. The results suggest that it is possible to witness an ETPA signal when measuring coincidences.

Quantum-enhanced Stimulated Raman Scattering with squeezed states of light

S. Panahiyan[1,2,3] **and F. Schlawin**[1,2,3]

[1]Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany
[2] The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, Hamburg D-22761, Germany
[2] University of Hamburg, Luruper Chaussee 149, Hamburg, Germany

The unique features of non-classical sources of light, namely quantum correlations, enable us to surpass the limits of classical sensing and enhance the detection of physical parameters. Squeezed light, as a non-classical source of light, has reduced quantum fluctuations at one quadrature at the expense of increased fluctuations in the other quadrature. This feature can provide an improved signal-to-noise ratio [1], hence improve the measurement precision of different light-matter interactions such as multiphoton absorption [2,3]. Motivated by this, we utilize the squeezed light to improve Stimulated Raman Scattering (SRS) spectroscopy. SRS is a real-time vibrational imaging of living cells and organisms technique [4,5]. In this technique, two laser beams (pump and probe) excite a selected molecular vibration of the sample. This is done by the annihilation of a photon from the pump beam and, the creation of a Raman-shifted photon in the background noise of the probe beam. We investigate different scenarios in which one or both of the pump and probe beams are squeezed light fields and find the conditions to maximally enhance SRS spectroscopy.

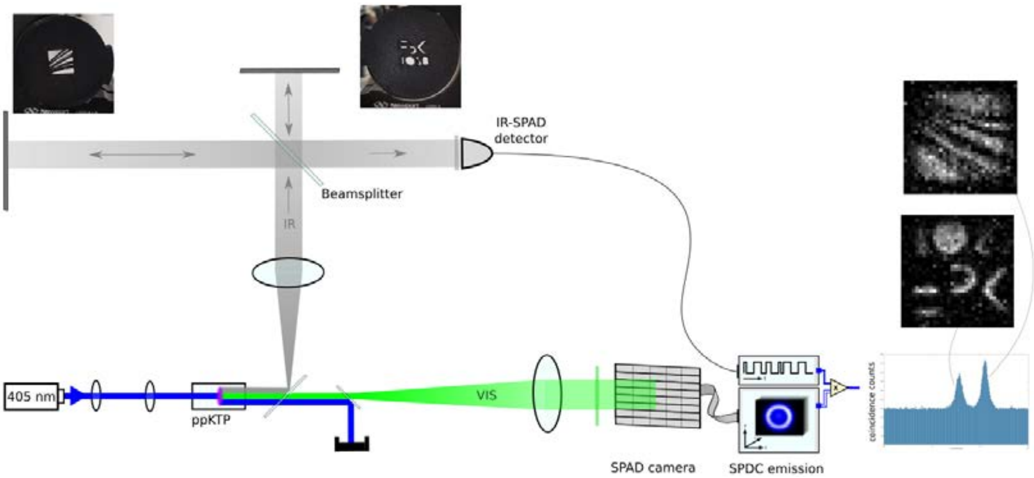
References

[1] B. J. Lawrie et al., ACS Photonics 6, 6, 1307 (2019).
[2] S. Panahiyan et al., Phys. Rev. A 106, 043706 (2022).
[3] S. Panahiyan et al., accepted for publication in PRL [arXiv:2209.02697].
[4] R. B. de Andrade et al., Optica 7, 470 (2020).
[5] C. A. Casacio et al., Nature 594, 201 (2021).

3-Dimensional Quantum Ghost Imaging

Carsten Pitsch[1,2] **Dominik Walter**[1], **Helge Bürsing**[1] **and Marc Eichhorn**[1,2]

[1]*Fraunhofer IOSB, Gutleuthausstr. 1, 76275 Ettlingen*
[2]*Karlsruhe Institute of Technology (KIT), IRS-Optronik, Fritz-Haber-Weg 1, 76131 Karlsruhe*



Quantum Ghost Imaging (QGI) is a highly promising imaging technique, which exploits both the temporal and spatial correlation of entangled photon pairs to allow imaging without a camera in the regime of interest. The scheme uses the temporal correlation of the pair to identify entangled partners, one of which is sent to an object for interaction (idler) and detected only temporally. From the spatial correlation of the pair, an image of the object is obtained when only the identified partner photons (signal) are recorded.

Usually the identification of entangled photon pairs is done by a heralding scheme, in which the detection of the interacting photon starts the measurement of the partner. However, due to signal delays and image-preservation constraints involved, heralding limits the capabilities of these setups, especially in the field of remote sensing. We present here an approach on QGI by asynchronous detection, overcoming these limitations.

Our approach, shown in [1], relies on a SPAD imager, allowing single photon detection in both time and space, and TCSPC electronics. TCSPC is needed in order to allow referencing the detections of the SPAD, which are always referenced to the start of its measurement window, and the detections of the interacting photon. Thereby, the start of each measurement is tracked in the same timebase as the detections of the interacting photons, allowing coincidence detection in a global timebase. In addition, it enables direct retrieval of Time of Flight (ToF) information via the interacting photon and thus 3D acquisition.

Here we present our first results for 3D imaging with this scheme [2], achieving a timing resolution of ~1ns, corresponding to a depth resolution of ~10cm at a spatial resolution of 32 ×32 pixels.

References

[1] Carsten Pitsch, Appl. Opt. **60**, F66-F70 (2021)
[2] Carsten Pitsch, Optica Open, „3D Quantum Ghost Imaging“, (2023)

Mid-IR hyperspectral imaging with undetected photons

Marlon Placke,[1] **Chiara Lindner**,[2] **Inna Kviatkovsky**,[1] **Helen M. Chrzanowski**,[1] **Frank Kühnemann**[2] **and Sven Ramelow**[1]

[1] *Physics Institute, Humboldt University Berlin, Newtonstraße 15, 12489 Berlin, Germany*

[2] *Fraunhofer Institute for Physical Measurement Techniques IPM, Georges-Köhler-Allee 301, 79110 Freiburg, Germany*

Mid-infrared (mid-IR) light has long held the promise of a new perspective for scientific and industrial imaging tasks - with the potential to obtain highly specific information on the composition of a sample without the need for labeling. Its manifestation as a cornerstone of imaging technologies has, however, been hampered by the technical challenges that arise with such long wavelengths; notably the absence of low-noise, high-performance, and inexpensive (multi-pixel) detection technologies. One approach that has seen growing interest utilizes quantum nonlinear interferometry to circumvent these limitations, namely quantum imaging with undetected photons (QIUP). While the existing work on this approach has shown the potential for imaging and microscopy in the mid-IR [1], experiments towards hyperspectral imaging have been limited to multi-spectral imaging based on narrowband, tunable emission [2] or consecutive filtering [1].

In this work, we combine the techniques of wide-field QIUP and Fourier-transform infrared (FTIR) spectroscopy [3, 4] for true hyperspectral imaging. This new approach enables us to record the hyperspectral cube of wavelength-resolved mid-IR images while eliminating the need for costly focal-plane mid-IR detectors, harnessing the maturity of CMOS and CCD technologies in the near-IR.

References

[1] I. Kviatkovsky et al., Sci. Adv. **6**, eabd0264 (2020)
[2] A. V. Paterova et al. Sci. advances **6**, eabd0460 (2020)
[3] C.Lindner et al., Opt. Express **28**, 4426–4432 (2020)
[4] C.Lindner et al., Opt. Express **29**, 4035–4047 (2021)

Integrated bright broadband PDC source for quantum metrology

R. Pollmann, **F. Roeder, V. Quiring, R. Ricken, C. Eigner, B. Brecht, and C. Silberhorn**
Paderborn University, Integrated Quantum Optics,
Institute for Photonic Quantum Systems (PhoQS),
Paderborn, Germany
E-Mail: Rene.Pollmann@upb.de

Broadband quantum light is a vital resource for quantum metrology applications such as quantum spectroscopy, quantum optical coherence tomography or entangled two photon absorption. For entangled two photon absorption especially, very high brightness combined with high spectro temporal entanglement is crucial to directly observe the absorption. So far, these conditions have been met by using high power lasers driving bulk degenerate type 0 spontaneous parametric down conversion (SPDC) sources. This naturally limits the available wavelength ranges and precludes deterministic control over the output state. In this work we show an integrated two colour SPDC source utilising a group-velocity matched lithium niobate waveguide, reaching both high brightness ($> 1.14 \cdot 10^{12}$ pairs/Ws) and large bandwidth (> 7 THz) while using less than 5 mW of continuous wave pump power. Since the product of the measured correlation time of the photons $\Delta\tau \approx 120$ fs and the pump bandwidth of $\Delta\omega_p \ll 1$ MHz violates the classical Fourier limit, the source shows very strong time frequency entanglement. Since this source is easily adapted to a wide range of central wavelengths, it promises to become a valuable tool for many quantum metrology applications.

Efficient OPA tomography

Éva Rácz[1], **László Ruppert**[1] **and Radim Filip**[1]

[1] *Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic*
E-mail: racz@optics.upol.cz

Building on the experimental results by Kalash et al. [1], we propose a generalization of their approach to estimating the quadrature distribution via optical parametric amplification. The key idea is that if one sufficiently amplifies the input state in a specific direction, the obtained photon-number distribution is a good proxy for the distribution of the square of the quadrature variable corresponding to that direction. Our method significantly broadens the range of applicability of OPA tomography since it allows for non-symmetrical input states by adding a displacement step to the scheme. This additional step also reduces estimation inaccuracies arising from detector dark noise. Consequently, our proposal also remarkably improves the distillation of squeezing, which is highly affected by dark noise.

Using a simplified model of the process, including noises, we numerically explored what ranges of parameters are optimal for different types of input states: squeezed states, mixtures of squeezed states, and Fock states $|1\rangle$ and $|2\rangle$. We can conclude that increasing OPA gain is unnecessary beyond a certain level. Furthermore, the displacement step improves estimation accuracy even for symmetric input states and relatively small displacement values. We also found that our method is fairly robust against different experimental imperfections.

Overall, we achieve a significant improvement in both the applicability and the accuracy of OPA tomography. Hopefully, our results will inspire the field, as pre-amplification with nonlinear crystals is a viable alternative to classical approaches in many scenarios.

References

[1] Mahmoud Kalash and Maria V. Chekhova. Wigner function tomography via optical parametric amplification, 2023, arXiv: 2207.10030.

The role of vibrational molecular structure in entangled two photon absorption: Perturbation theory limits

C. D. Rodríguez-Camargo[1] **and A. Olaya-Castro**[1]

[1]*Atomic, Molecular, Optical and Positron Physics (AMOPP) Group,*
Department of Physics and Astronomy,
University College London, London WC1E 6BT, United Kingdom

Entangled two photon absorption (ETPA) processes of a variety of atomic and molecular systems are currently the subject of intense research because of the potential of investigating such systems at lower fluxes and its possible applications to spectroscopy and microscopy. By utilizing photon-pairs in non-separable quantum-correlated states, photo-sensitive samples can be activated at much lower fluxes than standard laser light. While there has been significant theoretical and experimental work, fundamental questions remain unanswered. For instance, although theory has been successful in describing ETPA in simple systems, it is still unclear how the specific microscopic electronic-vibrational structure affects ETPA and what are the accuracy limits of perturbation theory when strong system-matter correlations emerge. In this work, we compare the obtained results by solving numerically the complete Schrödinger equation, which describes the two-step excitation of a diatomic molecular system by ultrabroad-band frequency entangled photons when the vibrational structure of matter is considered, and the results when second order perturbation theory (SOPT) is applied. We model the vibrational structure with Morse potentials and compare with harmonic potentials. By exploring the vibrational populations, we show that this potential choosing, and the photon entanglement, have an important influence in the selectivity and coherent control of the population of a single vibrational mode of the excited state, which is chosen to be resonant with the total energy of the incident field. Within the analytical expressions obtained with SOPT, we show where we could be losing important information when we deal with strong quantum correlations.

References

[1] H. Oka, Phys. Rev. A **97**, 063859 (2018).
[2] M. G. Raymer, T. Landes, and A. H. Marcus, J. Chem. Phys. **8**, 081501, (2021).
[3] F. Schlawin, and A. Buchleitner, New J. Phys. **19**, 013009, (2017).

Bi-photon correlation time measurements with a two-colour broadband SU(1,1) interferometer

F. Roeder[1], R. Pollmann[1], M. Stefszky[1], M. Santandrea[1], K.-H. Luo[1], V. Quiring[1], R. Ricken[1], C. Eigner[1], B. Brecht[1] and C. Silberhorn[1]

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

SU(1,1) or nonlinear interferometers have lately been used for several applications such as achieving super-sensitivity for quantum metrology or enabling spectroscopy and imaging with undetected photons [1-3]. So far, most of the developed interferometers are based on parametric down-conversion (PDC) from bulk crystals, limiting the brightness of the sources as well as integrability. Furthermore, only spectral or temporal interferograms have been investigated so far in one experiment. Here, we demonstrate spectral and temporal interferometry using an SU(1,1) interferometer based on ultra-broadband, non-degenerate dispersion-engineered parametric down-conversion in nonlinear waveguides. These PDC sources exhibit strong frequency correlations and, simultaneously, sub-100 fs photon-photon correlation times. These are challenging to measure as classical characterization techniques based on nonlinear processes, e.g., FROG, are not suitable at such low light levels.

We are therefore employing an SU(1,1) interferometer comprising two such PDC sources and measure spectral and temporal interferograms for different spectral shapes of the bi-photon and varying amounts of second order dispersion in the setup. We observe a good agreement with our theoretical predictions for different underlying spectral shapes of the bi-photon, which enables us to determine the correlation time of our photon pair source from these measurements. This does not only allow us to confirm the predicted correlation time without external dispersion, but also for the case of the measured non-vanishing dispersion as it is present in the actual setup. The knowledge about the correlation time is essential for further applications such as entangled two-photon absorption. Here, our results allow us to predict and maximize absorption cross sections. Having calibrated our interferometer, we can perform spectroscopy using only spectrally non-resolved temporal measurements with cheap avalanche single-photon detectors, only requiring knowledge about the underlying bi-photon spectrum.

References

[1] C. Lindner et al, Opt. Express **29**, 4035 - 4047 (2021).

[2] G. Lemons et al, Nature **512**, 409 - 412 (2014).

[3] P. Kaufmann et al, Opt. Express **30**, 5926 - 5936 (2022).

The “squeeze laser” and its applications

A. Schönbeck[1], **J. Südbeck**[1], **J. Zander**[1] **and R. Schnabel**[1]

[1]*Institut für Laserphysik, Hamburg, Germany*

High-precision laser interferometric measurements use quasi-monochromatic light with the Fourier spectrum of the signal band in the ground state (vacuum state). If the technical laser noise is not relevant, the measurement sensitivity can be further increased by increasing the light power and/or by extending the measurement time. Increasing the measurement time is generally not possible with transient signals. The scaling of the light power quickly reaches practical limits. Replacing vacuum states with squeezed vacuum states is a quantum technology. It improves the measurement sensitivity without increasing the power of the quasi-monochromatic carrier light. In 2010, the light output in the GEO600 gravitational wave detector could no longer be increased easily. Since then, the measurement sensitivity has been improved by squeezed light [1]. What is called a “squeezed vacuum source”, we call here a “squeeze laser” [2]. The *squeeze factor* quantifies by how much the squeezed states reduce the power spectral density of a laser interferometric measurement device beyond the vacuum noise reference. The power spectral densities of table-top laser interferometers were improved by a factor of 10 (10 dB) recently [3]. Potential new applications of squeezed vacuum states are manifold:

1) Laser light is used for analysing sensitive samples such as biological probes. Too high light power may destroy the sample under investigation [4].
2) Laser light is used for reading out tiny sensors. Absorbed laser light increases the temperature, reduces the resonance frequencies as well as the quality factors [5].
4) Squeezed states that experience optical loss become a mixed squeezed state. The “mixedness” is quantified by the product of the squeezed and anti-squeezed uncertainties. The increase of the uncertainty product was used for the absolute calibration of photo sensors [6].

References

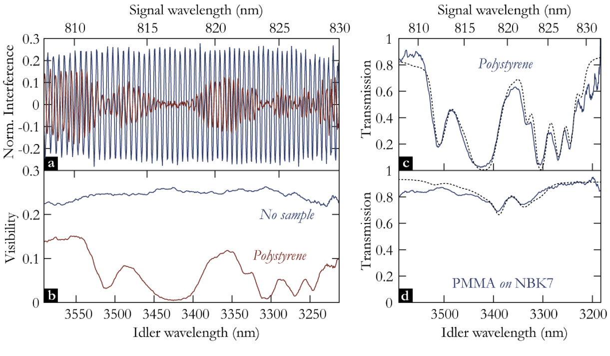
[1] The LIGO Scientific Collaboration, Nature Physics **7**, 962-965 (2011)
[2] R. Schnabel et al., IEEE Transactions on Quantum Engineering **3**, 1-9 (2022)
[3] J. Zander et al., Quantum Science and Technology **8**, 01LT01 (2023)
[4] C.A. Casacio et al., Nature **597,** 201-206 (2021)
[5] L. Kleybolte et al., Phys. Rev. Lett. **125,** 213601 (2020)
[6] H. Vahlbruch et al., Phys. Rev. Lett. **117**, 110801 (2016)

Enhanced Microplastic and Biosample Analysis using Mid-IR Spectroscopy with Undetected Photons in the 2900 cm-1 Window

A.Sherwani[1] **and S. Ramelow**[1,2]

[1] *Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany*
[2] *IRIS Adlershof, Humboldt-Universität zu Berlin, Berlin, Germany*

Microplastics are small, insoluble plastic particles that range in size from 1 to 10 microns. Despite their size, they pose a significant threat to the environment and biological systems, as they can enter the food chain and have harmful effects on wildlife and human health. Currently, FTIR and Raman spectroscopy are the most widely used techniques for identifying plastic polymers and biological samples, due to the presence of signature molecular and functional groups. However, these techniques have limitations when it comes to the detection of microplastics. Upgrades to the equipment are often necessary, which can be costly and time-consuming, and the low sampling rates and tedious sample preparation make these techniques less effective for microplastic analysis. A new technique called mid-IR spectroscopy with undetected photons has emerged as a promising alternative for microplastic analysis. This technique uses specially designed crystals to achieve high detection resolution without the technical limitations of optical detectors and sources, and has a high sampling rate, allowing for quick and efficient analysis. This research aims to demonstrate the effectiveness of this technique in identifying harmful microplastic particles in the environment and in the spectroscopic analysis of biological samples. By introducing more robust and reliable techniques for the analysis of microplastics, we can enhance our ability to accurately assess the impact of microplastics on the environment and human health. This will enable us to develop more effective strategies for mitigating this growing threat and promoting sustainable practices.



References

1. P. Kaufmann et al, Opt. Express **30**, 5926-5936 (2022)

On the validity of the Gaussian approximation of SPDC bi-photon states for quantum imaging based on position correlations

René Sondenheimer[1,2] **and Marta Gilaberte Basset**[2,3]

[1] *Institute of Solid State Theory and Optics, Friedrich-Schiller-University Jena,*
Max-Wien-Platz 1, 07743 Jena, Germany
[2] *Fraunhofer Institute for Applied Optics and Precision Engineering,*
Albert-Einstein-Strasse 7, 07745 Jena, Germany
[3] *Institute of Applied Physics, Friedrich-Schiller-University Jena, Abbe Center of*
Photonics, Albert-Einstein-Str. 6, 07745 Jena, Germany

E-mail: rene.sondenheimer@uni-jena.de
marta.gilaberte.basset@iof.fraunhofer.de

The resolution of quantum imaging with undetected photons is governed by spatial correlations of bi-photon states that are usually generated via spontaneous parametric down conversion (SPDC). Due to the intricate momentum dependency of the SPDC state, it is a nontrivial task to find a closed form expression for the joint probability density of the bi-photon when exploiting position correlations. However, this is crucial for a comprehensive understanding of the underlying physics, e.g., for determining resolution limits. Such quantities are usually studied in an approximative fashion. Commonly, the sinc structure, emerging from phase matching, is approximated by a Gaussian which can provide a first qualitative understanding. In order to improve predictions towards a quantitative level, the properties of the full sinc function have to be taken into account. On the one hand, this can be done numerically. However, this will be computationally cost inefficient if one is interested in many different parameter constellations. On the other hand, one could try to find improved models, e.g., a cosine-Gauss approximation that is able to catch additional information of the momentum dependencies. We will show that such extensions can suffer from two points. First, it is difficult to setup a scheme such that the approximate solution converges towards the solution obtained from the proper sinc-type SPDC state. Therefore, one has to deal with an inherent error whose impact is nontrivial to estimate. Second, albeit one might obtain higher fidelities for certain optimization parameters, we will demonstrate that situations can occur where the actual physics is not properly reflected within the approximated state. Eventually, we will introduce a new scheme that allows to circumvent these problems by systematically increasing the fidelity with higher approximation orders. We will apply this scheme to derive quantitative resolution limits for quantum imaging with undetected photons.

Mid-infrared frequency-domain optical coherence tomography with undetected photons

A. Vanselow[1,2], H. Chrzanowski[1,2], S. Ramelow[1,2] and R. Swarnkar

[1,2] Institut für Physik, Humboldt-Universität zu Berlin, Germany

Optical coherence tomography (OCT) is a well-established widely used non-invasive imaging technique that provides morphological information of sub-surface structures of the materials. This technique has found extensive use in biomedical imaging, particularly in acquiring 3D images of the human retina using near-infrared (near-IR) light. However, for non-destructive testing of strongly scattering materials such as ceramics and paint, OCT in the mid-IR range remains a challenge due to the lack of efficient detectors and cost-effective light sources. In this contribution, we summarize results on a novel approach to overcome these limitations using nonlinear interferometry based on quantum interference and correlated photon pairs, which we refer to as ”OCT with undetected photons”. We present an overview and the working principle and the implementation of this technique, which can offer significant advantages over previous time-domain implementations in terms of signal-to-noise ratio, stability, and speed as well as axial resolution reaching 10 µm. Moreover, our efficient detection requires only very low power levels of 200 pW on the sample, making it suitable for very sensitive biological samples or sensitive art works. In contrast, classical approaches use 20 mW, which is 10^8 times more. We demonstrate the applicability of our approach by scanning ceramics, which are materials of high practical relevance, and obtaining convincing images of these samples. We conclude from results that there are distinct advantages over classical approaches to mid-IR OCT, while being much simpler in terms of source and detection technology. Our results show that OCT with undetected photons is now a practical technology ready to enter commercial development.

References

[1] A. Vanselow, et.al., Optics Letters **44(19)**, 4638–4641 (2019)
[2] A. Vanselow, et.al., Optica **7(12)**, 1729–1736 (2020)

Image Distillation in Quantum Holography with undetected Light

J. Fuenzalida[1,2,*] and M. G. Basset[1,3,*] and S. Töpfer[1,2,*]
and J. P. Torres[4,5] and M. Gräfe[1,2,3]

[1]Fraunhofer Institute for Applied Optics and Precision Engineering IOF,
Albert-Einstein-Str. 7, 07745 Jena, Germany.
[2] Institute for Applied Physics, Technical University of Darmstadt,
Schloßgartenstraße 7, 64289 Darmstadt, Germany
[3]Friedrich Schiller University Jena, Abbe Center of Photonics,
Albert-Einstein-Str. 6, 07745 Jena, Germany
[4]CFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology,
08860 Castelldefels, Spain
[5]Dept. Signal Theory and Communications, Universitat Politecnica de Catalunya,
08034 Barcelona, Spain.
**These authors contributed equally*

Quantum imaging with undetected photons [1] has undergone fast development in the recent years. Because of this, it is possible that first applications for challenges outside the optical lab will emerge in the foreseeable future. This leads to an interest on how external factors influence this measurement scheme. In this work we studied the effect of external optical noise on the measurement accuracy of the quantum holography with undetected light scheme [2]. In this technique, the sample information is calculated from the recorded interferometric pattern, instead of the intensity images directly, which makes it intrinsically resilient to external noise. We show experimentally, that it is possible to extract the sample information, even if the external noise has an intensity 250 times higher than the measured signal light (see Fig.1) [3]. We believe this result gives important insights towards the applicability of quantum holography with undetected light.

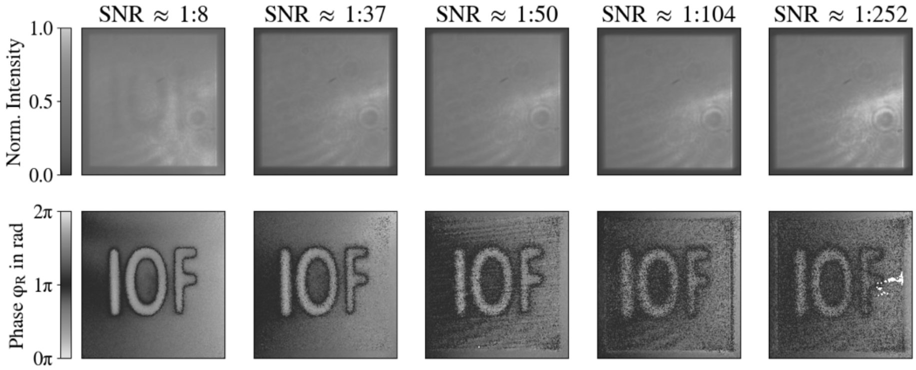


Figure 1: **Experimental Image Distillation.** Distillation results for noise intensities up to 252 times higher than the signal intensity, vgl. [3].

References

[1] G.B. Lemos et al., Nature, **512(7515)**, 409–412 (2014)
[2] S. Töpfer et al., Science Advances, **8**, 2 (2022)
[3] J. Fuenzalida et al, arXiv:2301.02529

Encoding images in quantum correlations of photons

<u>Chloé Vernière[1]</u> and Hugo Defienne[1]

[1] *Institut des Nanosciences de Paris, Sorbonne Université, Paris, France*

Quantum entanglement is a key property that allows to transmit information in a secure way. In this respect, entangled photons correlations can be used to carry information that classical intensity measurements cannot reveal. In this work, we explore the possibility of encoding and retrieving information in the second order correlations of spatially-entangled photon pairs produced by type-I spontaneous parametric down conversion in a β-barium borate non-linear crystal. The image of a real object is encoded in the photons correlations by directly imaging its Fourier transform onto the crystal. Photon pairs are thus only generated at positions corresponding to the Fourier transform of the object, which then appears in the correlation measurements. After propagation, photons are detected using an Electron Multiplier Charge-Coupled Device camera to reveal the correlation-encoded image. This information remains undetectable for intensity measurements. Our approach enables the transmission of complex, high-dimensional information using in quantum correlations of photons, which can be useful for developing quantum communication and imaging protocols.

Quantum-inspired multidimensional spectroscopy

Zhengjun Wang[1, 2] **and Frank Schlawin**[1, 2]

[1]*Max-Planck-Insitute for the Structure and Dynamics of Matter, Hamburg, Germany*
[2] *University of Hamburg, Hamburg, Germany*

Abstract

Recently, multidimensional spectroscopy techniques have been developed to characterize quantum states of matter. In addition, it is still very difficult to use quantum light to realize multidimensional quantum spectroscopy in experiments due to the weakness of quantum signals. This work presents a new measurement for quantum spectroscopy. we use a mapping of the quantum signal from the 2D spectroscopy setup to represent these quantum light effects.

References

[1] M. Kira, S. W. Koch, R. P. Smith, A. E. Hunter and S. T. Cundiff. Quantum spectroscopy with Schrödinger-cat state. *Nature Physics*, 7. 799-804 (2011).

Entangled two-photon absorption in 2D semiconductors

Till Weickhardt[1] **and Giancarlo Soavi**[1,2]

[1]Institute of Solid State Physics, Jena, Germany
[2] Abbe-Center of Photonics, Jena, Germany

Transition metal dichalcogenides (TMDCs) are a class of van der Waals layered semiconductor materials which, in the thickness limit of a single layer, have a direct bandgap. Due to the resulting quantum confinement in two dimensions, excitons (bound electron-hole pairs) dominate the optical transitions even at room temperature. These exciton states lead to resonant enhancement of second harmonic generation (SHG) and two-photon absorption (TPA) with huge cross sections and have been proposed as gates for valleytronics.[1] To generate detectable populations of excitons in two photon processes with classical light and not damaging the monolayer it is necessary to use a pulsed laser with a consequently broad spectrum. This limits the energy resolution of any experiment. In this work, we propose a possible way to solve this problem by using energy entangled photons from collinear spontaneous parametric down conversion (SPDC). This way, the photons are temporally synchronized in pairs and sum up to a precise and narrow energy spectrum while the distribution of single-photon energies can be broad.[2] This leads to higher efficiencies for TPA combined with spectral resolution beyond the Fourier limit. Entangled two-photon absorption (ETPA) has been demonstrated in fluorophores but never in solid-state systems.[3] If successful, ETPA in TMDCs could therefore also help to illuminate the process of ETPA itself. To achieve this, two experimental requirements must be met: (i) a tunable narrowband laser to precisely hit the excitonic resonances of the TMDC under investigation. (ii) a SPDC source with high photon-pair flux, leading to an average power of at least 100nm-1µW. While these requirements have already been met in our labs, first measurements of ETPA in TMDCs are still pending at this stage.

References

[1] Wang et al., Reviews of Modern Physics **90**, 021001 (2018)
[2] Dayan et al., Physical Review Letters **94**, 043602 (2015)
[3] Tabakaev et al., Physical Review A **103**, 033701 (2021)

Precise sensing via quantum weak measurement

<u>X.-Y. Xu</u>[1], G. Chen[1] and C.-F. Li[1]

[1]*Key Laboratory of Quantum Information, University of Science and Technology of China, CAS, Hefei 230026, People's Republic of China*

Weak values of observables have extensive applications in both fundamental and technical aspects, as they can take values beyond the eigenspectrum of the observables and can even be complex numbers. In the former, weak values are used to directly measure the quantum wave function, while in the latter, they are used for weak value amplification. In this study, we demonstrate that high-precision phase estimation can be achieved using a commercial light-emitting diode, based on weak value amplification. This method yields a sensitivity equivalent to detecting light pulses of the order of an attosecond and is robust against chromatic dispersion. Additionally, we show that by adding an extra bias phase, the sensitivity can be improved by two orders of magnitude. As a fundamental application of weak value amplification, we present a scheme for extracting a quantum-enhanced scaling and an experiment that demonstrates the approach of Heisenberg-scaling. We achieve this by utilizing mixed states with large uncertainty and post-selecting an additional pure system.

References

[1] Y. Aharonov, et al., Phys. Rev. Lett. **60**, 1351(1988)
[2] N. Brunner and C. Simon, Phys. Rev. Lett. **105**, 010405(2010)
[3] C.-F. Li, et al., Phys. Rev. A **83**, 044102(2011)
[4] X.-Y. Xu, et al., Phys. Rev. Lett. **111**, 033604(2013)
[5] Z.-H. Zhang, et al. Phys. Rev. A. **94**, 053843(2016)
[6] G. Chen, et al., Nat. Commun. **9**, 93(2018)
[7] G. Chen, et al., Phys. Rev. Lett. **121**, 060506(2018)

A student-lab setup for sensing with undetected photons

Marthe Zeja and Sven Ramelow

Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany

What is quantum sensing, how can samples be probed with "undetected photons" and what is the point of it all?

The discussion of these and similar questions is the goal of our compact student-lab experimental setup. In the interferometer, photon pairs with strongly different but correlated wavelengths are generated by means of spontaneous parametric down-conversion (SPDC) - in this case in the near-infrared (NIR) and mid-infrared (MIR) regions of the electromagnetic spectrum covering 2.6 - 5.6 µm. These two separate spectral regions are chosen with regard to the availability of high-performance and cost-effective silicon-based detectors (for NIR light around 800nm) and the demand for label-free spatio-spectral MIR analysis methods e.g. in biomedical applications.

In the interferometer, the sample's imprint (absorption and phase shift) onto the MIR photons is transferred to the NIR partners via entanglement and quantum interference. Subsequently, the spatial or spectral component of the imprint is recorded by sending the NIR light to either a camera or a spectrometer. Our multi-purpose nonlinear interferometer design allows for switching between imaging and spectroscopic examination of a sample. For the latter, students will examine their sample's mid-IR fingerprints and, with the aid of literature infrared absorption data, identify sample compositions in a label-free manner. Finally, the students are challenged with measuring the imaging capability (important for e.g. microscopic applications) and compare it against theoretically derived values for the resolution and field of view of the interferometric arrangement.

Nonlinear interferometers for imaging without detection

Jingrui Zhang[1] **and Alex Clark**[1]

[1]*University of Bristol, Bristol, United Kingdom*

With the advent and development of quantum optics during the second half of the 20th century, quantum imaging has gained traction as an immediate term quantum enhanced technology. Imaging in the infrared (IR) range, achieved by using nonlinear interferometers (NLI), is an example of this. It avoids the use of noisy and expensive mid-IR light sources and cameras, and leverages the huge amount of available technology for visible and near-IR systems such as lasers, detectors and optics, into the less-well-explored mid-IR spectral region. Based on parametric down-conversion (PDC), “imaging without detection” enables the illumination of an object at one wavelength to obtain its image by detecting light in a different region of the spectrum. However, to date most of the demonstrations of nonlinear interferometers using continuous wave lasers have shown significant limitation in gain which reduces the imaging sensitivity. We are building a pulsed NLI for hyperspectral quantum imaging with mid-IR undetected photons. With pulsed light, one can enhance the visibility of interference and compensate for losses in the interferometer. This will be particularly vital for applications where one wishes to image through lossy scattering media, such as biological systems or objects embedded in other materials. The laser source has short pulses that can reach high peak powers, while the attached optical parametric oscillator (OPO) system is broadly tunable providing light suitable for seeding an input of the nonlinear interferometer. We have investigated the phase matching wavelength ranges of nonlinear crystals like PPLN, AGS and AGGS – crystals that can cover the entire mid-IR region between 2-10 µm, that are suitable for most kind of organic samples. Our current PPLN crystal nonlinear interferometer is suitable for sample scanning ranges at 1.2-5 µm, while AGS and AGGS will enable the generation of photons up to 10 µm, covering the important “molecular fingerprint” region.