Sensing with Quantum Light 2020

A hybrid workshop
September 6 – 9, 2020
Local hub: Tagungshotel Kremmen/Berlin
Online hub: https://sql20.hu-berlin.de/

Introduction

Berlin, more than hundred years ago: Max Planck makes the first bold step towards quantizing light thereby igniting the initial spark for the development of quantum theory, including what will later be named the *second quantization* describing "Quantum Light".

Berlin, 2020: Worldwide the so-called "second generation" of quantum technologies draws steeply increasing attention by scientists, engineers, entrepreneurs and governments. It is based on the ability to prepare and manipulate quantum states at the individual level and is expected to leverage phenomena such as quantum entanglement and quantum superposition to revolutionize a wide range of fields in computing, communication and sensing.

The area of quantum sensing is widely considered to be one to most likely deliver real-world applications and products very soon. **Sensing with light** in the form of imaging, microscopy, spectroscopy or other interferometric methods has always played an enormous role. **Sensing with quantum light** now aims at utilizing the properties of quantum optical states to overcome classical limitations with respect to noise, resolution, sensitivity and other parameters. In addition, it offers completely new measurement modalities, for example by linking different wavelength regions.

For our workshop - thanks to the many contributions - we are this year able to compile a very interesting program of invited, contributed and short talks which cover a broad range of topics in the field of "Sensing with Quantum Light". The workshop aims at providing a vibrant forum for the exchange of ideas and discussion 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.

This year's workshop follows the 2018 Autumn School on »Quantum Enhanced Imaging and Spectroscopy« and the first SQL workshop 2019, both held at the Physikzentrum Bad Honnef.

2020 brought many challenges, not only for the scientific community. We are convinced that our **hybrid format** for the workshop – a local event together with the online meeting – will offer the best possibilities available for the scientific exchange and personal discussion, and we invite all of you to contribute actively to the meeting.

Welcome to SQL20!

The SQL20 Program committee

Dr. Frank Kühnemann	Fraunhofer IPM, Freiburg, Germany frank.kuehnemann@ipm.fraunhofer.de
Dr. Sven Ramelow	Humboldt University, Berlin, Germany sven.ramelow@physik.hu-berlin.de
Dr. Markus Selmke	Fraunhofer IOF, Jena, Germany markus.selmke@iof.fraunhofer.de

(Program changes may occur – please check postings at https://sql20.hu-berlin.de/)

Sunday, Sept. 6

From 14:00	***Arrival at Hotel***
18:00	***Welcome***
18:30	***Dinner***
19:30	***social evening***

Monday, Sept. 7

			Session 1
08:50			**Welcome**
09:00	**p**	**T1**	**Maria Chekhova** *(Inv)* **: Loss-tolerant squeezing-assisted interferometry**
09:40			Technical break
09:45		**T2**	**Shigeki Takeuchi** *(Inv)*: **Photonic quantum sensing using entangled photons**
10:25		**T3**	**Marco Barbieri** *(Inv)*: **Experimental function estimation: a new tool in quantum metrology**
11:05			**Coffee break**
11:35		**T4**	**Florian Kaiser: Two-photon phase-sensing based on single-photon detection**
12:00		**T5**	**Carlos Sánchez Muñoz: Squeezed lasing**
12:30			**Lunch**
			Session 2
13:40		**T6**	**Ulrik Andersen** *(Inv)*: **Quantum-enhanced Raman microscopy**
14:20			Technical break
14:25	**p**	**T7**	**Frank Schlawin** *(Inv)*: **Two-photon absorption of squeezed light**
15:05		**T8**	**Chiara Lindner: FTIR Spectroscopy with a nonlinear interferometer**
15:30	**p**	**T9**	**Mirco Kutas: Nonlinear interference with terahertz photons**
15:45			**Coffee break**
			Session 3
16:15		**T10**	**Jeff Ou** *(Inv)*: **Quantum sensing with SU(1,1) interferometers**
16:55		**T11**	**Tian Li: Observation of quantum advantage with squeezed light for absorption measurement**
17:20			Technical break
17:25		**T12**	**Jake Biele: Quantum absorption estimation for saturable samples**
17:50		**T13**	**Konstantin Dorfman: Multidimensional four-wave mixing spectroscopy with quantum and classical detection**
18:15		**T14**	**Kristen Parzuchowski: Setting bounds on two-photon absorption cross-sections in common fluorophores with entangled photon pair excitation**
19:00			**Dinner**

Tuesday, Sept. 8

			Session 4
09:00		**T15**	**Leonid Krivitsky** *(Inv)*: **Nonlinear interferometry for imaging and metrology**
09:40			Technical break
09:45		**T16**	**Milena D'Angelo (Inv): Quantum plenotic imaging**
10:25			**Coffee break**
10:55		**T17**	**Juan Torres** *(Inv)*: **Optical coherence tomography with nonlinear interferometers**
11:35	**P**	**T18**	**Patricia Bickert: Modeling and simulation of quantum sensing experiments based on nonlinear interferometers**
11:55	**P**	**T19**	**Helen Chrzanowski: Mid-IR OCT with undetected photons**
12:20		**T20**	**Anna Paterova: Nonlinear interferometry with infrared metasurfaces**
12:40			**Lunch**
			Session 5
13:15		**T21**	**Dan Oron** *(Inv)*: **Quantum-enhanced superresolution microscopy**
13:55			Technical break
14:00		**T22**	**Robert Fickler** *(Inv)*: **Single-Path Two-Photon Interference Effect in Spatial Modes**
14:40	**P**	**T23**	**Inna Kviatkowsky: Microscopy with undetected photons in the mid-infrared**
14:55			Technical break
15:10		**T24**	**Hugo Defienne: Entanglement-enabled quantum holography**
15:35		**T25**	**Sanjukta Kundu: Self referenced hologram of a single photon beam**
15:50			**Coffee break**
			Session 6
16:20		**T26**	**Miles Padgett** *(Inv)*: **Noise and background light rejection using quantum illumination**
17:00			Technical break
17:05		**T27**	**Alessio Avella** *(Inv)*: **Improving sub-shot-noise imaging and quantum ghost imaging**
17:45			Technical break
17:50		**T28**	**Anton Classen: Structured illumination quantum correlation microscopy**
18:15		**T29**	**Andrei Nomerotski: Multi-dimensional discrimination in quantum imaging**
19:00			**Dinner**

Wednesday, Sept. 9

			Session 7
09:00		T30	**Xiaoying Li** *(Inv)*: **Measuring multi-parameters beyond the standard quantum limit by using SU(1,1) interferometers**
09:40		T31	**Yiquang Yang: Stimulated emission tomography for entangled photon pairs with different detection spectral range**
09:55			Technical break
10:00	**P**	T32	**Joachim von Zanthier** *(Inv)*: **Quantum Imaging with incoherent X-rays**
10:40	**P**	T33	**Falk Eilenberger: Enhancing tests of quantum theories with single photons from 2D materials**
10:55			**Coffee break**
			Session 8
11:25		T34	**Evangelia Bisketzki: Fundamental limits of quantum spectroscopy**
11:50		T35	**Aiman Kahn: Model-Independent Simulation Complexity of Complex Quantum Dynamics**
12:05			Technical break
12:10		T36	**Radek Lapkiewicz: Modeling and simulation of quantum sensing experiments based on nonlinear interferometers**
12:35		T37	**Markus Gräfe: Digital Phase Shift Holography With Undetected Photons**
12:50			**Closing remarks**
13:00			**Lunch**
			Departure

Abstracts of the talks

(in chronological order)

T1 – Monday - 9:00 - Maria Chekhova (invited)

Loss-tolerant squeezing-assisted interferometry

Gaetano Frascella[1;2], Sascha Agne[1;2] Farid Ya. Khalili[3;4], Maria V. Chekhova[1;2]

[1] Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany
[2] University of Erlangen-Nuremberg, Staudtstr. 7/B2, 91058 Erlangen, Germany
[3] Russian Quantum Center, Bolshoy Bulvar 30/bld. 1, 121205 Skolkovo, Moscow, Russia
[4] NUST ”MISiS”, Leninskiy Prospekt 4, 119049 Moscow, Russia

Modern classical interferometry operates at the shot-noise limit, related to the photon structure of light and reached when an interferometer is fed with coherent light. Quantum optical methods enable overcoming this limit. Most practical solution is to feed an interferometer with squeezed light at one input port and with coherent light at the other input port. This is, for instance, how advanced LIGO and other gravitational-wave detectors work. However, the operation of squeezing-assisted interferometers is strongly degraded by loss – both inside the interferometer and outside it, at the stage of detection. While the former is unavoidable, the latter can be overcome, and we demonstrate it in a recent proof-of-principle experiment [1].

We overcome the detection loss and inefficiency, as well as the detection noise, by means of phase-sensitive parametric amplification before detection. A phase-sensitive parametric amplifier does not introduce additional noise, but it amplifies the fragile quantum signal and thus makes it tolerant to both loss and noise at the detection stage. In our experiment, we overcome the shot-noise limit in phase sensitivity by 6 dB with 1500 photons probing the phase, the detection efficiency being only 50%. Without parametric amplification, the shot-noise limit cannot be overcome with such a large loss. Moreover, with stronger amplification, we have overcome the shot-noise limit under detection efficiency as low as 13%.

This method is applicable to real-life interferometers such as LIGO. In addition, our results suggest a way to use squeezed light for sensing, where the detection efficiency cannot be very high, especially in spectral ranges like middle-infrared or terahertz.

[1] Gaetano Frascella, Sascha Agne, Farid Ya. Khalili, Maria V. Chekhova, Overcoming detection inefficiency in squeezing-assisted interferometers. arXiv:2005.08843v2 [quant-ph]

T2 – Monday - 9:40 - Shigeki Takeuchi (invited)

Photonic quantum sensing using entangled photons

Shigeki Takeuchi

Department of Electronic Science and Engineering, Kyoto University,
Kyotodaigakukatsura, Nisikyo-ku, Kyoto, 615-8510, Japan

Quantum technology has been attracting significant attention recently. It harnesses the intrinsic nature of quantum mechanics such as quantum superposition, the uncertainty principle, and quantum entanglement to realize novel functions. Recently, quantum metrology and quantum sensing are emerging as appealing applications of quantum technology. In this talk, we will report our recent progresses on the development of novel quantum entangled-photon sources and application to quantum sensing.

The first example is an entanglement enhanced microscope [1] which is the differential confocal microscope where an entangled photon pair source is used for illumination. We show that the S/N ratio of the image obtained by the entanglement microscope is 1.35 times better than that limited by the standard quantum limit.

Next example is the quantum optical coherence tomography (QOCT), which utilizes two-photon interference between entangled photon pairs, is a promising approach to overcome the problem with optical coherence tomography (OCT): As the resolution of OCT becomes higher, degradation of the resolution due to dispersion within the medium becomes more critical. We report on the realization of 0.54 μm resolution two-photon interference, which surpasses the current record resolution 0.75 μm of low-coherence interference for OCT. In addition, the resolution for QOCT showed almost no change against the dispersion of a 1 mm thickness of water inserted in the optical path, whereas the resolution for OCT dramatically degrades [2].

For the third topic, we will introduce our adaptive quantum state estimation (AQSE), by which we can estimate the true value of the parameter that specifies the unknown quantum state with the smallest uncertainty, such as the quantum Cramér-Rao bound. In addition to the first experimental demonstration for single parameter estimation of single photons [3], the estimation of single photonic qubit with better accuracy compared with conventional tomography [4]. Very recently, we have proposed and realized a novel AQSE applicable for quantum states changing in time [5]. We will also briefly introduce our efforts for on-chip frequency entangled photon sources [6].

These works were supported in part by JST-CREST (JPMJCR1674), Grant-in-Aid from JSPS no. 26220712 and MEXT Q-LEAP project (JPMXS0118067634).

[1] T. Ono, R. Okamoto and S. Takeuchi, Nat. Commun. 4, 2426 (2013).
[2] M. Okano, H. H. Lim, R. Okamoto, N. Nishizawa, S. Kurimura and S. Takeuchi, Sci. Rep. 5, 18042 (2015).
[3] R. Okamoto, M. Iefuji, S. Oyama, K. Yamagata, H. Imai, A. Fujiwara and S. Takeuchi, Phys. Rev. Lett. 109, 130404 (2012).
[4] R. Okamoto, S. Oyama, K. Yamagata, A. Fujiwara and S. Takeuchi, Phys. Rev. A 96, 022124 (2017)
[5] S. Nohara, R. Okamoto, A. Fujiwara and S. Takeuchi, Phys. Rev. A (R), accepted (2020).
[6] K. Sugiura, Z. Yin, R. Okamoto, L. Zhang, L. Kang, J. Chen, P. Wu, S. T. Chu, B. E. Little, and S. Takeuchi, Appl. Phys. Lett. 116, 224001 (2020).

T3 – Monday- 10:25 - Marco Barbieri (invited)

Experimental function estimation: a new tool in quantum metrology

Ilaria Gianani[1], Francesco Albarelli[2], Valeria Cimini[1], Marco Barbieri[1]

[1] Dipartimento di Scienze, Università degli Studi Roma Tre, Rome, Italy
[2] Faculty of Physics, University of Warsaw, Poland

Quantum sensors have demonstrated their capability of addressing single parameters, such as optical phases or field strengths. The interest is now rapidly moving towards the possibility of addressing the estimation of multiple parameters [1]; bringing this to the limit of a continuous set of parameters, as determined, for instance, by an external field, amounts to estimating a function.

Clearly, one can not directly measure a continuous of parameters, thus the target function is sampled with a certain step, and then interpolated. It is well established that quantum resources can improve the estimate of the sampled point, and the implications of this advantage for function estimation have been investigated in theory [2,3].

In this talk, we will report a recent investigation of quantum function estimation applied to the optical response of a liquid crystal [4]. Its phase response as a function of the voltage has been reconstructed by means of both classical and quantum phase estimation techniques. Our results illustrate that optimising the employ of our resources is not as straightforward as it may appear at a first glance: quantum advantaged becomes substantial only past a sampling rate that depend on the regularity properties of the function.

[1] M. G. A. Paris, Quantum estimation for quantum technology, Int. J. Quantum Inf. 07, 125 (2009)
[2] M. Tsang, H. M. Wiseman, and C. M. Caves, Fundamental Quantum Limit to Waveform Estimation, Phys. Rev. Lett. 106, 090401 (2011).
[3] N. Kura and M. Ueda, Standard quantum limit and Heisenberg limit in function estimation, Phys. Rev. Lett. 124, 010507 (2020).
[4] I. Gianani, F. Albarelli, V. Cimini, and M. Barbieri, Experimental quantum-enhanced response function estimation, arXiv:2007.15564 (2020).

Two-photon phase-sensing based on single-photon detection

Panagiotis Vergyris[1], Charles Babin[2], Raphael Nold[2], Elie Gouzien[1], Harald Herrmann[3],
Christine Silberhorn[3], Olivier Alibart[1], Sébastien Tanzilli[1], Florian Kaiser[1,2]

[1]Université Côte d'Azur, Institut de Physique de Nice (INPHYNI), CNRS, Parc Valrose, 06108 Nice Cedex 2, France

[2]3rd Institute of Physics, IQST, and Research Center SCoPE, University of Stuttgart, 70569 Stuttgart, Germany

[3]Integrated Quantum Optics, Universität Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany

Multi-photon number states allow performing quantum optical phase-sensing beyond the shot-noise limit. Key in those approaches is to extract the multi-photon state parity after interaction with the sample. State-of-the-art parity detection schemes usually come along with a hefty price tag, i.e. they require coincident single-photon detection proportional to the number of photons involved. As this is technically demanding and generally (very) inefficient, classical techniques remain to be preferred for many phase-sensing applications.

In this presentation, we introduce and experimentally demonstrate a new scheme for parity detection of photon number states based on simple and fast single-photon detection [1]. Our strategy is based on superposing the emission of two different parametric downconversion sources in a SU(1,1) interferometer arrangement [2]. Proper polarisation state engineering leads then to an effective transfer of a two-photon phase shift onto a single-photon polarisation state. Subsequent detection of the single-photon polarisation state allows then to reveal the two-photon phase shift information. Notably, without any multiphoton detection, we infer two-photon phase shifts by measuring the average intensity of the single-photon beam on a photodiode, in analogy to standard classical measurements.

Our current sensor achieves a phase sensitivity of ≈ 1 mrad/$\sqrt{\text{Hz}}$. As this sensitivity is already sufficient to operate in the audio band, we have realized a quantum microphone. The speech recording performance is currently benchmarked in an audiology clinical trial.

We will also detail possibilities to obtain another decisive performance enhancement of our approach in order to enable quantum enhanced imaging applications and label-free molecule detection.

In summary, we believe that our new scheme can have a significant impact in the field of quantum optical sensing science, as it combines the advantages of multi-photon sensing with the simplicity of classical light detection.

[1] P. Vergyris et al., Appl. Phys. Lett. 117, 024001 (2020)
[2] M.V. Chekhova and Z.Y. Ou, Adv. Opt. Photonics 8, 104-155 (2016)

T5 – Monday - 12:00 - Carlos Sánchez Muñoz

Squeezed lasing

Carlos Sánchez Munõz[1,2], Dieter Jaksch[1]

[1] Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

[2] Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC),
Universidad Autónoma de Madrid, Madrid, Spain

We introduce the idea of a squeezed laser, in which a squeezed cavity mode develops a macroscopic photonic occupation powered by stimulated emission [1]. Above the lasing threshold, the emitted light retains both the spectral purity inherent of a laser and the photon correlations characteristic of a photonic mode with squeezed quadratures. Our proposal, which can be implemented in optical setups, relies on the parametric driving of the cavity and dissipative stabilization by a broadband squeezed vacuum. We show that the squeezed laser can find applications going beyond those of standard lasers thanks to the squeezed character, such as enhanced operation in multi-photon microscopy or Heisenberg scaling of the Fisher information in quantum parameter estimation.

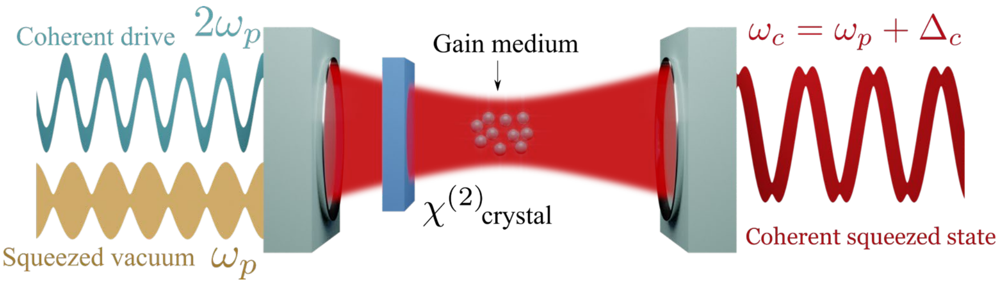


Figure 1: Sketch of the proposed setup: a single cavity mode of frequency $\omega c = \omega p + \Delta c$ (with $\Delta c \ll \omega p$) is parametrically driven through the down-conversion of pump photons of frequency $2\omega p$ by a non-linear crystal $\chi(2)$. The cavity includes a gain medium (e.g. an ensemble of two-level atoms) and is driven by a broadband squeezed vacuum centred at the frequency ωp to stabilize lasing action. If the laser is imposed a well-defined phase, the output emission corresponds to a coherent squeezed state of frequency $\omega s = \omega p + \Delta s$.

[1] C. Sánchez Munõz, D. Jaksch, Squeezed Lasing, arXiv:2008.02813

T6 – Monday - 13:40 – Ulrik Anderson (invited)

Quantum-enhanced Raman microscopy

Rayssa B. de Andrade[1], Hugo Kerdoncuff[2], Kirstine Berg-Sørensen[1], Tobias Gehring[1],
Mikael Lassen[2], and Ulrik L. Andersen[1]

[1] Center for Macroscopic Quantum States (bigQ), Department of Physics, Technical University of Denmark,
Fysikvej 307, DK-2800 Kgs. Lyngby, Denmark

[2] Danish Fundamental Metrology, Kogle Alle 5, DK-2970 Horsholm, Denmark

Stimulated Raman Scattering (SRS) spectroscopy is a very powerful technique to perform real- time vibrational imaging of living cells and organisms. It is based on the stimulated excitation of a Raman transition of the sample under interrogation, thereby resulting in a measurable stimulated Raman loss and gain of the two input beams. In SRS, the sensitivity and imaging speed are fundamentally limited by the noise level (often shot-noise) of the probing laser, but can in principle be arbitrarily improved by simply increasing the power of the input beams. However, in biological systems, especially in living systems, the power must be kept low to avoid changing the biological dynamics of the specimens, and in particular to avoid damage due to excessive heating. Leaving the optical power at a constant level, the sensitivity and bandwidth of the SRS can be boosted by reducing the shot-noise level using squeezed states of light. In this talk, we present a demonstration of a quantum-enhanced continuous-wave (cw) SRS spectrometer using amplitude squeezed light. We demonstrate its functionality and superiority by spectroscopically measuring the carbon–hydrogen (C-H) vibrations of polymethylmethacrylate (PMMA) and polydimethylsiloxane (PDMS) with a sensitivity improvement of approximately 56% relative to shot-noise limited Raman spectroscopy. Our measurement method has the potential to enable new measurement regimes of Raman bio-imaging that are inaccessible by conventional shot-noise limited Raman spectroscopy.

[1] Rayssa B. de Andrade, Hugo Kerdoncuff, Kirstine Berg-Sørensen, Tobias Gehring, Mikael Lassen and Ulrik L. Andersen, Quantum-enhanced continuous-wave stimulated Raman scattering spectroscopy, Optica 7, 470 (2020)

T7 – Monday - 14:25 – Frank Schlawin (invited)

Photon correlation spectroscopy

Frank Schlawin

Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

Quantum spectroscopy aims to exploit quantum properties of radiation to gain information on complex samples. Most research on the use of quantum light for spectroscopy to date concerns entangled photons and the possible role of entanglement in future spectroscopy technologies [1]. Much less attention has been paid to the spectroscopic information contained in the light emitted from a molecular sample.

In a number of publications, first steps have recently been taken to investigate how photon correlation measurements can reveal structural and dynamical information of complex quantum systems [2-5].

We will review these theoretical studies and show that there is a deep connection between the photon correlations emitted by a continuously driven quantum system and nonlinear optical signal extracted by strong laser pulses. We will then show that deviations from the counting statistics of independent emitters constitute a spectroscopic fingerprint of quantum coherence in the steady state [4].

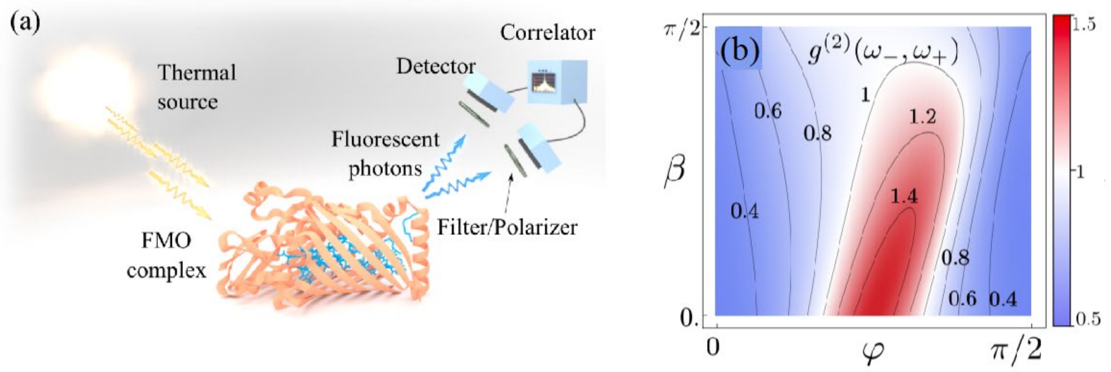


Figure 1: (a) Information about dynamics of a quantum system can be inferred from the emitted photon counting statistics. (b) Frequency-resolved $g^{(2)}$-measurements reveal coherent dynamics. From Ref. [4].

[1] S. Mukamel et al., Roadmap on quantum light spectroscopy, J. Phys. B **53**, 072002 (2020).
[2] D. I. H. Holdaway, V. Notarargio, and A. Olaya-Castro, Perturbation approach for computing frequency- and time-resolved photon correlation functions, Phys. Rev. A **98**, 063828 (2018).
[3] K. E. Dorfman and S. Mukamel, Multdimensional photon correlation spectroscopy of cavity photons, Proc. Nat. Acad. Sci. **115**, 1451 (2018).
[4] C. S. Muñoz and F. Schlawin, Photon correlation spectroscopy as a witness for quantum coherence, Phys. Rev. Lett. **124**, 203601 (2020).
[5] Z. Yang, P. Saurabh, F. Schlawin, S. Mukamel, and K. E. Dorfman, Multidimensional four-wave mixing spectroscopy with squeezed light, Appl. Phys. Lett. **116**, 244001 (2020).

T8 – Monday - 15:05 – Chiara Lindner

FTIR Spectroscopy with a nonlinear interferometer

Chiara Lindner, Simon Herr, Jachin Kunz, Jens Kießling, Sebastian Wolf, Frank Kühnemann

Fraunhofer Institute for Physical Measurement Techniques IPM, Georges-Köhler-Allee 301, 79110 Freiburg

Recently published works demonstrate different approaches to infrared spectroscopy using nonlinear interferometers. These devices open up new possibilities for metrology, as they are able to detect infrared information in the interference pattern of visible or near-infrared light, using correlated photons. This allows using high-performant silicon detectors instead of infrared detectors, which often require cooling.

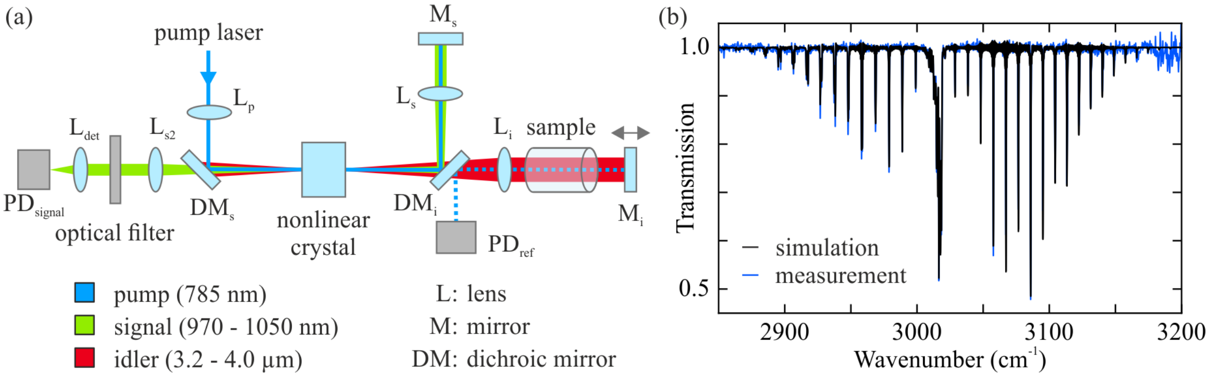


Figure 1: Nonlinear interferometer for Fourier-transform spectroscopy.
a) Sketch of the set-up in Michelson-geometry. b) Transmission spectrum of methane:
blue curve: measured with the nonlinear interferometer – detected with a single-pixel silicon detector,
black curve: Simulation based on HITRAN data [1]

In our work, we demonstrate broadband Fourier-transform infrared spectroscopy of gaseous samples with sub-wavenumber resolution, detected with a silicon photodiode. As a light source for correlated photons, we use spontaneous parametric down-conversion in periodically poled lithium niobate. The pump wavelength of 785 nm allows for broadband collinear phase matching [2]. The nonlinear crystal is arranged in a Michelson-geometry interferometer (Fig. 1a). Due to the induced coherence effect, the superposition of the two SPDC sources (direct and back-reflection) shows an interference pattern in both signal and idler light, which depends on the transmission and phases of all three beams. It was recently demonstrated [3], that the spectral information of the idler beam can be extracted from the signal interference pattern using a Fourier-transform when varying the delay between the interferometer arms (moving mirror M_i). This allows spectroscopic measurements without additional spectral selective or dispersive detection, in analogy to classical Fourier-transform infrared spectroscopy, but with near-infrared detection. In our contribution, we will present the steps towards and latest results on high-resolution spectra of gaseous samples (Fig. 1b) using a single-pixel silicon detector.

[1] I.E. Gordon et al., "The HITRAN 2016 Molecular Spectroscopic Database", J. Quant. Spectrosc. Radiat. Transfer **203**, 3-69 (2017)
[2] A. Vanselow, et al., “Ultra-broadband SPDC for spectrally far separated photon pairs”, Opt. Lett. **44**, 4638 (2019).
[3] C. Lindner et al., “Fourier transform infrared spectroscopy with visible light”, Opt. Express **28**, 4426-4432 (2020)

Nonlinear interference with terahertz photons

Mirco Kutas[1,2], Björn Haase[1,2], Patricia Bickert[1], Felix Riexinger[1,2],
Daniel Molter[1], and Georg von Freymann[1,2]

[1] Fraunhofer Institute for Industrial Mathematics ITWM, Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany.
[2] Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern (TUK), 67663 Kaiserslautern, Germany.

Nonlinear interferometers are based on the correlation of biphoton pairs generated in a nonlinear crystal. They show a great potential since it is only necessary to detect one of the photons to acquire information of its associated partner. The spectral regions that could benefit in particular from this technique are those with low photon energy, such as the terahertz frequency range, as detection there is still technically complex. In this case the extreme spread of wavelength between the photons involved is very challenging to handle, as the signal radiation is getting very close to the pump and linear properties of the nonlinear materials differ for the individual radiations. We report on the first demonstration of the concept of nonlinear interferometry with terahertz photons propagating in free space, determining properties like thickness of polytetrafluoroethylene plates only by detecting visible photons with an uncooled sCMOS camera. The signal photons are separated from the pump photons by narrowband and highly efficient volume Bragg gratings. The signal radiation is generated in a periodically poled lithium niobate crystal, placed in the center of a nonlinear Michelson-like interferometer pumped at 660 nm. Due to additional thermal background radiation at room temperature signal photons are generated in the Stokes as well as the Anti-Stokes region. In both cases interference is observable for the collinear forward generation caused by down- and up-conversion and additionally spontaneous parametric down-conversion. By evaluating the displacement of this interference caused by an object in the beam path one can measure the thickness of samples that are mainly transparent in the terahertz frequency range. Building on our first demonstration of thickness measurement with terahertz photons based on induced coherence without induced emission, we will report our most recent advances of this concept on its way towards industrial quantum sensing applications in the terahertz frequency range.

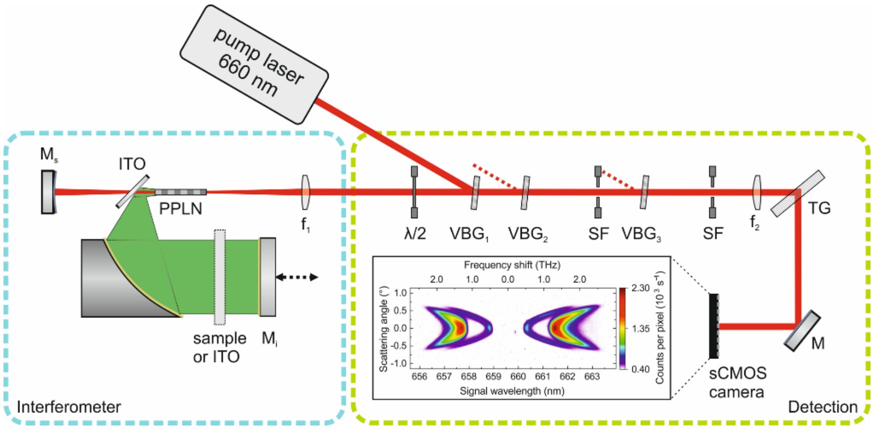


Figure 1: Schematic of the nonlinear interferometer with terahertz photons propagating in free space. The inset shows the frequency-angular spectrum of a 1-mm-long PPLN crystal with $\Lambda = 90$ µm [1].

[1] M. Kutas, B. Haase, P. Bickert, F. Riexinger, D. Molter, G. von Freymann, Terahertz quantum sensing. Sci. Adv. 6, eaaz8065 (2020).

T10 – Monday - 16:15 – Jeff Ou (invited)

Quantum Sensing with SU(1,1) Interferometers

Z. Y. Jeff Ou

Indiana University-Purdue University Indianapolis

SU(1,1) Interferometers replace beam splitters in traditional interferometers with parametric amplifiers for wave splitting and mixing. Because of this, some special characteristics are exhibited that are different from traditional interferometers. Applications of these characteristics lead to advantages over traditional interferometers.

In this presentation, we will review the basic operational principle and reveal the following properties of SU(1,1) interferometers:

(1) Interference fringes are enhanced due to parametric amplifications, leading to increased signal.
(2) The quantum noise, on the other hand, is not amplified accordingly due to destructive quantum interference or cancelation of quantum noise by quantum entanglement. Combined with (1), the measurement signal-to-noise ratio is enhanced compared to traditional interferometers.
(3) Interference fringe depends on the phase sum of the two interfering fields instead of phase difference in traditional interferometers. This can be used to further increase the signal.
(4) Quantum noise of the interferometer is mostly larger than or at least the same as the vacuum noise level. This property indicates that losses do not introduce extra noise and the interferometers are thus tolerant to detection and propagation losses.
(5) Parametric amplifiers can couple waves of different types, giving rise to hybrid interferometers with these different waves and broadening the applicability of the interferometers. This also leads to flexibility in detection method, that is, sensing with one wave but detection at another wave.
(6) Two outputs are available from the interferometers that can be used for quantum information tapping or for multi-parameter sensing.

We will review some of the variations of the SU(1,1) interferometer and realizations with different waves, and present our recent results in the demonstration of the properties listed above.

T11 – Monday - 16:55 – Tian Li

Observation of quantum advantage with squeezed light for absorption measurement

Tian Li[1,2], Fu Li[1,3], Marlan O. Scully[1,4,5] and Girish S. Agarwal[1,2,3]

[1]Inst. for Quantum Science and Engineering, Texas A&M University, College Station, TX 77843, USA
[2]Dept. of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843, USA
[3]Dept. of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
[4]Dept. of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA
[5]Quantum Optics Laboratory, Baylor Research and Innovation Collaborative, Waco, TX 76704, USA

Absorption measurements are routinely used in science and engineering, it is an exceptionally versatile tool for most applications. For absorption measurements using laser beams of light, the sensitivity is theoretically limited by the shot noise due to the fundamental Poisson distribution of photon number in laser radiation. In practice, the shot-noise limit can only be achieved when all other sources of noise are eliminated. Here, we use bright squeezed light to demonstrate that direct absorption measurement can be performed with sensitivity beyond the shot-noise limit. We present a practically realizable scheme, where the bright squeezed light is generated by the four-wave mixing process in an atomic rubidium vapor cell. This is a direct sub-shotnoise measurement of absorption that requires neither homodyne/lock-in nor logic coincidence detection schemes. More than 1 dB quantum advantage for the measurement sensitivity is obtained at faint absorption levels (see Fig. 1(b)). The observed quantum advantage when corrected for the losses in the optical paths of the twin beams would be equivalent to 3 dB (see Fig. 1(a)). We present detailed theoretical analysis of the expected quantum advantage. Our results are similar to those reported for phase measurements.

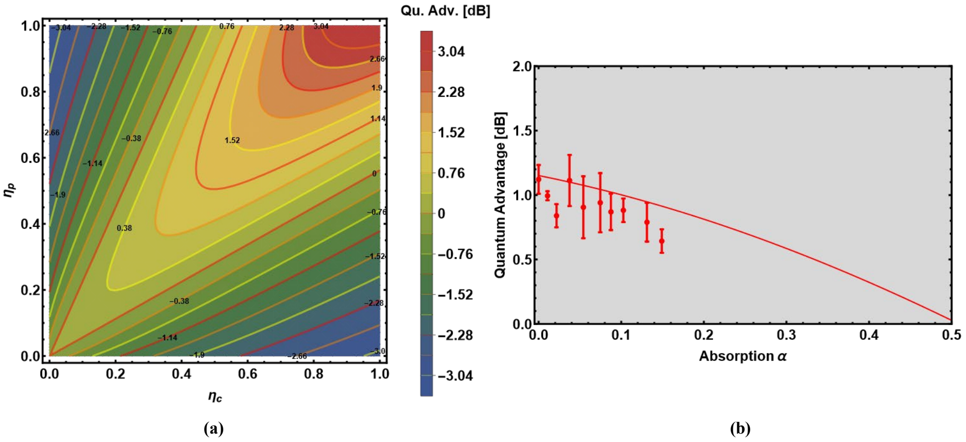


Figure 1: (a) Theoretical prediction for the quantum advantage (Qu. Adv.) for absorption $\alpha = 5\%$ as a function of optical loss η_p and η_c in the twin beams' paths. (b) Quantum advantage as a function of absorption α. Solid red line is the theoretical prediction with $\eta_p = 0.59$, $\eta_c = 0.63$.

T12 – Monday - 17:25 – Jake Biele

Quantum absorption estimation for saturable samples

Jake Biele[1,2], Joshua W. Silverstone[1], Jonathan C. F. Matthews[1], and Euan J. Allen[1]

[1] Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, Tyndall Avenue, BS8 1FD, United Kingdom

[2] Quantum Engineering Centre for Doctoral Training, H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, Tyndall Avenue, BS8 1FD, United Kingdom

Many optical sensors are restricted in probe power by sample saturation and are therefore fundamentally limited in precision by optical shot-noise. This constraint is particularly prominent in the sensing of biophysical and molecular systems due to relatively low saturation intensities [1-2]. In this case, one promising route to increased precision is through quantum sensing strategies and so it is vital that the effects of saturation on quantum and classical probes be fully understood. Here, we consider the effect of sample saturation on the performance of classical absorption probes and compare it to the ultimate quantum limit. We also consider the performance of bright squeezed states with intensities high enough to cause saturation. The optimal classical probe power is found to be lower bounded by the saturation intensity. With our model we demonstrate that a probe power reduction of three orders of magnitude can be gained by switching to the optimal quantum strategy. Furthermore, we show that squeezed states can perform to within 85% of the ultimate quantum limit demonstrating that overcoming saturation with non-classical states of light is possible with current technology.

[1] M. A. Taylor and W. P. Bowen, “Quantum metrology and its application in biology”, Physics Reports, vol. 615, pp. 1–59, 2016

[2] J. N. Henderson, H. W. Ai, R. E. Campbell, and S. J. Remington, “Structural basis for reversible photobleaching of a green fluorescent protein homologue,” Tech. Rep. 16, 2007

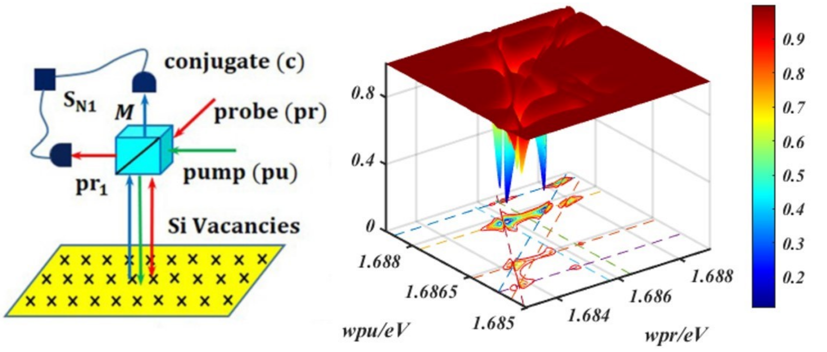
T13 – Monday - 17:50 – Konstantin Dorfman

Multidimensional four-wave mixing spectroscopy with quantum and classical detection

Konstantin E. Dorfman[1]

[1]State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai *200062*, China

The standard quantum optics treatment of the squeezed light generation the material susceptibility is taken as a constant prefactor. This treatment is justified when the fields are far off-resonant with respect to matter. Resonant nonlinear spectroscopy investigates material properties, which requires an explicit treatment of the matter response via nonlinear susceptibilities.



(a) (b)

Figure 1: Schematic of the single FWM-based measurment - (a). 3D spectra of the S_N Eq. (1) vs ω_{pu} and ω_{pr}.

We propose a set of nonlinear spectroscopic measurements with quantum light [1]. It involves a strong pump with frequency ω_{pu} and a weak probe at ω_{pr} interacting with a solid state target to generate a conjugated beam $\omega_c = 2\omega_{pu} - \omega_{pr}$ via nondegenerate four-wave mixing (see Fig. 1a). The $\chi^{(3)}$ susceptibility can be measured by the noise spectra of the intensity difference of the squeezed beams given by

$$S_N \equiv \frac{\mathrm{Var}(\hat{N}_{pr} - \hat{N}_c)}{\langle \hat{N}_{pr} \rangle + \langle \hat{N}_c \rangle} = \frac{1}{2G - 1}, \tag{1}$$

where $G(-\omega_{pr},-\omega_c;2\omega_{pu}) = \cosh^2[|\chi^{(3)}(-\omega_{pr},-\omega_c;2\omega_{pu})|]$ is the FWM gain governed by a third order susceptibility $\chi^{(3)}$. We further discuss three spectroscopic setups based on squeezed light: first, single four-wave mixing in a single crystal (see Fig. 1b); second, cascading scheme involving two crystals; third, an SU(1, 1) interferometer based on two separate four-wave mixing processes. We further investigate the microscopic noise and optical losses in all three setups.

Simulations are presented for silicon-vacancy color centers in diamond.

[1] Z. Yang, P. Saurabh, F. Schlawin, S. Mukamel, and K. E. Dorfman, *Appl. Phys. Lett.*, **116**, 244001 (2020).

T14 – Monday - 17:50 – Kristen Parzuchowski

Setting bounds on two-photon absorption cross-sections in common fluorophores with entangled photon pair excitation

Kristen M. Parzuchowski[1,2], Alexander Mikhaylov[2], Michael D. Mazurek[1,3], Ryan N. Wilson[1,2], Daniel J. Lum[4], Thomas Gerrits[4], Charles H. Camp Jr.[4], Martin J. Stevens[3], Ralph Jimenez[2,5]

[1]Department of Physics, 390 UCB, University of Colorado, Boulder, CO, 80309, USA
[2]JILA, 440 UCB, University of Colorado, Boulder, CO 80309, USA
[3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
[4]National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
[5]Department of Chemistry, 215 UCB, University of Colorado, Boulder, CO 80309, USA

Two-photon excitation microscopy is a widely used technique for cellular imaging deep within biological tissues. Two-photon absorption (2PA) is a weak nonlinear process typically observed only when using high-power coherent lasers that may inevitably damage biological tissues. Theoretical [1] and experimental [2,3] studies have reported that entangled photon pair excitation can lead to a significant "quantum advantage" in 2PA rates [1]. However, significant ambiguity and inconsistency remain in the literature about the absolute values of the crosssections for the corresponding process, entangled two-photon absorption (E2PA).

We performed classical (coherent) two-photon absorption (C2PA) and E2PA fluorescence based measurements in one experimental setup [4]. Although we do not detect measurable E2PA signals for any of the six fluorophores, we place upper bounds on their E2PA crosssections, σE, based on our E2PA detection sensitivity. These upper bounds are used with the C2PA measurements to bound the quantum advantage. Our established upper bounds on σE are up to four orders of magnitude lower than the smallest published value of σE [2]. For two of the samples, the upper bounds on σE are nearly four and five orders of magnitude lower than previously reported [2,3].

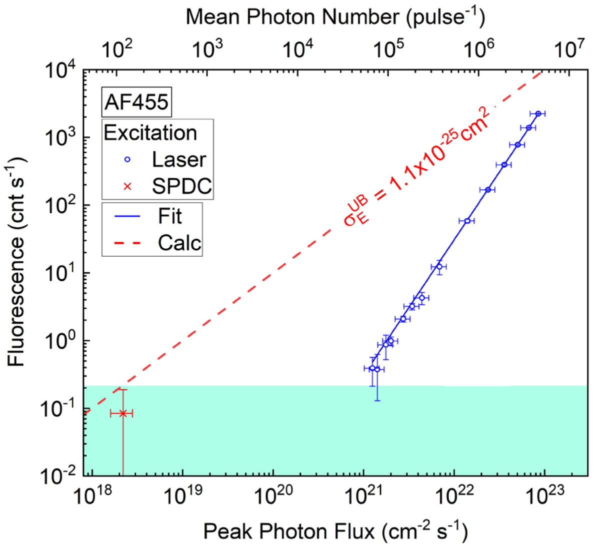


Figure 1: Measured (blue symbols) and fitted (blue solid line) C2PA fluorescence signal for a molecular sample of AF455 in toluene. The signal observed using entangled photon (spontaneous parametric downconversion, SPDC) excitation (red symbol) was indistinguishable from zero (light green region). An E2PA calculation (red dashed line) establishes the cross-section upper-bound (σEUB).

[1] J. Javanainen and P. L. Gould, Phys. Rev. A 41, 5088 (1990).
[2] D. Tabakaev *et al.*, arXiv:1910.07346 [quant-ph] (2019).
[3] A. Eshun *et al.*, J. Phys. Chem. A 122, 8167 (2018).
[4] K. M. Parzuchowski *et al.*, arXiv:2008.02664 [quant-ph] (2020).

T15 – Tuesday - 9:00 – Leonid Krivitskiy (invited)

Hyperspectral infrared microscopy with visible light

Anna V. Paterova[1], Sivakumar M. Maniam[2,3], Hongzhi Yang[1], Gianluca Grenci[2,4], and Leonid A. Krivitsky[1]

[1]Institute of Materials Research and Engineering (IMRE), Agency for Science Technology and Research (A*STAR), 138634 Singapore

[2]Mechanobiology Institute, National University of Singapore, 117411 Singapore

[3]National Institute of Education, Nanyang Technological University, 637616 Singapore

[4]Department of Biomedical Engineering, National University of Singapore, 117583

Hyperspectral microscopy is an imaging technique that provides spectroscopic information with high spatial resolution. When applied in the relevant wavelength region, such as in the infrared (IR), it can reveal a rich spectral fingerprint across different regions of a sample. Challenges associated with low efficiency and high cost of IR light sources and detector arrays have limited its broad adoption. We introduce a new approach to IR hyperspectral microscopy, where the IR spectral map of the sample is obtained with off-the-shelf components built for visible light [1]. The method is based on the nonlinear interference of correlated photons generated via parametric down-conversion. In our proof-of-concept demonstration, we perform the chemical mapping of a patterned sample, in which different areas have distinctive IR spectroscopic fingerprints. The method provides a wide field of view, fast read-out, and negligible heat delivered to the sample, which opens prospects for its further development for applications in material research, biological studies and semiconductor industry [2].

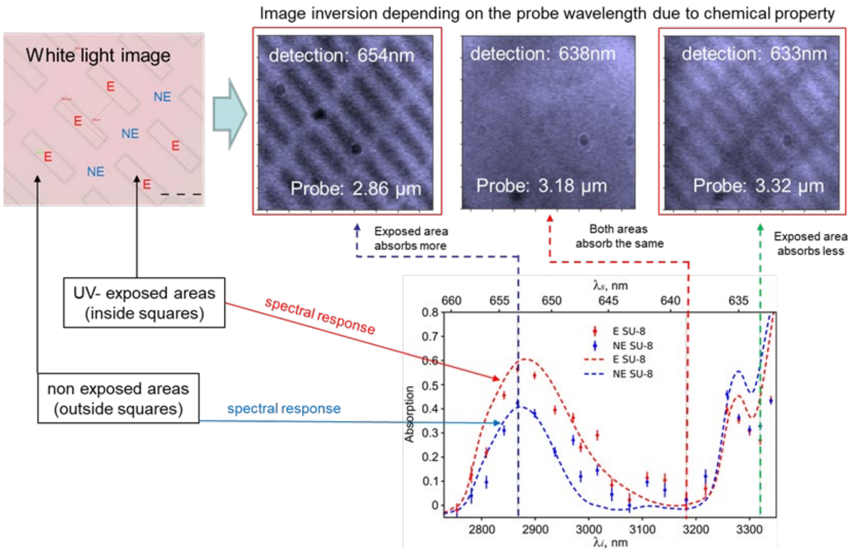


Figure 1: (top left) A microscope image of the sample. The areas inside the squares are exposed to UV light and the areas outside are not exposed. UV exposure changes the chemical composition and hence the spectroscopic response of the material. (top right) Images of the sample at different wavelengths of IR probe light. The detected wavelength is in the visible range. The images show contrast reversal due to the change in the chemical composition of the material of exposed and non-exposed areas. (bottom right) The measured spectral profiles of exposed and non-exposed areas.

[1] A. Paterova et al “Hyperspectral Infrared Microscopy With Visible Light” arXiv:2002.05956.
[2] A. Paterova et al “Quantum Imaging for Semiconductor Industry” Appl. Phys. Lett. 117, 054004 (2020) (Editor’s Pick).

T16 – Tuesday - 9:45 – Milena D’Angelo (invited)

Plenoptic quantum imaging, an overview

Milena D’Angelo[1,2], Francesco Di Lena[2], Augusto Garuccio[1,2], Davide Giannella[1], Alessandro Lupo[1],
Gianlorenzo Massaro[1,2], Francesco V. Pepe[1,2]

[1] Dipartimento Interateneo di Fisica - Università degli Studi di Bari, Via Amendola 173, 70125 Bari, Italy
[2] INFN – sez. Bari, Via Orabona 4, 70125 Bari, Italy

Plenoptic imaging (PI) is a recently established optical imaging technique that allows to collect the composite information on spatial distribution and direction of light coming from the scene of interest. The reconstruction of light paths is used, in post-processing, to refocus out-of-focus planes, change the point of view and extend the depth of field (DOF) within the three-dimensional scene of interest. PI is also one of the simplest and fastest methods to obtain three-dimensional images with the current technology [1]. In state-of-the-art plenoptic cameras, the composite information of spatial distribution and direction of light is collected by means of a microlens array, which imposes a significant resolution loss, well below the diffraction limit defined by the numerical aperture (NA) of the imaging system [1].

To overcome this limitation, we have recently proposed a fundamentally different approach, named correlation plenoptic imaging (CPI), where spatio-temporal quantum correlation properties of light are exploited to physically decouple the image formation from the retrieval of the propagation direction of light: diffraction-limited plenoptic imaging can thus be achieved by measuring correlations between two disjoint sensors [2,3].

In this talk we will introduce CPI for both chaotic light [2,3] and entangled photons illumination [4], together with several alternative configurations developed in recent years to improve noise performances [5-7], address specific applications, such as microscopy [8], or further improve the maximum achievable DOF [9]. This is achieved in our most recent proposal, named correlation plenoptic imaging between arbitrary planes, where we demonstrate the possibility of performing plenoptic imaging at the diffraction limit by measuring second-order correlations of light between two reference planes (CPI-AP), arbitrarily chosen, within the tridimensional scene of interest [9]. We will show that for both chaotic light and entangled photon illumination, the CPI-AP protocol enables to achieve an unprecedented combination of image resolution and DOF: in the considered CPI-AP protocol diffraction limited resolution is combined with a 10 times larger DOF than in conventional imaging.

The results lead the way towards the development of compact designs for correlation plenoptic imaging devices based on chaotic light, as well as high-SNR plenoptic imaging devices based on entangled photon illumination, thus contributing to make correlation plenoptic imaging effectively competitive with commercial plenoptic devices.

[1] R. Prevedel, et al., Nat. Meth. 11, 727–730 (2014)
[2] M. D’Angelo, et al., Phys. Rev. Lett. 116, 223602 (2016)
[3] F. V. Pepe, et al., Phys. Rev. Lett. 119, 243602 (2017)
[4] F. V. Pepe, et al., Technologies 4, 17 (2016)
[5] F. Di Lena, et al., Appl. Scie. 8, 1958 (2018)
[6] G. Scala, et al, Phys. Rev. A 99, 053808 (2019) and Proc. SPIE 11347, 1134713 (2020)
[7] E. De Scisciolo, et al., Int. J. Quant. Inf. 17, 1941017 (2020)
[8] A. Scagliola et al., Phys. Lett. A 384, 126472 (2020)
[9] F. Di Lena, et al., arXiv:2007.12033 (2020).

T17 – Tuesday - 10:55 – Juan Torres (invited)

Optical coherence tomography with a nonlinear interferometer in the high parametric gain regime

Gerard J. Machado[1], Gaetano Frascella[2], Juan P. Torres[1, 3] and Maria V. Chekhova[2, 4]

[1] ICFO - Institut de Ciencies Fotoniques, 08860 Castelldefels, Barcelona, Spain

[2] Max-Planck Institute for the Science of Light, Staudtstr. 2, Erlangen D-91058, Germany

[3] Dep. Signal Theory and Communications, Universitat Politecnica de Catalunya, 08034 Barcelona, Spain

[4] University of Erlangen-Nuremberg, Staudtstr. 7/B2, 91058 Erlangen, Germany

We demonstrate optical coherence tomography (OCT) based on a nonlinear interferometer with high-gain parametric down-conversion [1]. In the last few years, there has been a growing interest in a new type of OCT schemes that use so-called nonlinear interferometers based on optical parametric amplifiers. For imaging and sensing applications, our scheme promises to outperform previous experiments working at low parametric gain. In the low parametric gain regime, the number of photons per mode generated is much smaller than one. In the high parametric gain regime, the number of photons per mode is much higher than one. Higher photon fluxes allow using conventional charge-coupled device (CCD) cameras or spectrometers, instead of single-photon detectors or CCD cameras with very high sensitivities. Images with high signal-to-noise ratio can be obtained with shorter acquisition times. In addition, unlike in conventional OCT or in the case of low parametric gain, the detected power is considerably higher than the power probing the sample.

In our scheme, a parametric down-converter pumped by picosecond pump pulses generates a large flux of signal and idler photon pairs. The idler beam is reflected from a sample with an internal structure made of several layers, represented by reflectivity $r_i(z)$. z designates the distance along the direction of propagation of the light beam. The signal beam is reflected from a mirror. Both beams are injected into a second parametric down-converter. After the second pass by the nonlinear crystal, we measure the intensity (Time-domain OCT) or the spectrum (Fourier-domain OCT) of the signal beam, which both bear information of the value of the reflectivity $r_i(z)$ of the sample.

The experimental set-up is versatile, and can easily be transformed into an OCT system that makes use of the concept of induced coherence. For this one should prevent the signal wave from being amplified on the second pass through the nonlinear crystal. This can be done by changing the polarization of the signal beam to an orthogonal one with the help of a quarter-wave plate. Then, only the idler beam coming from the sample would seed the parametric amplification process in the second pass through the nonlinear crystal. In this case, one would distinguish three beams after the second pass by the nonlinear crystal: the idler beam and the two signal beams with orthogonal polarizations. The detection stage would measure the reflectivity of the sample measuring coherence induced between the two signal beams.

[1] Gerard J. Machado, Gaetano Frascella, Juan P. Torres and Maria V. Chekhova, Optical coherence tomography with a nonlinear interferometer in the high parametric gain regime, paper accepted for publication in the special issue Quantum Sensing with Correlated Light Sources of Applied Physics Letters (2020).

Modeling and simulation of quantum sensing experiments based on nonlinear interferometers

Patricia Bickert[1], Felix Riexinger[1,2], Mirco Kutas[1,2], Björn Haase[1,2], Daniel Molter[1], Michael Bortz[1], and Georg von Freymann[1,2]

[1] Fraunhofer Institute for Industrial Mathematics ITWM, Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany.
[2] Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern (TUK), 67663 Kaiserslautern, Germany.

Quantum sensing with nonlinear interferometers is ideally suited to access spectral regions where the detection of photons is technically challenging. Sample information is obtained in the spectral region of interest and via biphoton correlations transferred into a different spectral range, for which highly sensitive detectors are available. Therefore, quantum sensing and imaging are promising concepts for various applications ranging from the UV over the IR to the terahertz frequency range, where this scheme has been demonstrated recently [1].

Since quantum sensing experiments are complex and non-intuitive, modeling and simulation is important to understand and improve the measurements. We, therefore, develop a model for nonlinear interferometers starting with the simulation of the sources, which generate entangled photon pairs through spontaneous parametric down conversion. Based on the source properties, we can calculate the interference signals and other relevant quantities, e.g., visibility, resolution, or field of view. We employed our model for the simulation of the terahertz experiment and compared the results with experimental data [1]. In a next step, we also included aspects of the propagation of the photons through the optical system and performed a sensitivity study for misalignment effects. In this way, we are able to identify critical components and our work can help to reduce the overall cost and time for designing and performing experiments and applications.

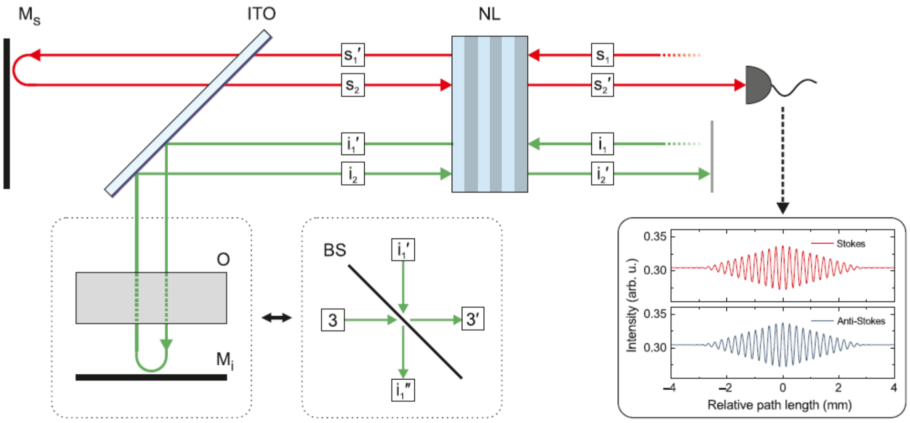


Figure 1: Scheme for the theoretical analysis of the terahertz quantum sensing experiment in [1].

[1] M. Kutas, B. Haase, P. Bickert, F. Riexinger, D. Molter, G. von Freymann, Terahertz quantum sensing, Sci. Adv. 6, eaaz8065 (2020).

T19 – Tuesday - 11:55 – Helen Chrzanowski

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

Helen Chrzanowski[1], Aron Vanselow[1], Paul Kaufmann[1],
Ivan Zorin[2], Bettina Heise[2], and Sven Ramelow[1]

[1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
[2]Research Center for Materials Characterization and Non-Destructive Testing GmbH, Science Park 2,
Altenbergerstr. 69, 4040 Linz, Austria

Traditionally, optical coherence tomography (OCT) has been a technology largely concerned with sensing in the visible or near-infrared (near-IR) [1]. However, for materials with strong scattering or absorption mid-infrared (mid-IR) OCT can be advantageous [2, 3], but has so far been hamstrung by the requirement for expensive and complex light sources and suffered from detector arrays with low efficiency and large noise. A novel mid-IR OCT method that only requires cost-efficient near-IR detectors and a visible laser source is based on quantum non-linear interferometry [4]. It uses spectrally entangled photon pairs to probe a sample with mid-IR idler photons while only detecting their partners, near-IR signal photons. Previously, only time-domain OCT was shown, with relatively low axial resolutions of 500 μm at 1550 nm [5] and 105 μm in the mid-IR [6].

Here, we implement for the first time mid-IR frequency-domain OCT with undetected photons [7]. Using a scheme based on nonlinear interferometry, we achieve a SNR of 48 dB at 8 ms integration time and demonstrate high axial (11 μm) and lateral resolution (14 μm). Maximum depths and integration times are comparable to – or better than – those of the classical approaches based on up-conversion or thermal detectors [2, 3]. To demonstrate the practical usefulness of our technique, we apply it to technologically relevant samples, including ceramics and paints. Our results show its practical relevance for real-world applications.

[1] D. Stifter, Appl. Phys. B 88, 337–357 (2007).
[2] N. M. Israelsen *et al.*, Light: Science & Applications 8:11 (2019).
[3] I. Zorin *et al.*, Opt. Express 26, 33428–33439 (2018).
[4] M. V. Chekhova & Z. Y. Ou, Adv. in Opt. and Phot. 8, 104–155 (2016).
[5] A. Vallés *et al.*, Phys. Rev. A 97, 023824 (2018).
[6] A.V. Paterova *et al.*, Quant. Sci. Tech. 3, 025008 (2018).
[7] A. Vanselow, *et al.*, arXiv:2006.07400v1 (2020).

T20 – Tuesday - 12:20 – Anna Paterova

Nonlinear interferometry with infrared metasurfaces

Anna V. Paterova, Dmitry A. Kalashnikov, Hongzhi Yang, Egor Khaidarov, Tobias W. W. Mass, Ramon Paniagua-Domínguez, Arseniy I. Kuznetsov, and Leonid A. Krivitsky

Institute of Materials Research and Engineering (IMRE), Agency for Science Technology and Research (A*STAR), 138634 Singapore

The optical elements comprised of sub-diffractive light scatterers, or metasurfaces, hold a promise to reduce the footprint and unfold new functionalities of optical devices. A particular interest is focused on metasurfaces for manipulation of the phase profiles of light beams. Characterisation of metasurfaces is typically performed using interferometry, which however, may be cumbersome, specifically in the infrared (IR) range. Here, we realise a new method for characterising IR metasurfaces based on nonlinear interference, which uses accessible components for visible light [1]. Correlated IR and visible photons are launched into a nonlinear interferometer [2, 3] so that the phase profile, imposed by metasurface on the IR photons, modifies the interference at the visible photon wavelength, see Fig. 1. Furthermore, we show that this concept can be used for broadband manipulation of the intensity profile of the visible beam using a single IR metasurface. Our method unfolds the potential of quantum interferometry for characterization of advanced optical elements.

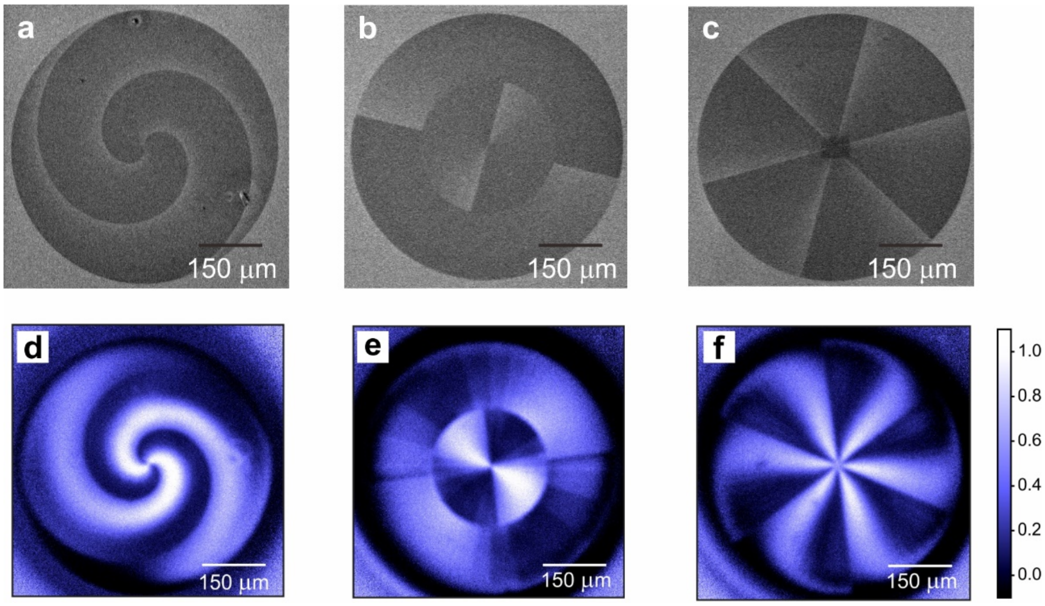


Figure 1: (**a-c**) SEM images of metasurfaces designed for 1550 nm wavelength. (**d-f**) Interference patterns measured at 810 nm wavelength in the nonlinear interferometer, when the metasurfaces are placed in into the path of IR photons. Results for (**a**, **d**) vortex with topological charge l=2, m=2; (**b**, **e**) Laguerre Gaussian beam with l=2, m=1; (**c**, **f**) vortex with topological charge l=6, m=1, where l is the azimuthal index and m is the radial index of the structures. The scale in the bottom right shows the normalized intensity of the interference pattern for results in (d-f).

[1] A. Paterova et al “Nonlinear interferometry with infrared metasurfaces” arXiv:2007.14117.
[2] A. Paterova et al “Hyperspectral infrared microscopy with visible light” arXiv:2002.05956.
[3] A. Paterova et al “Quantum imaging for semiconductor industry” Appl. Phys. Lett. 117, 054004 (2020) (Editor’s Pick, special issue “Quantum Sensing with Correlated Light Source”).

T21 – Tuesday - 13:30 – Dan Oron (invited)

Quantum enhanced superresolution microscopy

Dan Oron

Dept. of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 7610001, Israel
dan.oron@weizmann.ac.il

Far-field optical microscopy beyond the Abbe diffraction limit, making use of nonlinear excitation (e.g. STED), or temporal fluctuations in fluorescence (PALM, STORM, SOFI) is already a reality. In contrast, overcoming the diffraction limit using non-classical properties of light is very difficult to achieve due to the difficulty in generating quantum states of light and their inherent fragility. Here, we experimentally demonstrate practical superresolution microscopy based on quantum properties of light naturally emitted by fluorophores used as markers in fluorescence microscopy. Our approach is based on photon antibunching, the tendency of fluorophores to emit photons one by one rather than in bursts.

Since the non-classical intensity correlations carry higher spatial frequency information, they can be utilized to enhance image resolution. We demonstrate how antibunching can improve the resolution capabilities of image-scanning confocal microscopy in all three dimensions[1], and show how the synthesis of classical and quantum information enables us to apply algorithmic resolution augmentation methods[2]. Finally, we show that these methods are compatible with currently developed SPAD arrays, serving as small single-photon imaging detectors, and thus require little infrastructure investment[3].

Notably, the use of photon antibunching readily lends itself to quantitative imaging modalities since the degree of antibunching is intimately related to the emitter density. Potential approaches to such quantitative superresolution microscopy using a simple confocal microscope setup will be discussed.

[1] R. Tenne et al., “Super-resolution enhancement by quantum image scanning microscopy”, Nature Photonics 13, 116 (2019).
[2] U. Rossman et al., “Rapid quantum image scanning microscopy by joint sparse reconstruction”, Optica 6, 1290 (2019).
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T22 – Tuesday - 14:15 – Robert Fickler (invited)

Single-Path Two-Photon Interference Effect in Spatial Modes

Robert Fickler[1], Markus Hiekkamäki[1]

[1]Tampere University, Photonics Laboratory, Physics Unit, Tampere University, Tampere, FI-33720, Finland

Imaging and sensing often relies on advanced methods of controlling the spatial domain of photons. A powerful way to describe any spatial structures in the paraxial limit is using orthogonal transverse spatial modes e.g. Laguerre-Gauss (LG) modes. One special feature of higher order LG modes is their twisted phase front, to which an theoretically unbound orbital angular momentum (OAM) can be attributed. Amongst its many applications, this twisted phase front has allowed an enhanced angular sensitivity when [1]. In the quantum domain, spatial modes prominently serve as powerful implementations of high-dimensional quantum states [2].

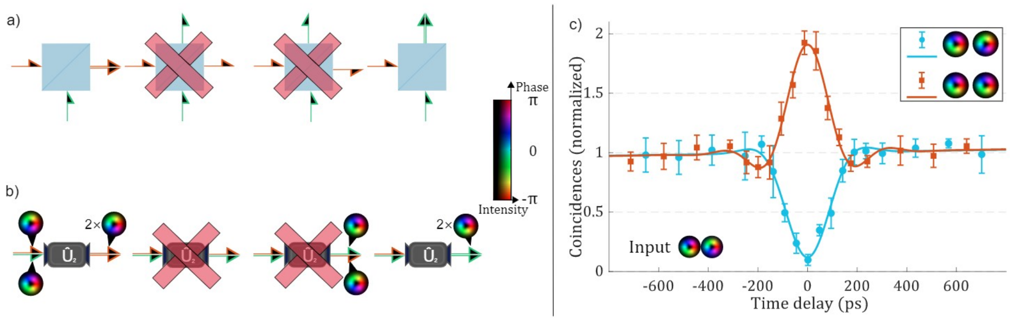

Figure 1. Sketch displaying the similarity and difference between two-photon interference a) between paths and b) between spatial modes. c) Measured two-photon interference between two spatial modes. The inset depicts in which mode the photons were detected.

In this talk, we present the implementation of two-photon interferences between higherorder spatial modes in a single beam line. Instead of the commonly used multi-path optical networks of beamsplitters and phase-shifters, we implement high-dimensional unitary operations for spatial modes using the recently introduced techniques of multi-plane light conversion [3] and wavefront matching [4]. We demonstrate two-photon interference in a two-dimensional spatialmode state space (shown in Fig. 1), which is the direct analogue to the original Hong-Ou-Mandel experiment. Moreover, benefiting from the ease of generating high-dimensional states and their superpositions, we study complex interference effects in different high-dimensional multiports, i.e. tunable linear optical networks along a single path [5].

Finally, we show that this ability enables the generation of spatial-mode NOON-states, which are known to offer phase super-sensitivity. In our case, this feature translates to angular supersensitivity, which not only scales with the OAM value but also the number of involved photons.

[1] D'ambrosio, et al., Nature Communications 4, 1 (2013)
[2] Erhard, et al., Light: Science & Applications 7, 17146 (2018)
[3] Labroille et al., Optics Express, 22, 15599 (2014).
[4] Fontaine et al., Nature Communications, 10, 1 (2019).
[5] Hiekkamäki et al., arXiv:2006.13288 (2020).

T23 – Tuesday - 14:55 – Inna Kviatkowsky

Microscopy with undetected photons in the mid-infrared

Inna Kviatkovsky[1], Helen M. Chrzanowski[1], Ellen G. Avery[2,3,4,5], Hendrik Bartolomaeus[2,3,4], Sven Ramelow[1,6]

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

[2]Experimental and Clinical Research Center, a cooperation of Charité - Universitätsmedizin Berlin and Max Delbrück Center for Molecular Medicine, Berlin, Germany.

[3]DZHK (German Centre for Cardiovascular Research), partner site Berlin, Germany.

[4]Berlin Institute of Health (BIH), Berlin, Germany.

[5]Freie Universität Berlin, Germany.

[6]IRIS Adlershof, Humboldt-Universität zu Berlin, Berlin, Germany.

Owing to its capacity for unique (bio)-chemical specificity, microscopy with mid-IR illumination holds tremendous promise for a wide range of biomedical and industrial applications. The primary limitation, however, remains detection; with current mid-IR detection technology often marrying inferior technical capabilities with prohibitive costs. This has led to approaches that shift detection to wavelengths into the visible regime, where vastly superior silicon-based camera technology is available. Here, we experimentally show how nonlinear interferometry with entangled light can provide a powerful tool for mid-IR microscopy, while only requiring near-infrared detection with a standard CMOS camera. In this proof-of-principle implementation, we demonstrate intensity imaging over a broad wavelength range covering 3.4-4.3 µm and demonstrate a spatial resolution of 35 µm for images containing 650 resolved elements. Moreover, we demonstrate our technique is fit for purpose, acquiring microscopic images of biological tissue samples in the mid-IR (see Figure 1). These results open a new perspective for potential relevance of quantum imaging techniques in the life sciences.

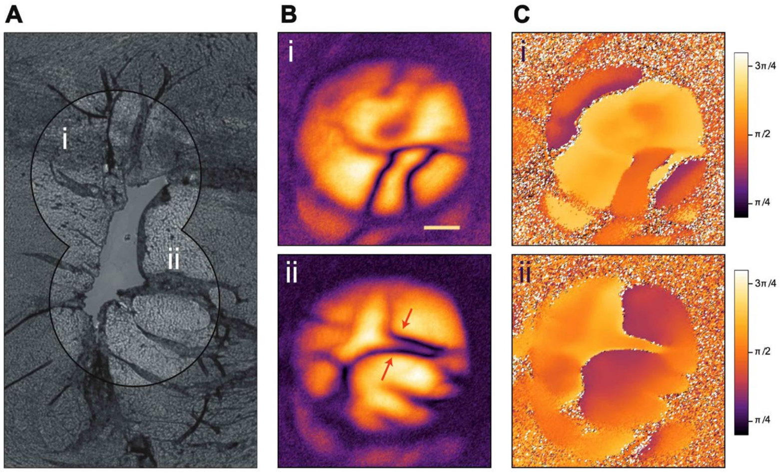

Figure 1. Bioimaging: Imaging of a histology sample of a mouse heart with (**A**) bright field microscopy, and absorption (**B**) and phase imaging (**C**) with mid-IR quantum light. Scale bar corresponds to 200μm.

Entanglement-enabled quantum holography

Hugo Defienne[1], Bienvenu Ndagano[1], Ashley Lyons[1] and Daniele Faccio[1]

[1] School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

Holography is a cornerstone characterisation technique that can be applied to the full electromagnetic spectrum, from X-rays to radio waves or even particles such as neutrons. The key property in all these holographic approaches is coherence that is required to extract the phase information through interference with a reference beam - without this, holography is not possible. Here we introduce a holographic imaging approach that operates on intrinsically incoherent beams, so that no phase information can be extracted from a classical interference measurement. Instead, the holographic information is encoded in the second order coherence of entangled states of light. Using spatial-polarisation hyper-entangled photons pairs, we remotely reconstruct phase images of complex objects. Information is encoded into a decoherence-free subspace of the entangled state, allowing us to image through dynamic phase disorder and even in the presence of strong classical noise, with enhanced spatial resolution compared to classical coherent holographic systems. Beyond imaging, quantum holography quantifies hyper-entanglement distributed over 10^4 modes via a spatially-resolved Clauser-Horne-Shimony-Holt inequality measurement, with applications in quantum state characterisation.

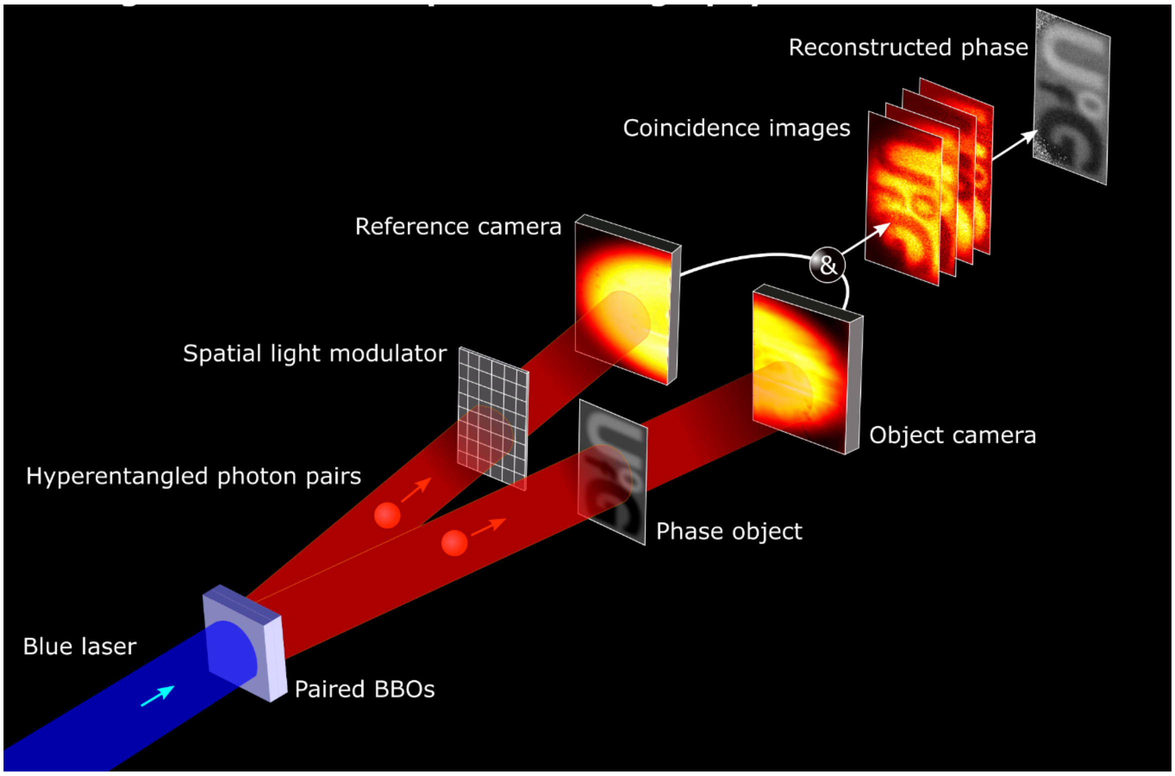

Figure 1: Simplified experimental setup of the quantum holographic system [1]. By exploiting spatial and polarization entanglement between photon pairs, the image of a phase object (UofG) may be reconstructed even if the light is totally incoherent (first order). Our protocol scheme achieves resolution-enhanced measurement of phase objects, including biological samples, through random phase disorder and stray light, with practical advantage over classical holography.

[1] Defienne, H., Ndagano, B., Lyons, A., & Faccio, D. (2019). Entanglement-enabled quantum holography. arXiv preprint arXiv:1911.01209.

T25 – Tuesday - 15:40 – Sanjukta Kundu

Self-referenced hologram of a single photon beam

Wiktor Szadowiak[1a], **Sanjukta Kundu[1a]**, Jerzy Szuniewicz[1], Radek lapkiewicz[1*]

[1] Institute of Experimental Physics, Faculty of Physics,
University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
[1a] These authors contributed equally to this work
[1*] radek.lapkiewicz@fuw.edu.pl

Complete quantitative characterization of the spatial structure of single photons is essential for free space quantum communication and for the efficient extraction of information from the light in quantum imaging. We introduce and experimentally demonstrate an interferometric technique[1] which enables characterization of a two-dimensional probability amplitude of a single photon without using a reference photon. Our setup comprises of a heralded single photon source with an unknown spatial phase and a modified Mach-Zehnder interferometer with a spatial filter in one of its arms. In contrast to methods[2] which use a reference photon for the phase measurement, our technique relies on a single photon interfering with itself. The spatial filter in one arm of our interferometer removes the unknown spatial phase and the filtered beam interferes with the unaltered beam passing through the other arm of the interferometer. We experimentally confirm the feasibility of our technique for heralded single photons, by reconstructing their spatial phase profile using the lowest order interference fringes. This technique can be applied to the characterization of arbitrary pure spatial states of single photons.

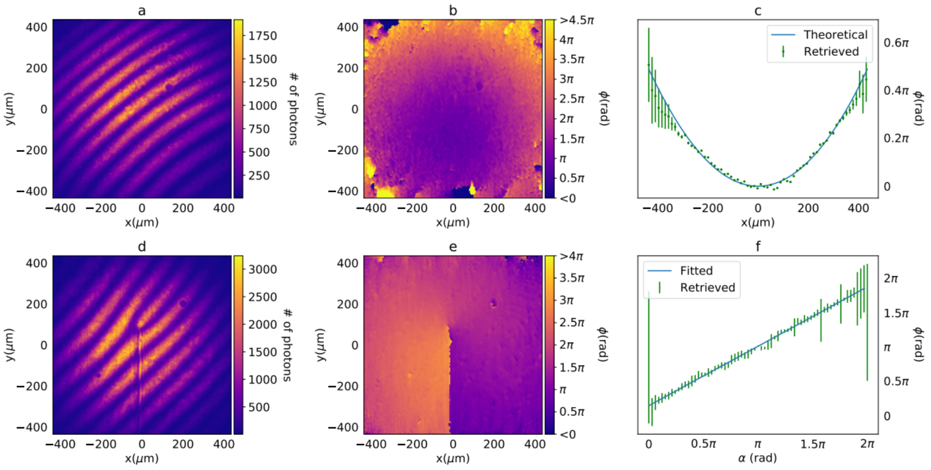

Figure 1: Results: (a) and (d) recorded interferograms for 2D quadratic and spiral phases respectively; (b) and (e) the corresponding reconstructed phases; (c) plots of the theoretical quadratic phase (blue solid line) and the reconstructed phase (dots) averaged over middle 50 columns of the plot in b with standard deviation in case of spherical phase mask applied (f) plots of the reconstructed phase in case of spiral phase mask with standard deviations versus the azimuthal angle α and a fitted linear function.

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T26 – Tuesday - 16:30 – Miles Padgett (invited)

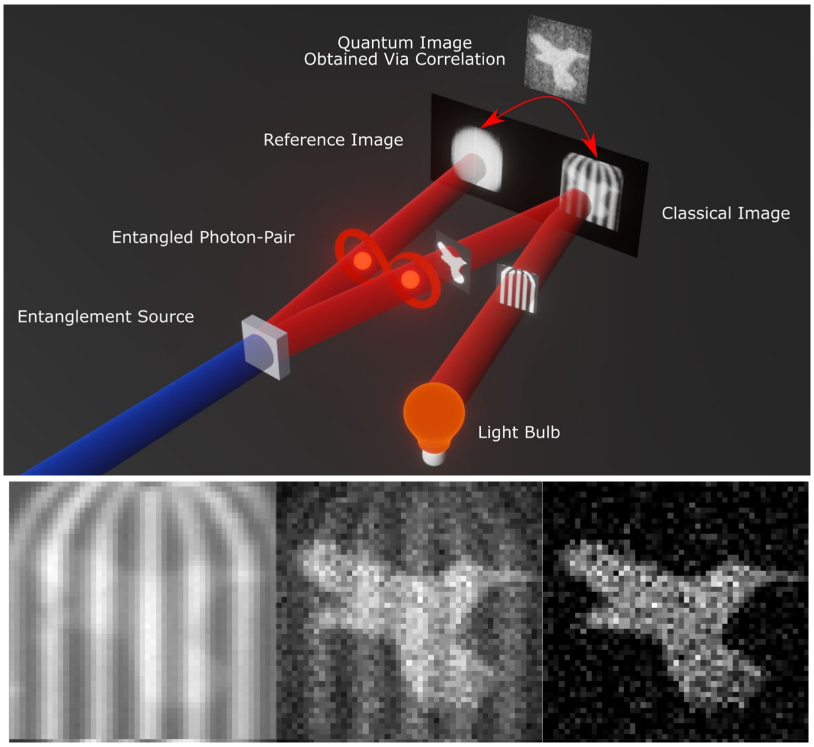
Noise and background light rejection using quantum illumination

T. Gregory, P.-A. Moreau, E. Toninelli, M. J. Padgett

School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

Both the contrast and signal to noise of an image can be degraded by the presence of background light and/or sensor noise. One approach to overcoming this degradation is through the use of a photon pair sources and the application of quantum illumination protocols [1]. We demonstrate a full-field imaging system using one such pair source and quantum illumination. Key to our approach is the use of an electron-multiplying CCD camera and appropriate processing of its analogue data output as a spatially resolved detection of photon pairs.

Importantly, the quantum illumination protocol differs from many quantum schemes in that the advantage is maintained even in the presence of noise and loss. We achieve a significant rejection of background light and an image contrast improvement, which is resilient to both a structured optical background and transmission losses. Our approach may enable laboratory-based quantum imaging to be applied to real-world applications where the suppression of background light and noise is important, such as imaging under low photon flux and quantum LIDAR.



All photon image   Joint detection image   Recovered image

Figure 1: Using entangled photons as probe and reference, their joint detection can be used to eliminate noise and background light from an image.

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[2] T. Gregory, P.-A. Moreau, E. Toninelli and M. J. Padgett, Imaging through noise with quantum illumination. Sci. Adv. 6, eaay2652 (2020).

T27 – Tuesday - 17:15 – Alessio Avella (invited)

Improving sub-shot-noise imaging and quantum ghost imaging

Alessio Avella [1], Elena Losero [1], Nigam Samantaray [2], Olga Sambataro [3], Alice Meda [1],
Ivano Ruo-Berchera [1] and Marco Genovese [1]

[1] INRIM, Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, Torino 10135, Italy
[2] Quantum Engineering Technology Labs, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1FD, United Kingdom
[3] Dipartimento di Fisica, Università degli Studi di Torino, Via P. Giuria 1, 10125 Torino, Italy

Sub-shot-noise quantum imaging, realized for the first time in 2010 [1], exploits quantum correlations to provide genuine quantum enhancement in realistic situations. In particular, a true and significant quantum enhanced sensitivity is extraordinarily important when it is necessary to image photosensitive systems using a small number of incident photons. Applications can involve many fields ranging from fundamental physics research to biology. In 2017, it was reported the first realization of a wide-field sub-shot noise microscope [2]. In 2020 we report a method allowing an optimisation of sub-shot-noise imaging protocol in order to significantly improve the resolution without giving up the quantum advantage in sensitivity [3]. Quantum correlations are a formidable tool also for enahncing the performance of ghost imaging in regime of low photon flux. A significant improvement has been obtained applying the differential ghost imaging protocol in the quantum regime [4].

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[2] N. Samantaray, I. Ruo-Berchera, A. Meda and M Genovese. Realization of the first sub-shot-noise wide field microscope. Light: Science & Applications volume 6, pagee17005(2017).
[3] I. Ruo-Berchera, A. Meda, E. Losero, A. Avella, N. Samantaray, and M. Genovese. Improving resolution-sensitivity trade off in sub-shot noise quantum imaging. Appl. Phys. Lett. 116, 214001 (2020).
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T28 – Tuesday - 18:00 – Anton Classen

Structured illumination quantum correlation microscopy

Anton Classen[1], Joachim von Zanthier[2], Girish S. Agarwal[1]

[1] Texas A&M University, College Station, Texas 77843, USA
[2] Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91052 Erlangen, Germany

We propose to use the antibunching feature of quantum emitters in conjunction with an intensity correlation analysis and structured illumination to achieve a spatial resolution in microscopy reaching far beyond the Rayleigh limit. Combining intensity measurements and intensity autocorrelations up to order m creates an effective PSF that is shrunk by the factor $\sqrt{m}$ [1,2]; or vice versa an OTF that is enlarged by the same factor [see the blue disks in Fig. 1(a)]. Structured illumination microscopy (SIM) [3], on the other hand, enhances the resolution by a factor of 2 through spatial frequency mixing; a principle well-known from moiré fringes. In Fourier space this corresponds to the additional Fourier components shown as green circles in Fig.1(a). Here, we show that for linear low-intensity excitation and linear optical detection, the simultaneous use of both techniques leads to an in theory unlimited resolution power, with the improvement scaling favorably as $m + \sqrt{m}$ [4], which is due to higher harmonics in the signals [red and black disks in Fig.1(a)] and enlarged OTFs. This yields the technique to be of interest for microscopy including imaging of biological samples. We present the theory, which applies both for 2D and 3D structured illumination (and other variants), and simulations that demonstrate the superresolution capability [Fig. 1(b)].

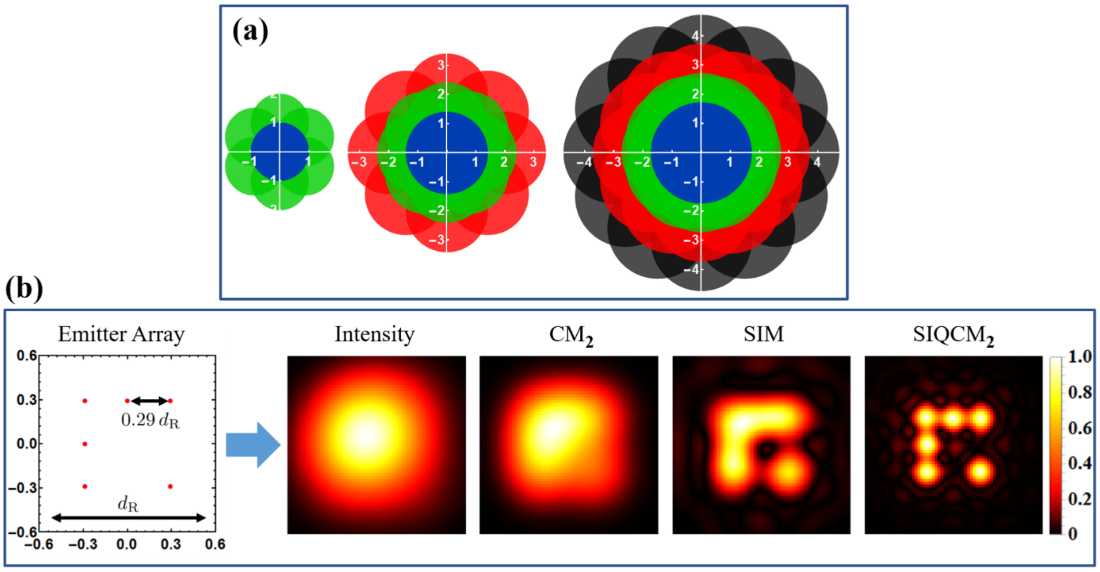

Figure 1: (a) OTF support of SIM, and SIQCM of second and third order. The central blue circle that represents the standard OTF is enlarged with rising correlation order m. (b) Emitter Array with a spacing of 0.29 times the Rayleigh limit d_R. The images show the simulation results for regular microscopy, (second-order) CM, SIM and (second-order) SIQCM.

[1] [1] T. Dertinger et al., PNAS 106, 22287 (2009)
[2] O. Schwartz et al., PRA 85, 033812 (2012)
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[4] A. Classen et al., Optica 4, 580 (2017)

T29 – Tuesday - 18:25 – Andrei Nomerotski

Multi-dimensional discrimination in quantum imaging

Andrei Nomerotski

Brookhaven National Laboratory, Upton NY 11973, USA

We describe multi-dimensional discrimination of signal and background in quantum imaging using an example of simple multivariate technique of likelihood ratios applied to quantum target detection. The technique combines two independent variables, time difference and summed energy, of a photon pair from the spontaneous parametric down-conversion source into an optimal discriminant. The discriminant performance was studied in experimental data and in Monte-Carlo modelling with clear improvement shown compared to previous techniques. As novel detectors with simultaneous access to spatial and temporal observables become available, we expect this type of multivariate analysis to become increasingly important in multi-dimensional quantum imaging. The optical camera used for the measurements, Tpx3Cam, is based on a technology originating in the high-energy physics that has been adapted for optical detection by bonding a fast readout chip to an optical sensor. A so-called data-driven readout, where only pixels with signal exceeding a threshold are read out, allows continuous operation and efficient time stamping with nanosecond resolution. By appending an image intensifier, the camera can be made to detect single photons, bringing a paradigm shift in quantum imaging devices. This analysis was performed on two-dimensional data but can be easily extended to higher dimensions.

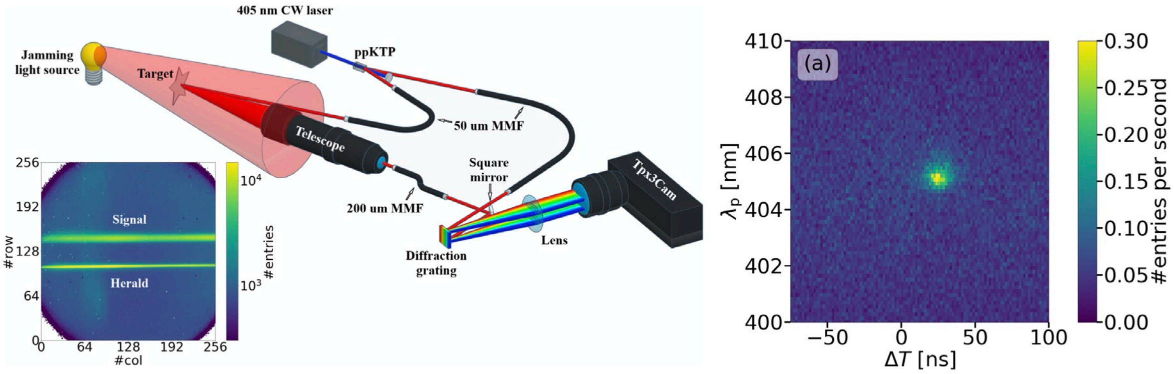

Figure 1: Left: Schematic view of the experimental setup. Inset: x, y distribution of pixel occupancy in the camera. Right: Two-dimensional distribution of spectroscopic and temporal variables in the data.

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[2] Multidimensional quantum-enhanced target detection via spectro-temporal correlations, Y.Zhang, D.England, A.Nomerotski, P.Svihra, S.Ferrante, P.Hockett, and B.Sussman, Phys. Rev. A 101, 053808 (**2020**).

[3] Counting of Hong-Ou-Mandel Bunched Optical Photons Using a Fast Pixel Camera, A.Nomerotski, M.Keach, P.Stankus, P.Svihra, and S.Vintskevich, *Sensors* **2020**, *20*, 3475.

[4] Fast camera spatial characterization of photonic polarization entanglement, Ianzano, C.; Svihra, P.; Flament, M.; Hardy, A.; Cui, G.; Nomerotski, A.; Figueroa, E., *Scientific Reports 10*. 6181 (**2020**).

[5] Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, A. Nomerotski, Nuclear Instruments and Methods Section A, 937, 26 (**2019**).

T30 – Wednesday - 9:00 – Xiaoying Li (invited)

Measuring multi-parameters beyond the standard quantum limit by using SU(1,1) interferometers

Xiaoying Li

College of Precision Instrument and Opto-Electronics Engineering, Key Laboratory of Opto-Electronics Information Technology, Ministry of Education, Tianjin University, Tianjin 300072, P. R. China

Heisenberg uncertainty relation in quantum mechanics sets the limit on the measurement precision of non-commuting observables in one system, which prevents us from measuring them accurately at the same time. With squeezed states, one can measure one observable more precisely than the standard quantum limit (SQL) at the expense of worse precision in the conjugate observable. In some applications, however, we need to obtain the information embedded in two or more non-commuting observables. For example, the real and imaginary parts of the linear susceptibility of an optical medium correspond respectively to the phase and amplitude modulation of an optical field passing through the medium. Quantum entanglement between two systems allows us to infer through Einstein-Podolsky-Rosen correlations two conjugate observables with precision better than SQL. Recently, a new type of nonlinear interferometers, called SU(1,1) interferometer (SUI), has attracted a lot of attentions. Different from the traditional interferometers, such as Mach-Zender interferometer, the SUI exploits optical parametric amplifiers (OPAs) for wave splitting and combination. The quantum behavior stems from the parametric amplifiers, which produce quantum entangled fields for probing the signals encoded in the interferometer. Moreover, this type of quantum entangled interferometer has the advantage over the traditional beam splitter-based interferometer in the sense that it is less sensitive to the losses outside the interferometer. Moreover, this type of quantum entangled interferometer has the advantage over the traditional beam splitter-based interferometer in the sense that it is less sensitive to the losses outside the interferometer such as propagation loss and detection loss.

In this talk, we describe the noise performance of SUI in the high gain regime and demonstrate its application in multi-parameter measurement [1]. When the signals are encoded in non-commuting observables of one optical field in SUI, the sensitivity can beat the SQL in the joint measurement of multiple non-commuting observables, including the phase and amplitude as well as an arbitrarily rotated quadrature-phase amplitude [2]. Moreover, we analyze the precision limits for a simultaneous estimation of a pair of conjugate parameters in a displacement channel using Gaussian probes and find precision bounds, which reveal the optimal measurement scheme and allows us to quantify the best precision for one parameter when the precision of the second conjugate parameter is fixed [3]. According to the interesting effect of resource partition in the joint measurement of two orthogonal observables, we construct a dual-beam sensing SUI to devote all the quantum resource to phase measurement only. The results show that comparing with the SUI with one beam function as the sensing field, the SUI with dual beam sensing can achieve another 3 dB improvement in phase measurement.

[1] J. Li, Y. Liu, L. Cui, N. Huo, Syed M. Assad, X. Li* and Z. Y. Ou, “Joint measurement of multiple noncommuting parameters,” Phys. Rev. A, 97(5), 052127 (2018)
[2] Y. Liu, J. Li, L. Cui, N. Huo, S.M. Assad, X. Li and Z. Y. Ou, “Loss-tolerant quantum dense metrology with SU(1,1) interferometer,” Opt. Express, 26(21), 27705 (2018)
[3] S. M. Assad, J. Li, Y. Liu, N. Zhao, W. Zhao, P. K. Lam, Z. Y. Ou and X. Li, “Accessible precisions for estimating two conjugate parameters using Gaussian probes,” Phys. Rev. Research, 2(2), 023182 (2020)

Stimulated emission tomography for entangled photon pairs with different detection spectral range

Yiquan Yang, Peiyu Zhang, and Xiao-song Ma

National Laboratory of Solid State Microstructures, School of Physics and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing, China

Frequency non-degenerate entangled photon pairs have been employed in quantum communication, imaging, and sensing. To characterize quantum entangled state with long-wavelength (infrared, IR or even terahertz, THz) photon, one needs to either develop the single-photon detectors at the corresponding wavelengths or use novel tomography technique, which does not rely on single-photon detections, such as stimulated emission tomography (SET). We use standard quantum state tomography and SET to measure the density matrix of entangled photon pairs, with one photon at 1550 nm and the other one at 810 nm, and obtain highly consistent results, showing the reliability of SET. Our work paves the way for efficient measurement of entangled photons with highly dissimilar frequencies, even to the frequencies where single-photon detections are not available [1].

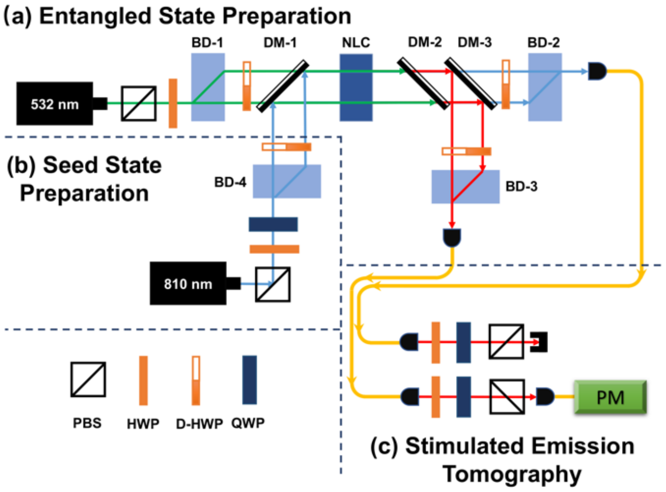

Figure 1: Schematic of the experimental setup for stimulated emission tomography (SET). Three modules include (a) entangled state preparation, (b) seed state preparation and (c) stimulated emission tomography.

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T32 – Wednesday - 10:00 – Joachim von Zanthier (invited)

Quantum imaging with incoherently scattered x-rays from a free-electron laser

J. von Zanthier[1,2,3]

[1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

[2]Erlangen Graduate School in Advanced Optical Technologies, Universität Erlangen-Nürnberg, Germany

[3]International Max Planck Research School-Physics of Light, MPI for the Science of Light, Erlangen, Germany

For more than 100 years, x-rays have been used in crystallography to determine the structure of crystals and molecules utilizing coherent diffraction methods. With the advent of accelerator-driven free-electron lasers (FEL) new avenues for high-resolution structure determination are explored that go even beyond conventional x-ray crystallography [1-3]. Yet, all of these techniques rely on coherent scattering, whereas incoherence due to fluorescence emission or wave front distortion is considered detrimental for these approaches. Here we show that with methods from quantum optics, i.e., by exploiting higher order photon correlation functions, the full 3D arrangement of sources can be resolved that scatter incoherent radiation [4-8]. We discuss a number of properties of the incoherent diffraction imaging methods that are conceptually superior to those of conventional coherent x-ray structure determination and point out that current FELs are ideally suited for the implementation of these approaches [7]. We also present an experimental demonstration in the soft x-ray domain, where we used higher-order photon correlation functions to achieve higher fidelities in the image reconstruction and potentially sub-Abbe resolution [8].

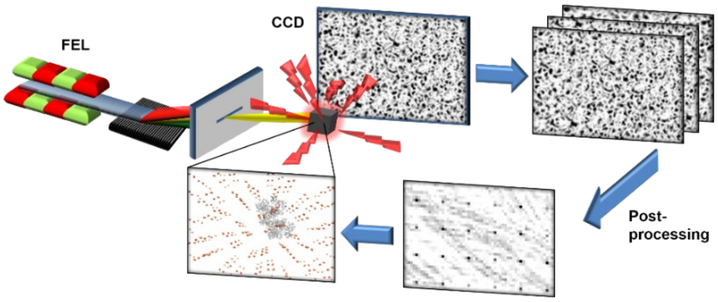

Figure 1: Illustration of incoherent diffraction imaging: A large number of diffraction snapshots of incoherent X-rays scattered by a 3D source arrangement is recorded by a CCD; the photon correlations of each snapshot are determined individually; averaging over many snapshots leads to a pattern that yields the initial 3D distribution of the sources.

[1] H. N. Chapman et al., Nature Phys. 2, 839 (2006).
[2] H. N. Chapman et al., Nature 470, 73 (2011).
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[4] C. Thiel, T. Bastin, J. Martin, E. Solano, J. von Zanthier, G. S. Agarwal, Rev. Lett. 99, 133603 (2007).
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T33 – Wednesday - 10:40 – Falk Eilenberger

Enhancing tests of quantum theories with single photons from 2D materials

Tobias Vogl[1,2], Ping Koy Lam[3], and Falk Eilenberger[1,3,4]

[1] Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, 07745 Jena, Germany
[2] Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom
[3] Centre for Quantum Computation and Communication Technology, Department of Quantum Science, Research School of Physics and Engineering, The Australian National University, Acton ACT 2601, Australia
[4] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str 7, 07745 Jena, Germany
[4] Max Planck School of Photonics, Albert-Einstein-Str. 6, 07745 Jena, Germany

Some the basic principles of quantum physics, like Born's rule, are based exclusively on postulates without the necessity for them to be true for the framework of quantum mechanics to work. The validity of Born's rules must thus be tested experimentally. Any deviation from Born's rule would result in higher-order interference [1], which we test for, using a three-path interferometer.

Here we demonstrate and experimentally verify that a highly integrated single photon source, based on a color center in hexagonal boron nitride (hBN) coupled to a microcavity [2,3], leads to superior measurement accuracy in such a three-path interferometer, if compared to a coherent light source. We show that in a real-world system, the enhanced measurement accuracy is true for both the low-power regime, were quantum noise dominates, as well as, for high-power regimes, where systematic instrument errors dominate.

Irrespective of the specific science case behind our interferometer, we therefore argue that for a wide class of interferometric sensing problems our work indicates, that quantum states of light can be a bona-fide path towards enhanced sensitivity and reduced noise.

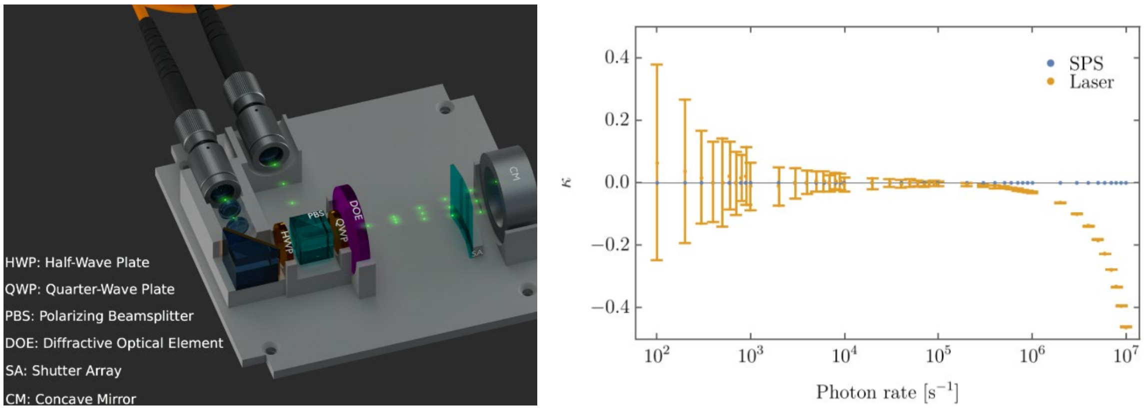

Figure 1: (left) Artists impression of the three-path interferometer used to detect possible deviations from Born's rule. (right) Measurement of the relative strength of third order interference κ as function of the photons rate for (brown) a coherent laser source and (blue) an ideal single photon source.

[1] R. D. Sorkin, Mod. Phys. Lett. A 9, 3119 (1994).
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T34 – Wednesday - 11:25 – Evangelia Bisketzki

Fundamental limits of quantum spectroscopy

Evangelia Bisketzi, Animesh Datta

Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom

Quantum spectroscopy is a newly emerging field in which the quantum nature of light is exploited to reveal information about the properties of matter. It has been shown that entangled light has an intensity scaling which allows to perform spectroscopy with lower photon fluxes [1] and allows photon coincidence counting as a new measurement tool [2]. In this work we quantify the advantage of quantum versus the classical light in spectroscopy by using the techniques of Quantum Estimation Theory (QET). We obtain the ultimate precision limit in the parameters of matter that we are interested in estimating, such as the dipole moment of the atoms, their lifetimes or the interatomic couplings. QET also enables us to compare the performance of different states of light. This allows us to choose the light that will reveal the most information when probing the matter. Furthermore, using QET we can compare the precision which different measurement techniques can achieve with the fundamental quantum limit. Hence, it allows the identification of the best current measuring scheme and it will motivate the search for better detection systems that can achieve the ultimate precision.

[1] S. Mukamel et al, “Roadmap on quantum light spectroscopy” J. Phys. B: At. Mol. Opt. Phys.53 072002 (2020).
[2] A. Yabushita, T. Kobayashi, “Spectroscopy by frequency-entangled photon pairs”, Phys Rev A 69, 013806 (2004)

T35 – Wednesday - 11:50 – Aiman Khan

Probing Dynamical Complexity of Diverse Quantum Systems

Aiman Khan , Max Marcus and Animesh Datta

Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom

For an arbitrary quantum system evolving via the action of a time independent Hamiltonian Hˆ0 interrupted by finite, well-separated perturbations Vˆi(t), such that [Hˆ0, Vˆi(t)] = 0, we show that an adapted time-series analysis, originally proposed in [3], can be used to infer the dimension of Hilbert space in which the Hˆ0-dynamics happen. We further show that this model-independent witness of quantum dimension can be interpreted as a measure of simulation complexity for general open system dynamics, via a singular spectrum-like analysis that we then use to investigate simulated and actual frequency-integrated data from polarization controlled pump-probe experiments performed on the allophycocyanin (APC) dimer [1] and Fenna-Matthews-Olsen (FMO) complex [2] respectively. For the former, such an analysis, using the third-order pump-probe spectroscopic signal as the elemental quantity of the time series, yields the dimension of the singly excited manifold (SEM), reinforcing the notion that such a setup probes SEM dynamics only. For the latter, we find that the experimental signal corresponding to a sequence of four pulses with parallel polarizations yields a smaller average numerical complexity than that generated using a sequence of two perpendicularly-polarized pairs, broadly showing that the first configuration of pulses produces a signal that is dominated by intramolecular vibrations whereas the signal resulting from the second configuration corresponds to the cross-pigment dynamics that happen in a larger Hilbert space.

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[2] E. Thyrhaug, R. Tempelaar, M. J. Alcocer, K. Zˇ´ıdek, D. B´ına, J. Knoester, T. L. Jansen, and D. Zigmantas. Identification and characterization of di- verse coherences in the fenna–matthews–olson complex. Nature Chemistry, 10(7):780–786, 2018.
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T36 – Wednesday - 12:10 – Radek Lapkiewicz

Quantum-classical imaging: a report of a cross-border worker

Radek Lapkiewicz

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

Single fluorescent emitters in biological samples are probably the most common sources of quantum light. Nevertheless, their quantum optical properties are rarely exploited. I will discuss how fluorescence microscopy can benefit from measurements of quantum correlations. Such measurements allowed counting emitters within a diffraction-limited spot [1] and enhancing the resolution of classical super-resolution methods further beyond the diffraction limit, as in the case of recently introduced Quantum Image Scanning Microscopy (QISM) [2].

We found that the classical analog of QISM relying on classical light correlations offers a higher SNR at short measurement times and is less demanding experimentally. This method, termed Super-resolution optical fluctuation image scanning microscopy (SOFISM) [3], exploits fluorescent emitter blinking as its image contrast. SOFISM offers a robust path to achieve high-resolution images with a slightly modified confocal microscope, using standard fluorescent labels and reasonable acquisition times.

I will describe one more classical analog of a quantum optical experiment that can be used for imaging. Building on the idea of two-photon interference for single-photon wavefront measurement [4], we introduced an interferometric method of phase imaging, which is resistant to phase noise [5]. Although it does not involve quantum two-photon interference, it accesses information present only in intensity correlations.

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T37 – Wednesday - 12:35 – Markus Gräfe

Digital Phase Shift Holography With Undetected Photons

Sebastian Töpfer[1], Marta Gilaberte Basset, and Markus Gräfe[1,2]

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

Optical imaging is one of the major tools for making observations in life sciences, ranging from fundamental research towards diagnostics. In doing so, due to absorption and scattering it can be rather challenging to obtain an image with sufficient contrast of a specimen, in particular when considering *in vivo* cells. Hence, an elaborate treatment with contrast agents becomes necessary [1]. An expedient to this situation is by exploiting the objects phase for visualization. Here, holography is a common approach now. In detail, digital phase shift holography allows to reconstruct the three-dimensional distribution of both, amplitude and phase of a specimen [2].

Apart from classical approaches quantum-inspired sensing techniques allow new imaging capabilities. One prominent example is "imaging with undetected photons" which allows to illuminate an object with light of one wavelength and to record its image on a camera at another wavelength [3]. Naturally, both spectrally different beams are correlated to each other. This can be achieved, e.g., by using signal and idler beams from a parametric down conversion process.

In this work we present the combination of both approaches described above. We successfully implement the digital phase shift holography technique in an imaging setup "with undetected photons". We experimentally verify its feasibility on both, amplitude and phase objects.

This paves the way towards more efficient quantum imaging devices. It simplifies the measurement of amplitude and phase objects at maximum contrast.

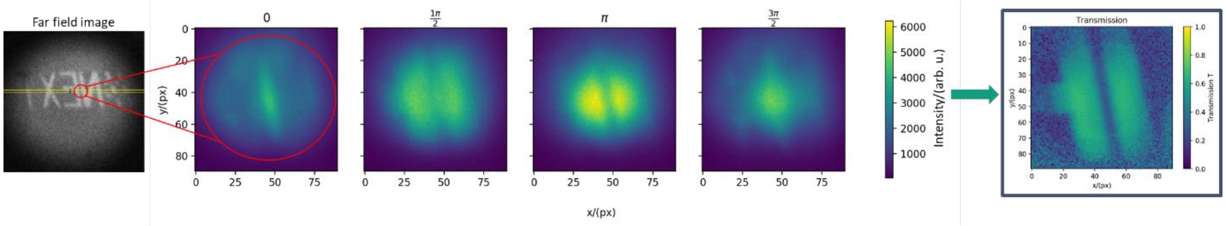

Figure 1: This false-color image from a nonlinear interferometer. The first image shows the far field ("#NEXT" upside down). The following four images show the enlarged region (marked with a red circle) for different phase settings. The last image on the right show the reconstructed digital phase shift holography image.

[1] Popescu, Quantitative phase imaging of cells and tissues, McGraw-Hill (2011).
[2] Yamaguchi and Zhang, Optics Lett. **22**, 1268 (1997).
[3] Lemos et al., Nature **512**, 409 (2014).

See you again next year!

What: WE-Heraeus-Seminar “Sensing with Quantum Light” SQL21

When: September 26 – 29, 2021

Where: Physikzentrum Bad Honnef

Information available at:

https://www.we-heraeus-stiftung.de/veranstaltungen/seminare/2021/sensing-with-quantum-light/main/

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